Climate and Hydrology Datasets for RMJOC Long-Term Planning Studies: Second Edition (RMJOC-II)

Part II: Columbia River Reservoir Regulation and Operations—Modeling and Analyses

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River Management Joint Operating Committee (RMJOC)

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Cover photo: Grand Coulee Dam includes three major hydroelectric power-generating plants and the John W. Keys III Pump-Generating Plant. The facilities provide power generation, irrigation, flood risk management, and streamflow regulation for fish migration. Additional incidental benefits include providing flows for navigation and recreation. Image source: https://media.defense.gov/2019/Apr/21/2002118949/-1/-1/0/161118-A-A1408-021.JPG

Abbreviations, Acronyms, and Terminology

2010L	2010 Level
AOP	Assured Operating Plan
BC Hydro	British Columbia Hydro and Power Authority
BC	British Columbia
BCSD	Bias-Corrected Spatial Disaggregation
BECC	Base Energy Content Curve
BPA	Bonneville Power Administration
CanESM-2	Canadian Earth System Model v2
CCSM4	Community Climate Systems Model v4
cfs	Cubic Feet per Second
CMA	Centered Moving Average
CMIP-5	Coupled Model Intercomparision Project Phase 5
CNRM-CM5	Centre National de Recherches Météorologiques v5
CRD	Columbia River Datum
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation Mk3.6.0 Climate Model
DOP	Detailed Operating Plan
ECC	Energy Content Curve
EOM	End of Month
ESP	Ensemble Streamflow Predictions
FCRPS	Federal Columbia River Power System
FOM	First of Month
FRM	Flood Risk Management
GCM	Global Climate Model (also known as General Circulation Models)
HadGEM2-CC	Hadley Centre Global Environmental Model v2 – Carbon Cycle
HadGEM2-ES	Hadley Centre Global Environmental Model v2 – Earth System
HEC	Hydrologic Engineering Center
HRFCPPA	Hanford Reach Fall Chinook Protection Program Agreement
HYDSIM	Hydrosystem simulation program
ICF	Initial Control Flow
IJC	International Joint Commission
inmcm4	Institute of Numerical Mathematics Climate Model v4
IPSL-CM5-MR	Institut Pierre Simon Laplace Climate Model v5 – Medium Res.
kcfs	Thousand Cubic Feet per Second
M&I	Municipal and Industrial
MACA	Multivariate Adaptive Constructed Analog
Maf	Million Acre Feet

MFL	Modified Flow-Like
MIROC5	Model for Interdisciplinary Research On Climate v5
MW	Megawatts
NGVD29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
NRNI	No Regulation No Irrigation
OPER	Operational model
OSU	Oregon State University
PNCA	Pacific Northwest Coordination Agreement
PRMS	Precipitation Runoff Modeling System
PUD	Public Utility Department
RAS	River Analysis System
RCP	Representative Concentration Pathway
Reclamation	U.S. Bureau of Reclamation
ResSim	Reservoir System Simulation
RMJOC	River Management Joint Operating Committee
RMJOC-I	First Edition: Climate and Hydrology Datasets for Long Range Planning (Published in 2010–11)
RMJOC-II	Second Edition: Climate and Hydrology Datasets for RMJOC Long-Term Planning Studies
RVIC	Routing Variable Infiltration Capacity
SRD	Storage Reservation Diagram
SSARR	Streamflow Synthesis and Reservoir Regulation
SWE	Snow Water Equivalent
TDG	Total Dissolved Gas
TSR	Treaty Storage Regulation
URC	Upper Rule Curve
USACE	U.S. Army Corps of Engineers
USGCRP	U.S. Global Change Research Program
UW	University of Washington
VDL	Variable Draft Limit
VECC	Variable Energy Content Curve
VIC	Variable Infiltration Capacity
WAT	Watershed Analysis Tool
WY	Water Year

Water Management Terminology

Columbia River Treaty	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.
Draft	When the rate of outflow of a reservoir is greater than the rate of inflow. This reduces the amount of stored water, lowering reservoir water-surface elevation. The most common reservoir drafts include releasing stored water in anticipation of future flood events to store inflows or to augment downstream flows.
Ensemble	A large group of model simulations often statiscially described as a group as opposed to individual simulations.
Firm Energy	
Guide Curve	A pattern of reservoir elevation reflecting operational objectives. Reservoirs outflows are adjusted to maintain this elevation pattern.
Hydroregulation	Routing of inflow through a series of reservoirs, altering natural river flow patterns.
Pool	Water stored behind a dam.
Project	A dam that is operated to meet hydroregulation objectives, such as hydrogeneration, flood risk reduction, navigation, water conservation, ecosystem, etc.
Refill	When the rate of outflow of a reservoir is managed to be less than the rate of inflow. This increases the amount of stored water, increasing the reservoir water-surface elevation. Reservoirs are commonly refilled to store inflow to reduce downstream flooding or to store water for other purposes later in the water year.
Run-of-River	Projects that have minimal to no reservoir storage. They are operated so that regulated outflow equals inflow
Rule Curves	Seasonal reservoir content curves that determines the timing of water releases and reservoir storage to achieve multiple operating objectives.
Spill	Dam outflow that is not released through hydropower turbines.
Water Supply Forecast	Seasonal prediction of the volume of water anticipated to flow through a location in the river network over a discrete time period. For example, water supply forecasts in the Columbia River Basin include prediction of the volume of streamflow from April to August. These are commonly monthly forecasts.
Water Year	A 12-month period used in hydrological analysis for which hydrological variables are annualized. In this report, *water year* refers to the period from October 1 through September 30.

Table of Contents

List of Tables

List of Figures

Preface

The overarching objective of the River Management Joint Operating Committee (RMJOC), which is composed of staff from the Bonneville Power Administration (BPA), the U.S. Army Corps of Engineers (USACE), and the U.S. Bureau of Reclamation (Reclamation), is to continuously evaluate and anticipate vulnerabilities, risk, and resiliency of the Federal Columbia River Power System (FCRPS). Assessments that RMJOC conducts include potential future changes to hydropower generation and reliability; flood risk management (FRM); water supply for irrigation, municipal, and industrial uses; recreation; cultural resources; fish; navigation; and functioning of the ecological system. Future conditions, including changes to the regional hydroclimatology, can challenge the purposes of the Columbia River reservoir system. A priority of RMJOC is to identify and anticipate the impacts of these changes in regional hydroclimatology to infrastructure and system objectives, regardless of what is driving the changes. This objective motivated RMJOC to work with the research community to update and improve the first climate change study, completed in 2009–2011.

This is the second report on projected climate change and hydroregulation effects in the Columbia River Basin. The report focuses on assessments related to flood risk management, hydropower generation, and water supply deliveries. These provide context for regional stakeholders as to how resilient the current operations of the reservoir system will be under a range of future hydrological conditions. This work represents novel developments to assess the effects of climate change on large reservoir systems. This report provides not only targeted benefits for long-term planning within the Columbia River Basin but also more general approaches and lessons learned for impact assessment of large, multipurpose reservoir systems.

Executive Summary

In 2013, the River Management Joint Operating Committee (RMJOC) commissioned a research team from the University of Washington and Oregon State University to develop a set of projections of natural streamflow from the latest Coupled Model Intercomparison Project Phase 5 (CMIP-5) Global Climate Model (GCM) projections. The team produced 172 projections of future weather and natural streamflows as documented in RMJOC-II *Part I: Hydroclimate Projections and Analyses* (RMJOC 2018).

The next step in the RMJOC-II study was to use the dataset of future projections with a set of reservoir operation models to evaluate the resilience and vulnerabilities of the Federal Columbia River Power System (FCRPS). The models were applied to reflect the current operating criteria of the reservoir system. Therefore, we did not modify the operational criteria, rule curves, or operating procedures to ameliorate the effects of climate change on meeting system objectives.

This study evaluated two future epochs and a historical baseline period. These epochs represent 30-year periods, centered on the reference decade. The baseline 30-year period represents historical conditions for water years (WYs) 1976 through 2005, the most recent 30 years in the historical datasets. The 2030s period is WYs 2020 through 2049; and the 2070s is WYs 2060 through 2089. The RMJOC agencies assessed potential changes in future conditions through comparative analyses between historical and future simulated water-surface elevations and regulated river flows.

The FCRPS operations and purposes they serve vary seasonally. The effects of climate change on streamflow patterns could have significant implications for seasonal operations. In the fall, winter, and spring, storage projects are operated to provide sufficient space for flood risk management, to meet power demand, and to provide flows for fish. Inflows in summer months are critical for meeting hydropower generation requirements along with managing flows for fish. Navigation, recreation, and irrigation are also dependent on summer flow volumes. As the seasonality of streamflow shifts to earlier in the year, meeting the system objectives that have seasonal dependence on flow volumes will become more challenging.

The RMJOC-II modeling and datasets identify potential consequences of climate change on meeting objectives of the Columbia River reservoir system under current operating criteria and highlight which current operations may be stressed under future hydrology. These analyses set the foundation for future work in identifying operational mechanisms and approaches to adaptively manage system operations to mitigate these consequences. A summary of this report’s significant findings is outlined below.

Flood Risk Management

- The spring snowmelt runoff is projected to peak at The Dalles approximately two weeks earlier for the 2030s and about a month earlier for the 2070s. Winter precipitation is very likely to increase and, due to warming temperatures, to result in increased rainfall runoff and less snow accumulation. The future projections indicate a potential overall increase in flood risk in the Columbia River Basin for both spring (April–May) and winter (November–March) flood events under current operating criteria.

- Identified shifts in runoff volume timing and variability in the spring could stress the reservoir system. Regulated spring high-flow events for the Lower Columbia River are projected to be similar to the historical baseline in the 2030s and increase modestly in the 2070s. Modeling outcomes of spring runoff also show increased local flood risk at other locations in the Columbia Basin. Bonners Ferry on the Kootenai River below Libby Dam, Columbia Falls on the Flathead River below Hungry Horse Dam, and Spalding on the Clearwater River below Dworshak show increasing flood risk in the 2030s and 2070s.
- The greatest identified change in future flood risk is from increased winter flood volumes throughout the Columbia Basin. The effect is most notable in the lower Columbia River. Projected increases in winter flood risk are primarily linked to increasing flows from the Columbia main stem. Projected increases in inflow from the Willamette River during winter events further exacerbate this increase in flooding.
- Increasing flood risk can be partially attributed to hydrological changes that differ from the historical hydrological characteristics that the system was designed for. That is, the current system operations for flood risk management (FRM) are not designed for the projected future hydroclimate of the basin. However, while changes to reservoir operating policies via adaptive management may partially ameliorate the climate effects, changes to operations are not anticipated to fully offset potential increases in flood risk.

Hydropower

- Projected increases in regulated streamflow during the winter and early spring increase the potential for hydropower generation for both the federal and the U.S. systems. Modeling results from a subset of 19 climate change projections used for the hydropower analysis show that between November and May, the monthly generation could substantially increase in both the 2030s and the 2070s.
- Projected decreases in regulated streamflow from June to October result in less modeled generation in both the federal and U.S. systems as compared to the historic baselines. During these months, modeling results from the subset of 19 climate change projections used for the hydropower analysis show that generation could decrease significantly in both the 2030s and the 2070s.
- The annual average generation for both the federal and U.S. systems are projected to increase in both the 2030s and 2070s as compared to the historical baselines. Depending on the probabilities compared, the federal system is projected to increase by as much as 500 MW for the 2030s and 850 MW for the 2070s. Although not fully modeled, the U.S. system shows a potential maximum increase of about 750 MW for the 2030s and 1100 MW for the 2070s. Future studies will need to be conducted to determine if future load demand, market conditions, and adaptive reservoir management practices will allow for these generation benefits to be realized and to ameliorate the projected critical decrease in generation in the summer and fall.
- Spill in the federal system increases substantially during the winter months, January–March, for both the 2030s and 2070s in the subset of 19 climate change projections used for hydropower modeling. This increase continues into the spring months of April and May

before tapering off in June for both epochs. The spill outlook changes in the summer, July–August, as the spill drops slightly for each month due to lower regulated flows in the summer throughout most of the basin.

- Projected increases in regulated streamflow during the winter and early spring in the subset of 19 climate change projections used for hydropower modeling increase the potential for a higher degree of operational flexibility for hydropower operations at Grand Coulee for both the 2030s and 2070s. The increased flexibility can be attributed to a combination of increased regulated inflows to Grand Coulee and a modeling trend showing less constrained fishery flow operations at Vernita Bar below Priest Rapids Dam and below Bonneville Dam for chum protection.
- The operational flexibility at Grand Coulee decreases in late summer and fall for both the 2030s and 2070s as compared with the historical baseline. By the 2070s, hydropower modeling of the subset of 19 projections suggests that Grand Coulee could draft below the end-of-September modeling target to help sustain minimum flows in the lower Columbia River. This limits the ability to use storage in the reservoir to manage regional power needs. This also occurs in October but to a much lesser degree.

Biological

- The projections indicate increased spring regulated flow volumes in the 2030s and the 2070s. The frequency of meeting spring fish- and habitat-based flow objectives is projected to increase.
- The projections indicate declines in regulated flow volumes in late summer in the 2030s and the 2070s. Meeting biological flow targets will likely be more difficult in the summertime, increasing the reliance on stored water, particularly in the tributary basins.
- Fish passage spill at the federal projects in the Lower Snake and Lower Columbia increases during the spring months, April and May, for both the 2030s and 2070s in the subset of 19 climate change projections. The spill outlook changes, however, in the summer, June–August, as the spill drops for each month for both the 2030s and 2070s. This is due to lower regulated flows in the summer throughout most of the basin.
- Projected increases in streamflow from November to April result in an increased ability to provide the minimum flow requirements for chum spawning below Bonneville Dam.
- Increased streamflow from November to April also lowers the likelihood of missing the April 10 elevation target at Grand Coulee to support minimum flows at Vernita Bar.
- Lower streamflow in September to October increases the likelihood of drafting Grand Coulee below modeling elevation targets to support downstream navigation requirements. The decrease in reservoir elevations in September and October will impact resident fish, specifically tributary access and shoreline spawning in Lake Roosevelt.

Navigation

- When Bonneville Dam outflow falls below 80 kcfs (thousand cubic feet per second), navigation in the Lower Columbia River is adversely affected. The projections indicate an increased likelihood of flows below this threshold from August to October. Water stored in Lake Roosevelt is projected to be released more frequently to maintain minimum outflows at Bonneville Dam.

Irrigation

- Many of the projections indicate lower summer (June–September) unregulated flows, particularly in the tributaries where water supply is already limited. All modeled projections indicate decreased deliveries of live flow and increased deliveries of stored water for irrigation in the 2030s and 2070s.
- The projections indicate earlier runoff and FRM draft requirements could lead to higher elevations of Lake Roosevelt during April and May. This could make water delivery to the Columbia Basin Project via pumps from Lake Roosevelt to Banks Lake more reliable.

1.0 Introduction

1.1 Background

The River Management Joint Operating Committee (RMJOC) is a subcommittee of the Joint Operating Committee and was established through direct funding Memorandum of Agreements between the Bonneville Power Administration (BPA), the U.S. Army Corps of Engineers (USACE), and the U.S. Bureau of Reclamation (Reclamation). 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 (FCRPS)[1] projects. In addition, RMJOC works to evaluate and anticipate vulnerabilities and risks to the FCRPS from potential future changes to the characteristics and nature of the region's hydroclimate.

In 2013, RMJOC commissioned a research team from the University of Washington (UW) and Oregon State University (OSU) to develop a set of natural streamflow[2] datasets from the latest global climate model projections of the Coupled Model Intercomparison Project Phase 5 (CMIP-5). The intent of this development was to provide the RMJOC agencies with state-of-the-science climate modeling that incorporates future temperature and precipitation projections and, ultimately, streamflow datasets that agencies could use for regional planning and adaptability studies. In 2018, upon completion of this portion of the study, the process and approach for developing these climate change datasets, as well as the resulting products, were documented in the *RMJOC-II Part I: Hydroclimate Projections and Analyses* report (RMJOC 2018).

1.2 Objective

The next step in the RMJOC-II study was to use these streamflow datasets with several FCRPS reservoir models to evaluate the resilience and vulnerabilities of the Columbia River reservoir system (**Figure 1**). The models reflect the current operational state of the Columbia River reservoir system, applying no modifications to the procedures and modeling process that would address changes in hydrology. Under this premise, the resulting modeled flows and reservoir storage represent a condition without intervention for changing conditions. Identifying the effects of climate change under the current operating condition is the first step in developing an understanding on which components of the current operations will require adaptation to continue to serve the purposes of the system. This report, *Part II: Reservoir Regulation and Operations—Modeling and Analyses*, documents the approach to reservoir operations modeling of the FCRPS, the results of that modeling, and the potential impacts of climate change on the reservoir system and the many purposes it serves.

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[1] FCRPS: The hydroelectric multipurpose facilities constructed and operated by USACE and Reclamation in the Pacific Northwest. This includes the transmission system constructed and operated by BPA to market and deliver electric power, whose costs are funded and repaid through BPA power and transmission rates.

[2] Natural streamflows are streamflows without the effects of dam construction and operations, irrigation withdrawals and returns, and other development that changed the natural flow regime.

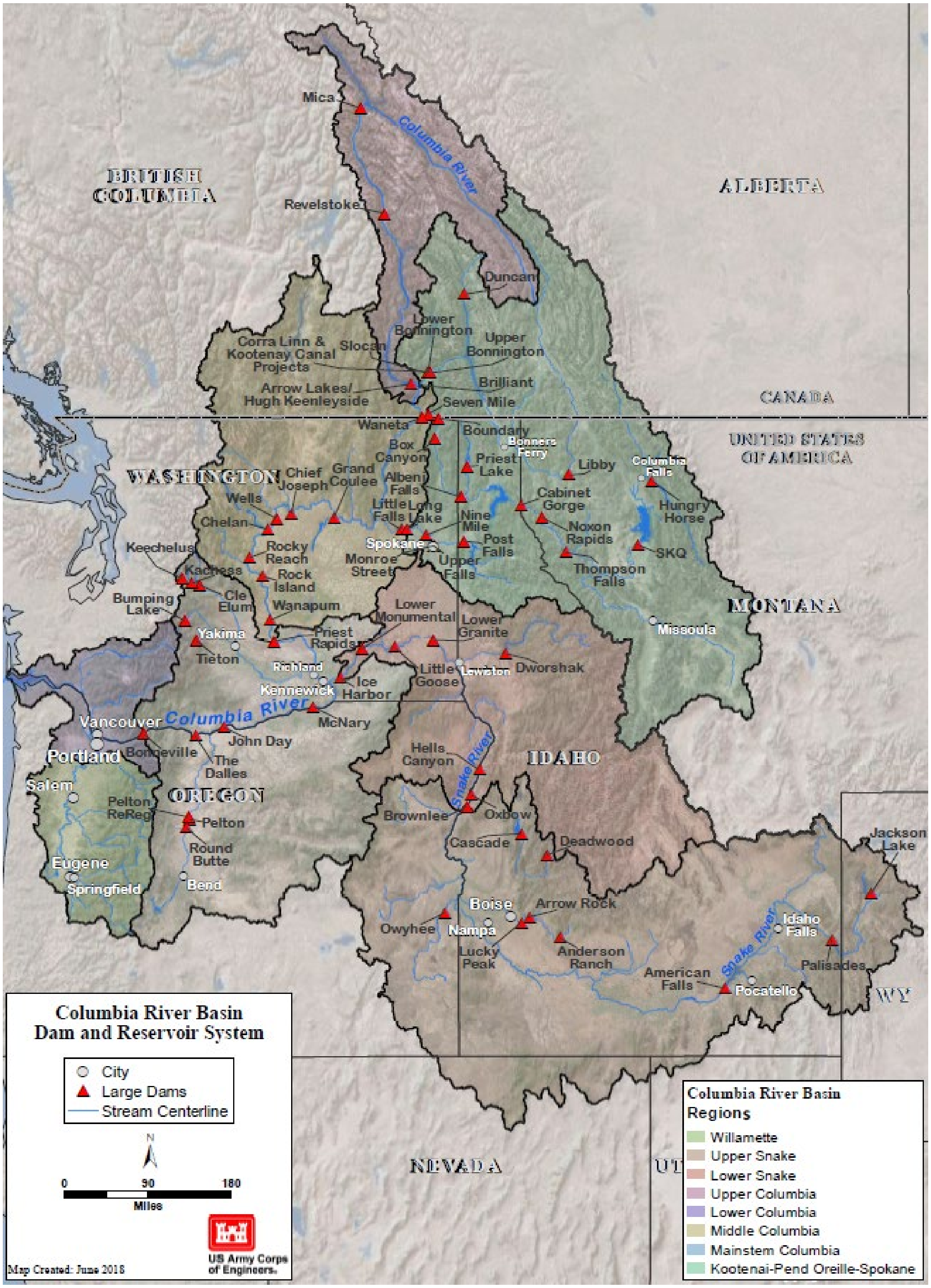

Figure 1. Site map showing the Columbia River Basin with the subbasins, large dams, and major tributaries (regions) noted.

1.3 Approach

The following sections in this chapter summarize the development of the hydroclimate and natural streamflow datasets that RMJOC-II *Part I: Hydroclimate Projections and Analyse*s (RMJOC 2018) documents. Subsequent chapters describe the reservoir system by basin; the general hydroregulation modeling approach; the preparation of model input data; and the modeling results specific to meeting the goals of flood risk management (FRM), hydropower production, fishery operations, and other nonpower uses.

1.4 Literature Review

Part I of the RMJOC-II study (RMJOC 2018) provides a thorough review of literature that addresses historical and future changes to the hydroclimatology of the region. Several additional studies have subsequently been published in peer-reviewed journals, further documenting and analyzing the future climate and hydrology datasets used in this study.

An analysis of trends and nonstationarities[3] for No Regulation No Irrigation (NRNI) was reported in RMJOC-II Part I (RMJOC 2018). Additional studies have focused on historical changes in streamflow in the Columbia River Basin. Forbes et al. (2019) applied a trend detection and attribution analysis based on the NRNI dataset developed as part of RMJOC-II Part 1, in conjunction with land surface modeling. They found significant declines in annual flow volumes in all subbasins (Figure 1) except the Middle and Upper Snake and Upper Columbia. Decline in June–October streamflows largely drove these trends. They also identified increasing trends in May streamflow. The effects of climate dominated the signals in streamflow trends; other drivers analyzed (e.g., land use and land cover change, carbon dioxide concentration, and nitrogen deposition) contributed little to the observed trends.

The research community has used the RMJOC-II future dataset to characterize how modeling elements and decisions in the projection development process affect the range in streamflow projections. Chegwidden et al. (2019) found that the emissions scenario (Representative Concentration Pathway [RCP]) and choice of global climate model explain the most variance of the spread of projected shifts in snowmelt streamflow timing and annual volumes, respectively. The hydrological model explains the most variance of projected spread in low flows. These results can help inform the design of future studies directed at a particular impact of interest.

Several groups of researchers have also analyzed the RMJOC-II unregulated flow dataset to describe projected changes in the flooding and flood generation processes. Queen et al. (2020) found that the magnitude of annual maximum daily mean discharge is projected to increase in the majority of locations in the Columbia River basin. They found that the largest changes occur in upstream locations, and decrease with increasing drainage area. This general pattern is

[3] The assumption of stationarity (statistical characteristics of hydrological time series are constant through time) has been a pillar of water management (Milly et al. 2008). This assumption has enabled the use of well-accepted statistical methods in water resources planning and design that rely primarily on the observed record. Climate change has the potential to undermine this assumption. Recent issuance of USACE civil works policy guidance includes methodologies for detecting nonstationarities in streamflow in support of USACE project planning, design, construction, operations, and maintenance (ECB 2016-25, USACE 2016b; ETL 1100-2-3, USACE 2017).

reversed in the Snake River basin, where increases in flood magnitude increase moving further downstream. Chegwidden et al. (2020) describe physical mechanisms underlying these projected changes in unregulated flood magnitudes. They found that annual maximum flow events projected for the future are less frequently caused by snowmelt and more frequently associated with rainfall events.

The research community has further analyzed statistical downscaled products that RMJOC-II Part I used. Alder and Hostetler (2019) analyzed six different statistically downscaled datasets to show influences of downscaling techniques on hydrological projections across the western United States. One of these techniques, Multivariate Adapted Constructed Analogs (MACA), is used in RMJOC-II. Alder and Hostetler found that Global Climate Model (GCM) projections are the largest source of uncertainty in monthly water-balance simulations; however, downscaling techniques can also drive large differences in seasonal projections. In snow-dominated regions, a principal difference between simulations is linked to statistical downscaling techniques and is attributed to what historical dataset was used for bias correction. The amount of high-elevation observation stations and assumptions on atmospheric lapse rates applied in the historical dataset have a strong influence on air temperature at high elevations. This provides further evidence for air temperature artifacts described in RMJOC-II Part I and should be considered in the development of future datasets.

1.5 Summary of RMJOC-II *Part I: Hydroclimate Projections and Analyses*

The selection and development of the foundational climate projections and resulting streamflow inputs used in the hydroregulation modeling are detailed in the RMJOC-II Part I report (RMJOC 2018). For background and reference, the following provides a general overview of the relevant information documented in Part I.

Regional temperatures have increased over the historical period of observation which extends back to early in the twenty century for many measurement locations. They are expected to continue to increase (U.S. Global Change Research Program [USGCRP] 2017; RMJOC 2018). Because of these rising temperatures, other aspects of the climate are changing as well, such as receding glaciers, diminishing snow cover, shrinking sea ice, rising sea levels, and increasing atmospheric water vapor (USGCRP 2017). According to the Fourth National Climate Assessment (USGCRP 2017), annual trends toward earlier spring melt and reduced snowpack are already affecting water resources in the western U.S., and these trends are expected to continue. Numerous studies have projected that as warming continues, snowpack in the Columbia River Basin is likely to decline, winter streamflows will tend to increase, peak seasonal snowmelt will tend to occur earlier in the spring, and summer flows will likely decrease (RMJOC 2018).

RMJOC-II Part I (RMJOC 2018) reported several findings for the 160 hydrologic projections (80 projections for both RCP4.5 and RCP8.5) for 2020–2049 (referred to as the 2030s) and 2060–2089 (referred to as the 2070s):

- Temperatures in the region have already warmed about 1.5°F since the 1970s. They are expected to warm another 1°F to 4°F through the 2030s under both emissions scenarios.

The projections for the 2070s show warming of 3°F to 6°F and 4°F to 10°F above current levels for the RCP4.5 and RCP8.5 emissions scenarios,[4] respectively.

- Warming in the region is likely to be greatest in the interior with a greater range of possible outcomes. Less-pronounced warming is projected near the coast.
- Future precipitation trends are more uncertain, but a general upward trend is likely for the rest of the 21st century, particularly in the winter months. Already dry summers could become drier.
- Average winter snowpack is very likely to decline over time as more winter precipitation falls as rain instead of snow, especially on the U.S. side of the Columbia River Basin.
- By the 2030s, higher average fall and winter flows, earlier peak spring runoff, and longer periods of low summer flows are very likely. These patterns continue through the 2070s, with further amplification associated with the higher-emissions scenario (RCP8.5).
- The projections highlight that seasonal patterns of streamflow within the Snake River Basin are among the most sensitive to climate warming. However, this region also displays the widest spread in projections.
- In the Willamette Basin, fall and winter flows are likely to increase. A longer period of low summer flows is also likely.

Projected change in the region's hydrologic cycle, summarized above, will likely confound hydroregulation in the Columbia River Basin. As discussed in the following subsection, increasing temperatures drive change in the SWE and atmospheric circulation patterns generally, resulting in significant shifts in seasonal runoff patterns. The hydroregulation of the Columbia River system is attuned to historical timing of peak flows and to low water periods. The seasonal changes to more volume in the winter and less in the summer, with variable fall and spring seasons, will be the largest stressors for water management.

1.6 Summary of RMJOC-II Part I: Natural Streamflow Projections

UW produced a set of 172 projections of natural streamflow (RMJOC 2018). The RMJOC team used 160 of these projections for the analyses in Part 2. We did not use the 12 hybrid downscaled projections due to temporal limitations (simulations ended in 2050) and anomalously poor performance as compared to observations over the historical period (RMJOC 2018). These projections represent different combinations of modeling elements that are used to translate future greenhouse gas emissions scenarios to projections of streamflow volumes. The modeling elements represented in this project include two emissions scenarios, ten GCMs, two statistical downscaling methods that translate the coarse GCM output to 1/16° gridded resolutions, two hydrological models, and three separate parameterizations of one of those models. **Figure 2** depicts each of these modeling elements and the resulting 160 projections

[4] RCPs represent a range of projected carbon dioxide, methane, nitrous oxide, and other greenhouse gas concentrations that would result in a certain radiative forcing by 2100. RCP4.5 and RCP8.5 are defined in RMJOC-II Part I, Section 4.2.1.

(small colored boxes). This set of projections, often referred to as an ensemble, is the basis for all of the analyses presented in Part 2, including the subset of 19 projections used in the hydropower modeling.

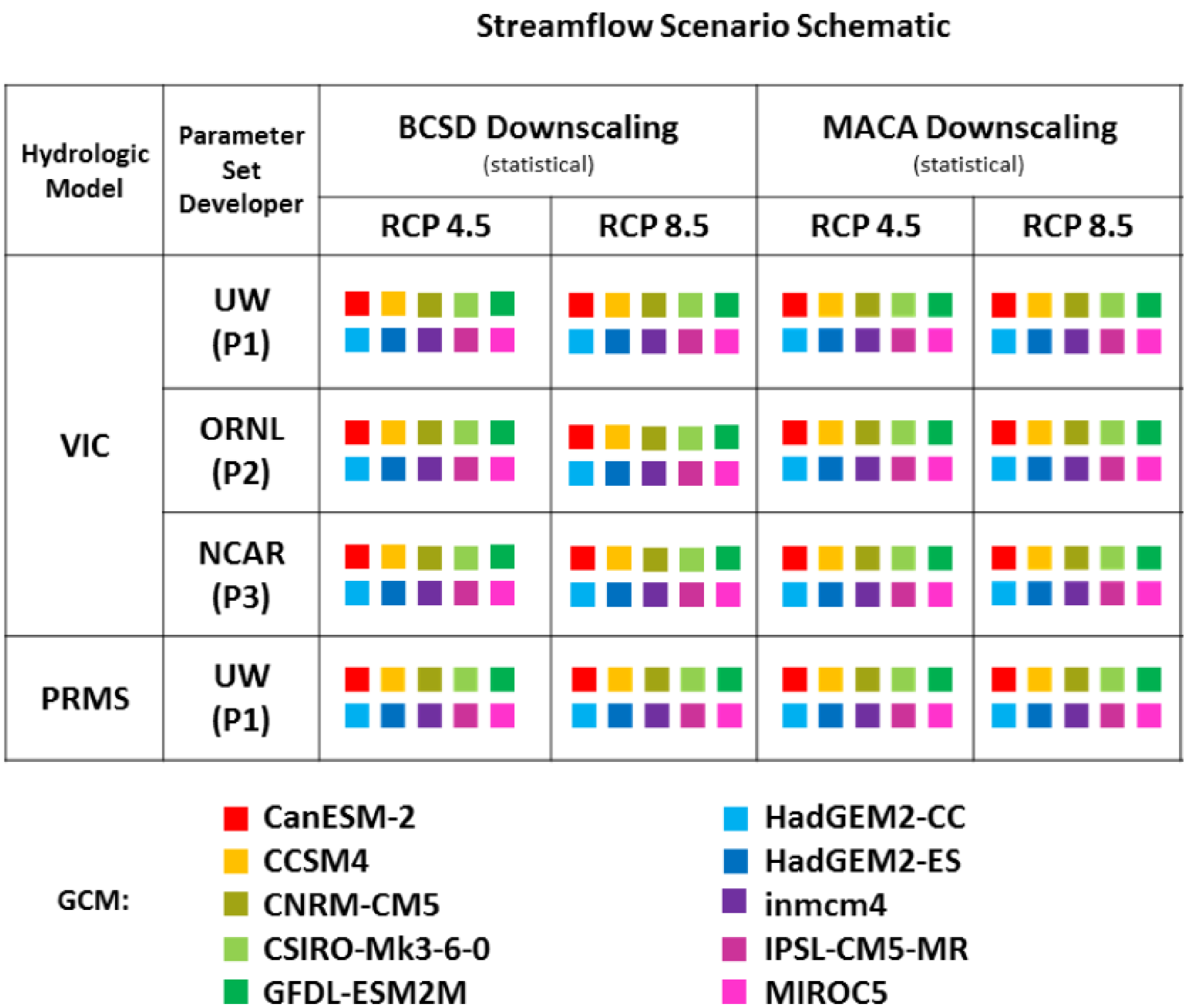

Figure 2. Matrix showing the modeling components (hydrological model, hydrological model parameter set, downscaling method, greenhouse gas emissions scenario, and GCM) that UW used to develop the 160 hydrological projections (*small colored boxes*). See acronym list for full model names.

For the Columbia River Basin as a whole, the warming temperatures and tendency for increased precipitation, particularly in the already wet winter months, result in higher winter and spring volumes with earlier spring flow peaks. In the summer, low-flow conditions will likely occur earlier in the summer and last for longer periods starting in the 2030s and continuing through the end of the century. However, these results are not necessarily universal across all basins. The Willamette Basin and coastal drainage areas have a tendency towards lower spring flows, and there is variability across models in the Snake River Basin where some scenarios show the possibility of increased fall streamflows (RMJOC 2018). **Figure 3** shows the projected changes in seasonal streamflow by location across the Columbia River Basin.

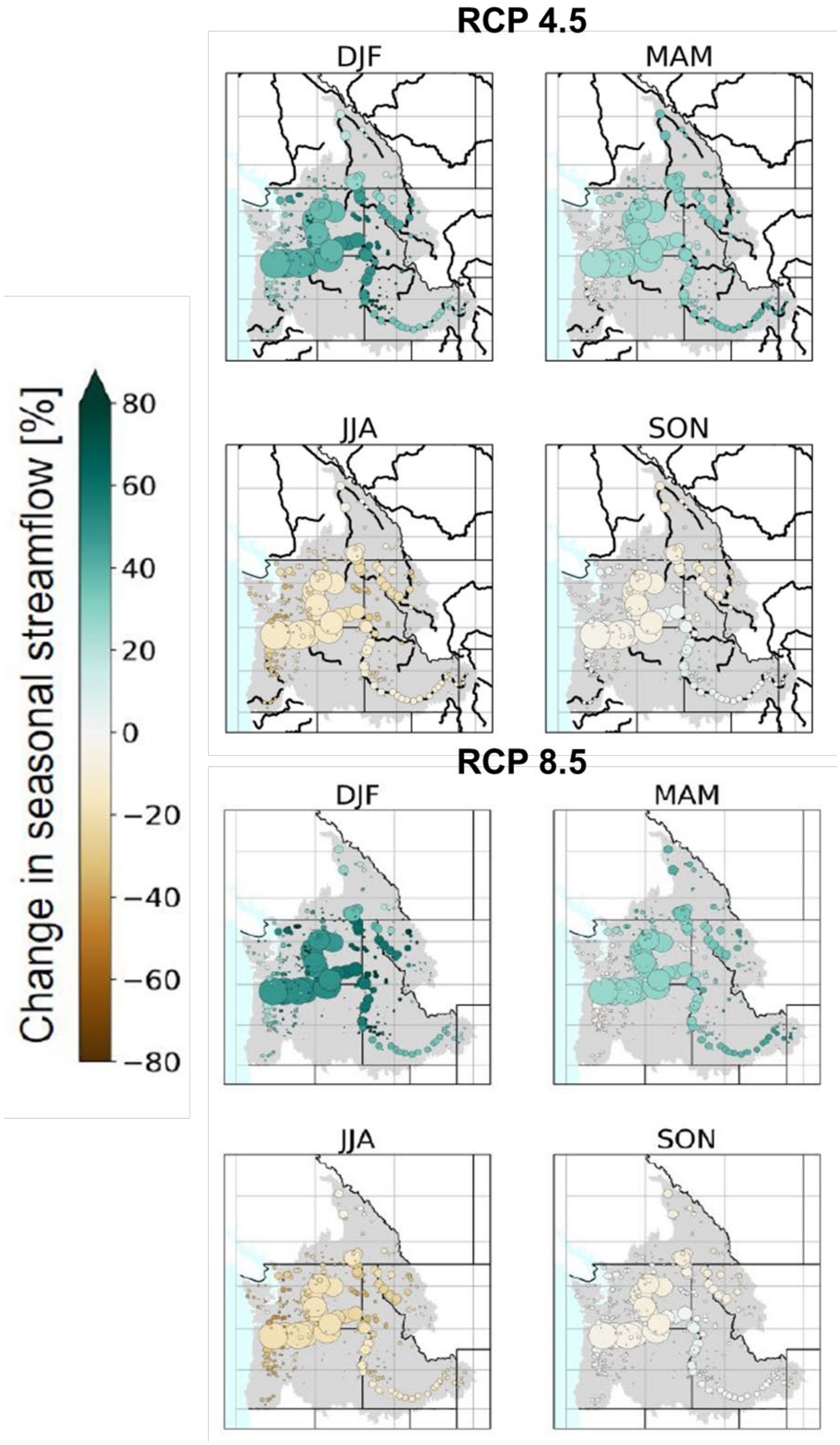

Figure 3. Percent change in annual volume from the historical period (1976–2005) and the 2030s (2020–2049) by season (*DJF*: December–February, winter; *MAM*: March–May, spring; *JJA*: June–August, summer; and *SON*: September–November, fall). Circle size denotes relative annual volumes in the historical (1976–2005) period. (Image by UW.)

1.6.1 Seasonal Changes in Natural Streamflow Projections

Throughout, this report presents analysis metrics to describe the range of hydrologic projections. The set of projections is often referred to as an *ensemble* and the range as a *spread*. We compared the future projections to historical (baseline) conditions represented with four different simulations. Each of the four combinations of hydrologic models and parameterizations used a common historical meteorological dataset (Livneh et al. 2013) to force the physically based model simulations. These base cases, referred to in this report as the *historical baselines*, limit the influences of hydrologic model biases on the climate change signal inferred from period-based comparative analyses. The climate change signal inferred from direct comparisons to observations would be influenced by systematic model biases introduced by the hydrologic models. Chapter 4.0, *RMJOC-II Hydroregulation Streamflow Datasets*, further describes modeled historical baselines.

Many of the analysis metrics this report uses are based on summaries of monthly statistics. In traditional hydrological studies, summaries of flows and water levels are commonly presented as “summary hydrographs” to describe the range of values observed throughout the year over a historical period of observation

The objective of the analyses and visuals presented in this report is to describe the potential uncertainty in what these summary statistics of median and extreme high and low conditions may be in the future. The spread of the ensemble of projections is used to describe this uncertainty. Actual uncertainty is unknown. Here, it is defined by and limited to the spread of projections developed for this study. A metric can be calculated independently for each projection and each period. This would result in 80 different estimates of that metric in a future period for each emissions scenario, 160 estimates in total for both RCPs. The statistical distribution of those estimates can then be presented with descriptors such as median, interquartile range, outliers, etc., to describe the range of projections and the relative amount of agreement or disagreement of projections. It should be noted that the range of historical baselines cannot be compared to the range in future projections. The range in the historical baselines are the product of one meteorological dataset and four different hydrological models, thus is solely influenced by the hydrology model. The range of the future projections for a single RCP and epoch is the product of ten different GCMs downscaled two different ways and four hydrology models, which inherently includes more meteorological variability than the four historical baselines.

Figure 4 presents an annotated example showing projections of high (90th percentile) monthly mean unregulated flow of the Snake River at Lower Granite Dam. The black dots represent the four historical baseline flows simulated by the four hydrologic models and parameter sets used in this study for the historical period (1976–2005). The historical baselines contextualize the relative change projected in future periods.

Box plots show the spread in metrics for each future epoch (2030s and 2070s) and each emission scenario (RCP4.5 and RCP8.5). For example, as shown in the inset of **Figure 4**, the dark red box plot represents the ensemble of projections of 90th percentile monthly unregulated flow for April under RCP8.5 for the 2070s. This boxplot represents 80 individual projections of 90th percentile flow for April, one from each RCP8.5 ensemble member.

Note that the upper, middle, and lower lines of the box represent the 75th, 50th, and 25th percentiles of the data, respectively. The interquartile range is the distance between the 75th and 25th percentile. The upper and lower whiskers extend to 1.5 times the interquartile range in both directions, while individually plotted points are beyond this threshold.

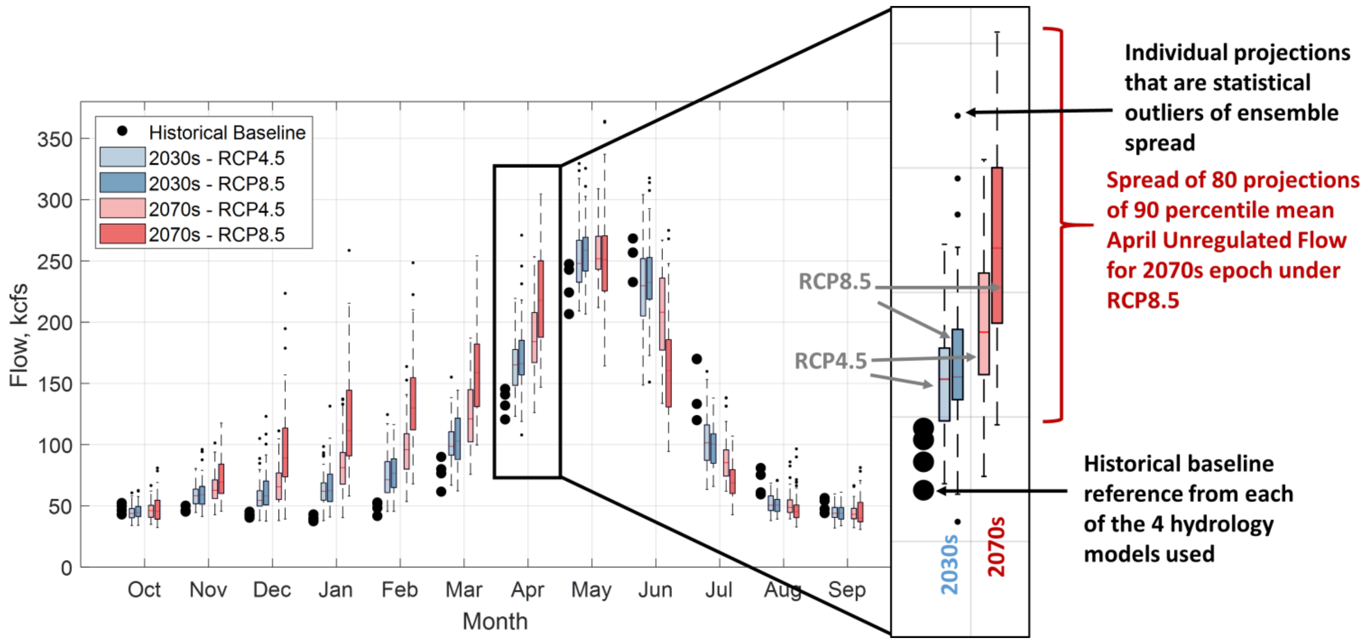

Figure 4. Example visual of historic and future predictions of 90th percentile monthly mean unregulated flow of the Snake River at Lower Granite Dam. Projections for the month of April are enlarged and annotated to describe the presentation of content.

The following sections summarize the ensemble of natural flow projections of each future epoch for the Upper Columbia above Grand Coulee, the Snake River, the Lower Columbia, and the Willamette River basin (see **Figure 1**).

1.6.2 Upper Columbia above Grand Coulee

The accumulated natural streamflows of the Columbia River from the basin upstream of Grand Coulee Dam show modest change, as snowpack at high elevations of the upper basin display less sensitivity to warming. In portions of the upper basin, winter precipitation will continue to fall as snow in the higher elevations for some time. The projections show increasing flows November–April through the 2030s. These relative changes are larger for high flows (90th percentile) and are further amplified through the 2070s with RCP8.5 showing large changes in high flows with respect to historical conditions. For the 2030s, the highest flows of the spring freshet are projected to occur in June, the same month as historical baselines. In the 2070s, the center of timing shifts to May, with many projections showing median and 90th percentile values greater than historical values. The projections indicate that flow volumes for July–September are likely to decrease through the 2030s and 2070s (see **Figure 5**).

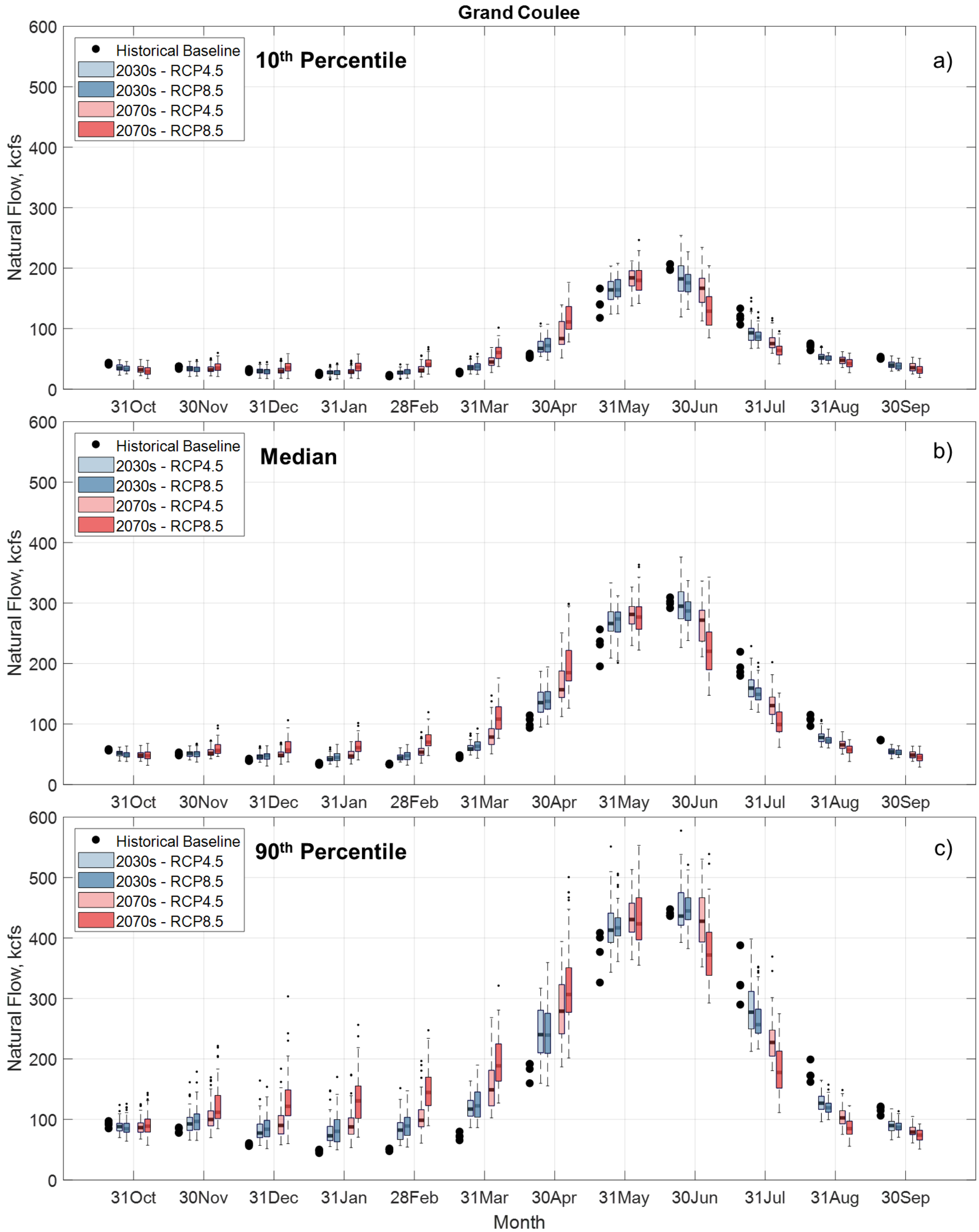

Figure 5. Modeled historical baseline and projected (*a*) 10th percentile, (*b*) median, and (*c*) 90th percentile unregulated monthly streamflow of the Columbia River at Grand Coulee Dam.

1.6.3 Snake River

In the Snake River Basin, most projections indicate greater warming than the other regions of the Columbia River Basin but with a larger range of possible temperature outcomes. Precipitation is projected to increase in both winter and spring. Projections for summer precipitation are more uncertain with most indicating drier summers but some suggesting a potential for wetter summers. Models suggest that as early as the 2030s, snowpack in this basin is likely to decrease with streamflow timing changes appearing earlier here than other parts of the Columbia River Basin. The natural streamflow projections generally have higher fall and winter flows and earlier and higher spring flow peaks. The relative changes in median and high (90th percentile) flows are higher than in other tributaries. On average, summer flow volumes are projected to decrease; however, little change or only small increases are projected for extreme low flows (10th percentile; see **Figure 6**).

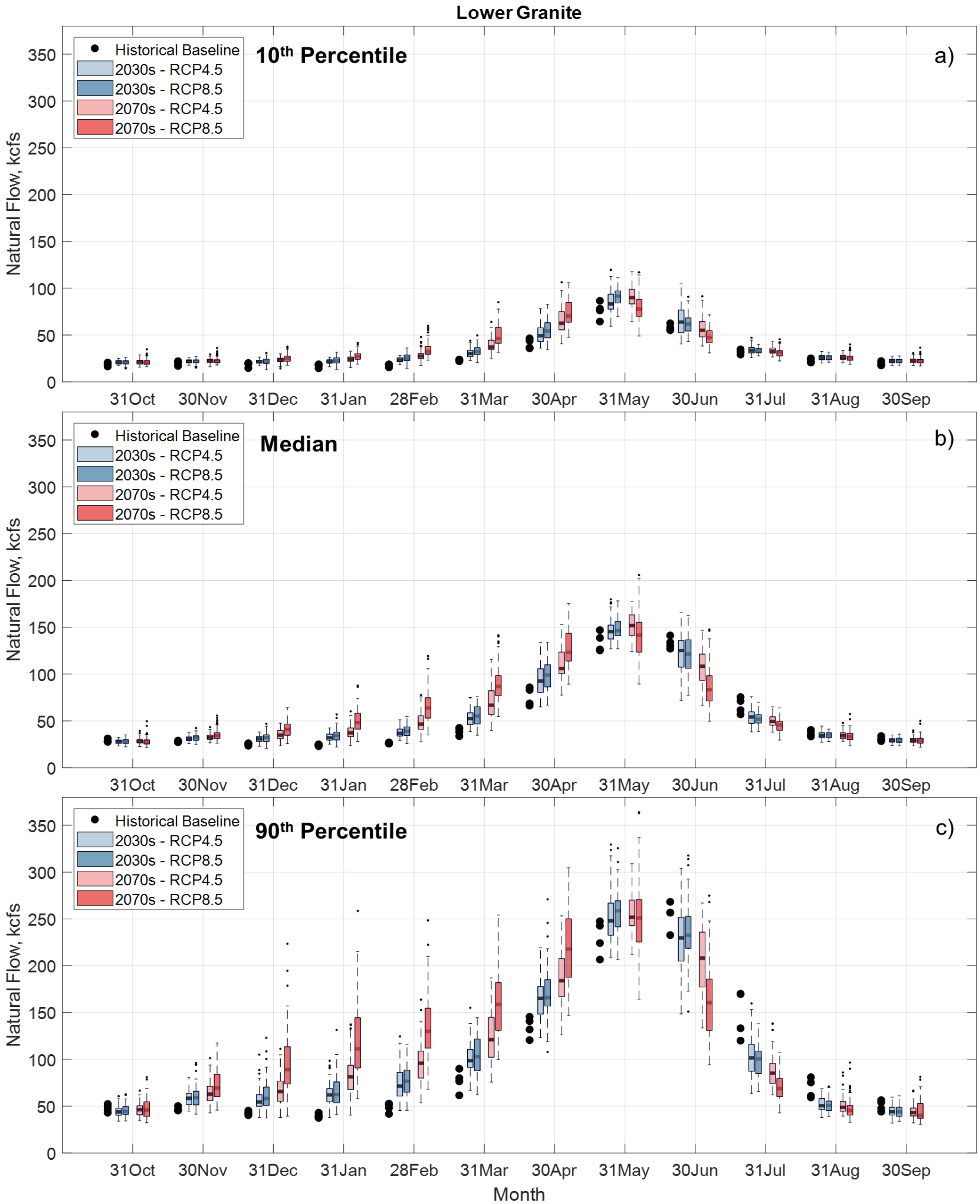

Figure 6. Modeled historical baseline and projected (*a*) 10th percentile, (*b*) median, and (*c*) 90th percentile unregulated monthly streamflow of the Snake River at Lower Granite Dam.

1.6.4 Lower Columbia River

The Lower Columbia River region (Columbia River below the confluence of the Snake River) integrates the flow volumes projected for upstream basins described in preceding sections. Consistent with projected changes in precipitation and changes in seasonal snowpack, changes in volume are concentrated by season, with higher winter and spring volumes and generally lower summer volumes. The projections predict the greatest amount of change for high-flow extremes during winter months (see **Figure 7**).

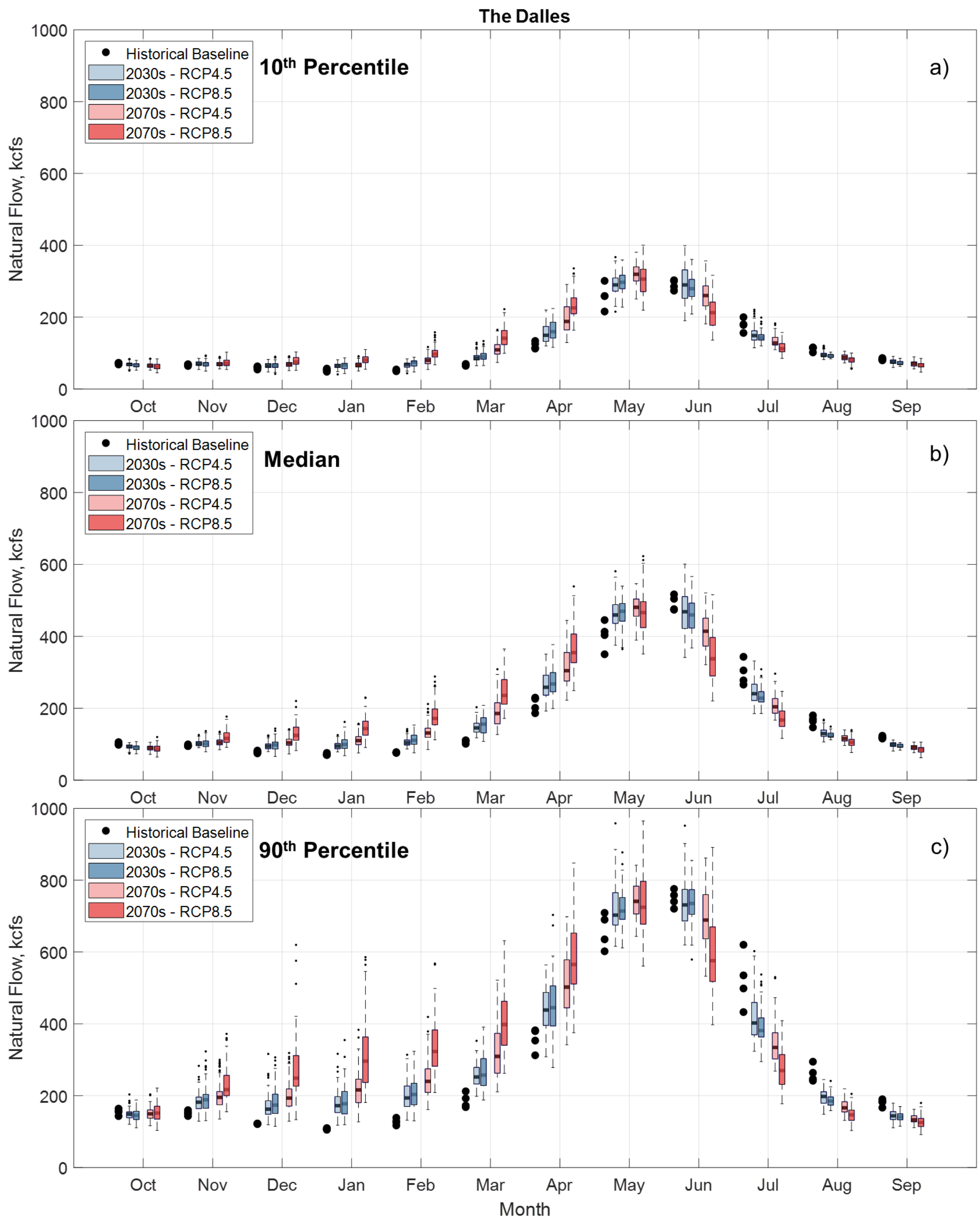

Figure 7. Modeled historical baseline and projected (*a*) 10th percentile, (*b*) median, and (*c*) 90th percentile unregulated monthly streamflow of the Columbia River at The Dalles Dam.

1.6.5 Willamette River

The Willamette River flows into the Columbia downstream of Vancouver, Washington. The Willamette basin represents a small fraction of the total drainage area of the Columbia River Basin but is an important influence on water levels in the Lower Columbia River below Bonneville Dam.

High flows, as represented through 90th percentile monthly flows (**Figure 8**) are projected to increase above historical levels during December–March in the 2030s and 2070s under both emissions scenarios. The largest changes are projected for January and February, where nearly all projections estimate 90th percentile monthly flow volumes to be greater than historical under RCP8.5. Many projections indicate decreased flow volumes through spring and early summer, April–July.

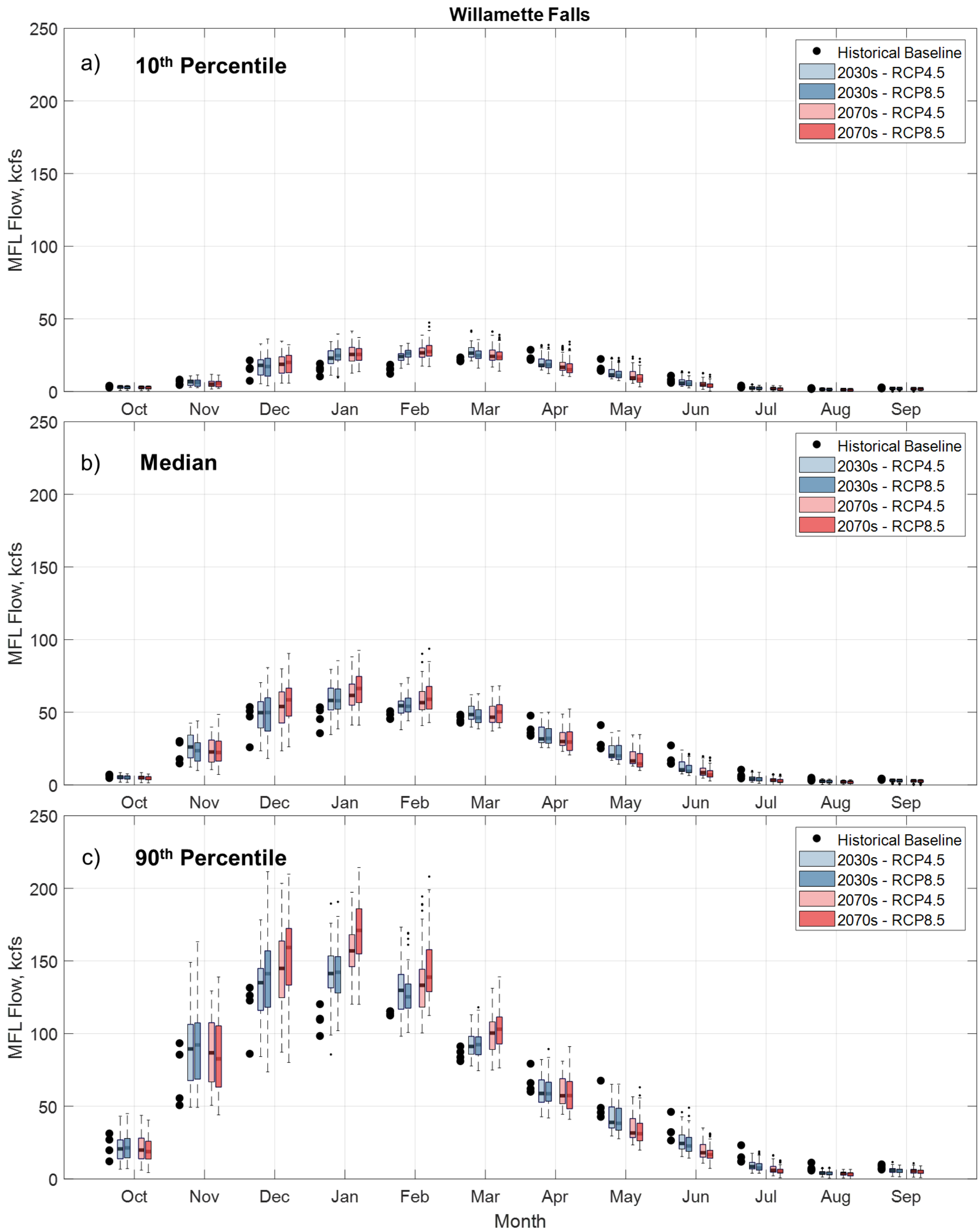

Figure 8. Modeled historical and projected (*a*) 10th percentile, (*b*) median, and (*c*) 90th percentile unregulated monthly streamflow of the Willamette River at Oregon City, Oregon.

2.0 Description of Basins and Reservoir Systems

2.1 Main Stem Columbia River Basin

The main stem Columbia River extends over 1,000 miles from its headwaters in British Columbia (BC) to the Pacific Ocean. Major tributaries to the Columbia River include the Snake River, Kootenai River, Pend Oreille River, Spokane River, Yakima River, Deschutes River, and Willamette River basins. Together the Columbia River and its tributaries above The Dalles Dam compose a drainage basin of more than 258,000 square miles.

There are 31 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. Both of the power-producing and non-power-producing projects in the Basin are currently operated for a variety of purposes, including FRM, navigation, irrigation, hydropower production, fish habitat support, and recreation. This multipurpose vision of the Columbia River has been a goal of the projects since their construction. **Figure 1** shows the location of major projects owned and operated by USACE and Reclamation in the Columbia River basin, as well as numerous nonfederal projects, including those owned and operated by the British Columbia Hydro and Power Authority (BC Hydro) and other utilities in Canada. **Figure 9** shows Pacific Northwest Reservoir System schematic, including all the major hydroregulation projects and regulation points.

2.2 Upper Columbia (Canada)

There are three major dams on the Canadian portion of the main stem Columbia River. From upstream to downstream, these projects are Mica, Revelstoke, and Arrow (**Figure 9**). Mica and Arrow regulate large reservoirs and are important for both hydropower production and as system FRM. Revelstoke Dam is a run-of-river project due to minimal fluctuations of storage. These projects are owned by BC Hydro, but operation is influenced by the Columbia River Treaty (Treaty) between the U.S. and Canada. Discharge from Arrow, seasonal flood control space, and draft and refill for hydropower are coordinated pursuant to the Treaty, which 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.

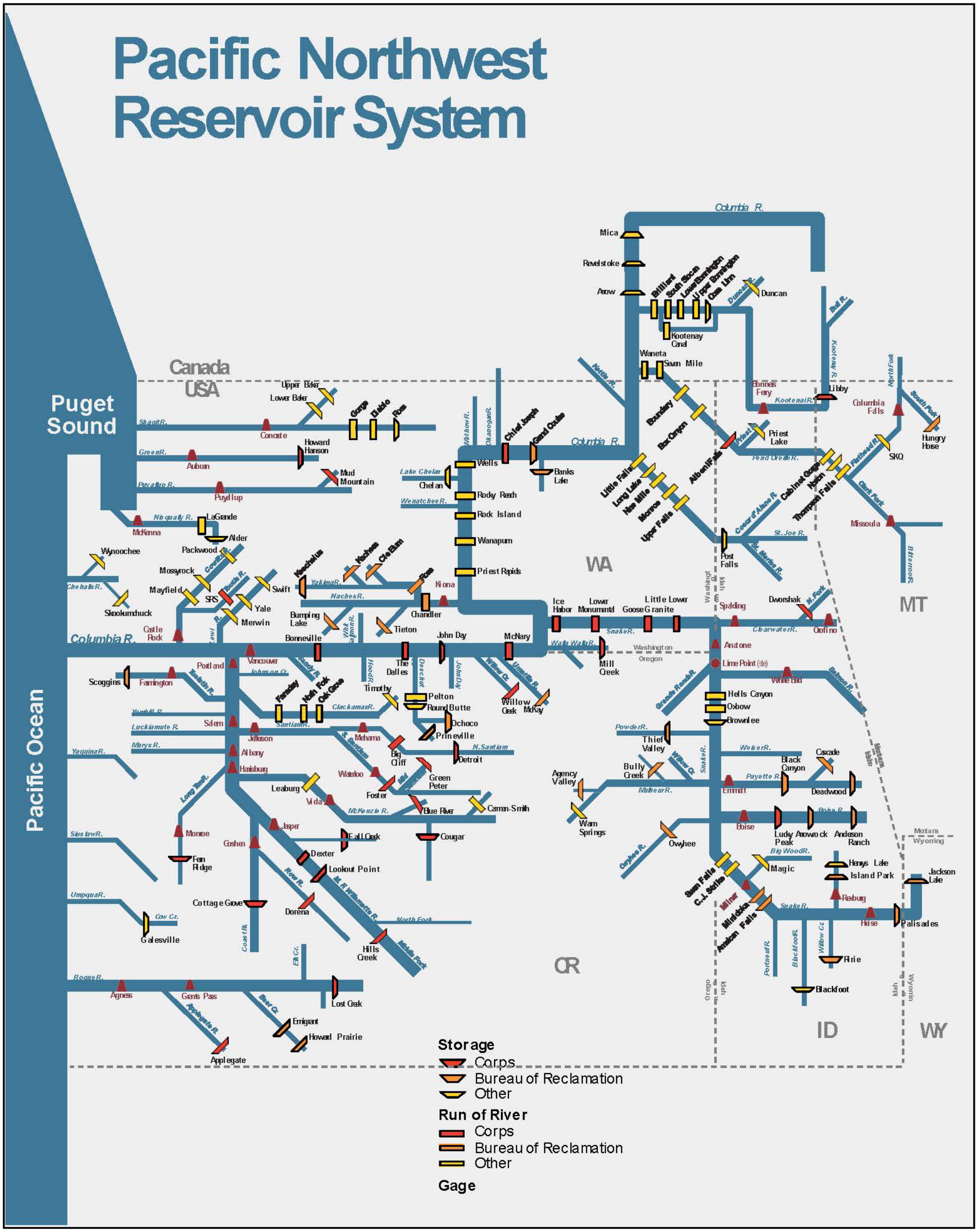

Figure 9. Pacific Northwest Reservoir System network. (Image by the USACE Northwestern Division.)

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

2.3.1 Kootenay Basin

The headwaters for the Kootenay River are in eastern BC. The river flows south into Montana before flowing northwest through the Idaho Panhandle and back into BC to join the Columbia River downstream from Arrow. Straddling the U.S.-Canadian border is Lake Koocanusa, the reservoir upstream of Libby Dam. Libby Dam is operated by USACE; and its authorized purposes include FRM, hydropower production, fish habitat support, and recreation. Outflow from Libby Dam flows north through Bonners Ferry, Idaho, and into Kootenay Lake in BC. 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 into Kootenay Lake for BC Hydro. Duncan is used for local and system FRM, and its operations are coordinated through the Columbia River Treaty. Kootenay Lake is a natural glacial lake that is controlled to a degree by Corra Linn Dam. However, a channel restriction upstream of the dam influences the elevation of Kootenay Lake and its outflow during the peak spring freshet. At these times, the lake is susceptible to local shoreline flooding. Downstream from Kootenay Lake, outflow can travel through either four run-of-river hydropower projects or a power canal. All of the flow then passes through Brilliant Dam prior to joining the Columbia River just downstream from Arrow Dam. All of these projects are owned and operated by Canadian utility companies. Because this basin includes both U.S. and Canadian interests, Kootenay Lake elevations are influenced by the International Joint Commission (IJC) order signed in 1938. The IJC established the operating limits for Corra Linn Dam. **Figure 9** shows the locations of the Kootenay projects.

2.3.2 Pend Oreille Basin

The Pend Oreille Basin includes portions of northwestern Montana, southeastern BC, and northern Idaho. Locations of U.S. and Canadian projects in the Pend Oreille basin are shown in **Figures 1** and **9**. 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 of the Flathead River about 5 miles above the confluence with the middle and north fork. It is operated by Reclamation for hydropower, FRM, water supply, recreation, and fish habitat support.

Downstream from Hungry Horse, the Flathead River flows into Flathead Lake, a natural lake where water levels are raised and regulated by Seli'š Ksanka Qlispe' Dam, a nonfederal project owned and operated by the Confederated Salish and Kootenai Tribes. Flathead Lake outflows can be limited due to a natural channel restriction between the dam and the lake. Because of this constriction, the maximum discharge depends on lake elevation. However, even at full pool, channel restrictions can cause the lake elevation to rise during periods of high inflows, resulting in local flooding around the lake.

Below Seli'š Ksanka Qlispe' 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. It possesses a minimal amount of usable storage and is considered a run-of-river project. Thompson Falls is a nonfederal project owned and operated by NorthWestern Energy. 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 nonfederal projects owned and operated by Avista Energy.

Below Cabinet Gorge, the Clark Fork flows into Lake Pend Oreille, another natural glacial lake similar to Kootenay and Flathead Lakes. The elevation of Lake Pend Oreille is managed by Albeni Falls Dam unless the dam is on “free flow,” and a natural constriction controls elevations. USACE operates the dam for hydropower, FRM, fish habitat support, and recreation. The natural channel restriction upstream of the dam can limit discharge from the lake, leading to higher lake elevations and shoreline flooding.

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.-Canadian border. There are four dams downstream of Albeni Falls Dam on the Pend Oreille River. All are nonfederal projects with minimal storage that are operated for hydropower production. Box Canyon is the most upstream of these projects and is owned and operated by Pend Oreille Public Utility Department (PUD). The next project is Boundary, which is owned and operated by Seattle City Light. The last two projects, Seven Mile and Waneta, are in BC and are operated by Canadian utility companies.

2.3.3 Spokane Basin

The Spokane River flows west from central Idaho and Washington into Lake Roosevelt on the Columbia River. The watershed includes two storage projects and four run-of-river projects. All projects are nonfederal. Post Falls is the most upstream project, located near the outlet of Lake Coeur D’Alene. Similar to Kootenay and Flathead Lakes, water levels in Lake Coeur D’Alene are artificially maintained by Post Falls Dam; but under certain conditions, natural channel restrictions limit outflow from the lake. Downstream from Post Falls are five small run-of-river projects—Upper Falls, Monroe, Nine Mile, Little Falls and Long Lake. Locations of projects in the Spokane Basin are shown in **Figures 1** and **9**.

2.4 Mid-Columbia

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 (**Figures 1** and **9**). Grand Coulee Dam is operated by Reclamation for hydropower production, FRM, irrigation, navigation, recreation, and Endangered Species Act (ESA) listed and nonlisted fish species and to minimize total dissolved gas (TDG) production when possible. The Spokane River joins the Columbia River upstream from Grand Coulee Dam. Also located near Grand Coulee Dam is the John W. Keys pump generating plant that pumps water from Lake Roosevelt into Banks Lake. Banks Lake provides irrigation March–December. 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. **Figures 1** and **9**shows the locations of Grand Coulee, Banks Lake, and the other Mid-Columbia projects.

Downstream from Grand Coulee Dam is Chief Joseph Dam, operated by USACE. Because of minimal storage, this is a run-of-river project and is not used for system flood control. Below

Chief Joseph Dam is a series of nonfederal dams. From upstream to downstream, these projects are Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids (**Figures 1** and **9**). Wells is owned and operated by Douglas County 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. Chelan County PUD also owns and operates Chelan Dam on the Chelan River, which joins the Columbia River between Wells and Rocky Reach.

The Mid-Columbia projects have relatively little storage and are run-of river projects. Some small seasonal fluctuation of storage is typically assumed for Lake Chelan. Real-time operation of the Mid-Columbia projects is highly dependent on the outflow of Chief Joseph for daily hydropower production. In addition, the operation of these projects can be influenced by the many external parties who own shares in the generation. These parties can include both other regional utilities and power marketers.

The portion of the Columbia River just downstream of Priest Rapids Dam is known as Vernita Bar (or Hanford Reach). It importantly provides critical spawning habitat for fall Chinook salmon. As a result, guidance from fish managers can influence operations of Priest Rapids and the other upstream Mid-Columbia projects during the fall spawning. In winter and spring, water may need to be drafted from Grand Coulee Dam to support water levels and to ensure juvenile fish 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.

2.5 Snake River Basin

The drainage area above Brownlee Dam is referred to as the Upper Snake River Basin. Numerous projects are in the Upper Snake River Basin. These include a mix of projects operated for water supply for irrigation and municipal and industrial (M&I) uses, FRM, and hydropower production. The projects of the Upper Snake are owned by the Reclamation, USACE, and various nonfederal entities. Brownlee Dam, part of the Hells Canyon complex (Brownlee, Hells Canyon, and Oxbow Dams) is owned and operated by Idaho Power Company for system FRM and for hydropower production. The lower two (Hells Canyon and Oxbow) are run-of-river projects operated for hydropower production.

The Lower Snake River Basin starts below Hells Canyon Dam and continues to the confluence of the Columbia River near Pasco, Washington. It is composed of the Clearwater and Salmon Rivers, along with the lower portion of the Snake River below Hells Canyon Dam. USACE operates Dworshak Dam on the North Fork Clearwater and the four dams below Lewiston, Idaho: Lower Granite, Lower Monumental, Little Goose, and Ice Harbor (**Figures 1** and **9Error! Reference source not found.**). Dworshak is operated for FRM, hydropower production, and fish habitat support; and the four lower Snake projects are operated for navigation, hydropower production, and fish habitat support.

2.6 Lower Columbia

The Lower Columbia runs east to west along much of the border between Washington and Oregon. Four main stem Columbia River projects—McNary Dam, John Day Dam, The Dalles Dam, and Bonneville Dam—are located here. USACE owns these large projects and operates them mainly for hydropower production, navigation, and fish habitat support. John Day Dam is authorized for FRM and can help reduce flows at Vancouver. The storage in the Lower Columbia reservoirs is relatively small compared to the volumes they pass during the spring freshet, but they can be beneficial to reducing peaks in the lower Columbia River from short, intense, winter rain-driven events. Outside of these events, they are generally operated and modeled as run-of-river projects. **Figures 1** and **9** shows the locations 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 nonfederal and federal projects. The federal projects are owned and operated by Reclamation.

2.7 Willamette Basin

The Willamette River Basin covers approximately 11,500 square miles in northwest Oregon and is part of the lower Columbia River watershed. The basin spans east to west from the southern Cascades to the Coast Range and north to south from Portland, Oregon, to the headwaters of the Middle and Coast Fork Willamette Rivers. The Willamette Basin includes six subbasins and a system of 14 multipurpose dams and reservoirs operated by federal agencies (**Figures 1** and **9**). USACE operates 13 projects upstream of Salem, Oregon. Reclamation operates Scoggins Creek project in the Tualatin River basin. There are also several nonfederal dams in the basin. Each project contributes to an overall water resource management plan designed to provide FRM, hydroelectric power, irrigation, navigation, recreation, and downstream water quality improvement for the Willamette River and many of its tributaries.

While the confluence of the Willamette River with the Columbia is downstream of storage projects on the Columbia River system, flow from the Willamette River can influence Columbia River system operations because of its effect on stages of the lower Columbia River. In winter, high flows from the Willamette River create a backwater effect in the lower Columbia River that elevates river stages. This has a significant impact on stages associated with winter flooding and can influence stage and flow targets used for biological-based operations.

2.8 Nonfederal Projects

Private utility companies own and operate numerous nonfederal projects throughout the Columbia Basin. Examples of some large nonfederal projects include Seli'š Ksanka Qlispe', Chelan, and the Mid-Columbia Projects. To achieve the best operation of the Columbia River, many projects are regionally coordinated under the Pacific Northwest Coordination Agreement (PNCA). However, projects are not required to participate in the PNCA. The largest nonparticipating project is the Hells Canyon complex.

3.0 Hydroregulation Modeling in the Columbia River Basin

Hydroregulation—regulating water—is the process planners and operators in the region use to make decisions about the movement of water through the series of multipurpose projects in the Columbia River Basin. Those decisions aim to most efficiently manage water in the river and to meet multiple objectives and purposes in the basin. These objectives include FRM, navigation, hydropower production, irrigation and water supply, recreation, fish habitat, and ecosystem function.

Hydroregulation modeling uses one or more computational models that simulate operation of river-system projects over time. Different hydroregulation models are used in sequence to compute outputs needed to evaluate the effects of variations in streamflow on meeting system objectives. Model inputs and parameterization reflect a combination of physical components and operational conditions. Once a model is configured with the physical components and operational requirements or objectives, a series of streamflows are input. These simulate the storage, release, and movement of water through the system. The input hydrology dataset can reflect historical or future inflows.

3.1 Hydroregulation and the Columbia River System

Modeling the Columbia River reservoir system entails simulating the operation of a complex system of reservoirs and projects given a broad set of objectives, constraints, and hydrologic conditions. While this report does not attempt to describe all the details involved in the actual hydroregulation modeling, it does provide a general overview of the major features, constraints, and operating criteria of the system. Our study primarily focuses on impacts for the Columbia River reservoir system. Although results for some major tributaries (e.g., Snake, Deschutes, Willamette, etc.) were used as inputs to our modeling, details of effects to project-specific purposes, like irrigation deliveries, are not summarized.

3.1.1 Multiple Projects

The Columbia River reservoir system is composed of over 250 reservoirs located on its tributaries and down through the main stem. The primary focus of this study and its results is the FCRPS; however, depending on the hydroregulation model, additional reservoirs and projects are included to ensure accurate representation of the flow regime

3.1.2 Storage and Run-of-River Projects

Projects in the RMJOC-II hydroregulation modeling effort fall into two broad categories: storage and run-of-river projects. Storage is key to operating the FCRPS for multiple uses. The total active water storage available in the reservoirs on the Columbia River and its tributaries is approximately 55 million acre-feet (Maf). Approximately 20 Maf of that storage capacity is in Canada; the remaining 35 Maf of active storage comes from federal and nonfederal U.S. projects. Of the total storage capacity, approximately 40 Maf is available for system FRM. In general, the storage reservoirs are operated to draft during the fall and winter and refill during the spring and early summer snowmelt periods. Refill is managed to reduce downstream flooding and to store water for periods of relatively low streamflows during late summer and fall.

Run-of-river projects have limited storage capacity. These projects release water at the dam at nearly the same rate it enters the reservoir. Reservoirs behind run-of-river projects often are operated for hydropower, resulting in frequent, small fluctuations in water levels. These levels typically vary only 3 to 5 feet in normal operations. Depending on the objective of the modeling, the hydroregulation model may be set up to just pass inflow and maintain a constant reservoir level or be allowed to fluctuate.

The metrics in this report will focus on eight projects in the U.S.-Canada Columbia River reservoir system that are critical to meeting the multipurpose objectives. These are Libby, Hungry Horse, Albeni Falls, Grand Coulee, Dworshak, Brownlee, Palisades, and American Falls. This report also refers to six federal run-of-river projects: Lower Granite, Ice Harbor, McNary, John Day, The Dalles, and Bonneville Dams. Three Canadian projects, Arrow Lakes, Mica and Duncan, are also subject to limited analysis in Chapters 7.0 and 8.0 of this report.

3.2 Operations Overview

Each new operating year begins in the fall. To prepare, overarching guidelines called *rule curves* are developed that indicate (or “shape”) the timing of water releases and storage for reservoirs to achieve multiple objectives. Once the basic annual operating plans are set, the reservoir system is operated to meet several related, but sometimes conflicting, objectives.

River managers operate the Columbia River System seasonally with varying objectives for each season. **Figure 10** provides a general overview of the type and timing of these operations throughout the year.

Note that fish operations shown in **Figure 10** are consistent with *Continued Operation and Maintenance of the Columbia River System Biological Opinion* (National Oceanic and Atmospheric Administration [NOAA] 2019) for 13 species of anadromous fish, the *Biological Opinion on Federal Columbia River Power System Operations* (U.S. Fish and Wildlife Service [USFWS] 2000), and the *Biological Opinion Regarding the Effects of Libby Dam Operations on the Kootenai White Sturgeon, Bull Trout and Kootenai Sturgeon Critical Habitat* (USFWS 2006).

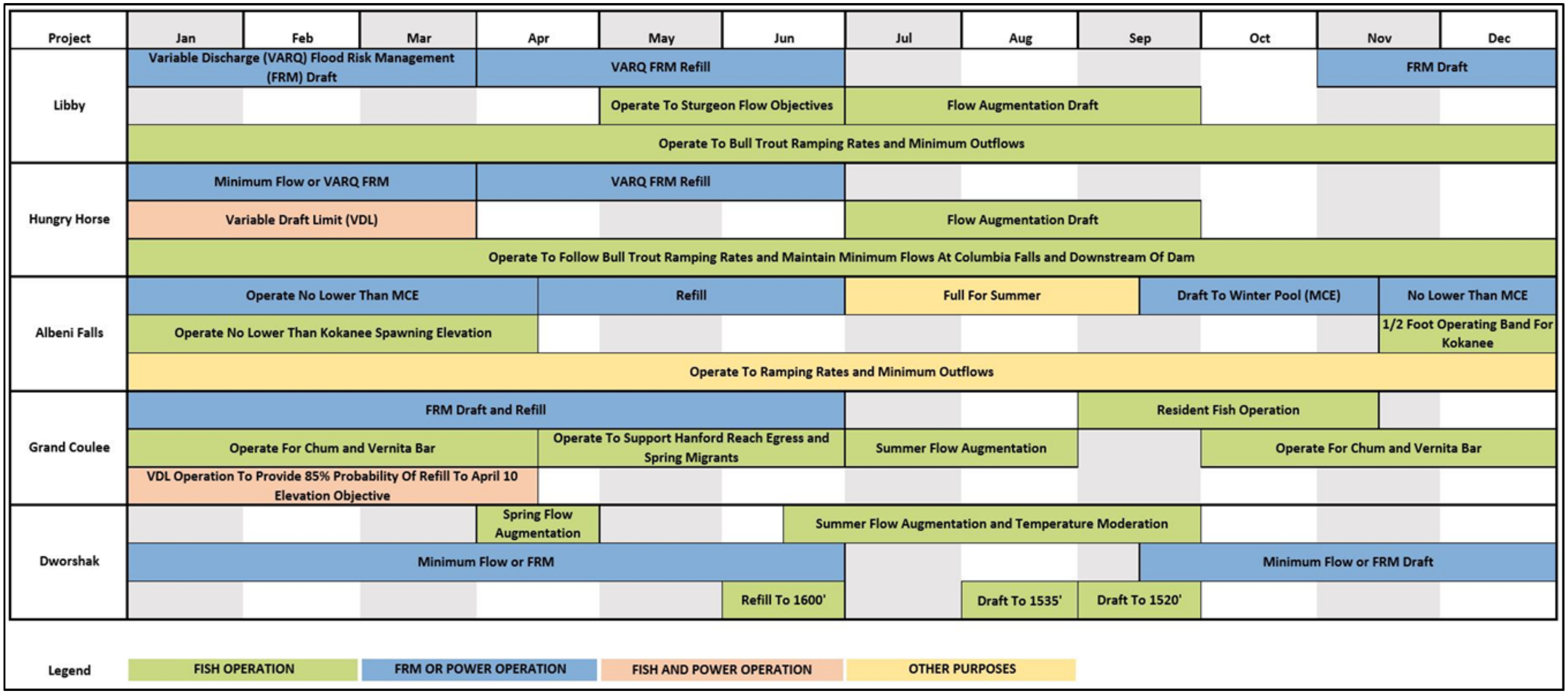

Figure 10. Seasonal operations at major Columbia River System Operations storage dams.

3.2.1 September through December

This period is the fixed reservoir drawdown season. During this time, storage reservoirs are lowered to predetermined levels to provide space for fall FRM and to position the reservoirs for further drafting in the winter months for power or for maintaining flow requirements for fish. Grand Coulee operates somewhat differently. For the months of September into the early fall, Grand Coulee operates for protecting Lake Roosevelt resident fish, providing power, maintaining fish flows below Priest Rapids Dam, and ensuring sufficient flows in the lower Columbia for navigation. Grand Coulee may be drafted as needed to manage Columbia River flows in order to aid the spawning of threatened chum salmon immediately downstream of Bonneville Dam. Spawning is almost always complete by the end of December, and a minimum flow level is established to protect the chum redds[5] through the rearing and emergence life cycle of the young salmon in the spring. Flows from Grand Coulee Dam are also scheduled in the fall to meet the requirements of the Hanford Reach Fall Chinook Protection Program. This is a multiagency agreement to aid Columbia River fall Chinook salmon (not listed under the Endangered Species Act) in both the spawning and rearing life-cycle periods in the Vernita Bar area of the Columbia River below Priest Rapids Dam.

3.2.2 January into April

This is the variable drawdown season when monthly forecasts of runoff volume guide reservoir operations. These forecasts estimate how much water will run off during the spring and summer snowmelt. This period is the most uncertain regarding the timing and volume of future runoff.

Reservoir levels are lowered based on forecasted seasonal water supply volumes during the winter and early spring primarily to provide space for water from later snowmelt and rain, helping reduce downstream flooding and unnecessary spill. The released water also produces electricity and helps maintain flows needed for fish. Operations are planned to hold enough water in storage to be available in early April to begin the spring flow season to aid juvenile salmon and steelhead in their annual downstream migration.

3.2.3 April through August

Spring and summer often see the highest flows of the year due to snowmelt. The snowmelt period also coincides with the primary fish passage season. During this time, the reservoirs are operated to manage flood risk and to refill reservoirs during the snowmelt period. Water is released from Columbia Basin reservoirs in support of flow objectives at Lower Granite Dam on the lower Snake River and at McNary Dam on the main stem of the Columbia River. These flows aid threatened and endangered anadromous fish as they migrate to the ocean. Specific spill operations are also necessary during this period to assist in the migration. This period requires

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[5] A salmon redd is a depression in the river bed created by the upstroke of the female salmon's body and tail. Her movement sucks up the river bottom gravel, which then drifts downstream with the river current. The female salmon dig a number of redds, depositing a few hundred eggs in each during the one or two days she is spawning.

balancing multiple objectives; system operators aim to capture the spring runoff and begin July with full reservoirs while also providing flows for fish and irrigation water supply. Filling reservoirs provides water for both summer recreation and summer fish flows for returning adult fish. It additionally positions the system to begin relatively full heading into the fall and winter, meeting needs for both power and for fish protection.

3.2.4 Additional Requirements and Constraints

Other uses of the river also influence management of the system and impact the hydroregulation modeling. For example, regulating water levels at Grand Coulee to allow spillway drum gate maintenance is a simulated operation. Hourly and daily operations, such as fishing access, project maintenance, short-term recreational events, and short-term pool regulations for navigation are not modeled.

3.3 Key Drivers: Flood Risk Management, Biological Opinion Operations, and Hydropower

While there are multiple uses and objectives driving the management of the Columbia River Basin and its complex system of dams and reservoirs, FRM, fish and wildlife conservation operations, and hydropower are the three primary drivers of the system operations. Chapter 8.0, “Flood Risk Management”; Chapter 9.0, “Hydropower”; and Chapter 10.0, “Hydroregulation Results for Ecosystem, Irrigation, and Navigation,” describe in more detail many of the operations specific to FRM, hydropower, and fish and wildlife conservation, respectively, that are reflected in the modeling presented in this report. Section 3.4 describes the general modeling approach applied in regional planning studies and the combination of different models deployed by USACE, Reclamation, and BPA.

3.4 Reservoir Regulation Models Used in this RMJOC-II Study

This study used multiple hydroregulation models because each agency has mission-specific models that previous studies have developed. The premise of this RMJOC study was to use existing tools that have been well vetted for regional planning studies. Each agency used hydroregulation tools that (1) required minimal development time for climate change projections, (2) provided accurate results that each agency had confidence in, and (3) met the modeling objectives of the RMJOC-II study scope. The subsequent sections describe each of these models.

3.4.1 MODSIM—Reclamation

MODSIM is a generalized modeling platform developed by Colorado State University (2017) that can be set up for specific river basins based on their configuration and operating criteria. It simulates complex river and reservoir systems that are operated for multiple purposes, including flood control, irrigation deliveries, and ecological flows. It uses a network optimization technique to determine water deliveries based on water rights and other priorities.

Our study used two basin-specific MODSIM models: one for the Upper Snake River and one for the Deschutes River Basins. These models were developed for the 2010 Level (2010L) Modified flows study (Reclamation 2009, 2010a), discussed further in Chapter 4.0. They are representative of operations, system configurations, and irrigation deliveries under 2008 conditions. Reclamation conducted model simulations for both models 1928 through 2008 at a monthly time step.

3.4.2 RiverWare—Reclamation

RiverWare is a modeling platform developed by the Center for Advanced Decision Support for Water and Environmental Systems at the University of Colorado, Boulder. It is a generalized platform that can be configured for individual river and reservoir systems and uses rule-based logic to simulate operations like flood control, irrigation deliveries, and outflows for ecological flows.

Our study used a RiverWare model of the Yakima River Basin, which was developed for the 2010 Level Modified Flows study (Reclamation 2010b). The model is representative of system configuration, irrigation deliveries, and operations at the 2010 Level and was run from 1928 through 2008 at a daily time step.

3.4.3 HEC-WAT ResSim—USACE

This study performed USACE reservoir modeling with the USACE Hydrologic Engineering Center's Watershed Analysis Tool (HEC-WAT). This tool can integrate various hydrologic and hydraulic models into a single framework. The Reservoir System Simulation model (HEC-ResSim) is used within the HEC-WAT framework to route and regulate flows through operationally complex basins. The HEC-WAT tool coupled with HEC-ResSim, referred to as WAT-ResSim, is ideal for simulating hydroregulation on the Columbia River and tributaries and their interconnected dams, reservoirs, and reaches. The Columbia Basin model used for RMJOC-II was developed from other comprehensive regional WAT-ResSim planning models used by USACE.

Modeling flood operations requires simulation at a daily time interval. These flood operations include robust rule sets simulating both spring and winter FRM operations. The WAT-ResSim framework also simulates other operations that constrain or affect USACE hydroregulation operations, including ecosystem, hydropower, and navigation requirements. Appendix A of this report, "Columbia River System HEC-WAT and HEC-ResSim Model Documentation," describes the Columbia River Basin's physical components, specific system, local operating rules, and criteria.

3.4.4 HYDSIM—BPA

The HYDSIM model was developed by BPA for long-term and short-term power planning. The HYDSIM model simulates power production for the operation of the Pacific Northwest hydropower system. Modeling inputs include reservoir inflows, regional power loads, physical plant data, and complex operating procedures and constraints for hydropower, FRM and ecosystem requirements. Modeling outputs include reservoir inflows, outflows, ending elevations and storage content, and hydropower generation.

The HYDSIM model is a deterministic model that uses project operating criteria and a number of different rule curves to achieve operating objectives for hydropower, FRM, and fishery operations. HYDSIM uses a 14-period time step, monthly for all months other than April and August, which are split into two half-periods to model the variability in streamflows during the normal initiation of reservoir refill and the transition to summer operations.

There are two types of HYDSIM studies: long-term studies and critical-period studies. Long-term studies include continuous and refill (noncontinuous) studies. The continuous study is used to assess the impacts to the hydrosystem under a long-term sequence of streamflow conditions. Project operations and reservoir levels flow continuously from one operating year to the next. Noncontinuous studies simulate the likelihood that reservoirs will refill over a year of operations. Reservoir levels and project operating criteria are preset for each operating year. Noncontinuous studies are essentially single-year studies within the historical sequence of years modeled.

Critical-period studies define the capacity of the hydropower system to meet firm energy during worst-case historical streamflow conditions. The critical period may be one or more years of the streamflow record, and the duration is related to the hydrosystem's storage capacity and the distribution of load over a year. Long-term continuous studies are used to determine the critical period.

The RMJOC HYDSIM studies applied long-term continuous modeling. Long-term refill studies and critical-period studies were not within the scope of the RMJOC effort and were not performed.

3.5 Datasets Required as Input to Hydroregulation Models

Both climate change streamflow sets and associated seasonal water supply forecast sets were prepared for the hydroregulation modeling. The natural climate change streamflows for the 160 scenarios were modified to reflect the irrigation and reservoir evaporation in the Columbia River. This process is described in Chapter 4.0, "RMJOC-II Hydroregulation Streamflow Datasets," and Chapter 5.0, "Conversion from Natural to Modified Flow-Like Flows." For the development of the operating rule curves for hydropower and FRM operations, seasonal volume water supply forecasts were developed for the appropriate sites for the 160 climate change scenarios. This work is described in Chapter 6.0, "Water Supply Forecast Development."

4.0 RMJOC-II Hydroregulation Streamflow Datasets

RMJOC-II created a suite of future hydroregulated streamflow datasets to inform future planning studies. RMJOC and others may also use them for future modeling projects. The creation of the RMJOC-II hydroregulation streamflow datasets was to facilitate evaluation of both current and future FCPRS hydrologic vulnerabilities, risks, and system resiliency. **Figure 11** outlines the general approach the project team used to create the RMJOC-II hydroregulation datasets. These hydroregulation products are termed Modified Flow-Like (MFL) and are described in Section 4.3 below.

The RMJOC-II hydroregulated streamflow datasets spanned three distinct 30-year periods of record. The 30-year window was chosen to balance the need for computational runtime efficiency while maintaining a statistically meaningful period for epoch comparison. The historical baseline period spans the most recent 30 years in the historical streamflow datasets, WYs 1976 through 2005. This period reflects the most current hydroclimate basin conditions. The two future period epochs are identified as the 2030s (WYs 2020–2049) and the 2070s (WYs 2070–2089).

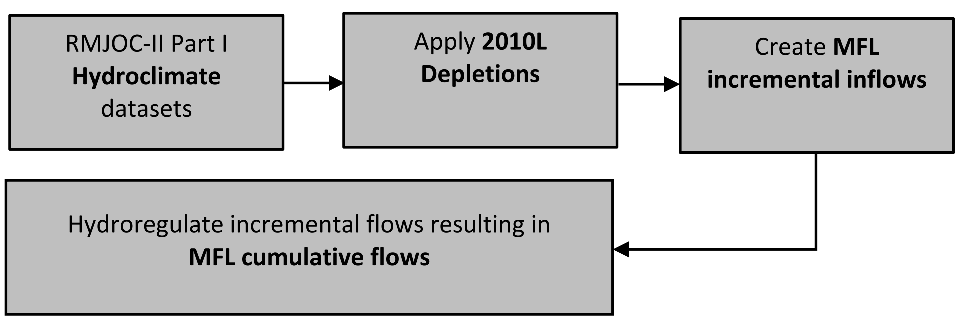

Figure 11. Flowchart of the streamflow development for the hydroregulation modeling process.

4.1 Baseline Historical Comparison Streamflow Datasets

To conduct comparative analyses, the RMJOC team developed current-condition historical baseline datasets. These datasets facilitate the comparison of current and future hydroclimates, identifying the potential climate change signal. The comparative analyses limit the introduction of hydrologic model bias on the climate change signal inferred from period-based comparisons.

The RMJOC-II project established four historical baselines (RMJOC-II Part I, Section 4.4). The historical simulations utilized the same gridded meteorological data developed by Livneh et al. (2013). The Variable Infiltration Capacity model (VIC, Liang et al. 1994) was used with three different parameter sets while the Precipitation Runoff Modeling System (PRMS) used one parameter set. UW developed historical streamflow datasets by forcing VIC and PRMS runoff models with the gridded data. We refer to the four baseline datasets by the corresponding hydrological model that was used for the simulation VIC_P1, VIC_P2, VIC_P3, and PRMS_P1. Choosing four historical baseline references removed the influence of hydrologic model biases on the results of epoch-based comparisons as these four hydrologic models were used for the future projections. RMJOC-II Part I more fully outlines biases identified in the projection development process in Section 4.1.2, "Systemic Biases in Modeling Framework and Historic Datasets."

As noted in Section 1.6.1, caution should be taken in comparing the total range of the four historical baselines to the range of future projections due to the amount of meteorological variability represented within each data source. With respect to meteorological variability, a major difference between the historical baselines and the future epochs is that for future epochs there are 10 different representations of meteorological variability (10 global climate models) that are represented 8 different ways (2 downscaling techniques, 4 hydrology models) for each emissions scenario. The historical base cases are limited to one sequence of natural variability represented with through 4 hydrology models. Ideally, the meteorological data for each historical baseline would come from the downscaled GCM historical period. This would result in a separate baseline for each of the 160 projections and increase the meteorological variability represented across an ensemble of historical baselines. Additionally, this would segregate any remaining biases introduced by the GCMs or downscaling methods. OSU downscaled and bias corrected the GCM output using the Livneh et al. (2013) meteorological dataset. The result of this bias correction and downscaling is that the monthly statistics of each projection in the historical period would be similar to the Livneh et al. (2013) dataset. Given this, the RMJOC team decided to reduce the amount of historical modeled baselines, focusing on representing each hydrologic model as the primary introduction of bias artifacts in period-based comparisons.

4.2 RMJOC-II Part I Hydroclimate Streamflow Datasets

UW produced an ensemble of streamflow projections spanning 1950 to 2099. The hydrological models used to generate the streamflow datasets simulate natural flow conditions. They do not include anthropogenic effects such as river hydroregulation or irrigation withdrawals for returns.

The RMJOC team ultimately used 160 projections (Figure 2, Section 1.6) as input to the WAT-ResSim, RiverWare, and MODSIM hydroregulation models. BPA also performed HYDSIM analyses using a subset of 19 of the 80 RCP8.5 projections, plus the four historical baselines. The smaller subset selection satisfied the specific purposes and needs to address RMJOC's salient concerns of projected future change for hydropower.

As detailed in RMJOC-II Part I, Section 8.2.2, the RMJOC team developed a technique to identify a subset of the ensemble of 80 RCP8.5 projections. The goal was to develop a select number of projections that capture key elements of potential changes in natural streamflow at key main stem, tributary, and headwater locations in the Columbia River Basin. Nonetheless, the selection of the subset might not fully represent the full range of future conditions at all sites in the basin. Furthermore, it is generally true that as a sample size increases, the findings become more statistically robust. Some differences between the hydropower subset metric statistics and the full 160 ensemble could likely be the result of the subset selection itself.

4.3 RMJOC-II Modified Flow-Like Dataset

The RMJOC-II Part I streamflow projections from UW represent natural conditions. RMJOC performs long-term planning studies and analyses using 2010L Modified streamflows. Modified streamflows are defined as historical streamflows that would have been observed if current irrigation depletions existed in the past and if the effects of river regulation were removed (RMJOC 2010). Modified flows represent simulated historical flow rates with depletion levels and loss rates as observed in WY 2008. They are the current basis for the majority of modeling and planning analyses for these RMJOC organizations and, therefore, are the reference point used by many regional modelers. The 2010L Modified Flows are defined for 80 years, WYs 1928–2008, for approximately 200 points in the Columbia River Basin.

For Part II of the RMJOC-II study, the 2010L depletion (the level observed in WY 2008) was applied to natural streamflow datasets produced by UW. This volumetric adjustment of the natural flow data was made for consistency with the assumed depletion levels of 2010L Modified flows used in other planning studies. The resultant RMJOC-II Part II hydroregulation streamflow datasets are termed *Modified Flow-Like* (MFL). Chapter 5.0 more fully describes the conversion of the UW "natural" flows to MFLs used in Part II. Chapter 5.0 also describes how data developed by Reclamation for the Snake above Brownlee, Yakima, and Deschutes Rivers were integrated into the suite of MFLs used for Part II hydroregulation modeling.

5.0 Conversion from Natural to Modified Flow-Like Flows

The 2010L Modified flows dataset (BPA 2011) is used by regional stakeholders that operate the FCRPS. The streamflow dataset is often used for planning and hydroregulation modeling studies. The 2010L NRNI streamflows dataset (RMJOC 2018) is a complementary dataset to the 2010L Modified flows. It represents the natural streamflow unaffected by human activity in the Columbia River Basin and other basins west of the Cascades, including the Willamette Basin.

RMJOC-II hydroregulation modeling require datasets spanning historical and future epochs. The resulting MFL dataset, the functional equivalent of the 2010L Modified streamflows, was created to meet this requirement. The UW natural flows were created as the first phase of the RMJOC-II study. The UW natural flows dataset serves as the basis of the MFLs. Unregulated MFLs were created from natural flows by applying current-level depletions and evaporation. The unregulated MFLs were then routed and hydroregulated to create cumulative the RMJOC II hydroregulated streamflow datasets. These were reported out for the historical, 2030s, and 2070s, 30-year epochs. This section describes the conversion process for converting natural flows to MFLs.

USACE and Reclamation each performed separate MFL conversions. Reclamation created regulated streamflows for the Snake River Basin above Brownlee Dam, the Deschutes River Basin, and the Yakima River Basin. Sections 5.2 and 5.3 describe Reclamation's assumptions for the development of MFLs. USACE created unregulated MFL streamflows for the rest of the Columbia River Basin. The development of regulated flows from Reclamation is consistent with the 2010L Modified flow process.

5.1 Methodology and Approach

Prior to the hydroregulation modeling, 160 natural streamflow projections were converted to MFLs that more closely resemble development assumptions and depletion levels from the 2010L Modified flows product. The conversion process also included creation of incremental daily MFLs. Resulting MFL incremental inflows were more consistent with observed local hydrology. A further constraint was to ensure that local inflow volumes were consistent with corresponding monthly total cumulative flow volumes.

USACE created MFL headwater and local incremental inflow datasets for WY 1950–2099. These incrementals were then routed (in WAT-ResSim) to create cumulative total MFLs. The total flows were created at the same locations as in the 2010L Modified flows dataset. The following equation identifies the primary components of an MFL streamflow dataset:

$$MFL = UW\ (N) + D\ (2010L) - E\ (2010L),$$

where

UW (N) = University of Washington, natural flows,
D (2010L) = irrigation depletions at 2010 levels, and
E (2010L) = evaporation at 2010 levels.

Table 1 below summarizes the data types used in the MFL development. The data types and nomenclature are consistent with those used in the 2010L Modified flows.

Table 1. MFL data types. (All use units of cubic feet per second.)

A—Average daily inflow into projects
L—Average daily local flow (incremental flow between adjacent stations or projects)
P—Average daily diversion to Banks Lake from Lake Roosevelt (via pumping)
G—Average daily diversion from Banks Lake to Lake Roosevelt (for generation)
ARF—Average daily unregulated flow based on Streamflow Synthesis and Reservoir Regulation (SSARR) routing
E—At-site evaporation (By convention, E is a positive value time series.)
D—At-site irrigation depletion (By convention, D is a negative value time series.)
EE—Accumulated evaporation for all upstream points
DD—Accumulated depletions for all upstream points

Source: BPA 2011

The irrigation depletions and reservoir evaporation values are detailed in the *2010 Level Modified Streamflow (1928–2008)* report (BPA 2011). Refer to Section 5.1.3 for additional detail on how this study specifically accounted for depletion and evaporation. Note that these values were not adjusted through the period of analysis to reflect changes in water use, crop type, or evapotranspiration.

USACE used a daily resolution HEC-ResSim model to create MFLs for the Columbia River watershed outside of Reclamation's tributary basins, the Upper Snake, Yakima and Deschutes Rivers. USACE requires a daily resolution to perform flood risk analyses. Upper Snake inflows were applied in the USACE modeling at Brownlee Dam on the Snake River. Yakima daily inflows were applied at the confluence of the Yakima River with the Columbia River while monthly average daily Deschutes River inflows were applied at the Columbia River, just upstream of the Dalles Reservoir.

At Brownlee Dam, USACE ran a daily ResSim model of the Upper Snake and then scaled the resultant Brownlee daily inflows so that USACE and Reclamation monthly volumes matched. For the other two Reclamation basins, daily Yakima inflows were input "as is" while Deschutes basin inflows were input as daily average flows for each month.

5.1.1 General Assumptions and Limitations

Understanding the assumptions and associated limitations of any dataset is important. Developing realistic and physically possible hydrology for the entire Columbia River Basin is challenging, especially when creating future streamflow projections. Development of this dataset used the following key assumptions:

1. Irrigation diversions are static and represent current-condition levels. They do not reflect future water and land use or cropping patterns. It is likely that agricultural practices will adapt with changes in climate. This may change the seasonal pattern of irrigation withdrawals and return flows. This would have the largest influence on modeled flows during the low flow season in smaller tributary systems where depletions represent a larger

fraction of instream flows. These changes are highly uncertain and the RMJOC team did not attempt to predict them.

2. Reservoir evaporation estimates are static through time and do not reflect the effects of increased temperature. However, historically, cumulative reservoir evaporation represents 0.24% of annual flow volume of the Columbia River at the Dalles on average. Climate change is not expected to change the relative contribution of evaporation on streamflow at the basin scale, however could be more influential at small reservoirs with shallow depths and limited inflow during the dry season.
3. Reservoir regulation for the Upper Snake, Yakima, and Deschutes River basins does not include water supply forecast uncertainty, which can affect both high- and low-flow regulation. For example over-forecasts could lead to failure to refill, reducing water available for summer augmentation, intensifying reductions in low flows. Under-forecasts could lead to increased flood peaks as less storage for inflow would be available during flood events. The relative volume of flow from the Yakima and Deschutes tributaries has little influence on the system scale analyses presented in this report. The relative role of the Upper Snake can be a larger component for low flows in the lower Snake River.

5.1.2 Generation of Local (Incremental) Inflow from UW Total Flows

Incremental local inflow time series were created at 87 locations. USACE used the routing VIC (RVIC) streamflow routing model (Lohman et al. 1996; Hamman et al. 2017) to route runoff and baseflow simulated by the VIC and PRMS hydrological models provided by UW in a 1/16-degree resolution gridded format. Runoff and baseflow volumes were routed for each reach in the ResSim reservoir model that require local flow input. These time series were then adjusted so that the monthly flow volumes matched those in the bias-corrected cumulative flow datasets provided by UW. **Figure 12** illustrates this process.

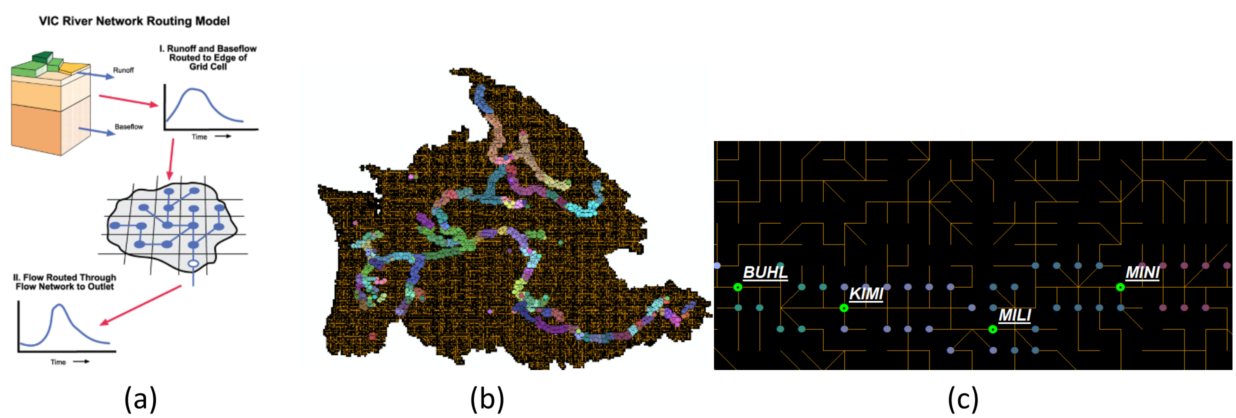

Figure 12. (*a*) Conceptual schematic of the RVIC routing process, (*b*) river reaches where local flow was simulated are denoted with different colors, and (*c*) an example of the Columbia River Basin routing network and local inflow points in the Upper Snake.

Generating the MFL incremental flows included the following steps:

1. Run the RVIC routing model for each local inflow reach using the VIC and PRMS gridded runoff and baseflow fields as input. This results in daily incremental inflow time series (not bias corrected).
2. Calculate monthly local inflow volume from bias-corrected UW total cumulative flows.
   Monthly incremental inflow volume = Downstream – Upstream
3. Adjust daily time series in step 1 to match monthly volumes in step 2.

UW applied a statistical bias-correction technique termed BMORPH to the simulated cumulative flow time series where corresponding NRNI data were available. BMORPH was derived from the bias-correction methodology of Pierce et al. (2015) and removes systematic biases of the daily streamflow while maintaining the ratio of the projected changes in annual volumes from the uncorrected hydrological model simulations. This bias correction was applied independently for each cumulative flow time series; the method does not consider conservation of mass between up- and downstream locations. Therefore, it may introduce mass inconsistencies between cumulative flow and cumulative flow from routed incremental flow. Overall, these mass inconsistencies are minor.

The process result was a dataset of incremental inflow at the daily step. The flow data have a daily hydrograph shape consistent with local hydrology and monthly volume consistent with bias-corrected total flow time series. USACE applied depletions to these local flow time series, then the ResSim model was used to route the incremental and Reclamation flows to create MFL total flows. The routing reflected does not explicitly include the effects of natural lakes.

5.1.3 Depletions and Evaporation

2010L irrigation depletion and reservoir evaporation rates (BPA 2011) were applied to the base UW natural flows to create MFL streamflows. The current-level depletions were applied by site and over all water years.

Historical irrigation withdrawals and return flows were derived using individual state and federal diversion reports along with streamflow gage records from the U.S. Geological Survey and from other available sources. The irrigation withdrawals were calculated using U.S. Department of Agriculture sprinkler and gravity depletions and monthly rates of depletion and returns and then applied on a daily time step for each month. Calculations were performed to add back the net loss volumes from estimates of historical daily depletions and return flows. Canadian site depletions were developed in a similar manner.

The MFL evaporation and transpiration time series accounts for differing vegetative cover before and after dam construction. In most cases, construction of a dam increases evaporation from the reservoir area through evaporation from the water surface. However, in some localized cases at northern latitudes where reservoirs replaced dense forests, evaporation from reservoir surfaces is less than evapotranspiration of the natural forested pre-dam surface condition (BPA 2011). In these cases where there was a change in local evaporation and transpiration numbers, postconstruction conditions showed gains in water.

5.1.4 Routing Incremental MFLs

USACE routed the headwater and incremental MFL flows using an unregulated HEC-ResSim model of the Columbia River. This model routed reaches for all locations outside of Reclamation basins (i.e., Upper Snake, Yakima, and Deschutes River basins). The ResSim routing model emulated the SSARR method to simulate cumulative MFL flows throughout the river network. USACE SSARR was the method used to route flows for 2010L Modified Flow and NRNI development. By incorporating SSARR routing parameters, the HEC-ResSim model was able to route and aggregate daily MFL headwater and incremental flows.

> The SSARR routing method is a “cascade of reservoirs” technique, wherein the lag and attenuation of the flood wave is simulated through successive increments of lake type storage. A channel can be visualized as a series of small “lakes” which represent the natural delay of runoff from upstream to downstream points.

The USACE ResSim model accounted for Reclamation basin outflows as inflow boundary conditions. Yakima daily flows were incorporated directly into the USACE ResSim model at the Yakima and Columbia Rivers confluence (i.e., just upstream of the McNary Dam reservoir). Deschutes River flows were incorporated into the ResSim model where the Deschutes River contributes to The Dalles pool (e.g., Lake Celilo). The Deschutes streamflow dataset was a monthly average format. Therefore, the data were converted to flat monthly average flows and brought directly into the ResSim model. Upper Snake flows were incorporated as Brownlee Dam inflows.

5.1.4.1 Grand Coulee Dam—Banks Lake Pumping

Grand Coulee Dam creates Lake Roosevelt, which provides irrigation water supply for the Columbia Basin Project and is managed by Reclamation. Water from Lake Roosevelt is pumped to an off-stream holding reservoir named Banks Lake, where outflows are used to meet irrigation demands. Reclamation provided the net pumping rates for Banks Lake used in MFL development. The annual net pumping at Grand Coulee is 3.3 Maf, representing the maximum annual amount that can be used for irrigation and M&I purposes. Previous net pumping used in the 2010 Level Modified flows was estimated to be about 2.9 Maf based on a 5-year average of actual deliveries.

The Banks pumping depletion was included in the routing model as a ResSim diversion object, defined between Banks Lake and Grand Coulee pool. It was defined with a seasonal flow table, representing the 14-period pump-out rates. This implementation is graphically shown in **Figure 13**.

Date	Diversion(cfs)
01Jan	57.0
01Feb	173.1
01Mar	1634.1
01Apr	7384.4
15Apr	8013.2
01May	8371.5
01Jun	8780.6
01Jul	9888.8
01Aug	7611.8
15Aug	5076.4
01Sep	6236.7
01Oct	4886.0
01Nov	457.7
01Dec	239.3

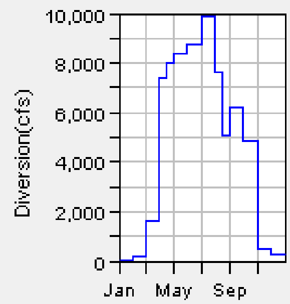

Figure 13. ResSim Banks Lake diversion schedule.

5.1.4.2 HEC-ResSim Natural Lakes Effects

The Columbia ResSim models were originally configured to run "natural lakes" because USACE had found that these locations could cause significant downstream attenuation. To be as comparable as possible to 2010L Modified flows, RMJOC decided that the natural lakes effect should not be included. Therefore, the influences of flow attenuation by the six locations listed below were removed from the unregulated WAT-ResSim modeling:

- Upper Arrow Lake
- Lower Arrow Lake
- Kootenay Lake
- Flathead Lake
- Lake Pend Oreille
- Lake Coeur d'Alene

5.1.5 Development of Daily Brownlee Reservoir Inflow Time Series

Brownlee inflow is a required upstream boundary condition for the USACE's Columbia River Basin WAT-ResSim hydroregulation model. WAT modeling required that the MODSIM flat monthly Brownlee flows be converted to a daily increment with a seasonally realistic hydrograph shape. This was particularly important for FRM modeling, which depends on accurate peak flow magnitude and timing accuracy.

To accomplish this, the modeling team created a daily Brownlee cumulative inflow by routing Upper Snake basin headwater and incremental flows through an existing Upper Snake (daily) ResSim model. Routing and regulation of daily incremental flows through the various Upper Snake projects would produce realistically regulated flow hydrographs at Brownlee. The final step of creating a viable input time series for WAT-ResSim was to scale the resulting daily flows such that the sum of ResSim daily flow volumes matched the Brownlee monthly volumes produced by Reclamation. **Figure 14** shows the Upper Snake ResSim model structure.

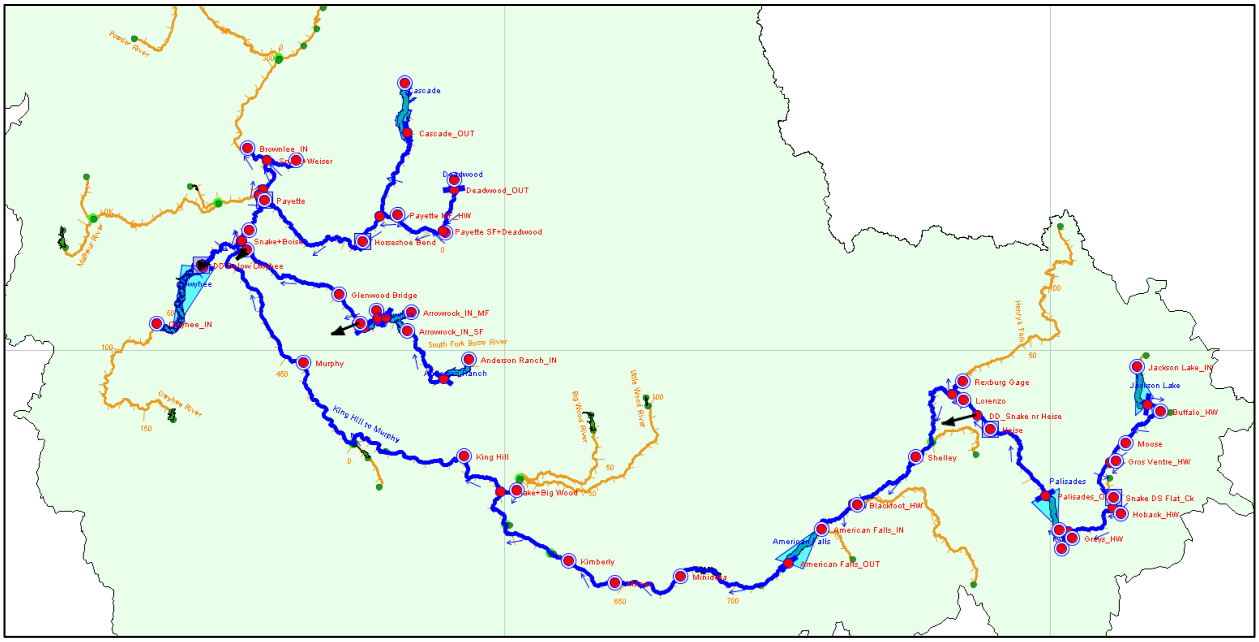

Figure 14. Upper Snake ResSim model, node, and reach locations.

The first step of the USACE process was to create MFL incrementals and route them to produce a daily hydrograph at Brownlee Reservoir. This time series was then shaped and scaled to match Reclamation's monthly flow volumes. **Table 2** below identifies the date through July forecast sites used by the Upper Snake upper rule curve model. Future year flows were used for water supply forecasts. Yakima flows were derived from Reclamation-provided data.

Table 2. Upper Snake ResSim.

Site	Name
HEII	Snake River near Heise, Idaho
LUC	Boise River Lucky Peak Inflow
HBD/HRSI	Payette River near Horseshoe Bend, Idaho
AMFI	Snake River at Neeley American Falls Inflow

USACE generated regulated ResSim daily flow time series for the Upper Snake. The outflow from Brownlee Dam is an important input for the MFL flows on the Snake River. Transitioning from the regulated monthly flows to daily values downstream required development of a process that conserved volume and provided realistic hydrograph shapes. To accomplish both of these criteria, the monthly flow time series was disaggregated to daily flows using the USACE Upper Snake ResSim model. The steps used in the disaggregation process are described below:

1. Input daily incremental MFL flows into the Upper Snake ResSim model.
2. Run the model and convert Brownlee daily inflow to monthly volumes.
3. Calculate the ratio of Reclamation monthly volume to ResSim monthly volume for each month in the record.
4. Multiply the ResSim daily flow by the ratio found in step 3 for each corresponding month.
5. Apply simple monthly boundary smoothing to remove end-of-month discontinuities.

6. Repeat steps 1–5.

Volume Scaling*:*

Daily Scaled = ResSim daily × (Reclamation Monthly Volume / ResSim Monthly Volume)

Smoothing:

End of Month (EOM) Smoothing = $(3*Q_{EOM} + Q_{FOM})/4$

First of Month (FOM) Smoothing = $(Q_{EOM} + 3*Q_{FOM})/4$

5.2 Reclamation Process for Generating Upper Snake Future Modified-Like Flows

Modified flows, as computed by Reclamation, are the historical unregulated monthly streamflow adjusted to reflect what would have occurred with 2010L reservoir regulation and 2010L demands. Reclamation produced these flows for the Upper Snake using a monthly MODSIM model of the basin.

Modified flows are generated using the following generalized process:

1. Unregulated reach gains and losses in the basin are developed using measured historical data (the process for each basin closely follows what is outlined in Reclamation, 2017).
2. Reclamation depletions were applied to select locations in the Upper Snake. Depletions reflected current-level conditions.
3. The regulation model is updated to include current-level reservoir operations.
4. The unregulated reach gains and losses are input into the model along with the current-level demand pattern. The output is an MFL future streamflow dataset.

For the future climate scenarios, gains and losses were calculated from natural RMJOC-II flows. Reclamation did this for each reach modeled in MODSIM by subtracting the upstream flows from the downstream flows between gages. The gains and losses for each of the 160 projections were input to 2010 Modified Flows MODSIM model. Then steps 2 through 4 were repeated. The output from these model runs at Brownlee was supplied to USACE for their analysis.

5.3 Reclamation Process for Generating Yakima and Deschutes River Basins Future Modified Flows

Reclamation computed the Modified Flows for Deschutes and Yakima using the same process outlined in Section 5.2. The Deschutes was modeled with a monthly MODSIM model with demand patterns representing 1993–2004. The Yakima was modeled with a daily RiverWare model with demand patterns representing 1991–2004. For the Deschutes and Yakima, three demand patterns were developed for years ranging from dry to average to wet.

Additionally, for the Yakima, the average and wet year diversion curves were used during non-drought years while the dry-year curves were used in the drought years for the non-prorated water and to limit the prorated water. The prorated water diversion was the minimum of either the dry-year curve or the prorated entitlement.

Similar to the process for the Upper Snake described in Section 5.2, the future climate scenario gains and losses were calculated from natural RMJOC-II Part I flows. This was done for each reach modeled in MODSIM or RiverWare by subtracting the upstream flows from the downstream flows between gages. The gains and losses for each of the 160 projections were input to the 2010 Modified Flows MODSIM model for the Deschutes and to the 2010 Modified Flows model for the Yakima. Then steps 2 through 4 were repeated. Reclamation supplied to USACE for their analysis the output from these model runs at Lake Billy Chinook on the Deschutes and Kiona on the Yakima.

5.4 Summary

Development of a future RMJOC-II MFL streamflow dataset was necessary for hydroregulation modeling of Columbia River reservoir system operations. The dataset was derived from UW natural streamflows (RMJOC 2018). They were converted into MFLs by including 2010L irrigation and evaporation rates. Resultant MFL inflows were then used as input to the ResSim and HYDSIM models (see Section 3.0) to perform hydroregulation given future climate conditions. The model results were used to determine both flood risk, hydropower, and water supply estimates for the Columbia River. Validation and quality checks were made during the MFL development. MFL results were validated by volumetrically comparing them with 2010L Modified Flow datasets (BPA 2011). The result was a characterization of result differences deemed within allowable error (0-3% annual volume) by the product development team. Results of the MFL development along with water supply volume forecasts (see Section 6.0) were used in the next steps of the hydroregulation analyses process.

6.0 Water Supply Forecast Development

6.1 Introduction

As described in Chapter 3, forecasts are an important part of overall operation of the Columbia River reservoir system. Unlike many rain-dominated systems, Columbia River flows derive mostly from snowmelt in higher elevations of the watershed, meaning snowpack is the primary input variable for water supply forecast models. Over the last several decades, studies have worked to quantify forecast uncertainty based on model type (Druce 2001) and to define accuracy limitations when using snowpack as an input variable (Lettenmaier 1984). In addition, studies have shown that forecast skill changes as hydroclimate variability increases. Pagano et al. (2005) found a decreasing forecast skill in the Columbia River Basin that may be related to increased streamflow variability. Changes to streamflow variability and persistence (consecutive wet or dry years) can also impact the forecast model skill (Pagano and Garen 2005).

Understanding how future hydroclimate trends will influence forecast accuracy in the Columbia River Basin is important. There have been many studies evaluating streamflow forecasting methods, accuracy, and sensitivities to changes in the hydroclimate (Li et al. 2010; Lehner et al. 2017). Fewer studies have quantified how climate change will affect forecasts in combination with reservoir operations. The forecasts created in the first RMJOC climate change study provide some information on how water supply forecasts will be affected in the future (RMJOC 2011a). Overall, there are limited studies that have attempted to quantify changes in forecast skill by using a robust set of hydroclimate projections. This RMJOC-II Part II study addresses these knowledge gaps for the Columbia River Basin.

In this study, 160 hydrologic projections based on various combinations of modeling chain elements (**Figure 2**) were used to create seasonal streamflow volume forecasts. These forecasts and associated forecast model errors were used directly by the reservoir models for determining operations (e.g., storage levels and outflows). A summary of the forecast locations, methods, skill and uncertainty are discussed in subsequent sections.

6.2 Forecast Locations

Figure 15 shows the nine forecast locations most critical for operations of the Columbia River reservoir system. Other locations are certainly important for local water supply allocations or recreational interests, but the nine locations selected are the primary projects that determine system operations for FRM, hydropower, water supply, and in-streamflow forecasts for meeting flow objectives and project purposes.

A variety of physical characteristics across the basin create unique hydrologic signatures for each of the forecast locations. Each of the hydrologic signatures will influence the forecast skill in this analysis. Factors that will influence the hydrologic signature of the basin include total precipitation timing and depth, snowmelt, land cover, and average soil moisture conditions. For example, the baseline hydrologic signature for the Columbia River at The Dalles includes a snowmelt peak in the late spring and early summer, which generates the majority of streamflow volume for the year. This is followed by a relatively long hydrograph recession down to a relatively steady baseflow condition through the summertime.

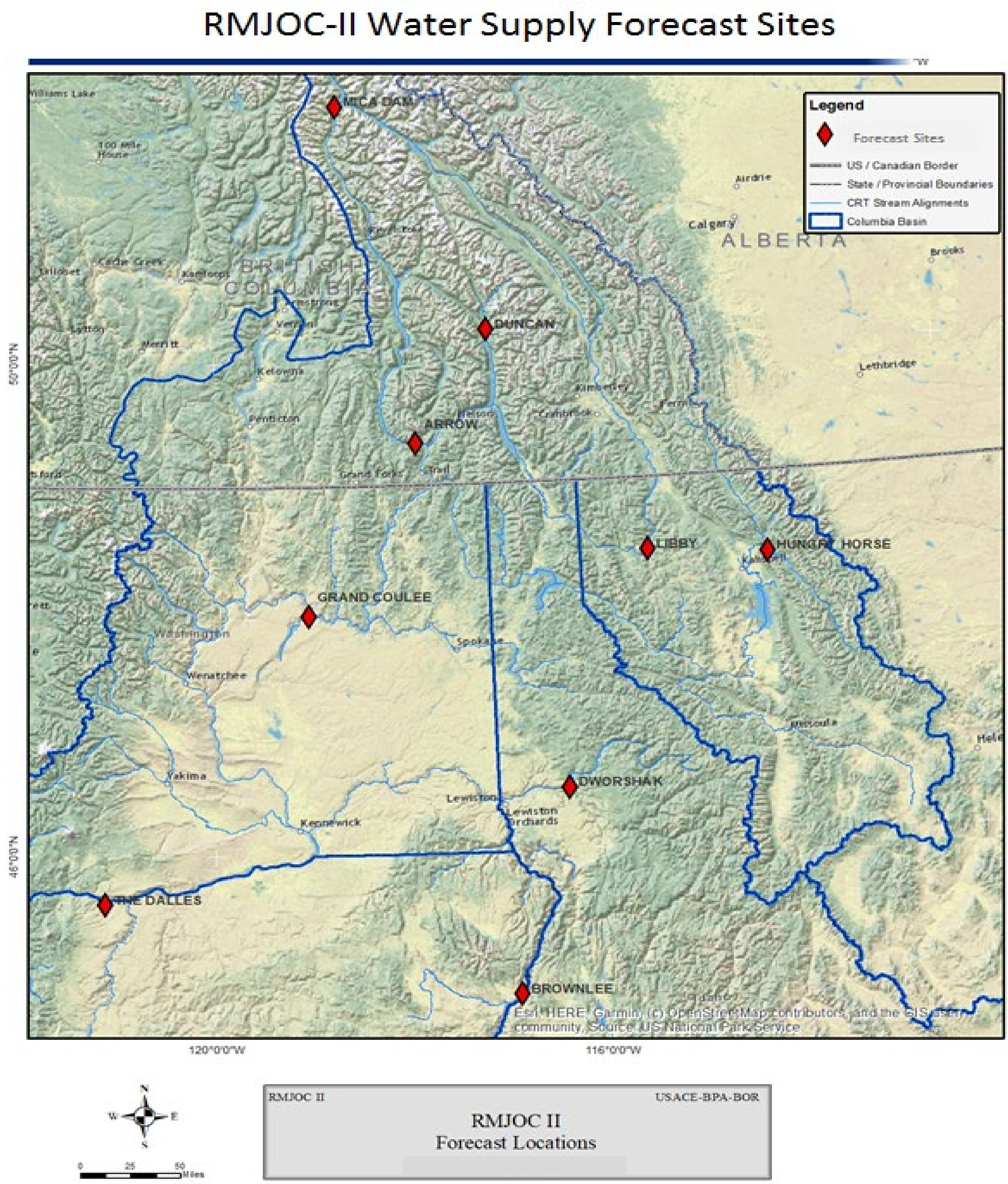

Figure 15. Water supply forecast locations.

6.2.1 Data

The data used for this analysis consisted of snow water equivalent (SWE) values generated from the VIC and PRMS hydrologic models, downscaled precipitation from GCMs, and the MFL streamflow time series described in Chapters 4 and 5. Precipitation and SWE values were both used as input variables for development of the statistical forecast modes, while the MFLs were temporally aggregated (e.g., January–August, April–July, May–September, etc.) to create the streamflow volumes used in model training. Each hydrologic projection had a unique SWE time-series output based on the modeling chain combination, while the precipitation values were common to multiple projections from the same GCM. Precipitation varied depending on the GCM and downscaling method while SWE varied depending on GCM, downscaling method, hydrologic model, and parameterization. Details about how each of these datasets is used in the forecasting analysis is summarized in Sections 6.2.2.

We performed initial investigations to determine if spatially averaged SWE and precipitation or if using individual grid cells representing ground-based stations (e.g., SNOTEL, automatic weather stations) should be used as input variables. In contrast to RMJOC (2010), we found the correlation between spatially averaged SWE and precipitation and MFL were higher and produced forecast skill that was more consistent with current real-time forecast skill. Furthermore, the spatial area represented by a model grid cell (1/16 degree) does not represent point locations of measurement stations that are located within a grid cell.

The data produced in the MFL development is substantial. The data used and subsequently produced during the forecast model development was even more extensive. Therefore, terminology is important when discussing the water supply forecasts for this study. **Table 3** defines terms commonly used in the forecast development discussion.

Table 3. Forecast development terminology.

Term	Definition
Training Period	Set of water years used to optimize the parameters of the statistical forecast model
Forecast Period or Simulation Period	Years used in the hydroregulation modeling (e.g., 2030s or 2070s)
Volume Period	Set of months where the MFL flow volume is temporally aggregated within a single water year
Forecast Month	Month the forecast is issued using SWE and precipitation information only up to that date

6.2.2 Snow Water Equivalent

Spatially averaged SWE values were computed using the National Hydrography Dataset watershed boundaries for each area upstream of the forecast location. Unlike precipitation, there was no temporal aggregation. The SWE values used to develop the forecast model were end-of-month values. These represent the basin SWE conditions at the beginning of a time step from when the forecast was developed. For example, the forecast model for April 1 used the spatially aggregated SWE values from midnight on April 1 for that projection. Again, each hydrologic projection had a unique SWE gridded time series associated with it because this variable was generated using hydrologic model algorithms.

Figure 16 shows an example watershed boundary and SWE grid (1/16 degree spatial resolution) for the Kootenai River basin. Grid cells with zero SWE values were also included in the spatially averaged result but do not have any shading in the example plot.

Basin averaged SWE values were used to train the forecast model and subsequently to produce the forecast values for each location and month during the forecast period (e.g., 2030s or 2070s). Forecast model performance depends on the degree of correlation between the input and output variables for both the training and forecast periods. Increased correlation will result in better forecast accuracy. The correlation between SWE and MFL volume was computed for each projection. The strength of the correlation varied substantially between projection, forecast location, and forecast period. To illustrate this point, **Figures 17** and **18** are flows at the Columbia River at the Dalles from the projection (RCP4.5 CNRM-CM5 BCSD VIC P1) for forecasts periods 2030s and 2070s, respectively. The correlation between SWE and streamflow for the 2030s (**Figure 17**) indicates minimal change in the correlation between the training (1991–2019) and forecast period (2020–2049). In contrast, the 2070s modeling (**Figure 18**) shows a relatively large decrease in correlation between the training (2030–2059) and forecast period (2060–2089) with an R^2 of 0.82 and 0.69, respectively. This change in correlation impacts the forecast error and, potentially, hydroregulation for the reservoir system.

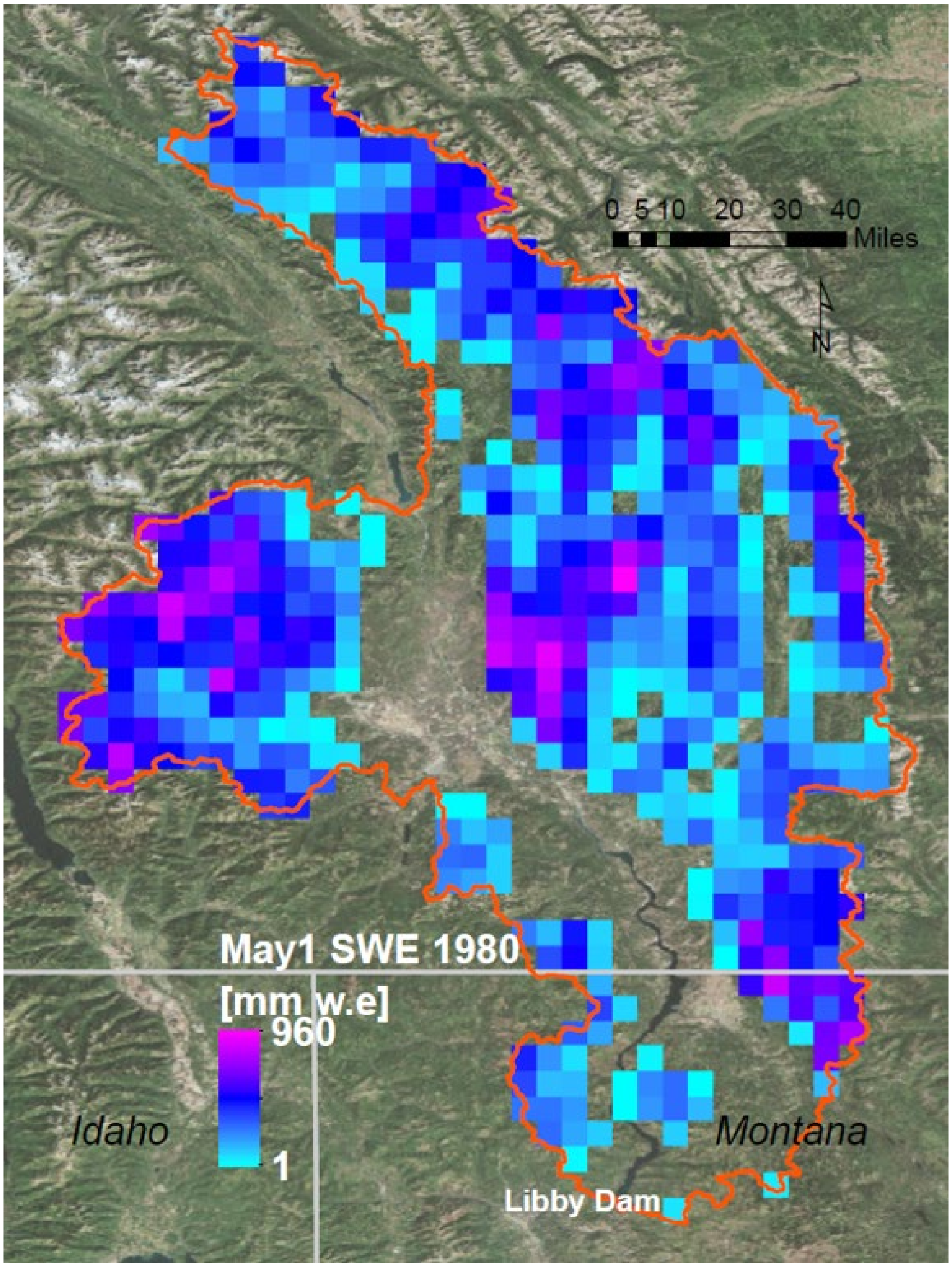

Figure 16. Example of the SWE dataset used in the basin-averaged calculation.

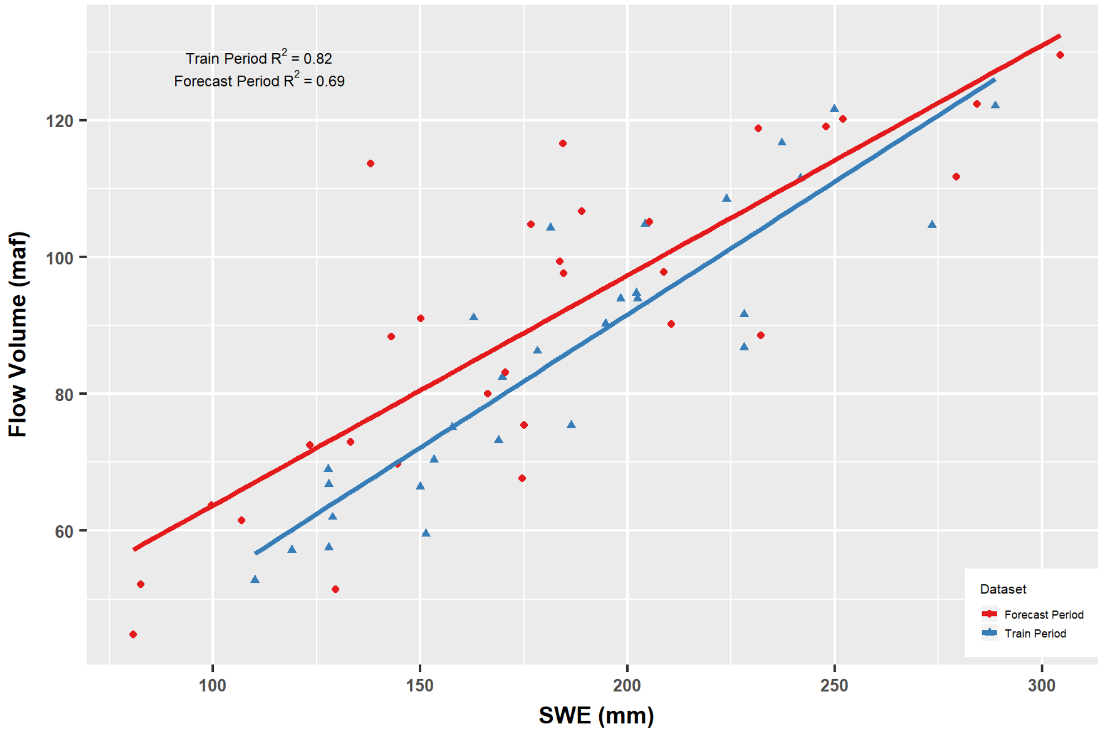

Figure 17. Example correlation of 1 April SWE and April–August MFL volume of the Columbia River at The Dalles, Oregon for 2030s training and forecast periods (RCP4.5 CNRM-CM5 BCSD VIC P1).

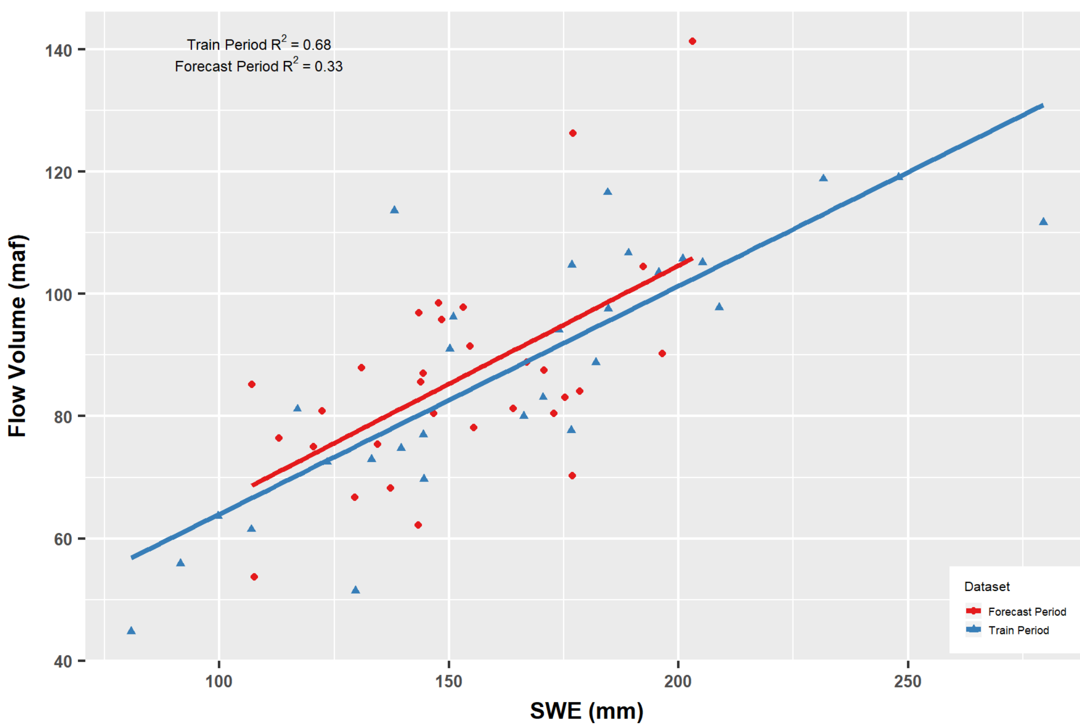

Figure 18. Example correlation of 1 April SWE and TDA April–August MFL volume for 2070s training and forecast periods (CNRM-CM5 RCP4.5 BCSD VIC P1).

6.2.3 Precipitation

UW provided the downscaling of precipitation from the GCMs. The downscaling process disaggregated gridded output from the respective GCMs to create the 1/16° resolution grid inputs for both the VIC and PRMS hydrologic models. To create the inputs for the statistical forecast model, we spatially averaged and temporally aggregated the downscaled precipitation grids to create an accumulated total seasonal precipitation time series. The temporal aggregation of precipitation was based on the month for which the forecast was being generated. For example, the April 1 forecast used November 1 through March 31 accumulated precipitation.

The precipitation time series were unlike the SWE datasets in that they were an input variable rather than an output variable for each hydrologic model used in the development of streamflow projections. Precipitation varied only by RCP, GCM, and downscaling method. This resulted in the same precipitation values being used to force both the VIC and PRMS hydrologic models. **Figures 19** and **20** show the correlation between spatially averaged accumulated precipitation and streamflow for the drainage area of the Columbia River at the Dalles, OR (TDA) for a single streamflow projection (CNRM-CM5 RCP4.5 BCSD VIC P1). Again, changes in the correlations between the training and forecast periods influenced the forecast error, which will be summarized later in this section. For this hydrologic projection, the correlation for the forecast period (R^2 = 0.85) is greater than for the training period (R^2 = 0.72) for the 2030s. The correlation between accumulated precipitation and April–August flow volume was very similar for the training and forecasts periods with R^2 = 0.68 and R^2 = 0.69, respectively.

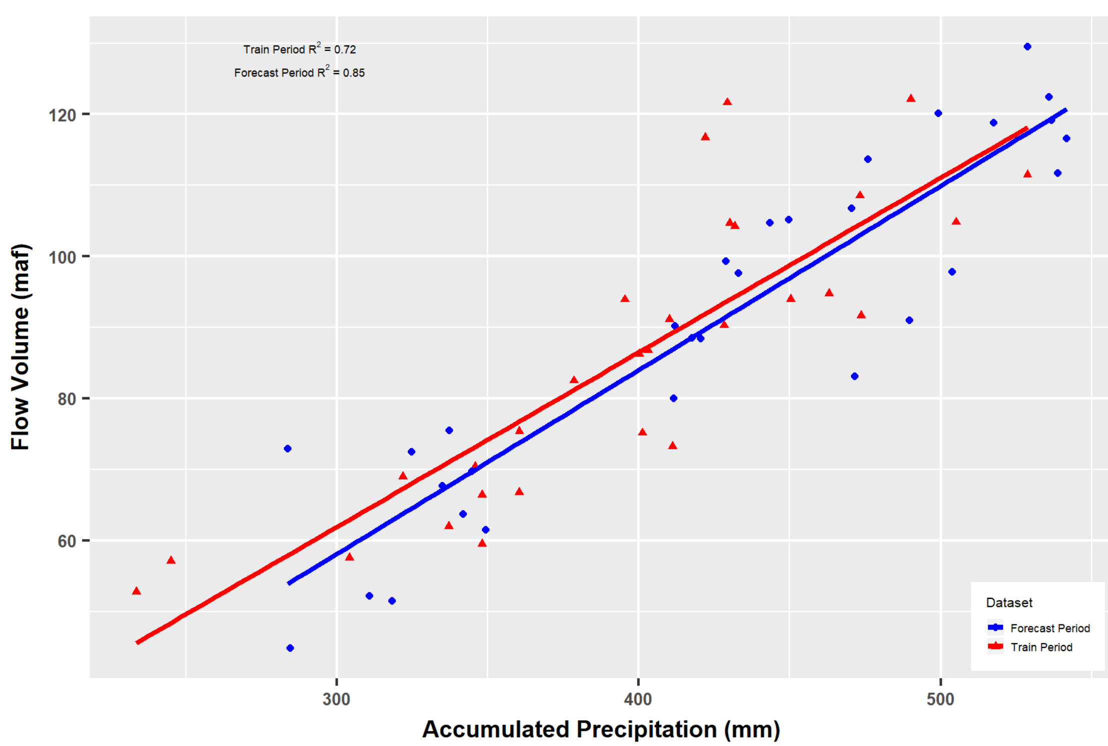

Figure 19. Example correlation of November–April accumulated precipitation and TDA April–August MFL volume for 2030s training and forecast periods (CNRM-CM5 RCP4.5 BCSD VIC P1).

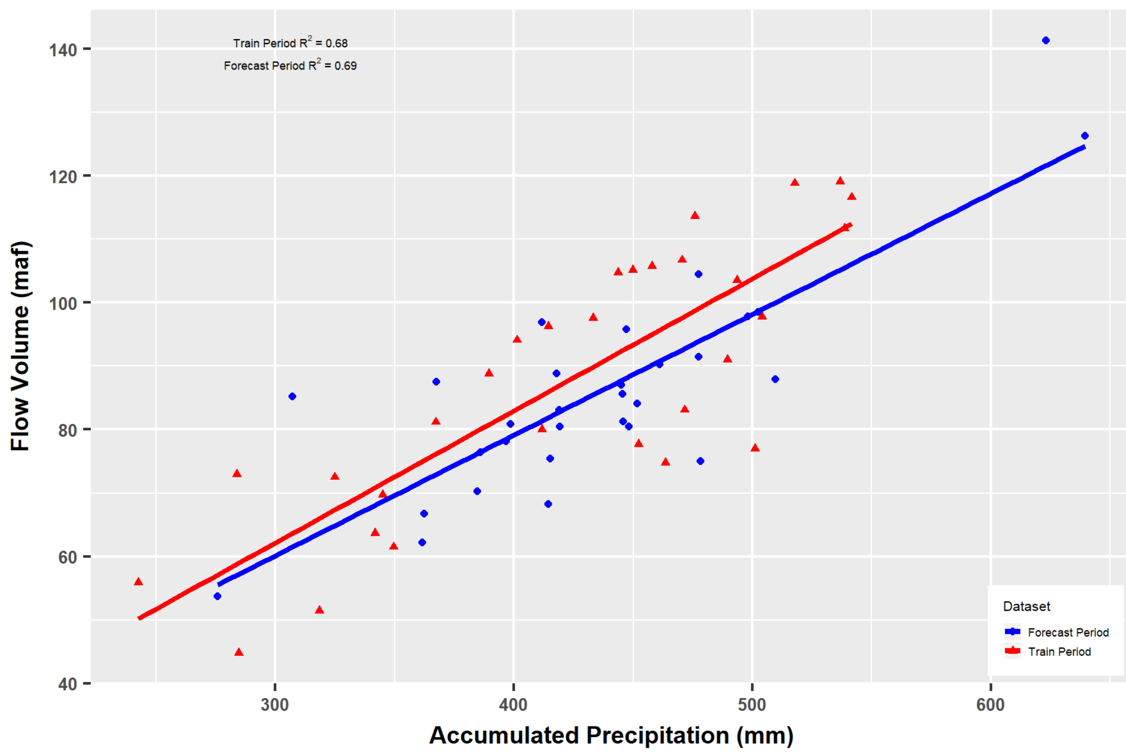

Figure 20. Example correlation of November–April accumulated precipitation and TDA April–August MFL volume for 2070s training and forecast periods (CNRM-CM5 RCP4.5 BCSD VIC P1).

6.2.4 Streamflow

The streamflows used for this analysis are the MFLs datasets described in Chapter 5.0. We developed these flows using a daily time step. Therefore, to derive seasonal volumes, daily flow rates were converted to volumes and summed over various periods (e.g., April–July, May–September). Forecast models were trained by seasonal MFL volumes, resulting in a forecast model for each season.

6.3 Methods

Various methods have been used to create water supply forecasts for both planning and operational studies. Until recently, statistical models were the primary tool for creating forecasts used in the Columbia River system. These statistical models were all based on regression methods that use variables such as precipitation, snow water equivalent and antecedent runoff as inputs. The other choice for developing water supply forecasts is to use ensemble streamflow prediction models, which use an assumed starting basin condition (i.e., initial snow water equivalent, soil moisture, etc.) and apply historical precipitation and temperature sequences in a hydrologic model to generate streamflow. This method has found success for real-time water management; however, hindcast frameworks for historical planning studies are less common.

Development of water supply forecasts for this analysis was based on a principal component regression process using accumulated precipitation and SWE spatially averaged over each forecasted drainage area. Principal components regression is a well-established forecast procedure used in the Columbia River Basin by the Natural Resources and Conservation Service, National Weather Service (Garen 1992), BChydro, Reclamation, BPA and USACE, and a straightforward multivariate method. The advantage of using principal components for this study is that highly correlated variables such as accumulated precipitation and SWE do not increase the variance of the regression coefficients as a result of multicollinearity. A brief description of the principal components process is provided in this section, followed by details related to the specific training and forecast datasets that were used.

The basic concept of principal components regression is to create indices (Z_1, Z_2, Z_p) that are a linear combination of p input variables X_1, X_2,…, X_p (see equation [1] below). For this study the input variables for forecast development are time series of accumulated precipitation and SWE. The indices or components are ordered so that Z_1 displays the largest amount of variation and Z_2 contains the second most variation. Additional components contain subsequently less variation or, in other words, var(Z_1) ≥ var(Z_2) ≥ … ≥ var(Z_p).

$$Z_i = a_{i1}X_1 + a_{i2}X_2 + \cdots + a_{ip}X_p, \tag{1}$$

where a_{i1}, a_{i2},…, a_{ip} are elements of the corresponding eigenvector. The eigenvector elements are constrained by $a_{i1}+a_{i2}+\ldots+ a_{ip} = 1$ (Manly and Navarro Alberto 2017). For additional information related to the principal components calculations and process, see Manly and Navarro Alberto (2017).

Once the principal components are computed, then linear regression between the components (Z vectors) selected and the dependent variable (streamflow volume) is performed. The coefficients for this regression then become the parameters for the statistical model used to generate the forecasts. For this analysis, the R library “pls” was used to create the principal components and to perform cross validation on the training-period data (Mevik et al. 2019).

The statistical forecast models for this study were intended to reflect processes currently used by USACE and Reclamation to create water supply forecasts. Conceptually, as water managers update statistical models, they will be using the most recent historical information available. Therefore, in our analysis, the most recent period prior to the simulation (forecast) period was used for model training. Once the statistical model parameters for each location were found using this training data, we did not make additional updates during the forecast period. In other words, the forecast model for each location was trained only once for each 30-year simulation (e.g., baseline, 2030s, and 2070s). **Table 4** lists the training and forecast periods for the baseline, 2030s, and 2070s simulations.

Any location in the hydroregulation modeling not shown in **Figure 15** simply used accumulated streamflow from the hydrologic projection to represent a forecast volume. This primarily includes the Upper Snake Basin above Brownlee Reservoir and the Yakima and Deschutes River basins. No forecast error was considered for these locations.

Table 4. Training and forecast periods used for seasonal volume forecasts.

Simulation Name	Training Period (WY)	Forecast Period (WY)
Baseline	1951–1975	1976–2005
2030s	1991–2019	2020–2049

2070s	2030–2059	2060–2089

6.4 Results

This analysis produced time series of water supply forecasts for each location and hydrologic projection. Each of these time series, along with the forecast error values, were used by hydroregulation models, HYDSIM, and WAT-ResSim models. A comparison between the historical baseline and future projections indicates how forecast error will change in the future. The focus of this section will be forecast results for all 160 hydrologic projections discussed in RMJOC Part I (RMJOC 2018). These results represent one forecasting technique, under one set of assumptions (e.g., training period, input variables). Other forecast methods exist and could result in a different outcomes.

The volume magnitude of forecast error can be important for many flood risk and hydropower operations. Changes in the forecast error distribution could result in more frequent occurrences of under- or over forecasting the seasonal water supply. The forecast error statistic often used is the cross-validation standard error (Abudu et al. 2010). This statistic represents the training error for the statistical model by using the leave-one-out average sum of squared errors.

The absolute magnitude of the forecast error can also be normalized using the seasonal flow volume for each year in the hydrologic projection. This provides a relative comparison that is independent of increasing or decreasing flow-volume trends. **Figure 21** shows the normalized forecast error at The Dalles for the April–August forecast. The hydrologic conditions wet and dry represent the highest and lowest 20 percent of forecast period volumes for each RCP and simulation period. The average plot includes the rest of the water years. Underforecasts are represented by negative error and overforecasts by positive error. When interpreting the range of error, it should be noted that the sample sizes of data vary between historical and future composites. The range of the historical data from the four baselines included is smaller and includes far less meteorological variability than the future composites. The results of the relative forecast error indicate two key points: (1) compared to the historical baseline, there is increased error early in the forecasting season (i.e., January) for the dry and wet water years; and (2) even during average water years, the relative forecast error for February–May, which have the least relative error in the historical baseline, are greater in future periods.

The average hydrologic conditions for the historical baseline indicate a similar range of error for each forecast month but shift in the median value. Overall, the historical baseline indicates an underforecasting trend for February, March, and April during average water years. When we compare the underforecasting trend for the future periods (2030s and 2070s) to the historical baseline, there is a shift from underforecasting April–August volume to an overforecast situation. This is attributed to not updating the equations through the 30 year period. Through the course of the 30 year period some of the spring runoff volume shifts earlier, outside of the April-August forecast window. Since the equations were trained on the 30 years prior to the 30 year simulation period, they tend to over predict volumes toward the end of the simulation period. The range of error for each forecast month is similar between the wet and average years. However, the range is much greater for the dry years.

Another important difference that can be gleaned from **Figure 21** is the change in median forecast error. The median error for average water years is generally close to zero. In contrast, the median error for wet years shows a tendency to underforecast while dry years tend to overforecast. This difference may be due to several reasons. The most basic is the statistical model will often underforecast wet conditions and overforecast dry water years. This statistical model characteristic are likely exaggerated for the transient hydrologic projections used in this study.

For all hydrologic conditions (e.g., wet, average, and dry), the range of forecast error varies substantially between RCP, period, and water year type when compared to the baseline. The 2030s forecast error distribution is generally greater than the historical baseline for all forecast months and hydrologic conditions. In dry years, the 2030s forecast error range is greater than the 2070s for January and February forecast months. During the 2030s under the RCP8.5 emissions scenario, the forecast error distribution is very similar to the 2070s for both March and April in all hydrologic conditions.

Another explanation for forecast error changes is the transient hydrology in each projection. Increased transient signals in the training-period hydrology will result in increased forecast error because of the correlation between flow volume and forecast inputs. Furthermore, as the hydroclimate conditions change and more runoff comes from rainfall instead of snowmelt, the correlation coefficient values with antecedent SWE and accumulated precipitation will decrease. The results of our analysis indicate substantial decreases in correlation coefficient values between input variables and flow volumes when comparing the historical baseline and future projections (**Figure 22**). The decreased correlation values within training periods would indicate that less of the seasonal volume variance is being explained by the SWE and accumulated precipitation input variables. The overall distribution of correlation coefficient values is reduced for the 2070s simulation period. Specifically, the median values for SWE in April and May are substantially decreased for the RCP8.5 emissions scenario.

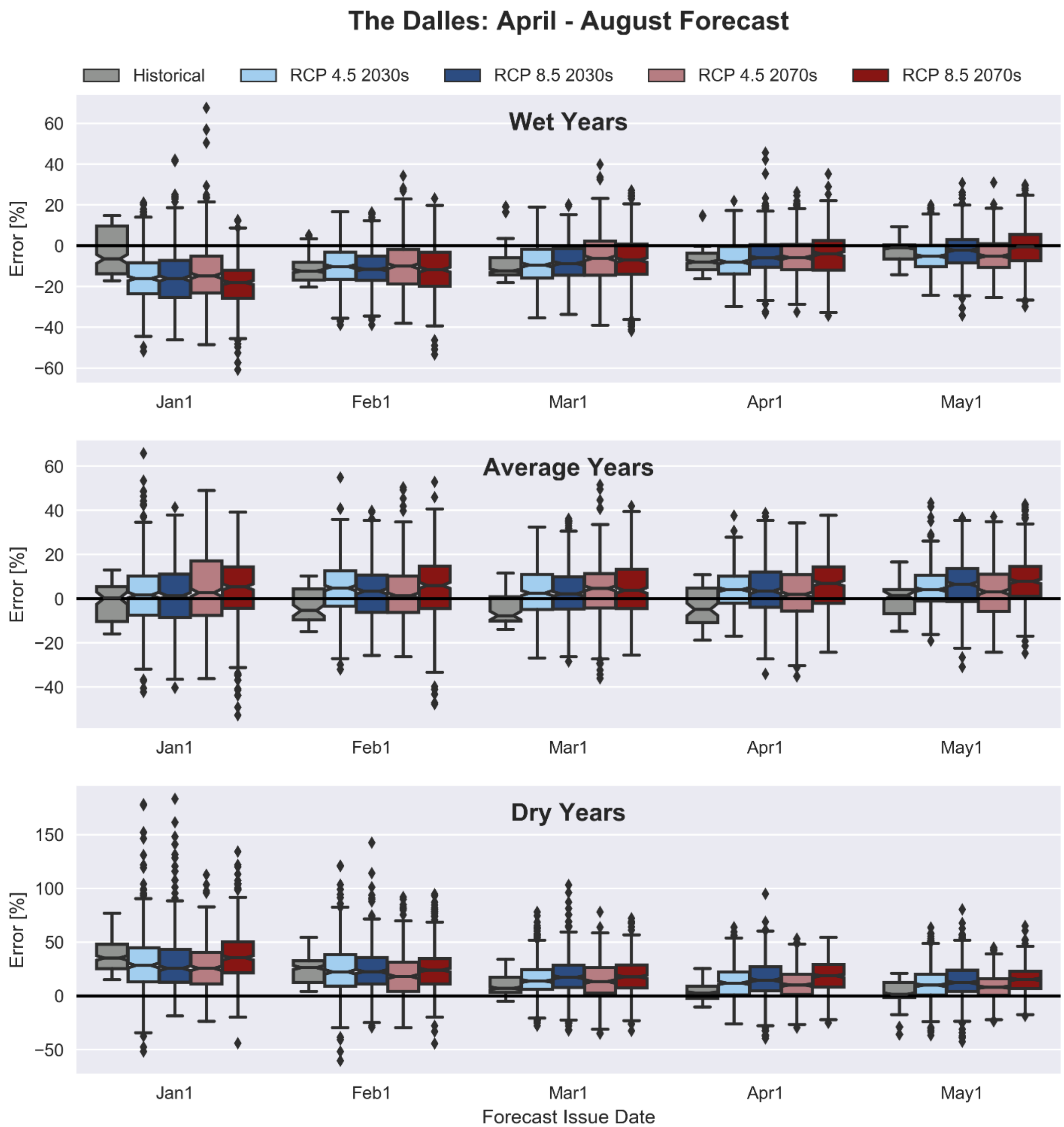

Figure 21. The Dalles relative forecast error for April–August volume.

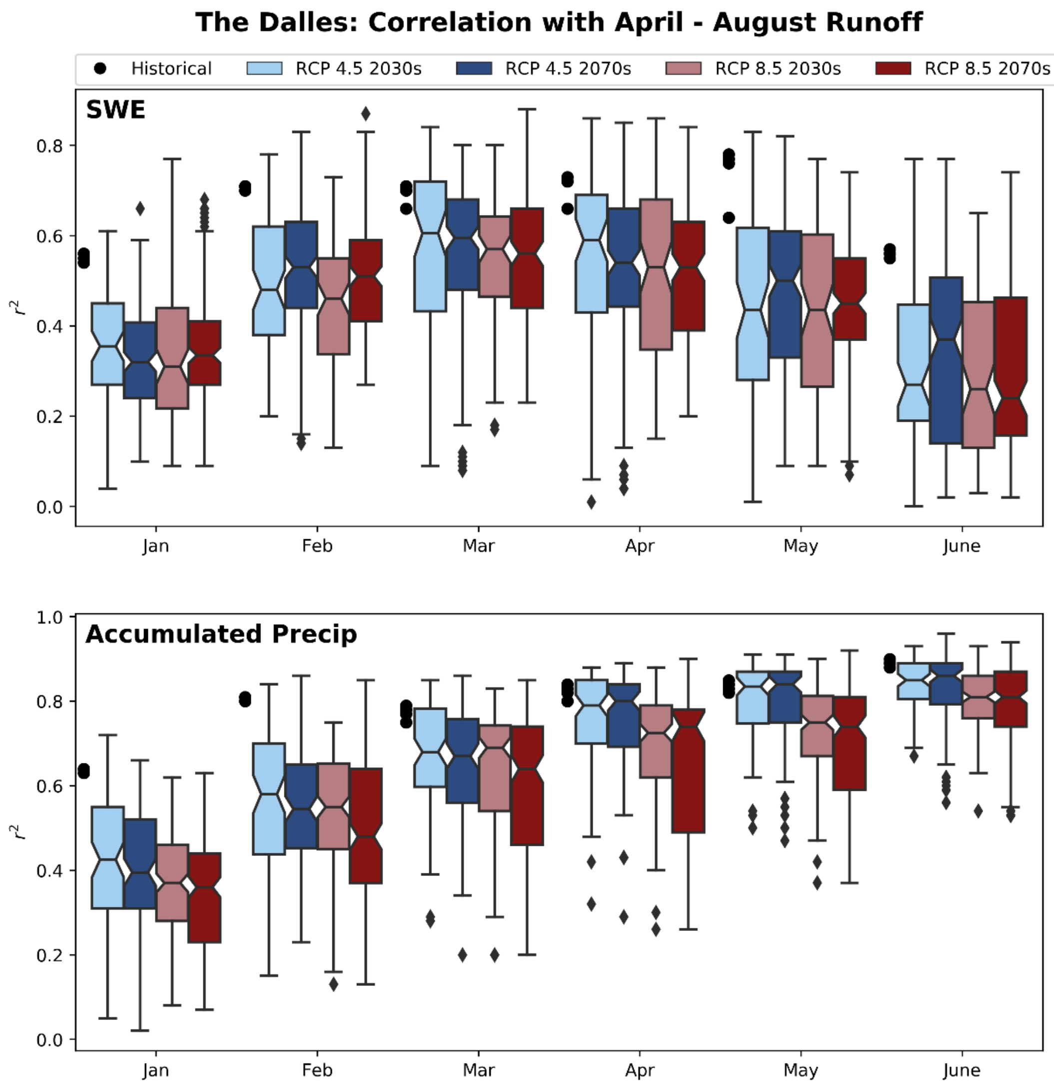

Figure 22. TDA correlation coefficient values between SWE and accumulated precipitation for April–August volume.

6.5 Summary

Development of seasonal volume forecasts will continue to be utilized to inform Columbia River reservoir system operations. Statistical forecast models will still be used to determine both flood risk and water supply estimates for the Columbia River. Our analysis uses the aforementioned assumption that statistical water supply forecast methods will continue to be used for operating the hydrosystem. Therefore we evaluated how well long-established statistical forecast models will perform with transient climate conditions. Statistical methods, machine learning, and ensemble streamflow prediction techniques continue to advance. Future efforts evaluating forecast skill under climate change could evaluate multiple methodologies and advances in forecast technologies.

Using basin-averaged precipitation and SWE values is representative of many spatial products that are currently available. The primary difference is that all ground-based and remote-sensing data have measurement uncertainty. This was not considered for our analysis because the precipitation and SWE values used to generate the streamflow are known exactly from the model chain output. Thus, all the forecast error for the seasonal volume forecasts is due to land surface processes in the hydrologic model and future precipitation changes, and effects of bias correction of streamflow.

Results of the volume forecasts indicate that changes in forecast error are related to shifts in both SWE and precipitation. This is likely due to the transition to winter precipitation being rain as compared to water stored in snowpack. Because of the transient climate signals used in the GCM models, the transition from snow to rain will be most prevalent in the 2070s across the watershed while some low-elevation locations may reflect this transition by the end of the 2030s. The change in forecast error distribution by the end of the 2070s will vary between location and hydrologic condition. As rainfall becomes a larger input to the seasonal runoff volume, the forecast error will increase, which will impact operational decisions for the FCRPS. These results represent the outcome of the single statistical method employed in this study, however, may be generalized to other methods that are reliant on the correlation of SWE and streamflow volume.

7.0 Summary of Projected Regulated Flows and Reservoir Storage

This chapter summarizes the projected flow rates and reservoir elevations at 12 reservoirs and downstream sites of importance and interest to system operations. These locations correspond to projects and downstream points with characteristics that relate to the objectives of the FCRPS (e.g., storage, power generation, critical flow constraints, etc.).

We conducted the summary analysis for monthly inflow, outflow, and end-of-month reservoir elevation simulated by the USACE WAT-ResSim model using the Columbia River Systems Operations Environmental Impact Statement "No Action Alternative" model operations. See Appendix A for further details of the WAT-ResSim model and modeled operations. Results from Reclamation MODSIM simulations were used for three locations in the Upper Snake River: Palisades, American Falls, and Brownlee Reservoirs. The results in this chapter represent the entire ensemble of 160 projections.

The RMJOC team developed statistical measures to represent median, high, and low conditions over the historical and future epochs. These conditions are represented by the 50th percentile (median value), 90th percentile value (high, value greater than 90 percent of other values), and 10th percentile value (low, value less 90 percent of other values) for the 30-year period of analysis for each time increment (month). For example, for the spring period where many reservoirs draft for spring FRM, the 10th percentile elevation value represents the deepest drafts for spring FRM in years with large snowpack that drives large water supply forecasts. The 10th percentile elevation value during summer, when most reservoirs are typically full, would reflect the driest conditions during the 30-year epoch, as reservoirs would struggle to refill, stay full, or have deeper summer drafts with decreased inflows. A further description of the graphical approach for presenting these projections is provided in Chapter 1.0.

The largest ranges of projections of monthly flow volume are for the months of May through July. This is also common for the 4 historical baselines. For the historical baselines these differences can be attributed to differences in flow timing between the hydrological models and parameterizations (see RMJOC-II Part 1 Section 4.1.2, "Systemic Biases in Modeling Framework and Historic Datasets."). The differences in flow timing can have a large influence on end of month reservoir elevations during the refill period.

The remainder of this report uses reservoir regulation terminology. *Draft* refers to lowering reservoir elevations. When drafting a reservoir, outflow is greater than inflow. This can reserve space for flood storage or release stored water to augment downstream flow. *Refilling* is when the reservoir captures water; outflow is less than inflow, increasing the elevation and stored water. Reservoirs often refill to capture inflow during flood events or to store water for conservation use later in the water year. When outflow from hydropower reservoirs is released through an outlet structures other than the hydropower turbines, this flow is *spill*.

The purpose of this Chapter is to summarize regulated flow projections. The chapter includes qualitative descriptions of the main patterns of projected change for each location. The patterns that we identified and discuss below are those with a strong consensus between projections that the future condition is different relative to the historical baselines. Specific impacts on system objectives are described in Chapters 8.0 through 12.0 of this report.

7.1 Mica Dam and Kinbasket Reservoir

7.1.1 Inflow

Inflow to Lake Kinbasket is not regulated by upstream dams. The projections indicate that inflow is to remain near historical values during winter months (November–March) through the 2030s epoch and to increase in the 2070s epoch under RCP8.5 (**Figure 23**). During the spring snowmelt freshet (May–June), 90th percentile flows are projected to increase in the 2030s and continue to increase in the 2070s. The models also project median May flows to increase in the 2070s, across both emissions scenarios. July–October statistical metrics show continued reductions in inflow through both emissions scenarios and epochs. Projected reductions are largest for median flows in the 2070s under RCP8.5. The shift to earlier inflow timing from July to June is evident in these projections with the largest seasonal peaks more concentrated in June.

7.1.2 Outflow

The model projects regulated outflow from Mica Dam to follow the same seasonal patterns, displaying high outflows in winter (December–February) and summer (July–August; **Figure 24**). The model projects the largest increases in outflow for median and high flow during April, June, and July. The largest reductions in outflow are during August for low, median, and high measures. Significant reductions in Mica's outflow in August are a product of reduced inflows and the August reservoir elevation requirement specified in the model.

7.1.3 Reservoir Elevation and Storage

The elevation of the water surface of Lake Kinbasket is projected to be lower than historical during September–January for median and low statistical measures (**Figure 25**). This period of projected decreases in pool elevations includes July and August for the 10th percentile elevation metric. The amount of reduction in pool elevation and the range of projections are largest for the 2070s epoch, particularly under RCP8.5. Reduced inflow in September and October with similar assumed outflow requirements leads to lower pool elevations carried throughout the fall. The general pattern of the draft for spring snowmelt remains consistent through historical and future epochs. The projections for deep drafts (10th percentile) are generally not as deep as historical baselines, whereas shallow drafts (90th percentile) are shallower during the 2070s, particularly under RCP8.5. Refill is projected to begin earlier with progressively higher pool elevations through the 2030s and 2070s epochs for May and June.

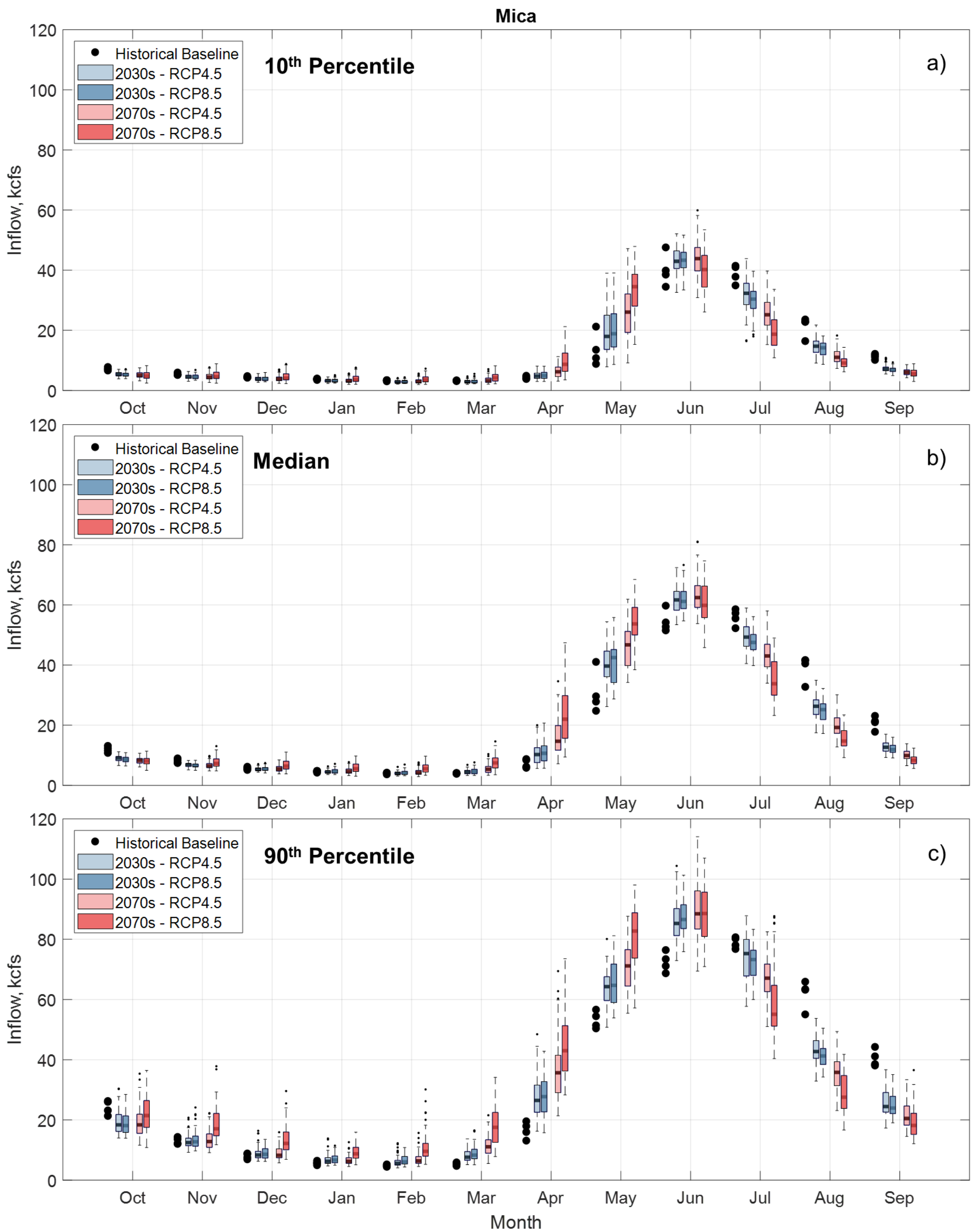

Figure 23. Projected monthly summary statistics for inflow at Kinbasket Reservoir: (*a*) monthly 10th percentile inflow, (*b*) monthly median inflow, and (*c*) monthly 90th percentile inflow.

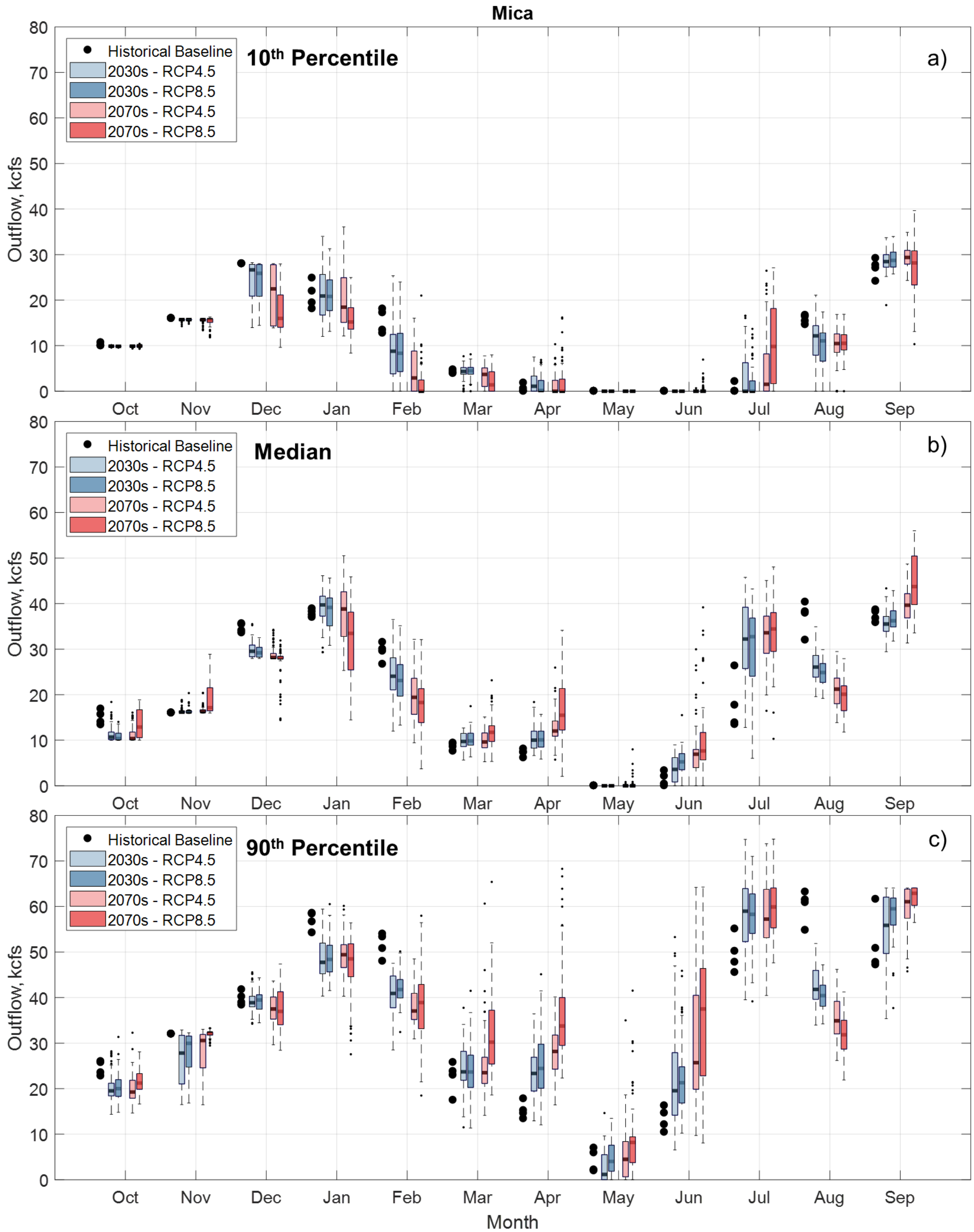

Figure 24. Projected monthly summary statistics for outflow from Mica Dam / Kinbasket Reservoir: (*a*) monthly 10th percentile outflow, (*b*) monthly median outflow, and (*c*) monthly 90th percentile outflow.

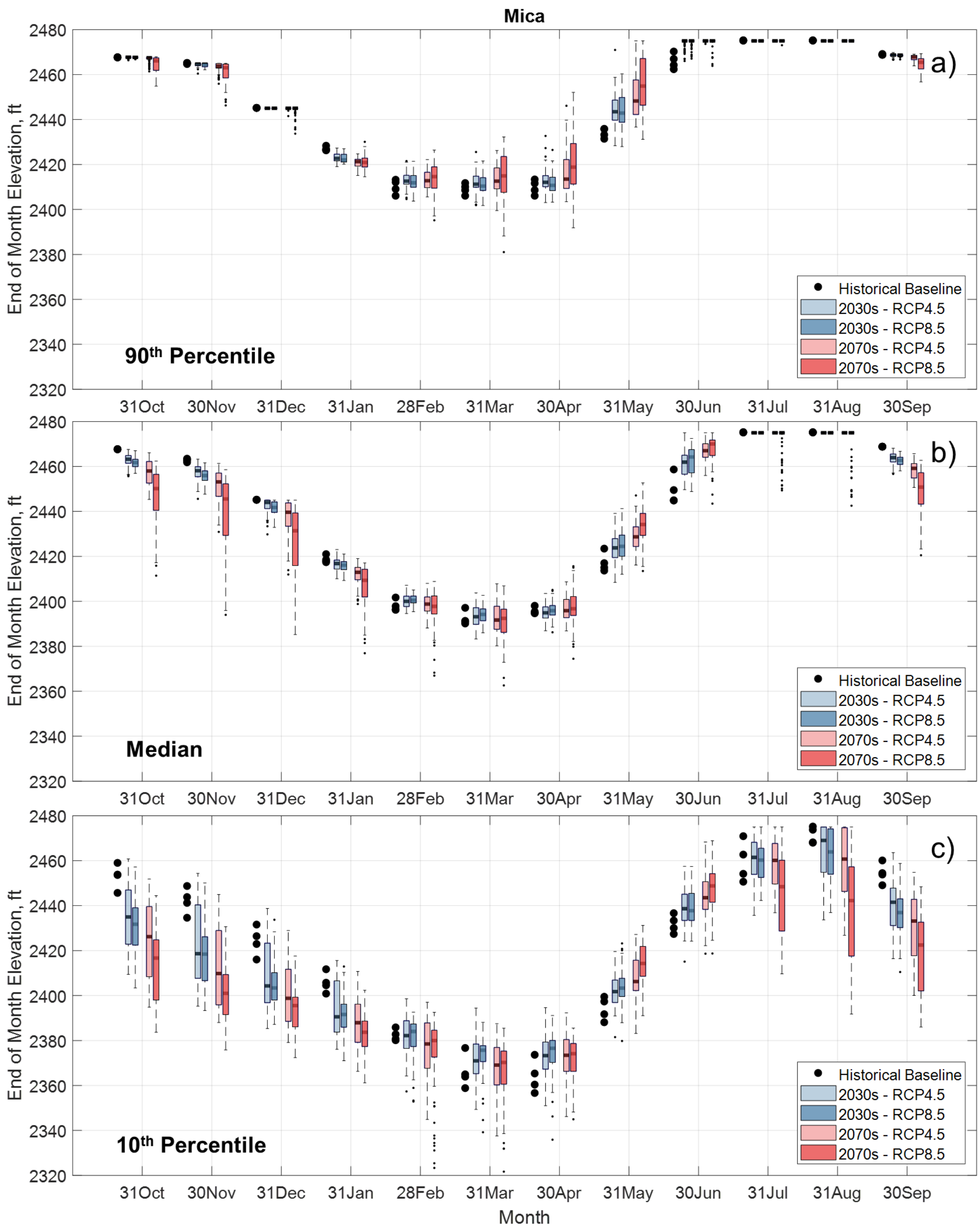

Figure 25. Projected monthly summary statistics for end-of-month elevation of Kinbasket Reservoir: (*a*) 90th percentile end-of-month elevation, (*b*) monthly end-of-month elevation, and (*c*) monthly 10th percentile end-of-month elevation.

7.2 Keenleyside Dam and Arrow Lakes Reservoir

7.2.1 Inflow

In this modeling, Arrow Lakes inflow (**Figure 26**) is the sum of outflows from Mica Dam and local inflow between Mica and Keenleyside Dams (Revelstoke Dam is run-of-river). During fall and winter (September–February), minor changes or reduced inflow is projected for median flow conditions. During November and December in the 2070s, increased inflow is projected for high-flow conditions, particularly under RCP8.5. Inflow is projected to increase through time for April and May, with the largest increases occurring in April. Nearly all projections for both periods and emissions scenarios indicate large decreases of inflow during August.

7.2.2 Outflow

Outflow is projected to be progressively less than historical base conditions for August–December for low and median conditions (**Figure 27**). High outflow conditions are projected to increase under RCP8.5 for December. The largest increases in outflow are projected in March, May, and June for all flow statistics.

7.2.3 Reservoir Elevation and Storage

The median seasonal pattern of elevation of Arrow Lakes Reservoir is projected to be similar to historical in the 2030s with the exception of the end of January and end of March (**Figure 28**). The projections indicate higher pool elevations at the end of January and lower pool elevations at the end of March. These patterns are projected to persist in the 2070s, however with reduced pool elevations June–October. Arrow's low elevation in August in the 2070s is a response to decreasing inflow from reduced outflows of Mica as it maintains a full reservoir (Section 7.1.2). The projections of reduced pool elevations in June–October are further amplified under low-pool conditions (10th percentile). A large range of 10th percentile end-of-month elevations was modeled for both historical and future conditions. During periods of low flow, discrete thresholds in forecasted volumes drive different uses of stored water in Arrow Lakes. Small differences in forecasted volumes for dry years can lead to relatively larger difference in reservoir elevation.

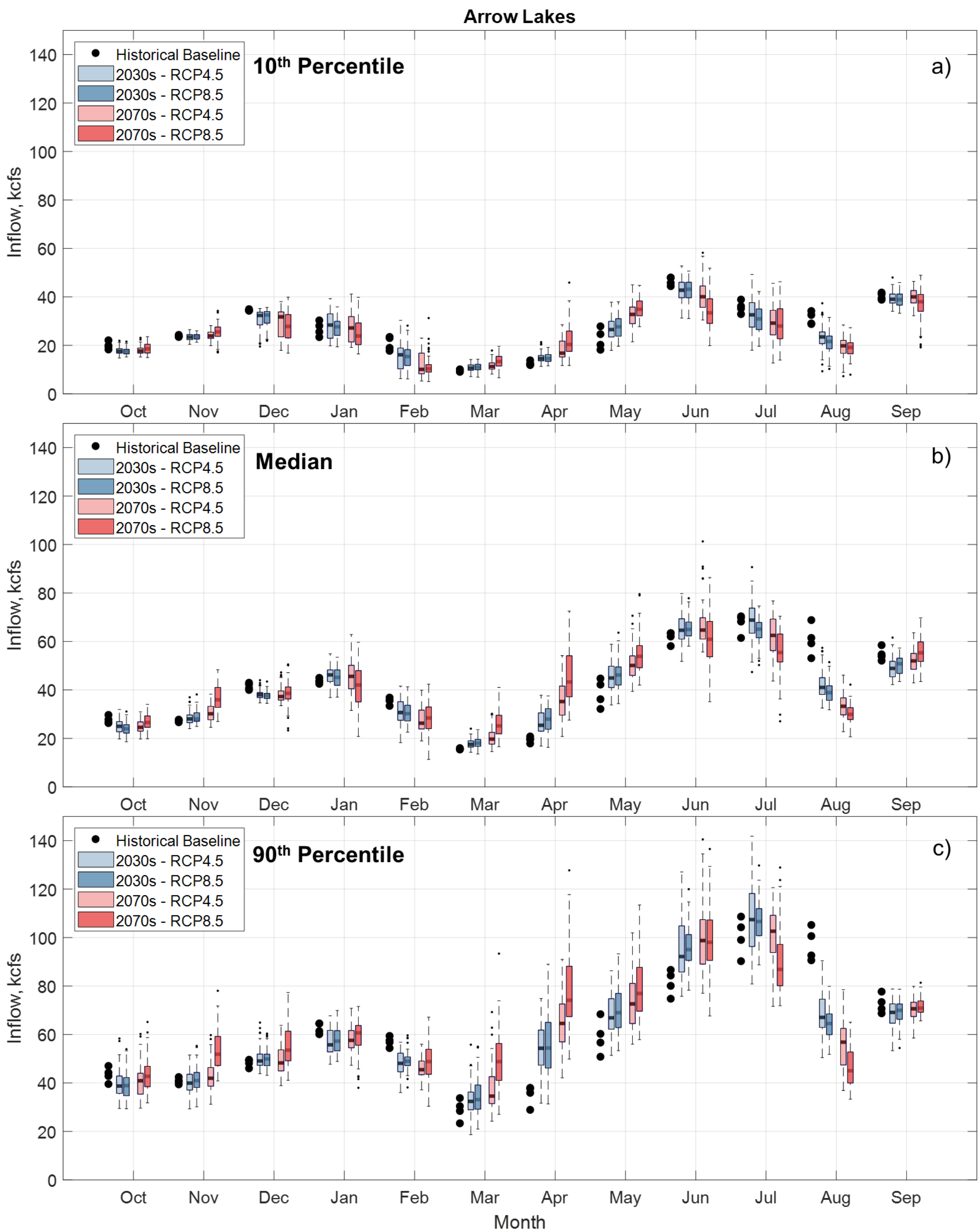

Figure 26. Projected monthly summary statistics for inflow to Arrow Lakes Reservoir: (*a*) monthly 10th percentile inflow, (*b*) monthly median inflow, and (*c*) monthly 90th percentile inflow.

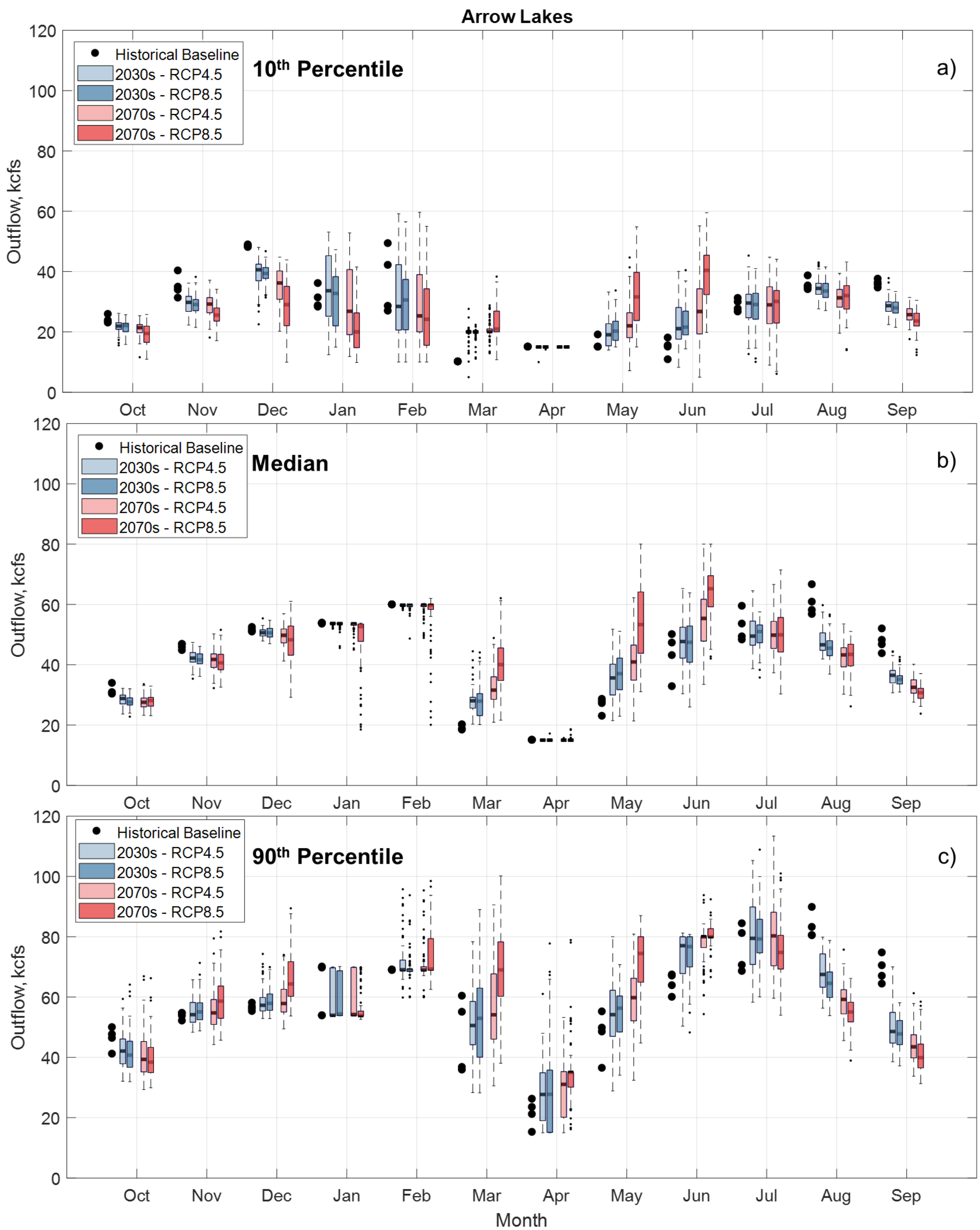

Figure 27. Projected monthly summary statistics for outflow of Arrow Lakes Reservoir: (*a*) monthly 10th percentile outflow, (*b*) monthly median outflow, and (*c*) monthly 90th percentile outflow.

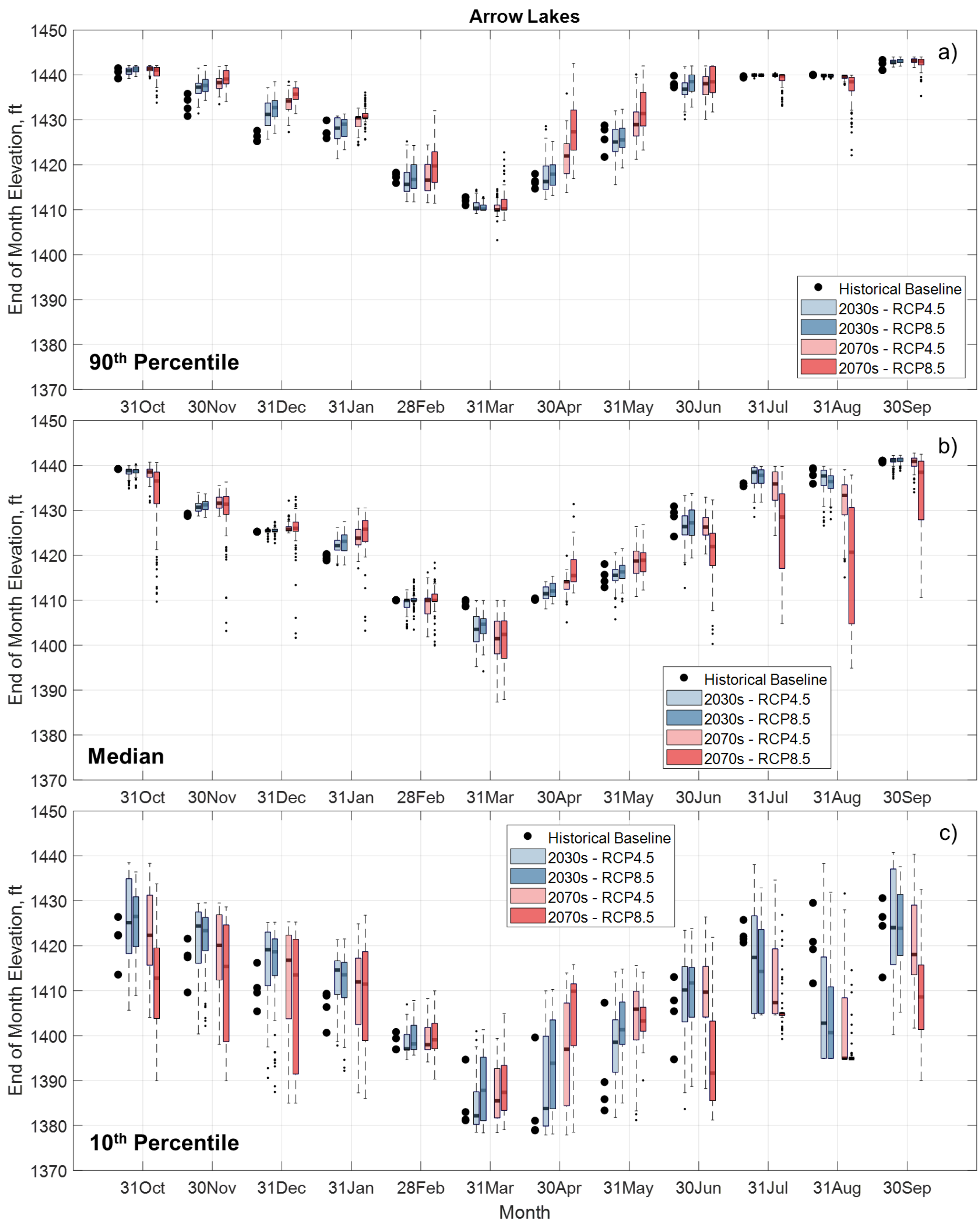

Figure 28. Projected monthly summary statistics for elevation of Arrow Lakes Reservoir: (*a*) 90th percentile end-of-month elevation, (*b*) monthly end-of-month elevation, and (*c*) monthly 10th percentile end-of-month elevation.

7.3 Libby Dam and Lake Koocanusa

7.3.1 Inflow

Median monthly Inflow to Lake Koocanusa is projected to remain similar to historical levels in October–February for both future epochs and emissions scenarios (**Figure 29**). As inflow timing shifts earlier, increased inflow is projected for March–May. The peak of the spring freshet is projected to be similar to historical levels and still occur in June in the 2030s. However, the peak of the inflow freshet is projected to be higher, and the timing will be centered in May in the 2070s. Progressive decreases in inflows are projected for July–September.

7.3.2 Outflow

In response to changing inflow and seasonal water supply forecasts, median monthly outflows from Libby Dam are projected to decrease in November and December and increase January–April (**Figure 30**). High outflow (90th percentile) is projected to increase February–April, and many projections show occurrences of outflow exceeding the capacity of the powerhouse (25 kcfs) in June in the 2070s under the RCP8.5 emissions scenario.

7.3.3 Reservoir Elevation and Storage

Changes in inflow timing and seasonal volumes drive the changes in reservoir storage of Libby Dam. The operations based on water supply forecasts adapt to these changes in hydrology. The spring draft increases for higher inflow volumes (2030s: RCP4.5, RCP8.5). The spring draft decreases and the reservoir refills earlier when volumes in the forecast period and shift to earlier in year (RCP8.5, 2070s). Seasonal median end-of-month elevations are projected to be deeper for February–April during the 2030s (**Figure 31**). This pattern is similar for the 2070s under RCP4.5; however, RCP8.5 projects higher pool elevations during the spring and earlier refill as indicated with high elevations at the end of April, May, and June. Similarly, the deepest drafts (10th percentile) are comparable to historical baseline condition for all projections except the RCP8.5 projections for the 2070s, which are shallower. Reservoir elevation at the end of August and September is projected to be lower than historical as driven by summer draft flow objectives coupled with reduced inflow. The reservoir stores inflows in a coordinated system operation to manage flooding in the Lower Columbia River during winter flood events. The reservoir is projected to fill above the end-of-month FRM objectives during November and December for some projections due to increased frequency of these events. Outflows after these events are limited to powerhouse capacity, which leads to storage of water above spring FRM objectives.

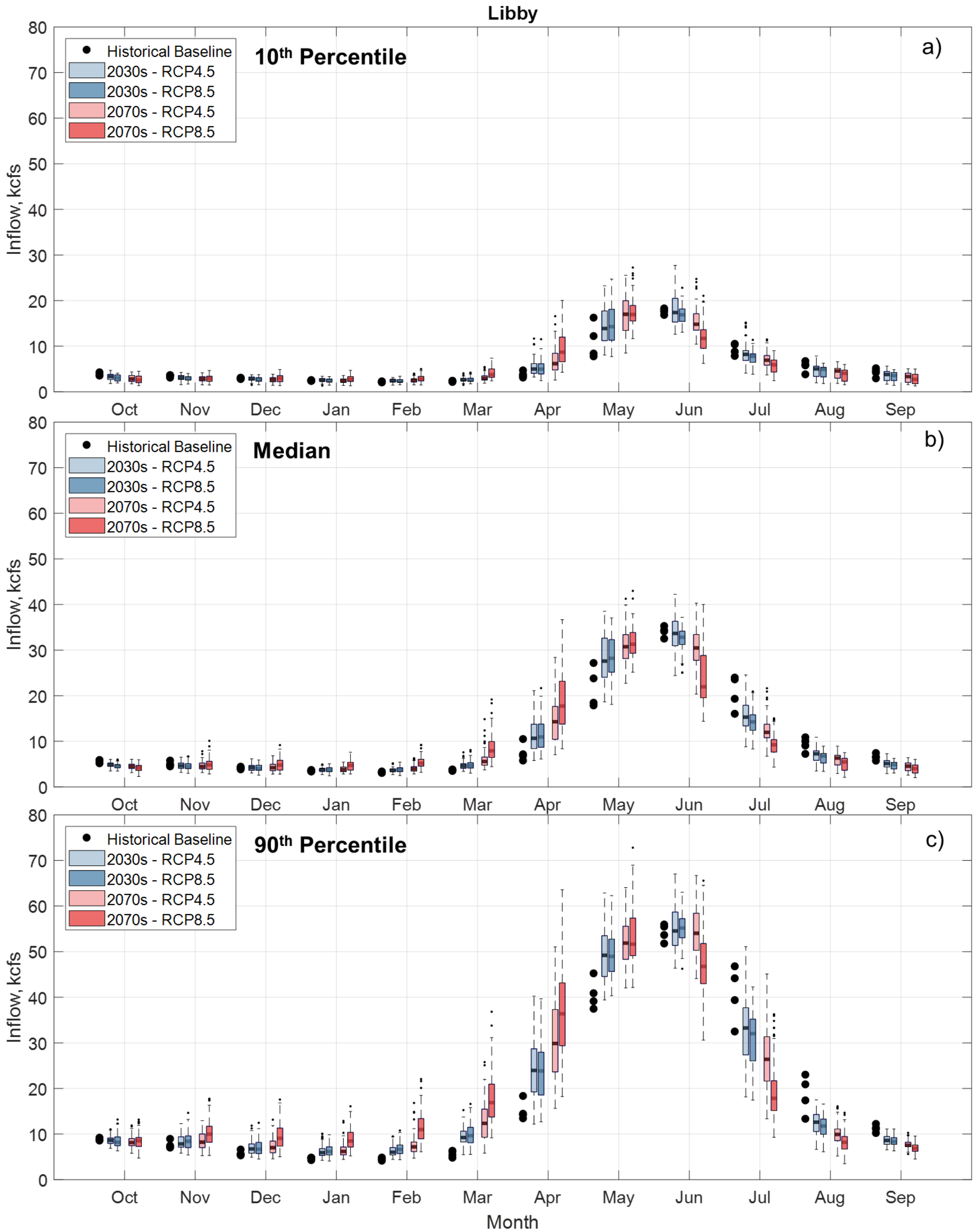

Figure 29. Projected monthly summary statistics for inflow to Libby Dam and Lake Koocanusa Reservoir: (*a*) monthly 10th percentile inflow, (*b*) monthly median inflow, and (*c*) monthly 90th percentile inflow.

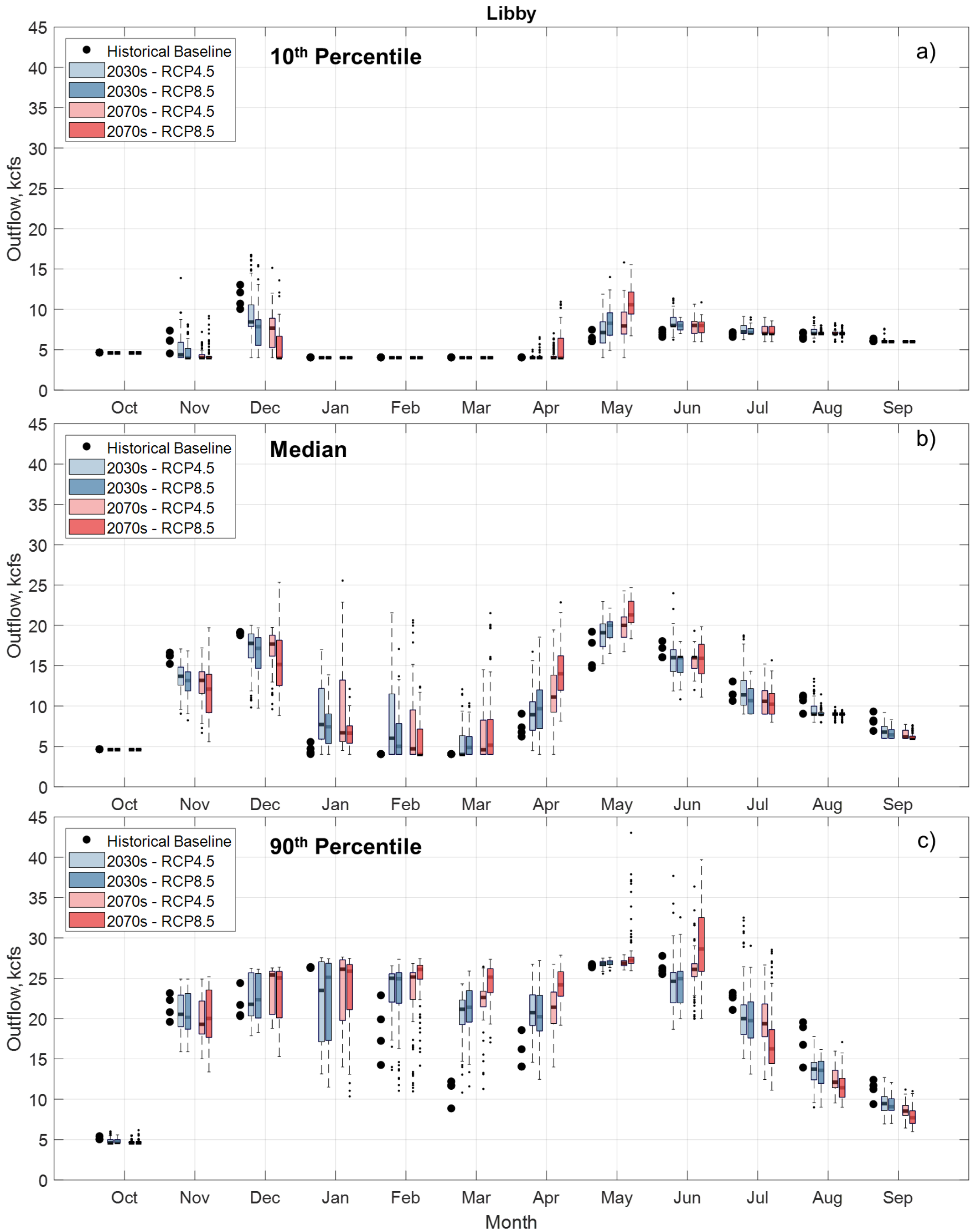

Figure 30. Projected monthly summary statistics for outflow of Libby Dam and Lake Koocanusa Reservoir: (*a*) monthly 10th percentile outflow, (*b*) monthly median outflow, and (*c*) monthly 90th percentile outflow.

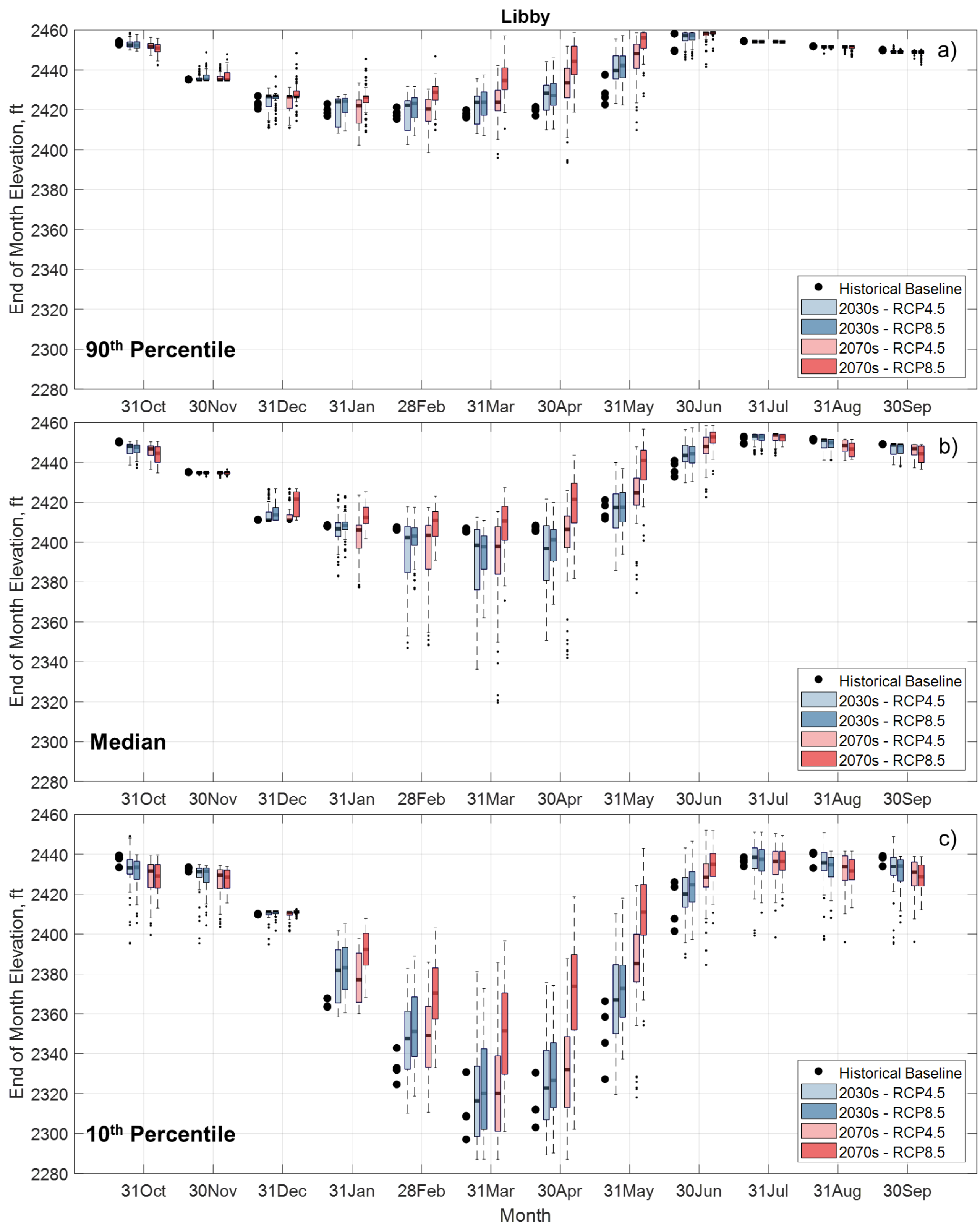

Figure 31. Projected monthly summary statistics for elevation of Lake Koocanusa: (*a*) 90th percentile end-of-month elevation, (*b*) monthly end-of-month elevation, and (*c*) monthly 10th percentile end-of-month elevation.

7.4 Hungry Horse Dam and Reservoir

7.4.1 Inflow

In the 2030s epoch, median monthly inflow is projected to increase in April and May, decrease in July, and remain near historical levels for the remainder of the year (**Figure 32**). In the 2070s, flows are projected to increase December–May, with large decreases in June and July. Larger relative increases are projected for high monthly inflows (90th percentile) November–May. Decreases in inflow are projected July–October for the 2030s and June–October for the 2070s. The relative change in the drier season is largest for median conditions.

7.4.2 Outflow

In both the 2030s and 2070s, large increases in outflow from Hungry Horse Dam are projected for March–May (**Figure 33**), which will likely result in more spill. This is most apparent in the 90th percentile when outflows are expected to be much higher than the baseline. Decreases in outflow are projected for July–August for median and low-flow conditions (10th percentile) through both epochs and emissions scenarios. The lower summer outflows may require the release of more storage to meet minimum flow requirements. Lower outflows are also projected for low-flow conditions (10th percentile) during the winter months, December–March.

7.4.3 Reservoir Elevation and Storage

In response to changing inflow volume and seasonal water supply forecasts, seasonal patterns of reservoir storage are projected to change (**Figure 34**). For the 2030s, many of the projections show the December–March reservoir elevations to be slightly higher than during the historical period. This signal is stronger for the 2070s, where the majority of projections show higher pool elevations and earlier refill as indicated with higher elevations in April–June. The interquartile range of the projections is greatest for the 2070s during these months, indicating a wider range of uncertainty; however, strong consensus on the direction of change is still evident. The higher spring elevations could impact the ability to conduct maintenance activities at the dam. In particular, the maintenance of the selective withdrawal structure slide gates requires a pool elevation of 3,525 feet or lower for two to three weeks. The higher pool elevations may require forced drafts in the future to conduct this maintenance. Outside of the winter and spring draft and refill period, the elevation (storage) of Hungry Horse Reservoir is projected to be similar to historical conditions.

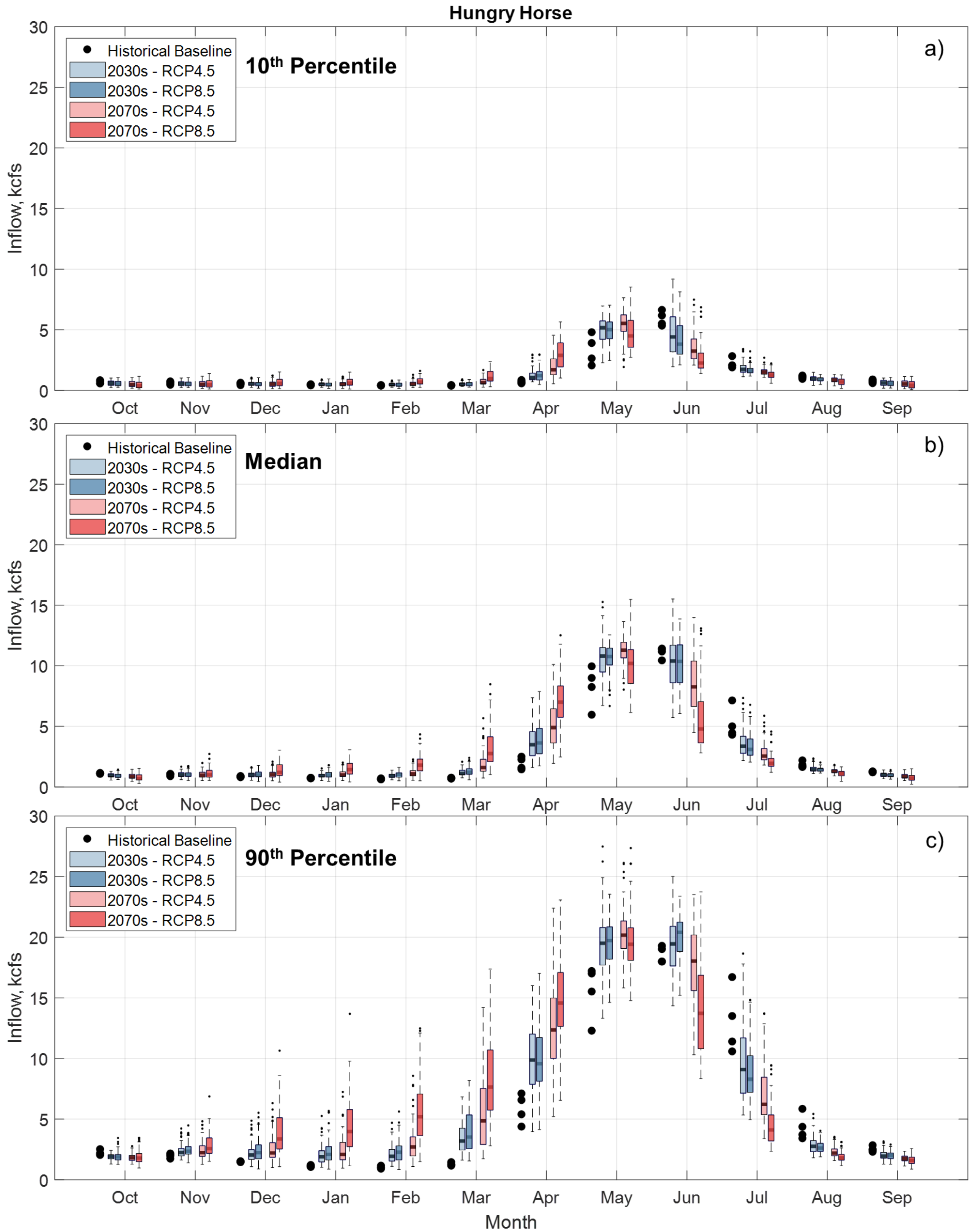

Figure 32. Projected monthly summary statistics for inflow to Hungry Horse Reservoir: (*a*) monthly 10th percentile inflow, (*b*) monthly median inflow, and (*c*) monthly 90th percentile inflow.

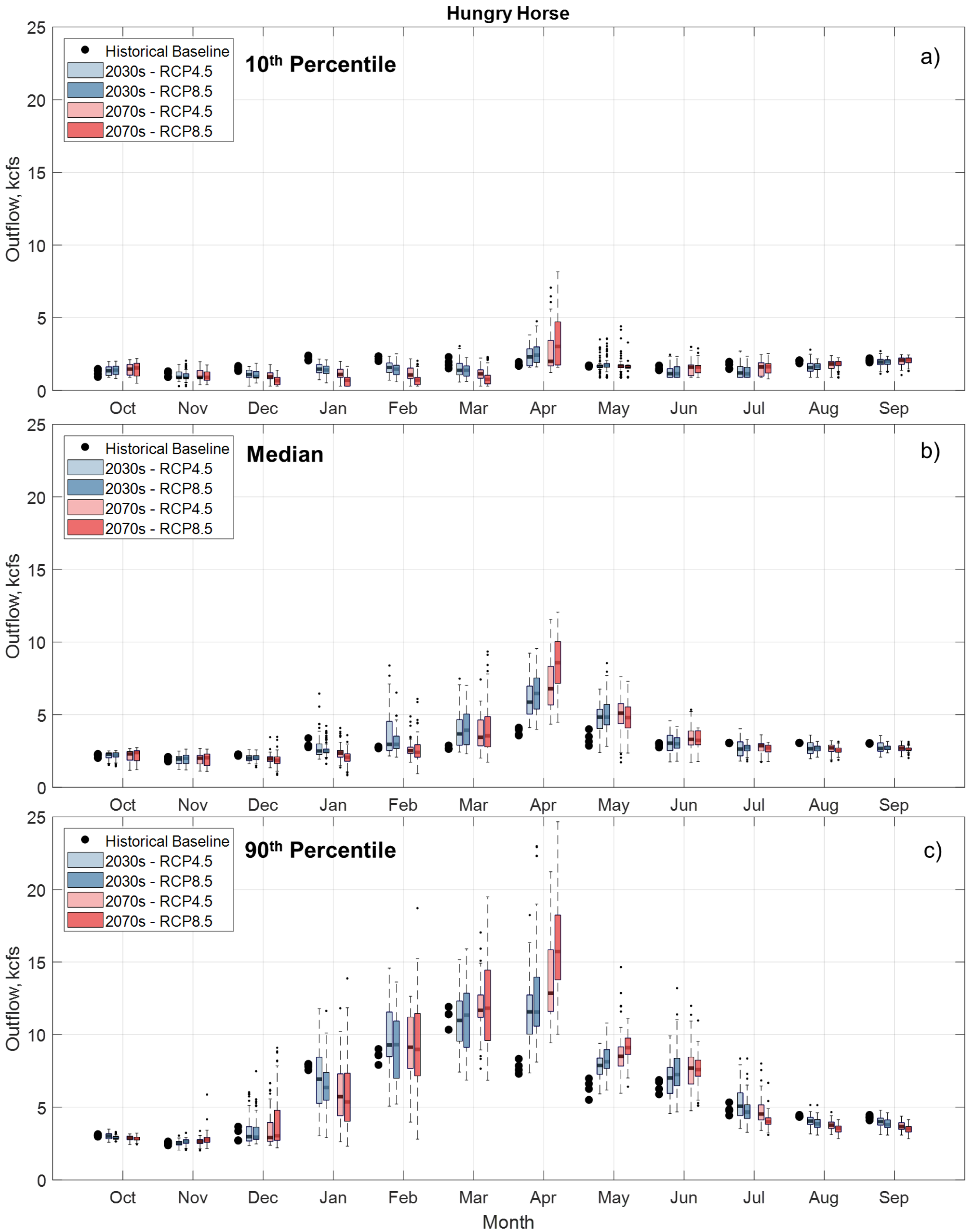

Figure 33. Projected monthly summary statistics for outflow of Hungry Horse Dam and Reservoir: (*a*) monthly 10th percentile outflow, (*b*) monthly median outflow, and (*c*) monthly 90th percentile outflow.

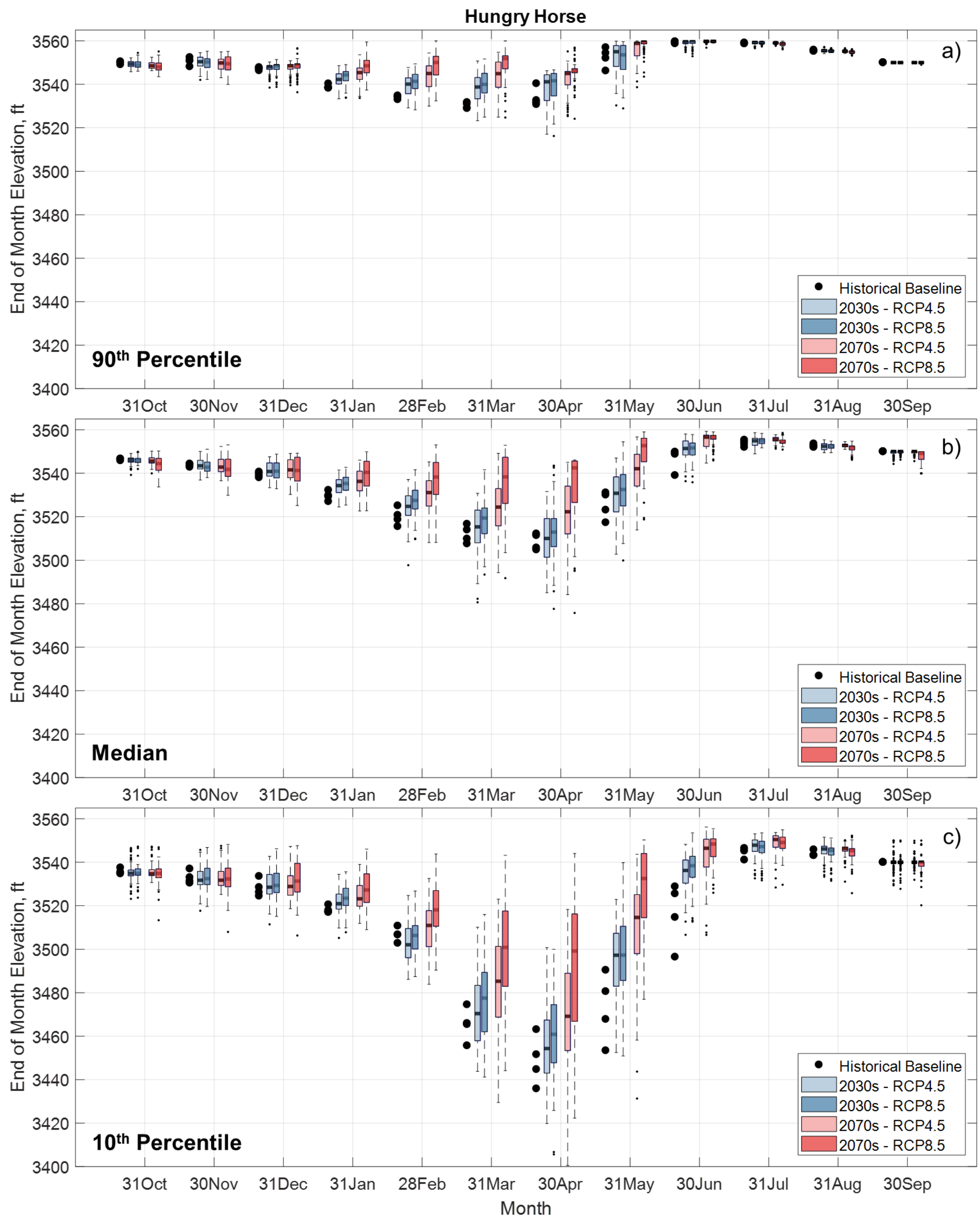

Figure 34. Projected monthly summary statistics for elevation of Hungry Horse Reservoir: (*a*) 10th percentile end-of-month elevation, (*b*) monthly end-of-month elevation, and (*c*) monthly 90th percentile end-of-month elevation.

7.5 Albeni Falls Dam and Lake Pend Oreille

7.5.1 Inflow

The projections show that inflow to Lake Pend Oreille will likely increase in the 2030s for January–May (**Figure 35**). These increases are projected to amplify further during the 2070s. The relative change is greatest for high-flow conditions (90th percentile), which are projected to increase in November–May. Peak inflow is projected to shift to May more frequently than in June, the peak of the historical period. Decreasing inflow is projected for June–September for median conditions.

7.5.2 Outflow

The projected changes in monthly outflow from Albeni Falls Dam (**Figure 36**) mimic the projected seasonal changes in inflow.

7.5.3 Reservoir Elevation and Storage

The operations of Albeni Falls Dam and storage of Lake Pend Oreille follow fixed seasonal elevation (storage) targets where the lake is kept at a low elevation November–March and refilled to maintain a higher elevation June–August (**Figure 37**). During winter, inflows to Lake Pend Oreille can be stored for the purposes of downstream FRM. Historically, modeled baselines follow the fixed seasonal elevation requirements with some variability in the rate of refill for high lake conditions in May. During the 2030s, increased frequency of storage for winter events is evident in many projections as the range of projected end-of-month lake elevations increases November–April (90^{th} percentile). This pattern is amplified in the 2070s, substantially under RCP8.5, where winter and early spring lake elevations are much greater than the historical baseline. The interquartile range of the projections is large. This is attributed to individual short-term extreme events included in each projection that drive high end-of-month elevation. Short-term events vary between projections. These patterns for the 2070s are also reflected in the median condition but are far less extreme. No change in lake elevation is projected for the summer recreation period.

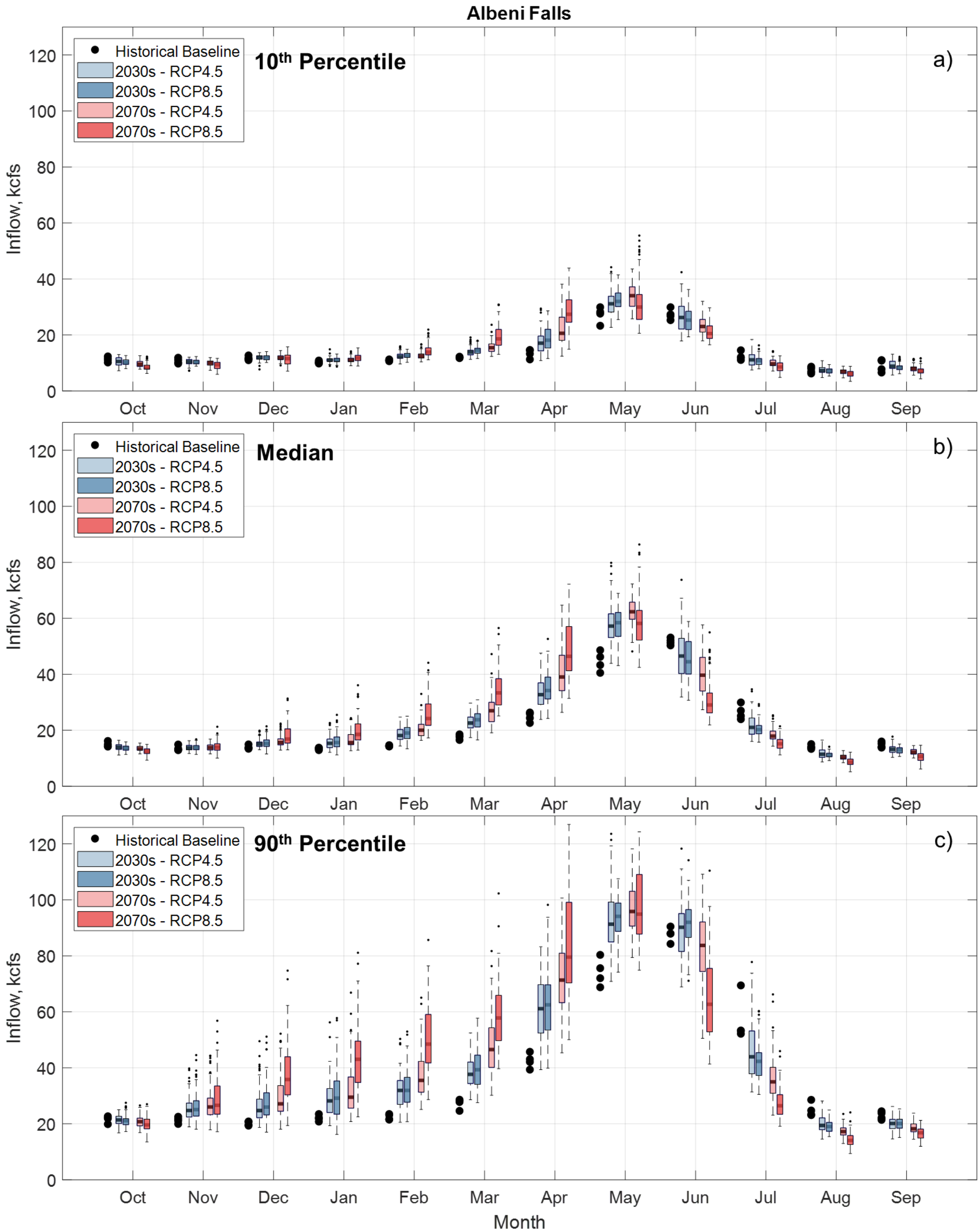

Figure 35. Projected monthly summary statistics for inflow to Lake Pend Oreille: (*a*) monthly 10th percentile inflow, (*b*) monthly median inflow, and (*c*) monthly 90th percentile inflow.

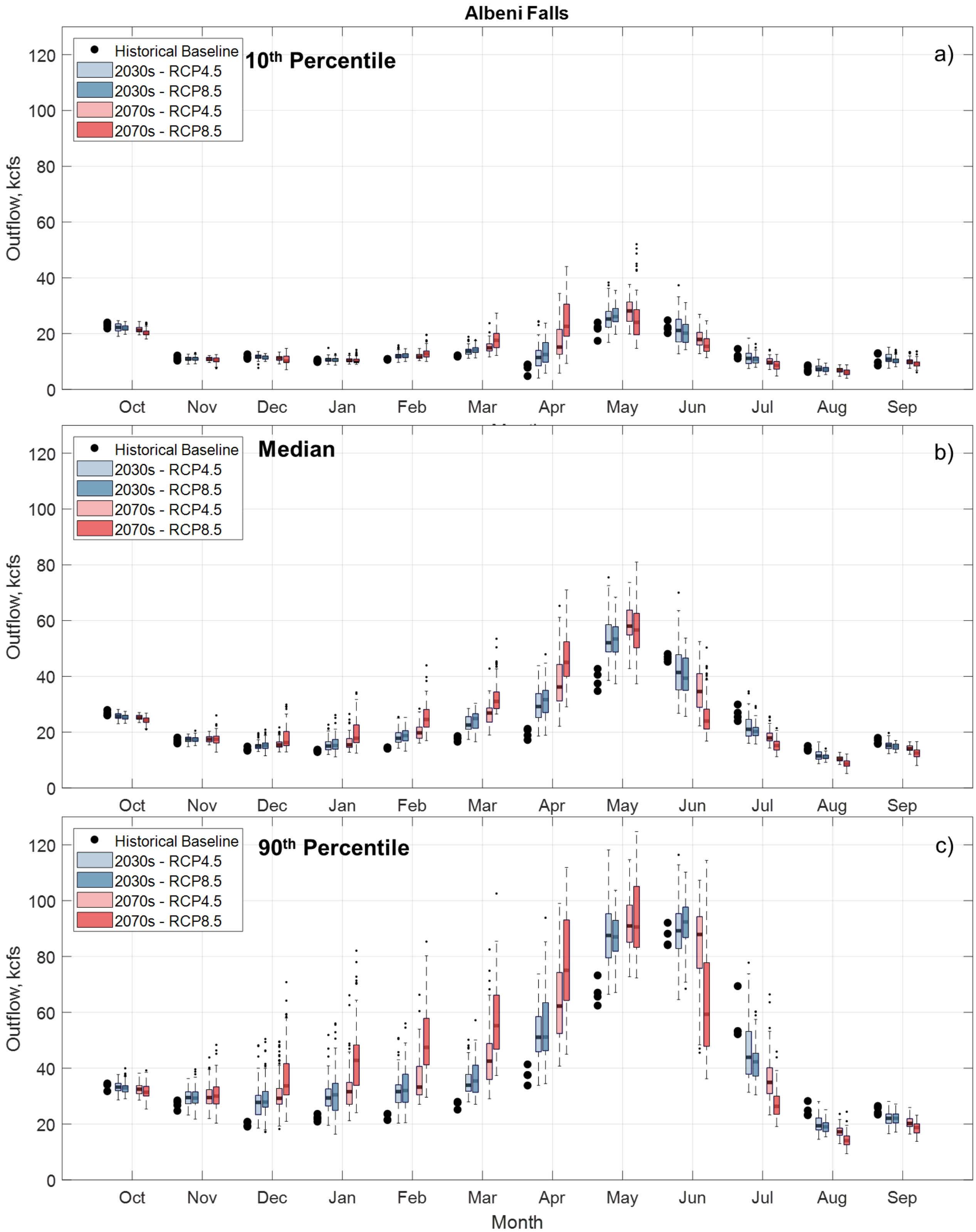

Figure 36. Projected monthly summary statistics for outflow of Albeni Falls Dam and Lake Pend Oreille: (*a*) monthly 10th percentile outflow, (*b*) monthly median outflow, and (*c*) monthly 90th percentile outflow.

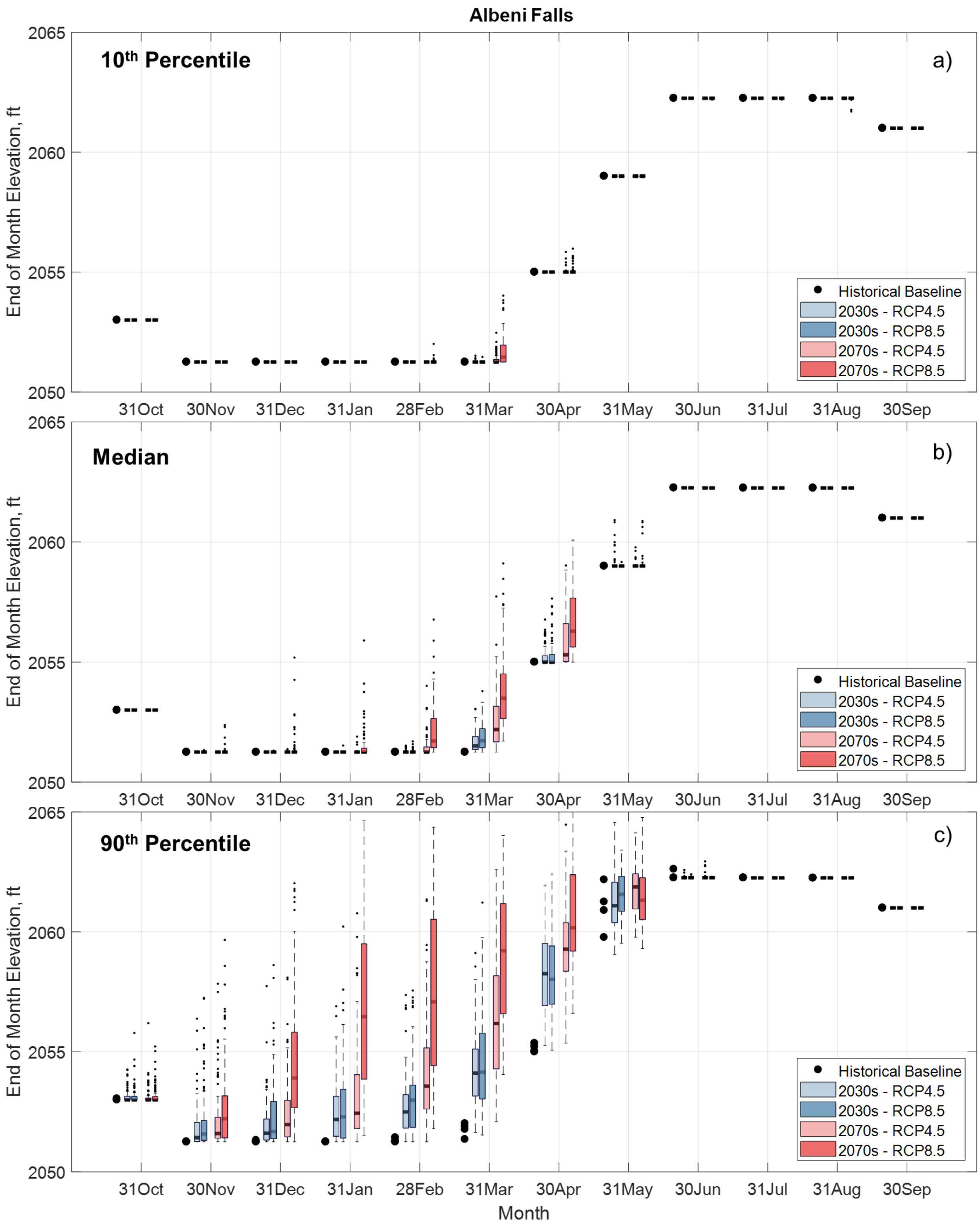

Figure 37. Projected monthly summary statistics for elevation of Lake Pend Oreille: (*a*) 10th percentile end-of-month elevation, (*b*) monthly end-of-month elevation, and (*c*) monthly 90th percentile end-of-month elevation.

7.6 Grand Coulee Dam and Lake Roosevelt

7.6.1 Inflow

Inflow to Lake Roosevelt is projected to increase January–May through the 2030s and 2070s and decrease June–October for median conditions (**Figure 38**). The largest changes are for high-flow conditions in March and April (90th percentile) where nearly all of the projections show increases, particularly in the 2070s under RCP8.5. The peak of spring inflow is projected to occur more frequently in May under median conditions; however, it is projected to be high in both May and June for high-flow conditions.

7.6.2 Outflow

A similar pattern is projected for outflows from Grand Coulee. Outflow is projected to increase for January–May and decrease for July–October for all combinations of statistical measures, future epochs, and emission scenarios (**Figure 39**). During the 2070s, under RCP8.5, many of the projections indicate that high outflows in February–April could be nearly as high as peak outflows in spring, May and June, the months with the historical annual maximum. During the 2070s under RCP8.5, July to October outflows are generally less than RCP4.5 due to less inflows from snowmelt. Outflows are reduced to maintain lake elevation when possible.

7.6.3 Reservoir Elevation and Storage

The seasonal patterns of elevation (storage) of Lake Roosevelt are projected to change (**Figure 40**). Through the 2030s, generally no significant differences from historical baselines are projected. However, for low storage conditions (deep spring draft), the reservoir is projected to be at a higher elevation at the end of May during the 2030s. Larger changes are projected for the 2070s under RCP8.5, where higher end-of-month elevations are projected for January–May. In the 2070s, the spring FRM space required at Grand Coulee will be generally less than historical levels; but the frequency and magnitude of drafts through Grand Coulee operations to mitigate winter flooding is projected to increase. See Chapter 8.0 for a discussion of impacts to FRM, Chapter 9.0 for impacts to generation and spill, and Chapter 10.0 for potential impacts to the Inchelium Ferry and drum gate maintenance.

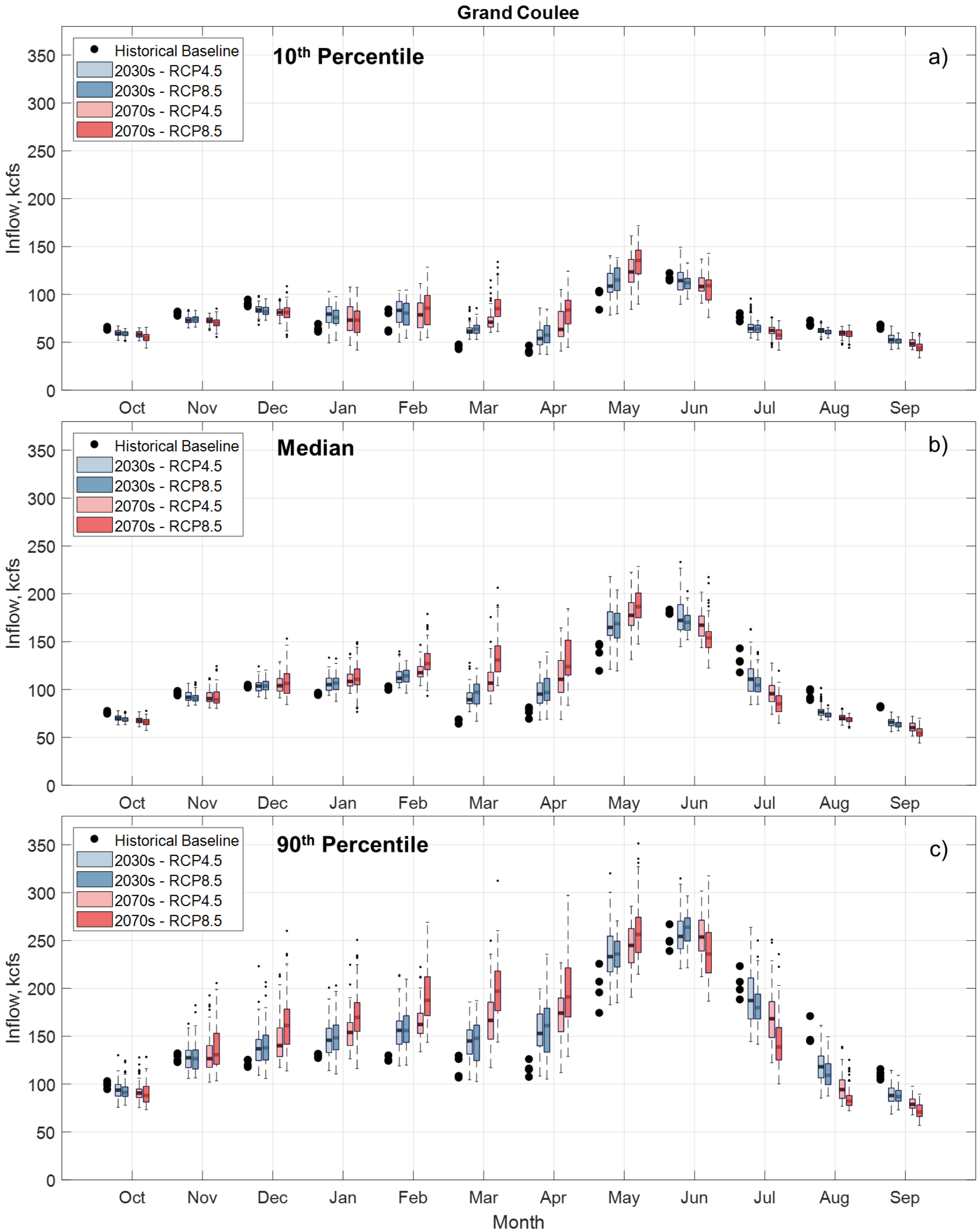

Figure 38. Projected monthly summary statistics for inflow to Lake Roosevelt (Grand Coulee Dam): (*a*) monthly 10th percentile inflow, (*b*) monthly median inflow, and (*c*) monthly 90th percentile inflow.

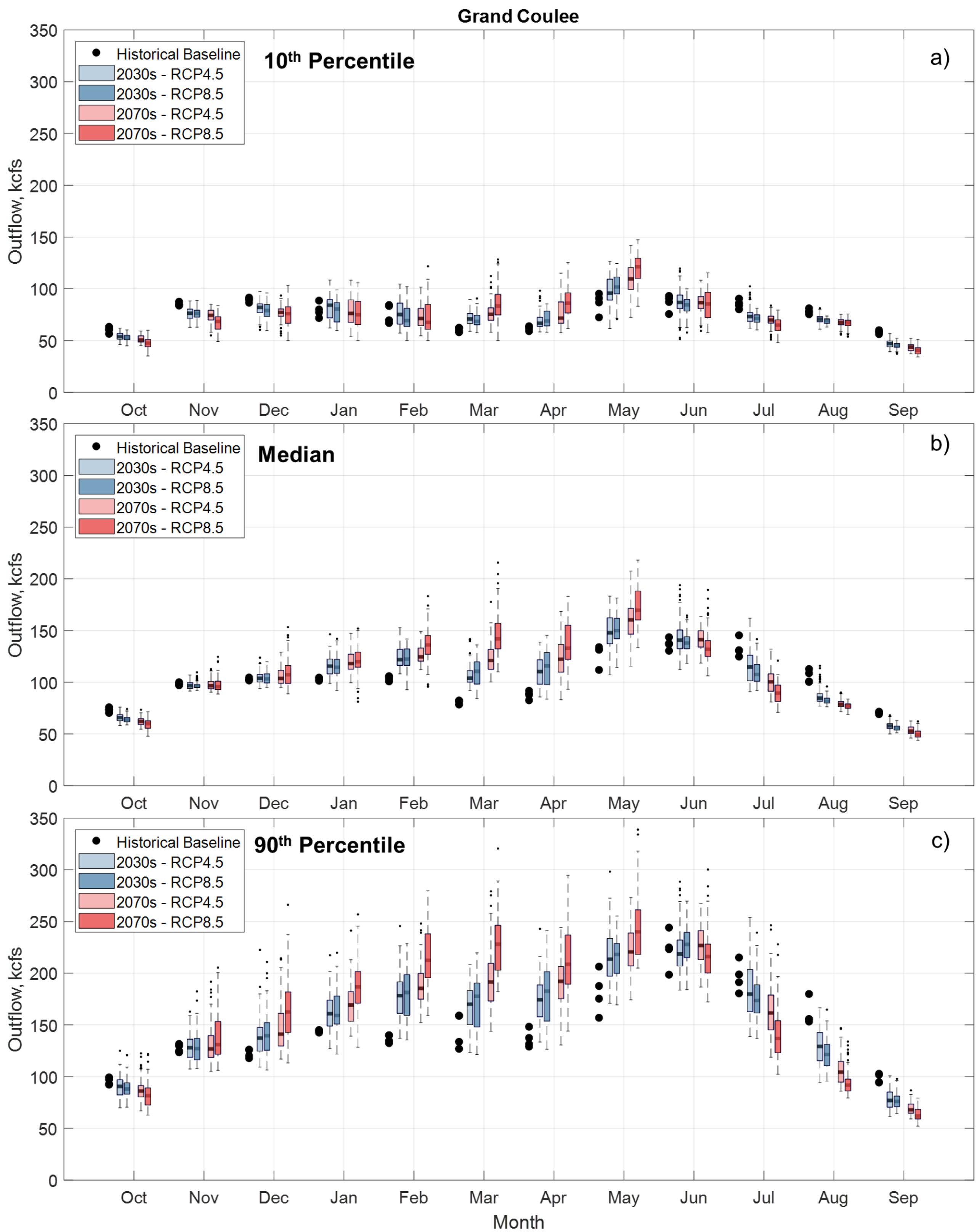

Figure 39. Projected monthly summary statistics for outflow of Grand Coulee Dam and Lake Roosevelt: (*a*) monthly 10th percentile outflow, (*b*) monthly median outflow, and (*c*) monthly 90th percentile outflow.

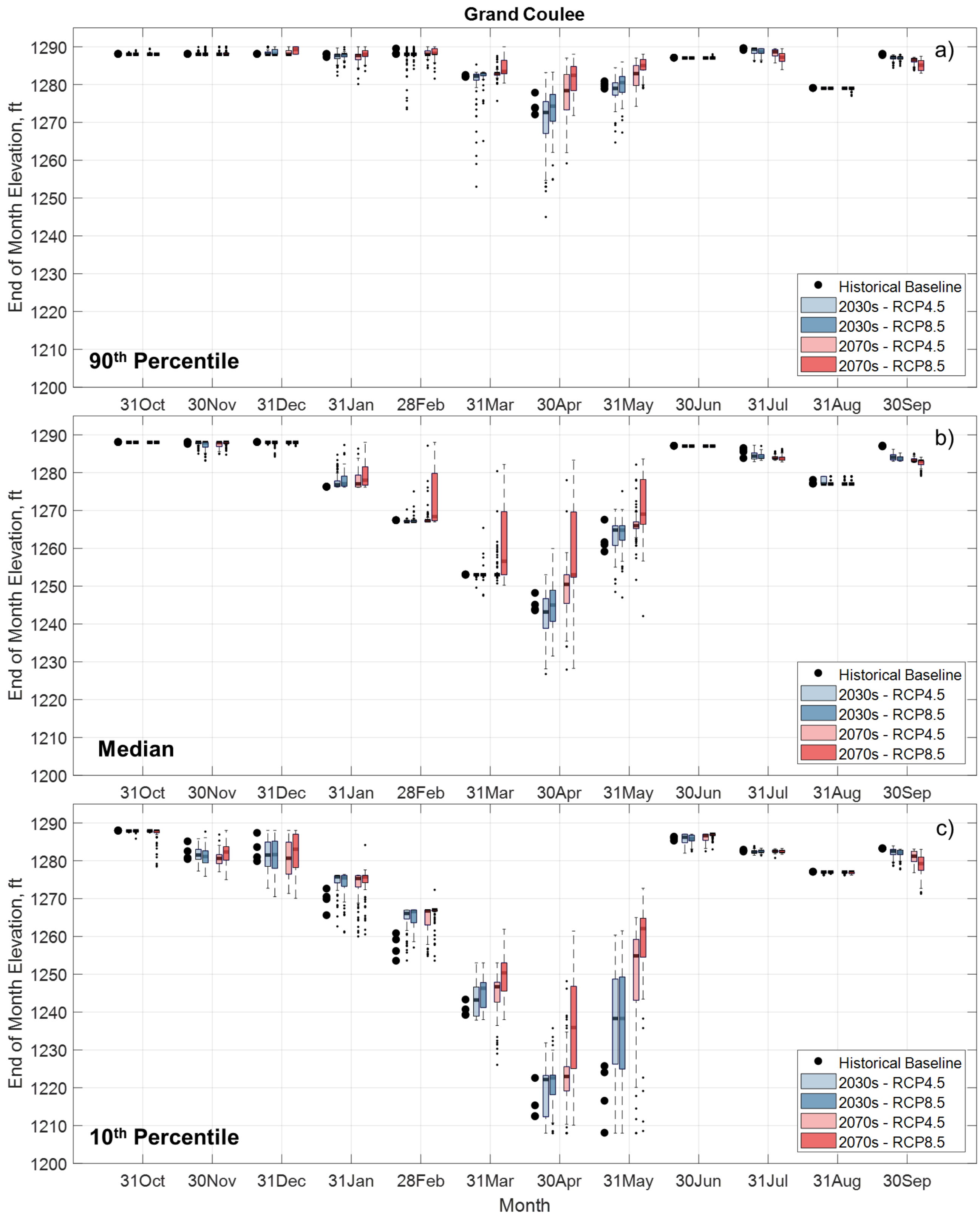

Figure 40. Projected monthly summary statistics for elevation of Lake Roosevelt (Grand Coulee): (*a*) 90th percentile end-of-month elevation, (*b*) monthly end-of-month elevation, and (*c*) monthly 10th percentile end-of-month elevation.

7.7 Dworshak Dam and Reservoir

7.7.1 Inflow

As a headwater project, Dworshak inflows are unregulated as there are no upstream storage projects. Nearly all projections show median inflow volumes greater than historical for December–March for the 2030s and the 2070s (**Figure 41**). Increases in winter inflows are more pronounced for high inflows (90th percentile). During summer months (July–September) the majority of projections show decreasing inflow volume for median and low (10th percentile) inflow conditions.

7.7.2 Outflow

Dworshak operations respond to climate-affected inflow and system-wide hydrology. Following increased winter flow, Dworshak outflow increases in February and March for median conditions and in January–March for extreme high conditions (**Figure 42**). The largest increases in winter outflows are modeled during March for the 2070s epoch. Dworshak Dam operates for winter system FRM, storing and evacuating water to mitigate high flows in the lower Columbia from short-term rain events. With increasing winter runoff events, this operation is triggered more frequently, leading to more variability and periods of higher outflows during winter. There are minimal changes to outflows projected for October–December. For the spring, most projections indicate that outflows in April and May could be greater than historical for both median and extreme high conditions. The projections indicate a potential for reduced outflow during June and July for 90th percentile flows. For August and September, the projections indicate a potential for reduced outflow under median conditions and no change for extreme low outflow conditions (10th percentile).

7.7.3 Reservoir Elevation and Storage

Projected changes to inflows and outflows of Dworshak Dam result in a different seasonal pattern of reservoir elevation and storage content (**Figure 43**). Generally, with increased warming (further into the future for the higher RCP8.5 emissions scenario), the elevation of Dworshak will be higher throughout the winter and spring runoff period (December–July) and will be impacted minimally through the remaining months of the year. For the 2030s, the spring draft in large water years is marginally less in April, where May elevations are higher than historical. During the 2070s, these extreme spring FRM drafts are considerably less. This is further amplified under RCP8.5. Changes to decreased spring FRM drafts are more pronounced for median conditions and drier spring conditions. Following a projected shift in inflow timing, Dworshak reservoir is projected to refill earlier. For example, under median conditions in the 2070s under RCP8.5, nearly all the projections show the reservoir being full by the end of May, a month earlier than historically.

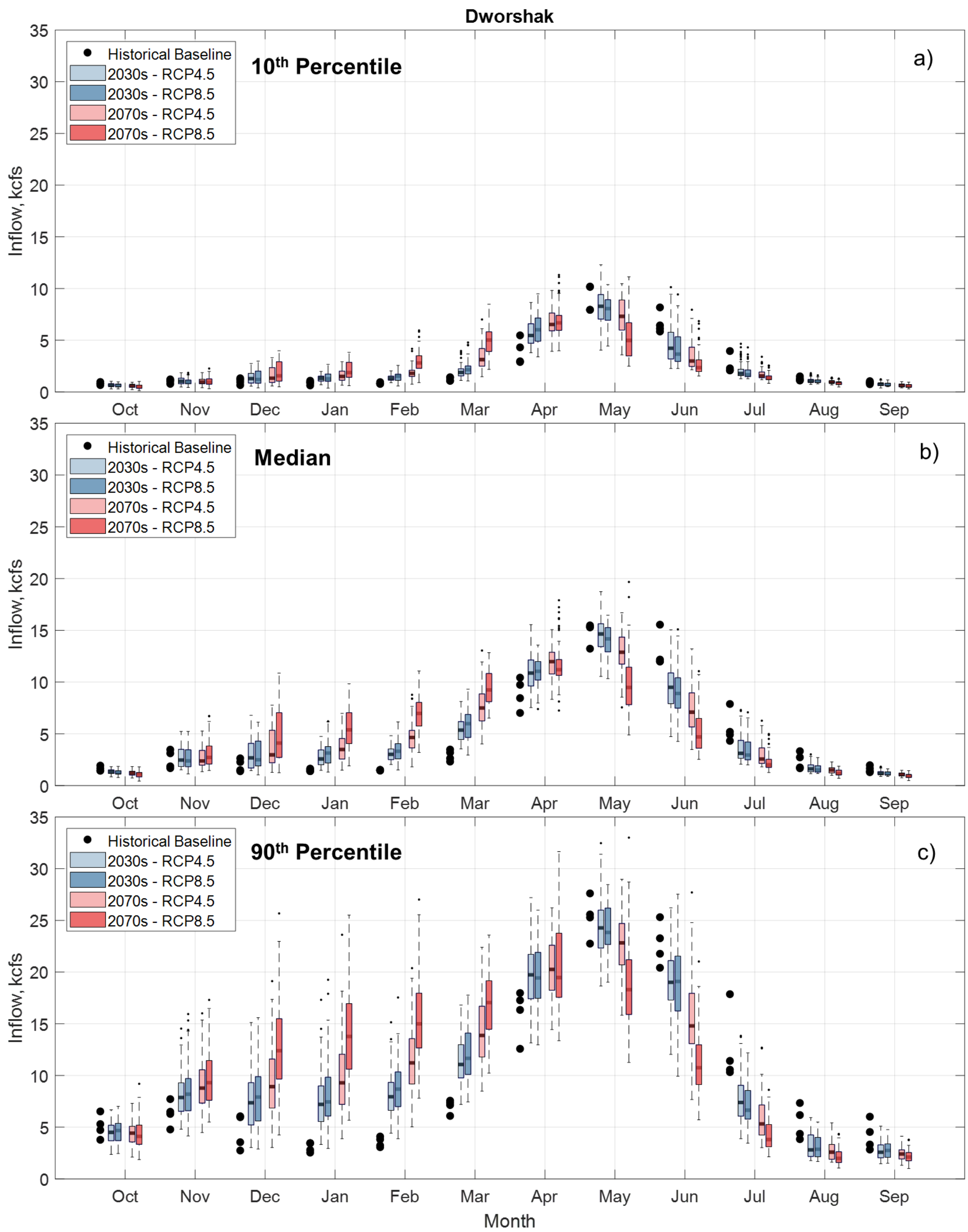

Figure 41. Projected monthly summary statistics for Dworshak Reservoir inflow: (*a*) monthly 10th percentile inflow, (*b*) monthly median inflow, and (*c*) monthly 90th percentile inflow.

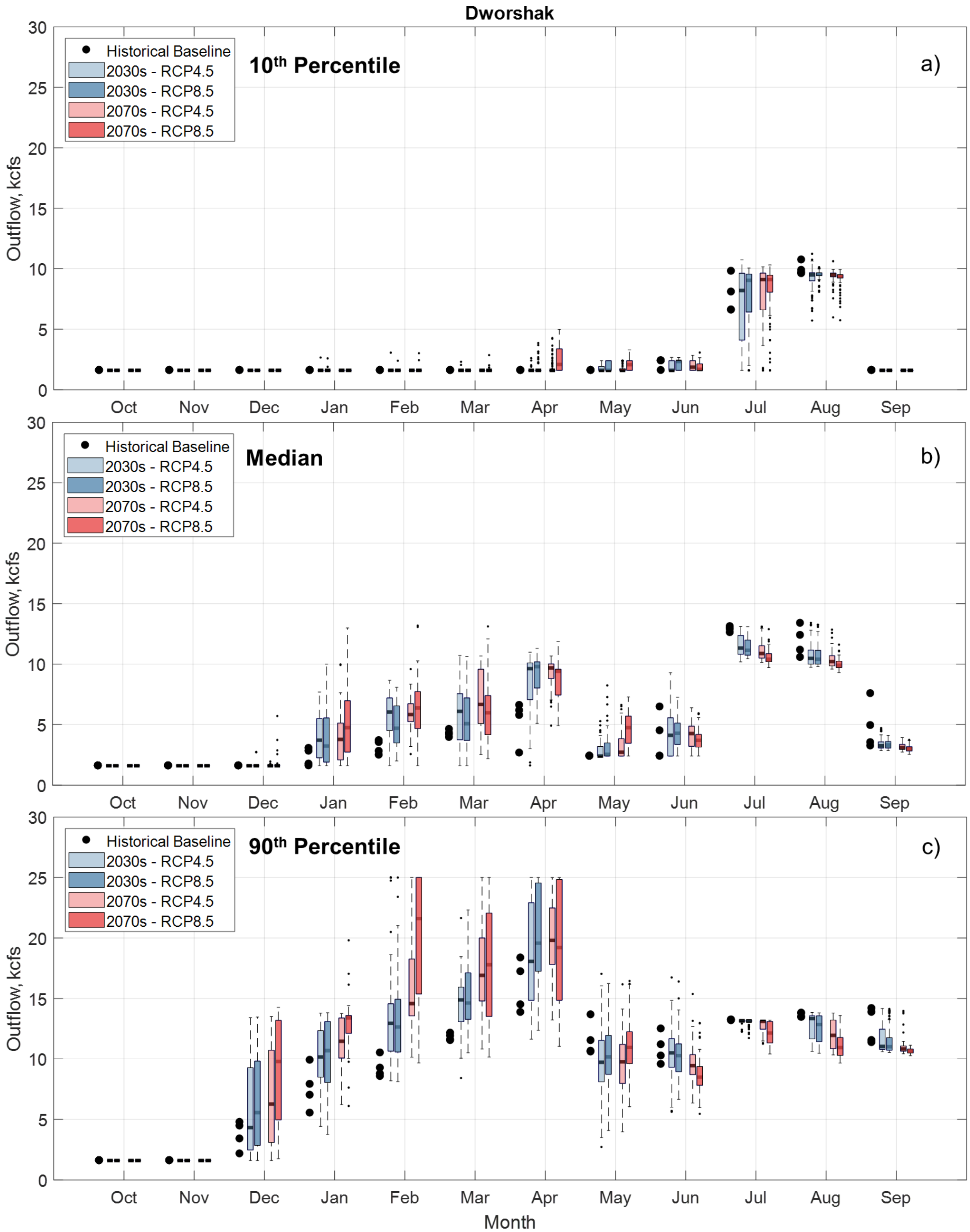

Figure 42. Projected monthly summary statistics for Dworshak Dam and Reservoir outflow: (*a*) monthly 10th percentile outflow, (*b*) monthly median outflow, and (*c*) monthly 90th percentile outflow.

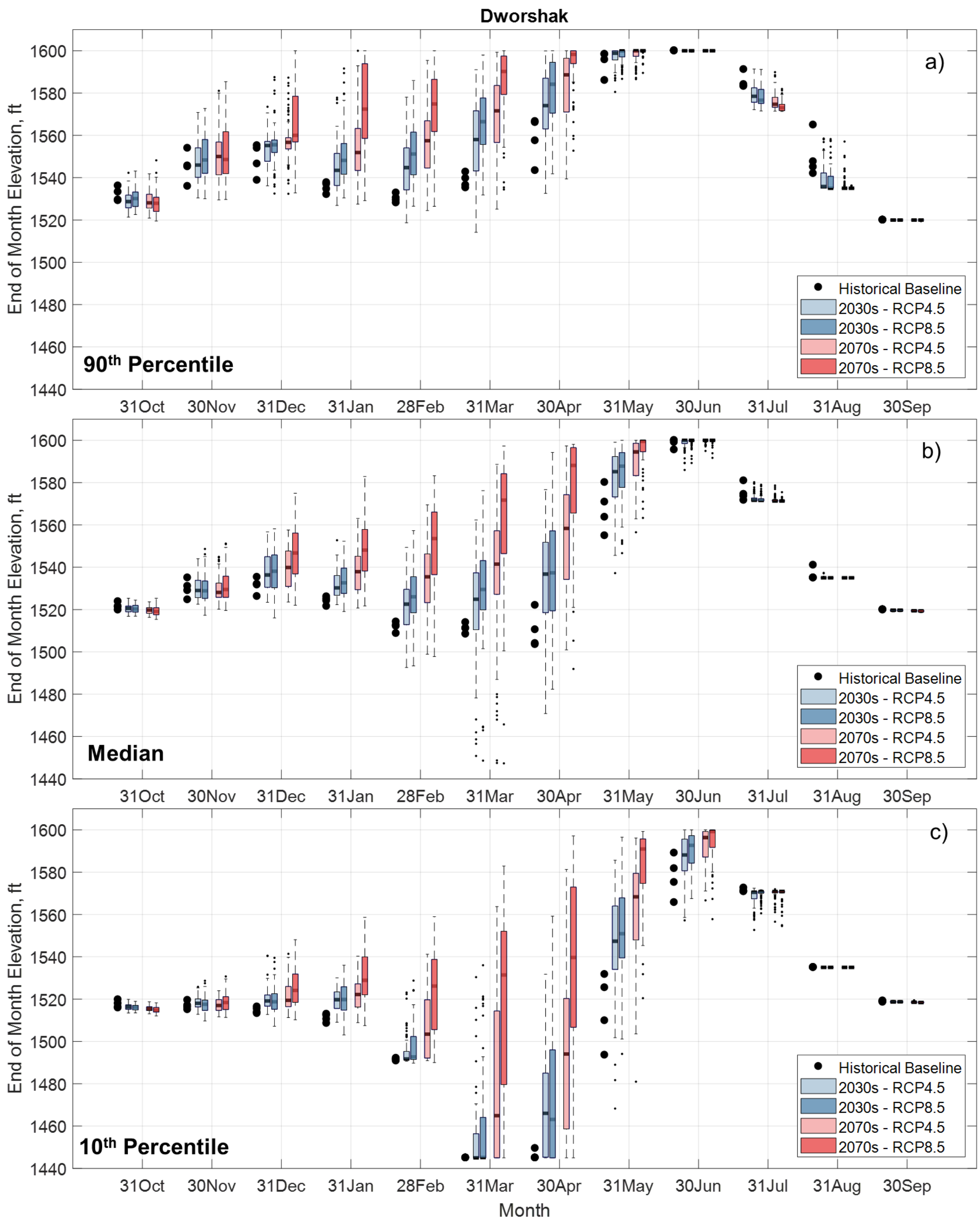

Figure 43. Projected monthly summary statistics for Dworshak Reservoir: (*a*) 90th percentile end-of-month elevation, (*b*) median end-of-month elevation, and (*c*) 10th percentile end-of-month elevation.

7.8 Palisades Dam and Reservoir

7.8.1 Inflow

In the 2030s, median monthly inflow is projected to increase in April and May, decrease in July and August, and remain near historical levels the remainder of the year (**Figure 44**). In the 2070s, flows are projected to increase in December–May, with similar decreases in July as projected in the 2030s. Larger relative increases are projected for high monthly inflows (90th percentile) in January–May. Decreases in inflow are projected in July and August for the 2030s and June–October for the 2070s. The relative change in the drier season is largest for the extreme high conditions (90th percentile), especially under RCP8.5, with flows projected to decrease starting in June rather than July.

7.8.2 Outflow

In both the 2030s and 2070s, increases in outflow at Palisades Dam are projected for March–May (**Figure 45**). Some decreases in outflow are projected for July and August for median and high outflow conditions (90th percentile) through both epochs and emissions scenarios. Outflows remained steady under low outflow conditions (10th percentile) during the summer, June–September, and the winter, December–March. This indicates that winter minimum flow targets and summer irrigation deliveries held relatively stable through all projections.

7.8.3 Storage

In response to changing inflow volume and seasonal water supply forecasts, seasonal patterns of reservoir storage are projected to change (**Figure 46**). For the 2030s, most of the projections show increased storage in May. For the 2070s, most of the projections show increased storage in April and May. The low storage condition (10th percentile) shows a wide range of end-of-month storage under both historical and projected future conditions. Palisades Dam and American Falls Dam (see the next section) are co-operated, with Palisades Dam being the upstream reservoir. Palisades Dam functions to hold stored water upstream through the refill period to be used through the summer to deliver irrigation water in the basin. If storage at American Falls Dam is low, then additional water is supplied from Palisades Dam to maintain stored water deliveries. Due to these operations, end-of-September storage is variable at Palisades Dam as shown in the low storage condition (10th percentile).

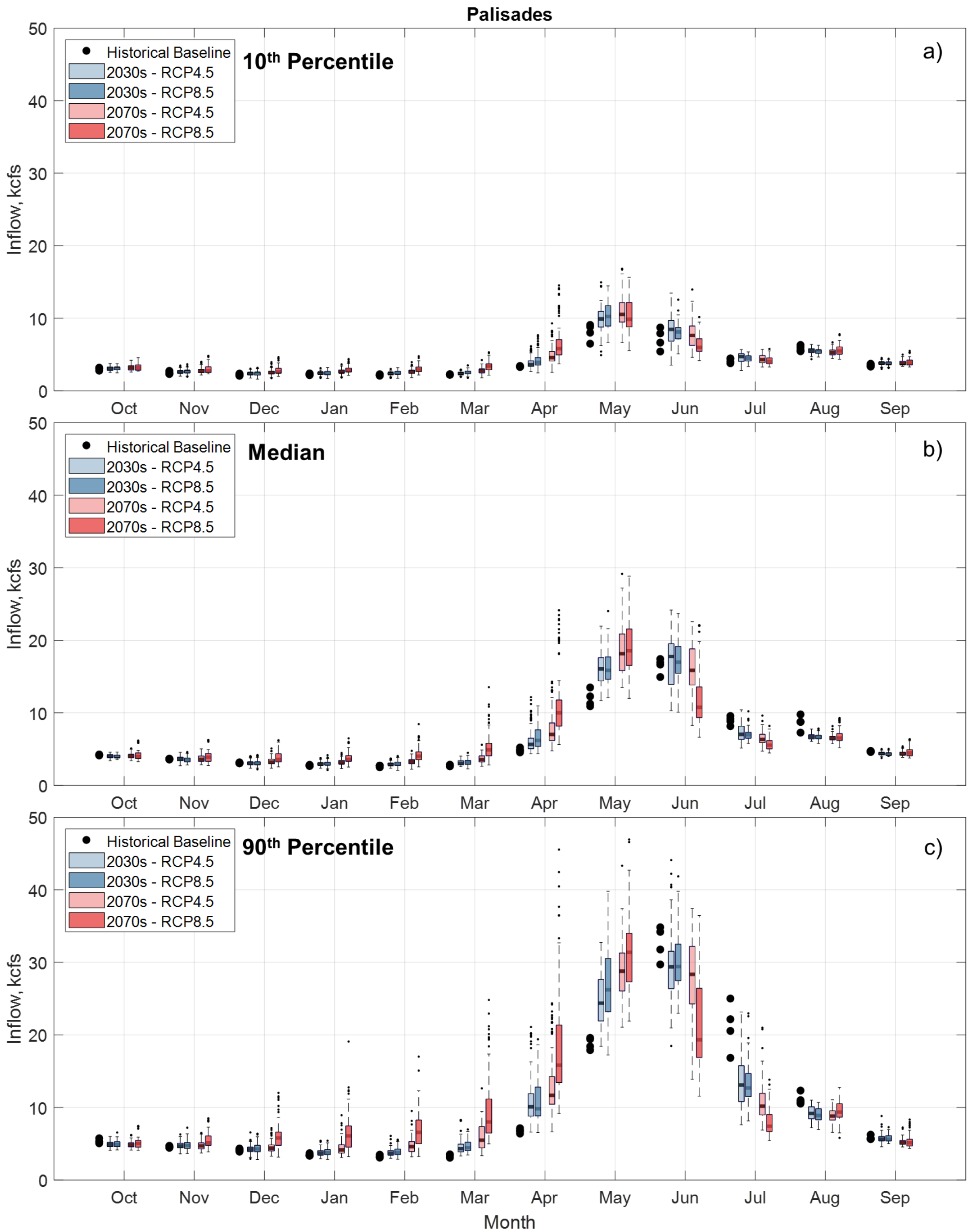

Figure 44. Projected monthly summary statistics for Palisades Reservoir inflow: (a) monthly 10th percentile inflow, (b) monthly median inflow, and (c) monthly 90th percentile inflow.

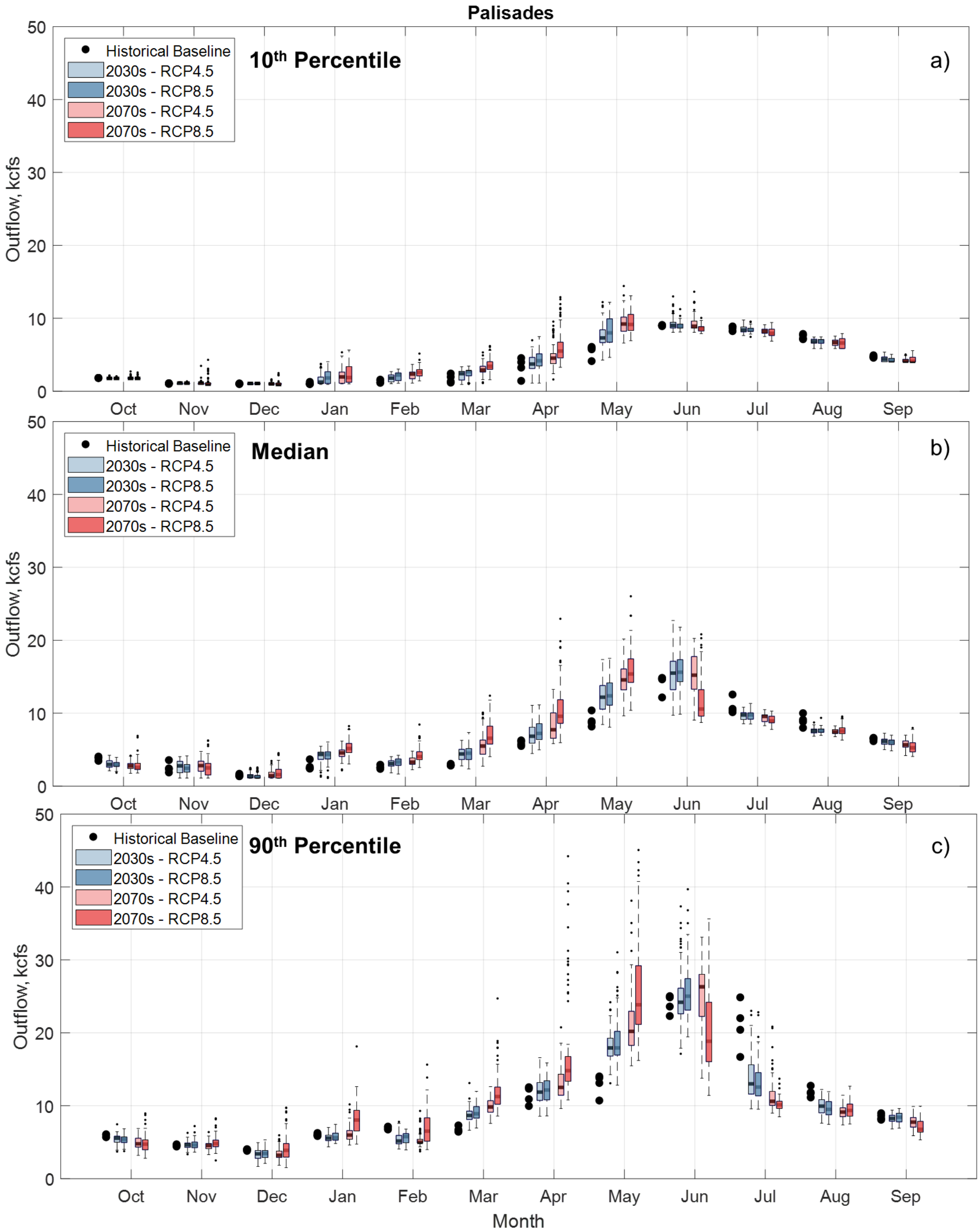

Figure 45. Projected monthly summary statistics for Palisades Dam and Reservoir outflow: (*a*) monthly 10th percentile outflow, (*b*) monthly median outflow, and (*c*) monthly 90th percentile outflow.

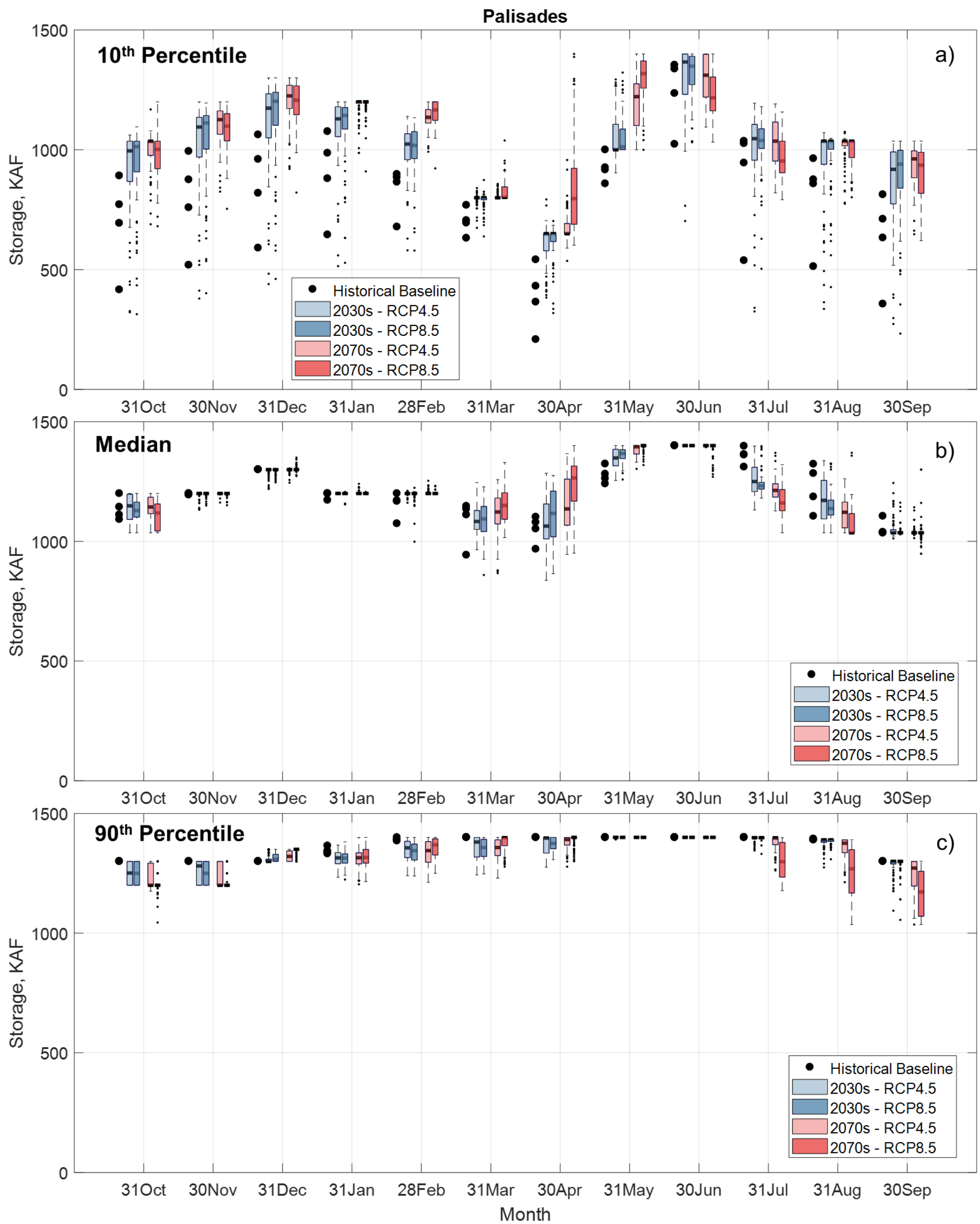

Figure 46. Projected monthly summary statistics for Palisades Reservoir: (*a*) 10th percentile end-of-month reservoir storage, (*b*) median end-of-month storage, and (*c*) 90th percentile end-of-month storage.

7.9 American Falls Dam and Reservoir

7.9.1 Inflow

In the 2030s, median monthly inflow is projected to increase from January through May, decrease in July and August, and remain near historical levels the remainder of the year for all projections (**Figure 47**). Larger relative increases are projected for high monthly inflows (90th percentile). Decreases in inflow are projected in July and August for the 2030s and the 2070s. The relative change in the drier season is largest for the extreme high conditions (90th percentile), especially under RCP8.5, with flows projected to decrease starting in June rather than July.

7.9.2 Outflow

In both the 2030s and 2070s, increases in outflow at American Falls Dam are projected for March–May (**Figure 48**). Outflows remained steady under low outflow conditions (10th percentile) during the summer, June–September, and the winter, December–March. The ability to meet winter minimum flow targets and summer irrigation deliveries remained relatively stable through all projections, indicating the ability to meet unofficial minimum flow target of 300 cfs. Summer releases were relatively stable across all projections, indicating no change to meeting summer irrigation deliveries.

7.9.3 Storage

Modeled storage conditions show a lesser impact from future climate change (**Figure 49**). In the future projections, the projected increased inflow in the winter is able to fill the reservoirs. This allows reservoirs to capture winter runoff before senior water rights natural flow diverters begin to call for water in April. See Chapter 10.0 for a discussion of the impacts to irrigation.

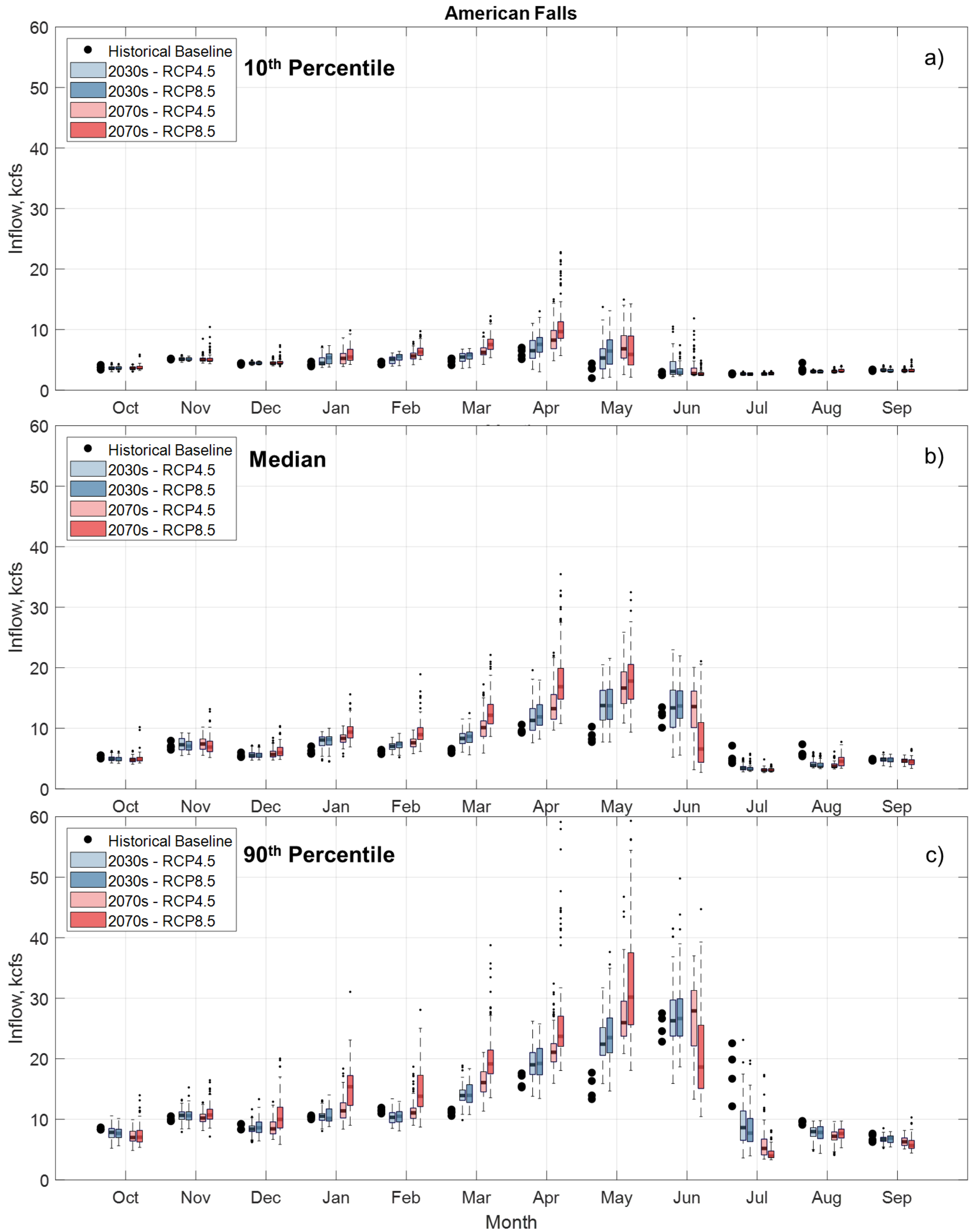

Figure 47. Projected monthly summary statistics for American Falls Reservoir inflow: (*a*) monthly 10th percentile inflow, (*b*) monthly median inflow, and (*c*) monthly 90th percentile inflow.

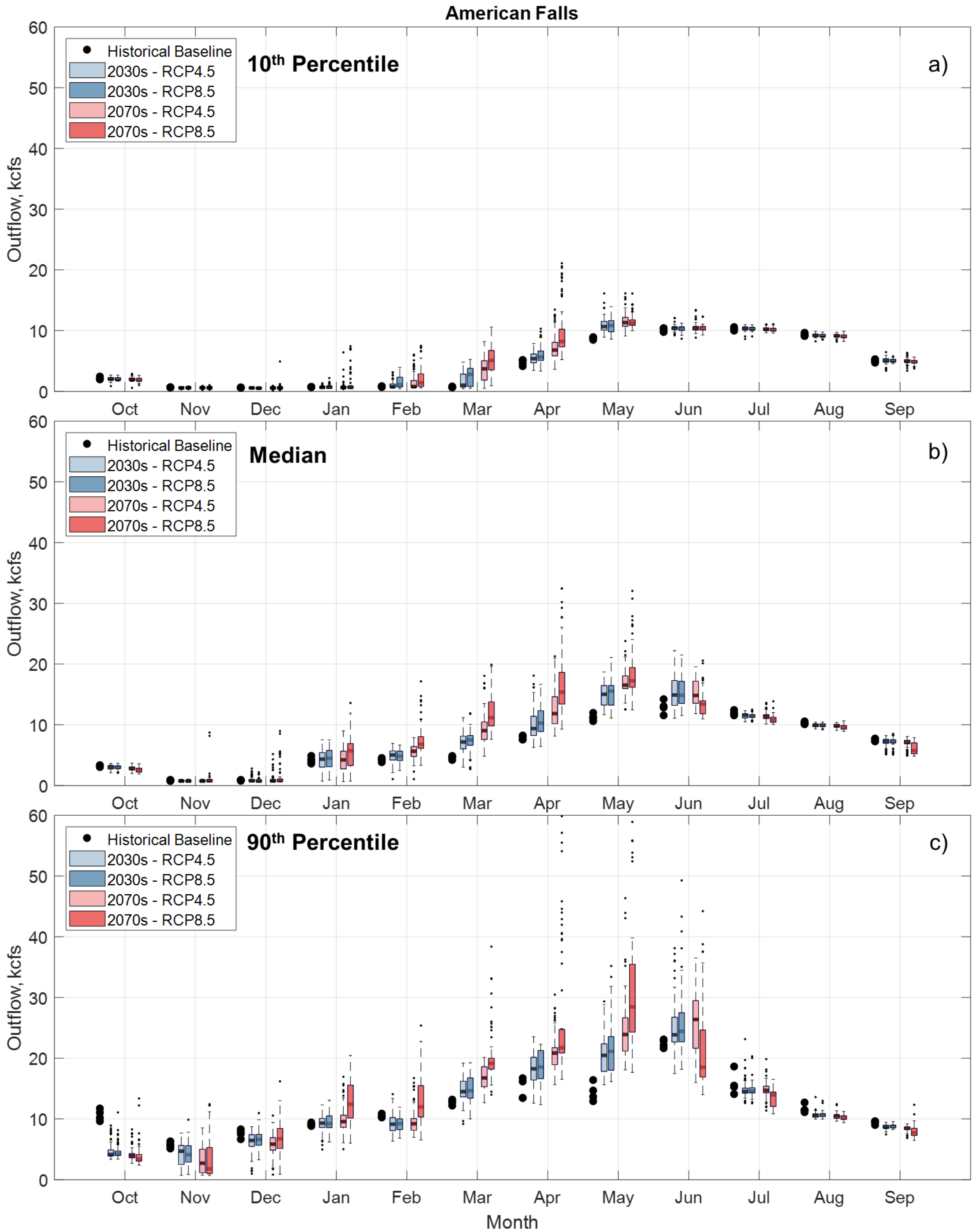

Figure 48. Projected monthly summary statistics for American Falls Dam and Reservoir outflow: (*a*) monthly 10th percentile outflow, (*b*) monthly median outflow, and (*c*) monthly 90th percentile outflow.

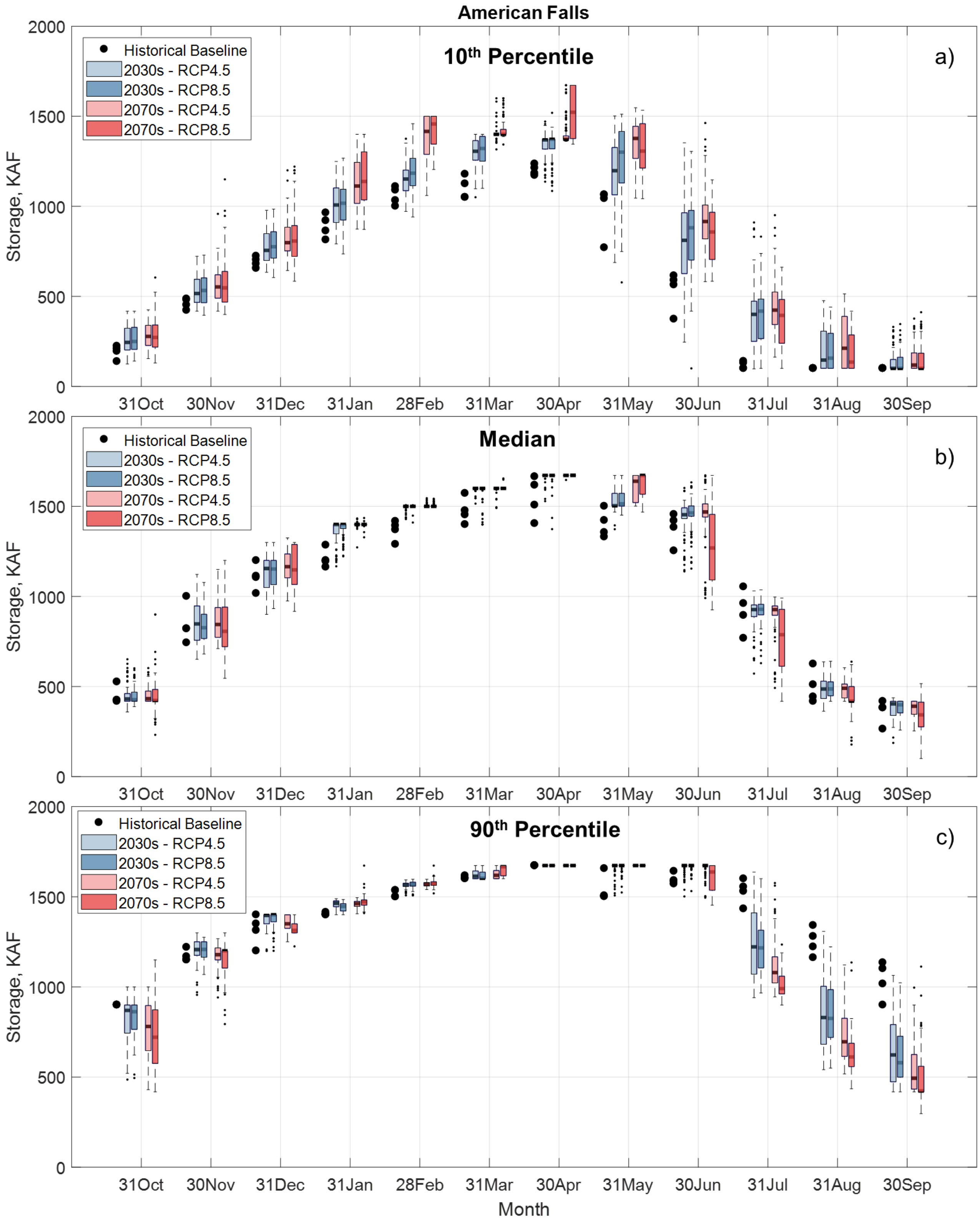

Figure 49. Projected monthly summary statistics for American Falls Reservoir: (*a*) 10th percentile end-of-month reservoir storage, (*b*) median end-of-month storage, and (*c*) 90th percentile end-of-month storage.

7.10 Brownlee Dam and Reservoir

7.10.1 Inflow

Inflow to Brownlee Reservoir was simulated using the Reclamation MODSIM reservoir operations model. Inflow to Brownlee Reservoir is projected to increase through the 2030s and 2070s for January–May for both emissions scenarios (**Figure 50**). Median Inflow during the summer and early fall low-flow season is projected to be slightly lower than the historical baseline. The 10th percentile during July–October increases slightly relative to the projected low-flow statistical composite. The largest projected changes are for the high-flow monthly statistic during the 2070s under RCP8.5 (90th percentile). For January–April, nearly all projections show marked increases in flow above historical baselines. The interquartile range of projections of 90^{th} percentile flow for March and April are above the historical maximum of 90th flow metrics, which occurred in June in the historical period.

7.10.2 Outflow

The projected patterns of changes in outflow mimic the directional and relative changes projected for inflow described above (**Figure 51**).

7.10.3 Reservoir Elevation and Storage

The seasonal pattern of reservoir elevation (storage) is projected to be similar to historical with the exception of end-of-April elevation (**Figure 52**). The spring draft of the reservoir is projected to be deeper than historical at the end of April.

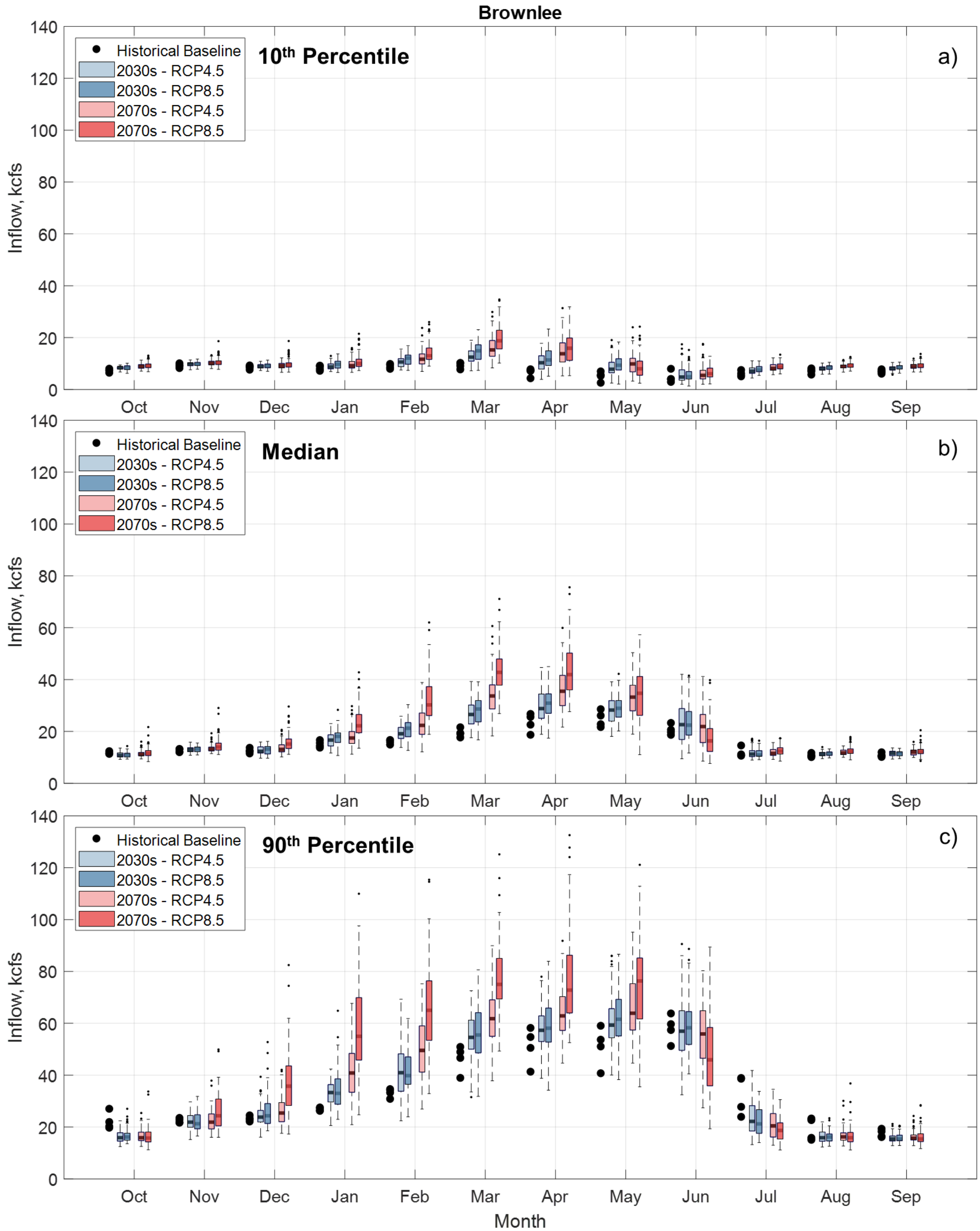

Figure 50. Projected monthly summary statistics for inflow to Brownlee Reservoir: (*a*) monthly 10th percentile inflow, (*b*) monthly median inflow, and (*c*) monthly 90th percentile inflow.

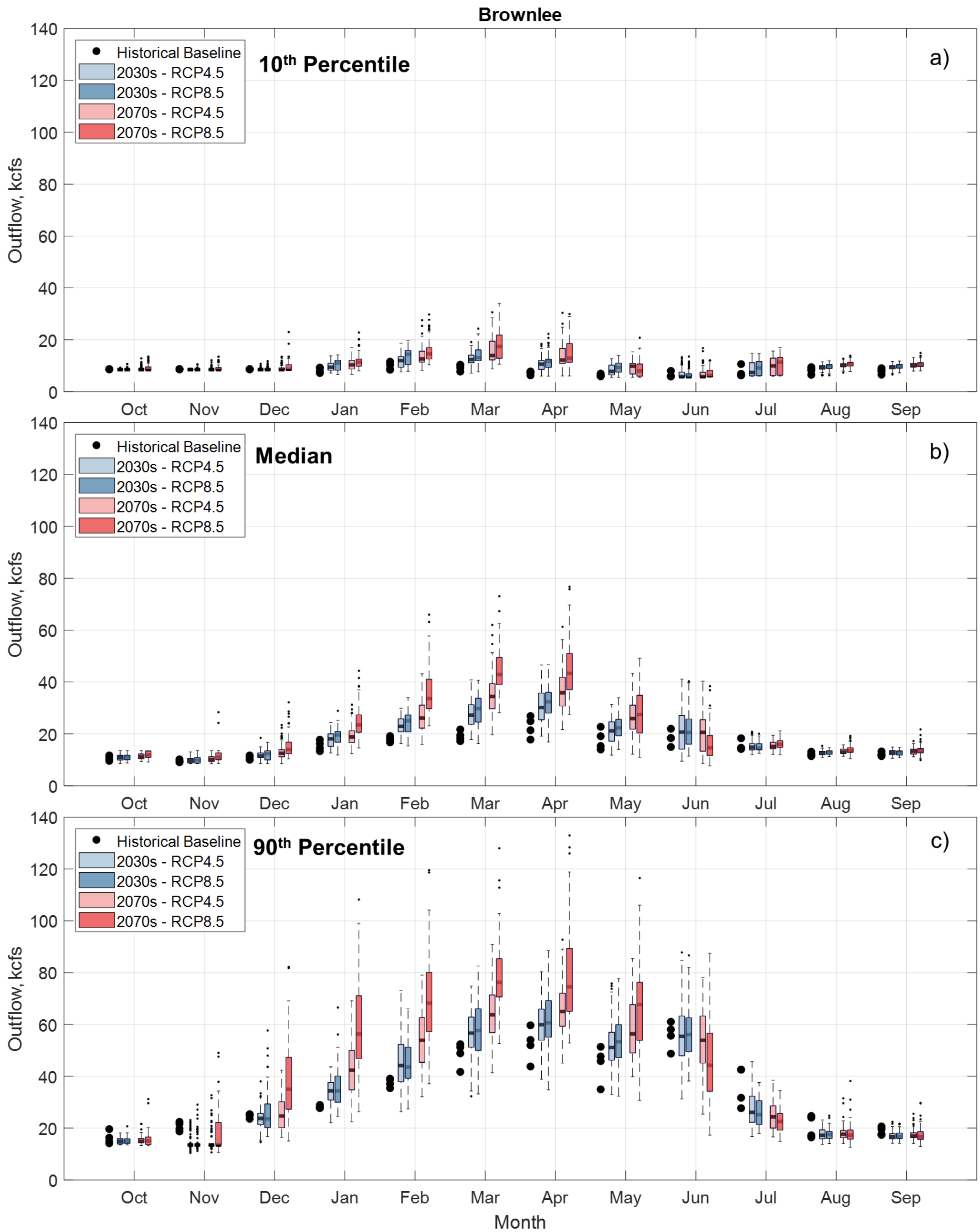

Figure 51. Projected monthly summary statistics for outflow of Brownlee Dam and Reservoir: (*a*) monthly 10th percentile outflow, (*b*) monthly median outflow, and (*c*) monthly 90th percentile outflow.

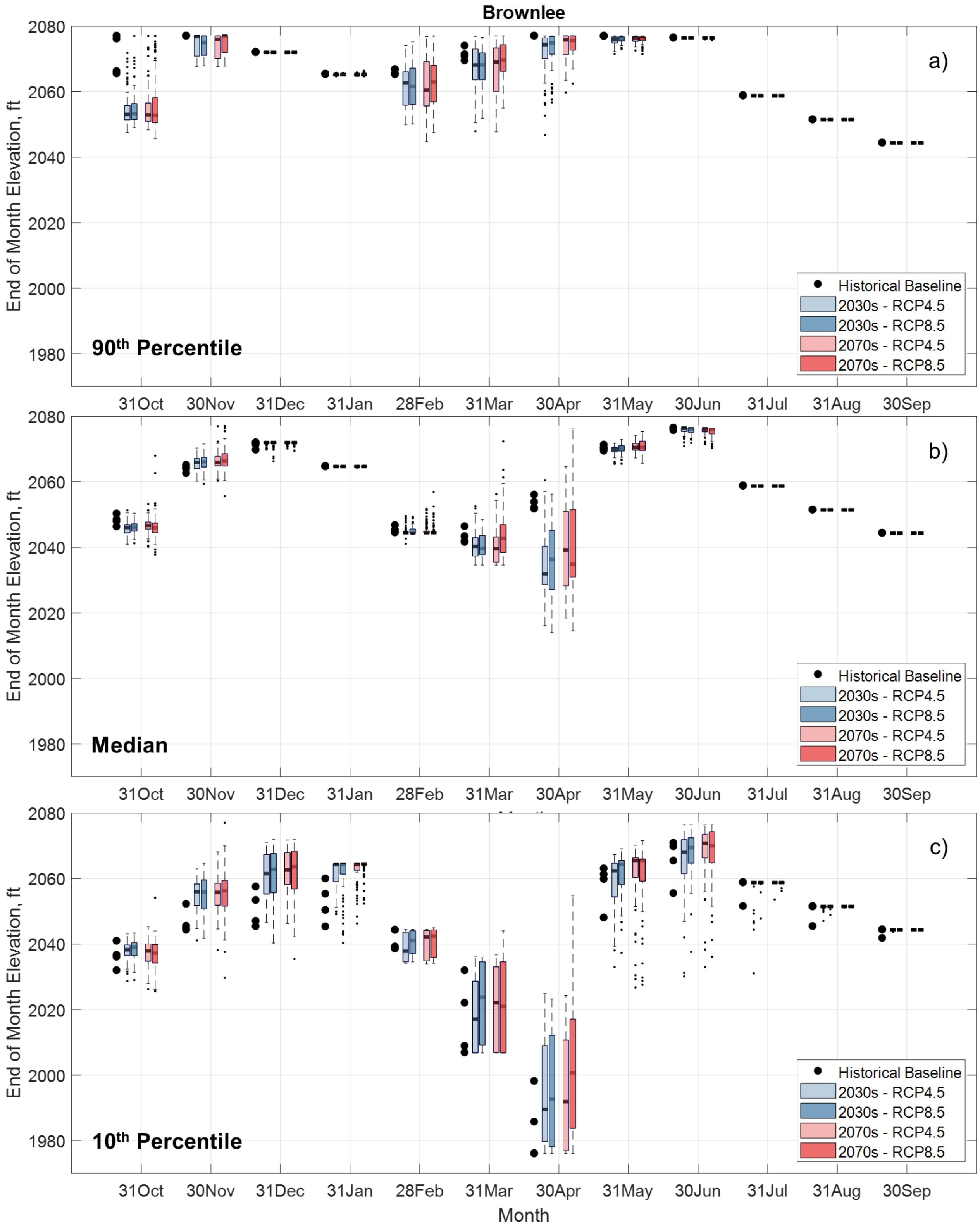

Figure 52. Projected monthly summary statistics for elevation of Brownlee Reservoir: (*a*) 90th percentile end-of-month elevation, (*b*) monthly end-of-month elevation, and (*c*) monthly 90th percentile end-of-month elevation.

7.11 Lower Granite Dam

Flow through Lower Granite Dam, a run-of-river project, is projected to increase through the 2030s and 2070s for December–May for both emissions scenarios (**Figure 53**). Flow is projected to decrease during July–August. Increased flow volumes are projected for the low-flow statistical measure (10th percentile) during July–October. The largest projected changes are for the high-flow monthly statistics during the 2070s under RCP8.5.

7.12 Columbia River at The Dalles Dam

The Dalles Dam is located on the Oregon-Washington border on the main stem of the Columbia River. This location is typically used to represent cumulative flows of the Columbia River as it corresponds to a flow measurement location that extends back to the late 1800s. Because of the length of the observation record, many statistical representations of flow frequency and thresholds used for system design and system operations are based on cumulative flows at this location. The Dalles is the primary control point for system design and operations. Outflows for The Dalles Dam are used here to describe changes in cumulative regulated flow projected for the upstream Columbia Basin.

The projected changes in regulated flow of the Columbia River at The Dalles Dam represent the cumulative effects of flow and seasonal storage at the upstream locations described in the preceding subsections. Broadly stated, the flow at of the Columbia River at The Dalles Dam is projected to increase through the 2030s and 2070s for December–May for both emissions scenarios. Flow is projected to decrease during June–October (**Figure 54**). The relative decreases for this low-flow season are less pronounced for the low-flow statistical measures (10th percentile) as compared to median or high-flow measures.

7.13 Summary

This chapter summarized the projected flow rates and reservoir elevations at 12 reservoirs and downstream sites of importance and interest to system operations. These locations correspond to projects and downstream points with characteristics that relate to the objectives of the FCRPS. The following chapters describe the effects to meeting operational objectives for FRM (Chapter 8.0); for hydropower (Chapter 9.0); and for ecosystem, irrigation, and navigation (Chapter 10.0).

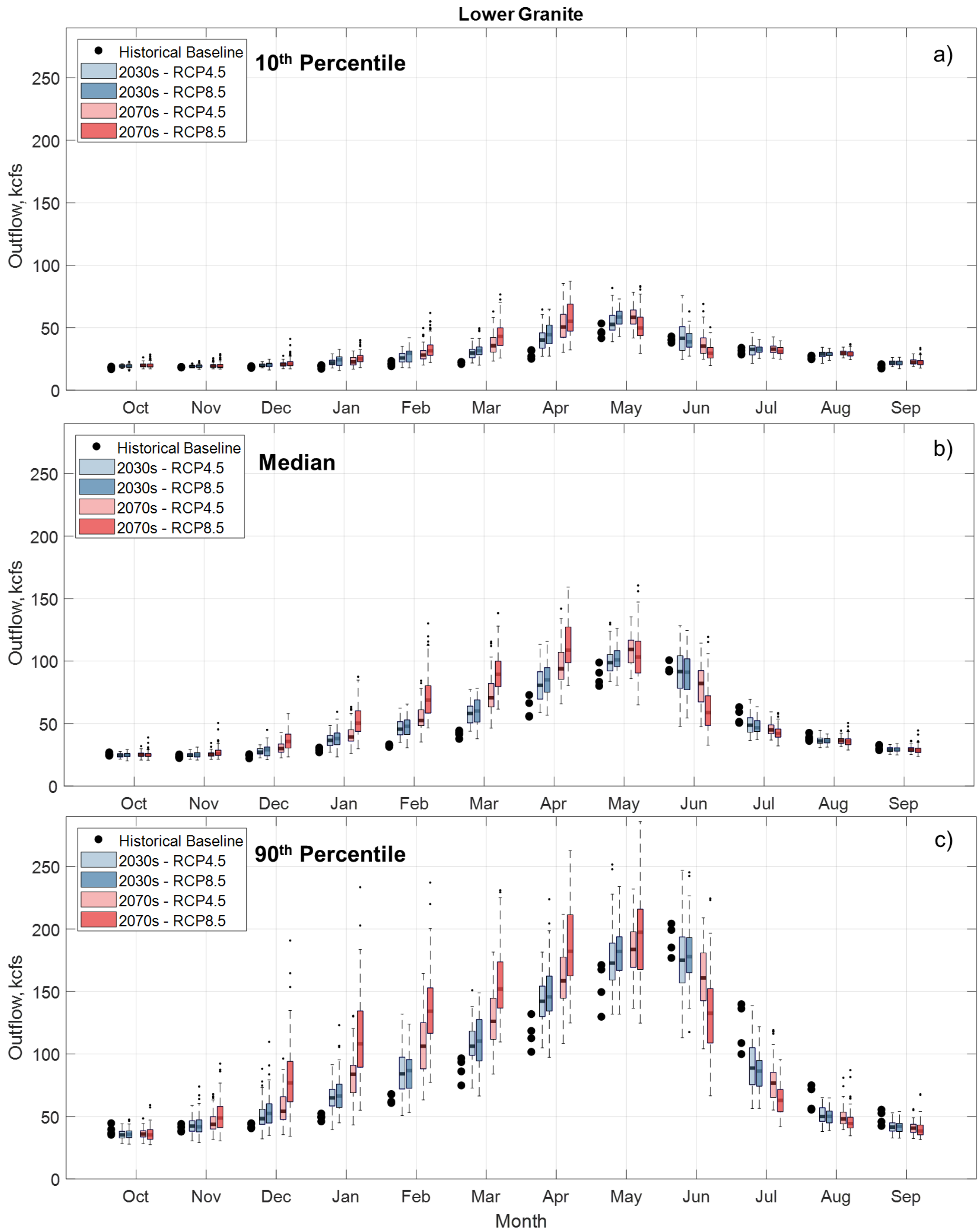

Figure 53. Projected monthly summary statistics for outflow of Lower Granite Dam: (*a*) 10th percentile monthly flow, (*b*) monthly flow, and (*c*) monthly 90th percentile monthly flow.

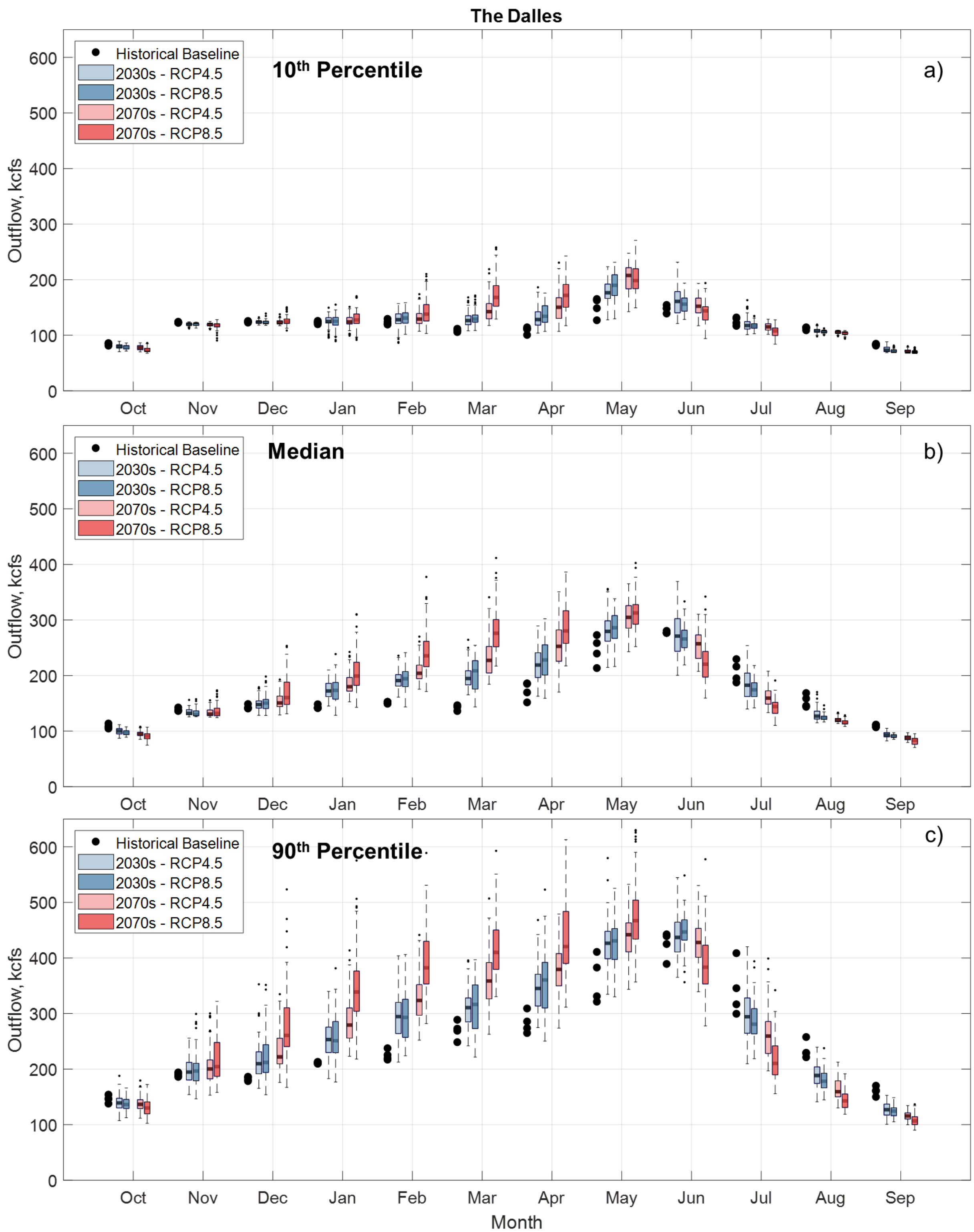

Figure 54. Projected monthly summary statistics for regulated flow of the Columbia River at The Dalles Dam: (*a*) 10th percentile monthly flow, (*b*) monthly flow, and (*c*) monthly 90th percentile monthly flow.

8.0 Flood Risk Management

USACE Northwestern Division, in cooperation with other federal and nonfederal stakeholders, operates the FCRPS for FRM. Columbia River system FRM operations occur over two seasons: spring and winter. Unique weather patterns drive each. The annual high flow of the Columbia River at The Dalles, Oregon, is the product of spring snowmelt (freshet) with peak flows occurring May through early July. Downstream of The Dalles, peak annual high water at Portland/Vancouver has also occurred in winter months in the Lower Columbia River. The winter flood season extends from November through March. Peak winter flows are driven by intense rainfall and in some cases contributions from low-elevation snowmelt.

Mean global temperature increases and changes to regional weather patterns could drive changes in runoff patterns in time and space throughout the Columbia River Basin. The primary concerns for flood risk are (1) changes to spring freshet volume and timing, (2) changes in the phase of cool-season precipitation (e.g., rain instead of snow) and winter runoff volumes, (3) changes to spatial distribution of the sources of runoff volumes that contribute to flooding, and (4) potential for increasing water supply forecast error.

8.1 Runoff Volumes Contributing to Large Floods

To investigate changes in runoff volumes contributing to large floods, it is necessary to quantify how these volumes are projected to change in space and time. Modeled unregulated flow volumes were evaluated to describe how the contributing sources could change in the future. UW developed unregulated natural flow projections. To focus the analysis on flood volumes, USACE analyzed the projections for winter and spring separately. For each projection and 30-year epoch (historical period, 2030s, 2070s), the top five flood events by volume were identified for each flood season. One historical baseline was used for comparison purposes. The historical composites in this section are based on the analysis of the historical period for each projection. Runoff volumes were composited for each local drainage area defined in **Figure 55**. For spring flooding, the April–August flow volume for the Columbia River at The Dalles, Oregon, was used to define large, system-wide floods. The April–August volume was also calculated from each local drainage area for each event.

For winter flooding, USACE identified flood events by peak flow at the confluence of the Willamette and Columbia Rivers during November–March. Local runoff volumes from each drainage area were calculated as the runoff volume over a 10-day period preceding the peak in the lower river. This is based on an approximate 10-day travel time of water to pass through the reservoir system.

For winter and spring, USACE used the mean of the top five local volumes to describe the runoff volumes corresponding to each epoch. A value was calculated for each of the 80 projections for each emissions scenario and time period for a total of 320 mean volumes. This was to demonstrate the spread of projections and provide a relative measure of uncertainty.

Figure 55. Drainage areas used to describe the runoff volumes contributing to large floods.

The changes in the amount of runoff generating large spring flood events is projected to vary across the major drainage areas of the Columbia River Basin (**Figure 56**). Many of the drainage basins show decreasing runoff volumes for large spring flood events. The projections for the lowest elevation drainage areas (Willamette, Lower Columbia, Yakima, and Lower Snake) display potential decreases in volume for both the 2030s and 2070s. In the 2070s, a larger fraction of the projections indicates decreasing volume from mid-elevation drainages: the Lower and Mid-Columbia, Lower Snake, and Pend Oreille.

In contrast, many projections indicate increasing unregulated volume originating in the Upper Snake and Upper Columbia drainages. These drainages are dominated by high-elevation topography whose winter temperature are likely to stay below freezing for some time, reducing the sensitivity to increasing temperatures. Thus, potential increases in cool precipitation projected in the future (RMJOC-II Part I, Section 1.2.1) could lead to increased snowpack and spring runoff volumes in these regions.

The projected changes in flood volumes in the winter season display more spatial uniformity than those for spring. The winter projections indicate that, based on the top five flood events on the main stem of the Columbia River at the confluence of the Willamette, the 10-day unregulated runoff volumes that precede large flood events could increase through the 2030s and 2070s (**Figure 57**) in nearly every drainage area. Volumetrically, the largest increases are projected for the Willamette River, especially in the 2070s, where the interquartile range of the ensemble of projections is outside that of the historical period for both RCP4.5 and 8.5 emissions scenarios. The largest relative changes were projected for the Pend Oreille River drainage. The medians of the projections indicate that the Mid-Columbia may have decreasing unregulated flood volumes for the 2070s; however, there is considerable range in the spread of projections, and the relative volume remains in comparison to the broader basin.

These changes are a product of the coupled effects of projected increases in cool season precipitation and warming air temperature (Chapter 1.0). As air temperature warms in the winter, precipitation will occur more often as rainfall instead snowfall, which results in more of the drainage area contributing to runoff during the winter. Further, as warmer air can hold more water (Held and Soden 2006), future rainfall intensity may increase.

This analysis of volumetrically large, unregulated events by major drainage area provides an initial description of the key runoff drivers that influence flood risk across the basin in space and time. The actual change to flood risk also depends on reservoir storage available, where it is located, and peak flow magnitude and timing of the large events.

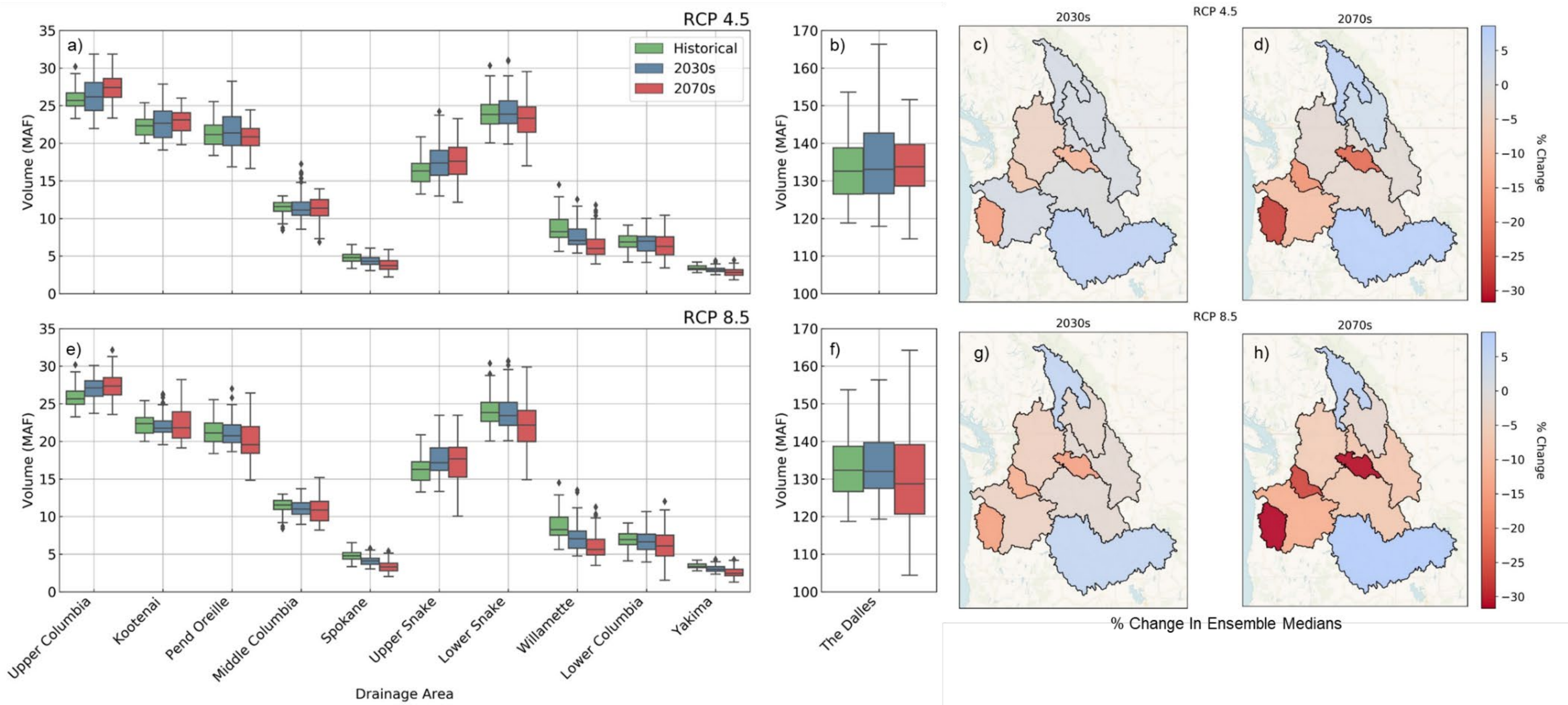

Figure 56. Unregulated April–August runoff volume that contributes to large spring floods for (*a,b*) RCP4.5 and (*e,f*) RCP8.5 for 10 drainage areas in the Columbia River Basin. The runoff volume contributing to large floods was calculated as the mean volume of the top five events in each 30-year epoch for each projection. The percent change plotted (*c*, *d*, *g*, *h*) represents the change in the median of the respective ensemble of projections from that of the historical epoch.

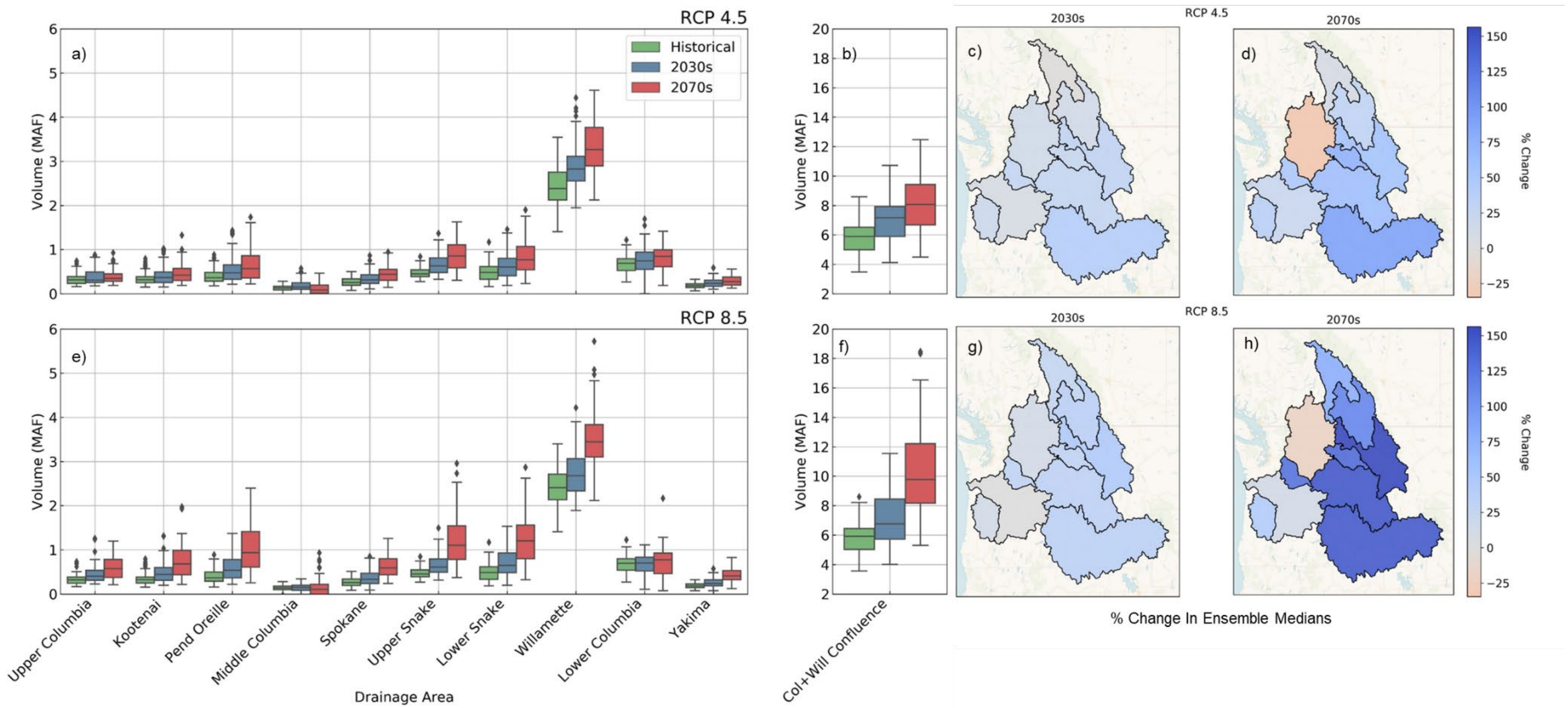

Figure 57. Unregulated runoff volume that contributes to large winter floods for (*a,b*) RCP4.5 and (*e,f*) RCP8.5 for 10 drainage areas in the Columbia River Basin. The volumes represent the total volume over the 10-days preceding the day of peak flow of the Columbia River at is confluence with the Willamette River. The runoff volume contributing to the largest winter floods was calculated as the mean volume of the top five events in each 30-year epoch for each projection. The percent change (*c,d,g,h*) represents the change in the median of the respective ensemble of projections from that of the historical epoch.

8.2 System FRM Operations

8.2.1 Spring

Overall, the FCRPS provides approximately 30 million acre-feet of committed flood storage space. The FRM objective is to operate Columbia River basin reservoirs to reduce flood flows at designated flood damage centers within the U.S. and Canada. As originally designed, the FRM operation focuses on spring snowmelt flooding.

Conceptually, the basic spring flood reduction operations are based on runoff volume forecasts (water supply forecasts) of the expected spring volume passing at The Dalles, Oregon. In anticipation of the annual spring peak flow, water managers determine required flood storage space at projects throughout the Columbia basin. The flood space requirements are calculated based on water supply forecasts and project-specific storage reservation diagrams (SRD), which dictate individual project flood space and draft timing levels for each month. If water is in the required space, it is released; and the reservoir pool elevations are lowered (drafted) in January–April based on the water supply forecasts and SRDs. Drafts for individual projects are also constrained by local flood control needs and may occur earlier, October–December. For example, Dworshak Reservoir drafts in early winter to provide storage for local downstream flood control on the Clearwater River.

To analyze how required spring FRM system storage may change in the future under current operations, we calculated the total system storage provided through reservoir drafts for FRM purposes (**Figure 58**). System storage is defined as the sum of space available for FRM across all major storage reservoirs in the basin on the date that refill is initiated. The calculation of total system storage includes Lake Pend Oreille (Albeni Falls Dam), Arrow Lakes, Brownlee Reservoir, Duncan Reservoir, Dworshak Reservoir, Lake Roosevelt (Grand Coulee Dam), Hungry Horse Reservoir, John Day Reservoir, Lake Koocanusa (Libby Dam), Kinbasket Lake (Mica Dam), and Flathead Lake (Seli'š Ksanka Qlispe' Dam). Under median conditions, the storage for FRM is projected to be similar to modeled historical levels for the 2030s. For high (90th percentile) and low (10th percentile) draft years, the projections indicate slightly less FRM storage for the 2030s. During the 2070s, the system draft for spring FRM is projected to be generally less than historical levels across all three statistical measures, particularly under the RCP8.5 emissions scenario. This reduction in total system draft is attributed to projected decreases in the runoff volume and associated runoff volume forecasts at The Dalles for the April–August period. This occurs for large flood events (**Figure 56f**). It is most pronounced for average (**Figure 59**) and low-flow conditions.

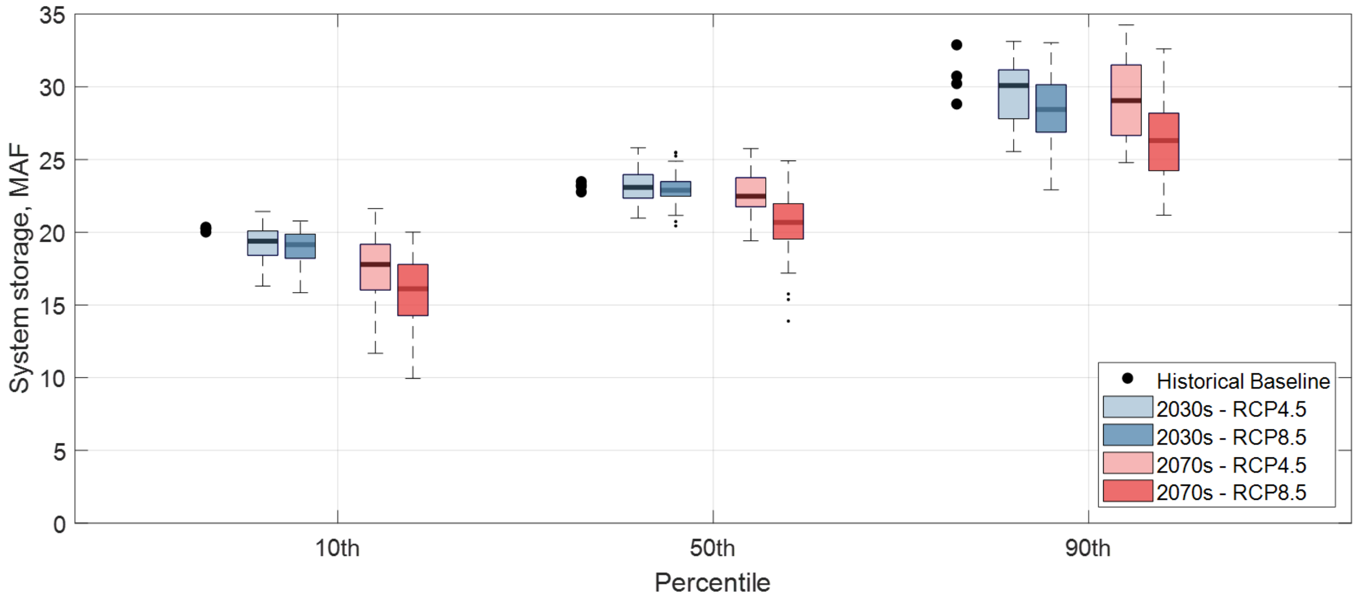

Figure 58. Modeled historical and future system storage available for FRM at the time refill is initiated.

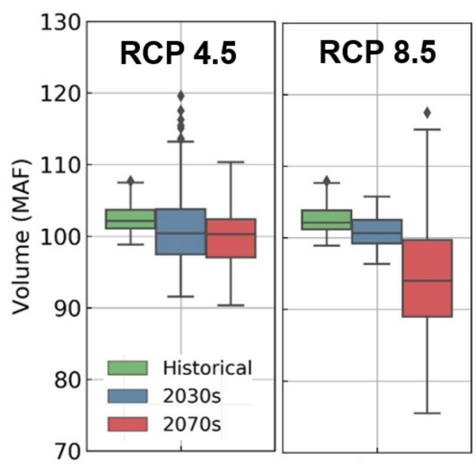

Figure 59. Modeled historical and future mean April–August runoff volume of the Columbia River at The Dalles, Oregon.

The *reservoir refill period* is when reservoirs begin to store inflows during spring runoff to reduce peak flows in the lower Columbia River as measured at The Dalles, Oregon. The basic objective of the system flood control operation during refill is to regulate the flood runoff to non-damaging levels if possible and to regulate larger floods that cannot be controlled to non-damaging levels to the lowest possible level with the available flood control storage space. Over the refill period, a controlled flow target is determined as an operational objective. The controlled flow is a function of the forecasted unregulated volume of runoff as measured at The Dalles and the amount of upstream storage available for system FRM. During refill, upstream storage projects are operated to maintain flows at or below this target. This operation will generally result in adequately meeting FRM objectives at other locations prone to flood damages. However, operations may be further modified by water managers following procedures outlined in the Flood Control Operating Plan (USACE 2003) to meet those objectives.

A controlled flow target as measured at The Dalles is set as refill commences. This first controlled flow target is the *Initial Control Flow* (ICF). **Figure 60a** displays the modeled historical and future date that the ICF was determined for each projection; this is equivalent to the date that system refill starts. For the earliest dates of refill in each projection (10th percentile), the projections show that refill initiation could have similar timing for the 2030s (mid to late April) but shift to early April in the 2070s. During the 2070s, the majority of projections show that the median condition of refill initiation could occur in mid to late April. A notable modeling assumption of current operations is that refill cannot be initiated before April 1.

The ICF of the Columbia River at The Dalles at the time when refill is initiated is indicative of the anticipated FRM objective in each water year. For median conditions (50th percentile), the projections generally indicate higher control flows than historical baselines for the 2030s; (**Figure 60b**). The high ICF for each projection (90th percentile) are similar in magnitude to historical baselines with respect to ensemble medians. However, the relative spread of projections for this metric is high, and both increases and decreases with respect to historical baselines are projected.

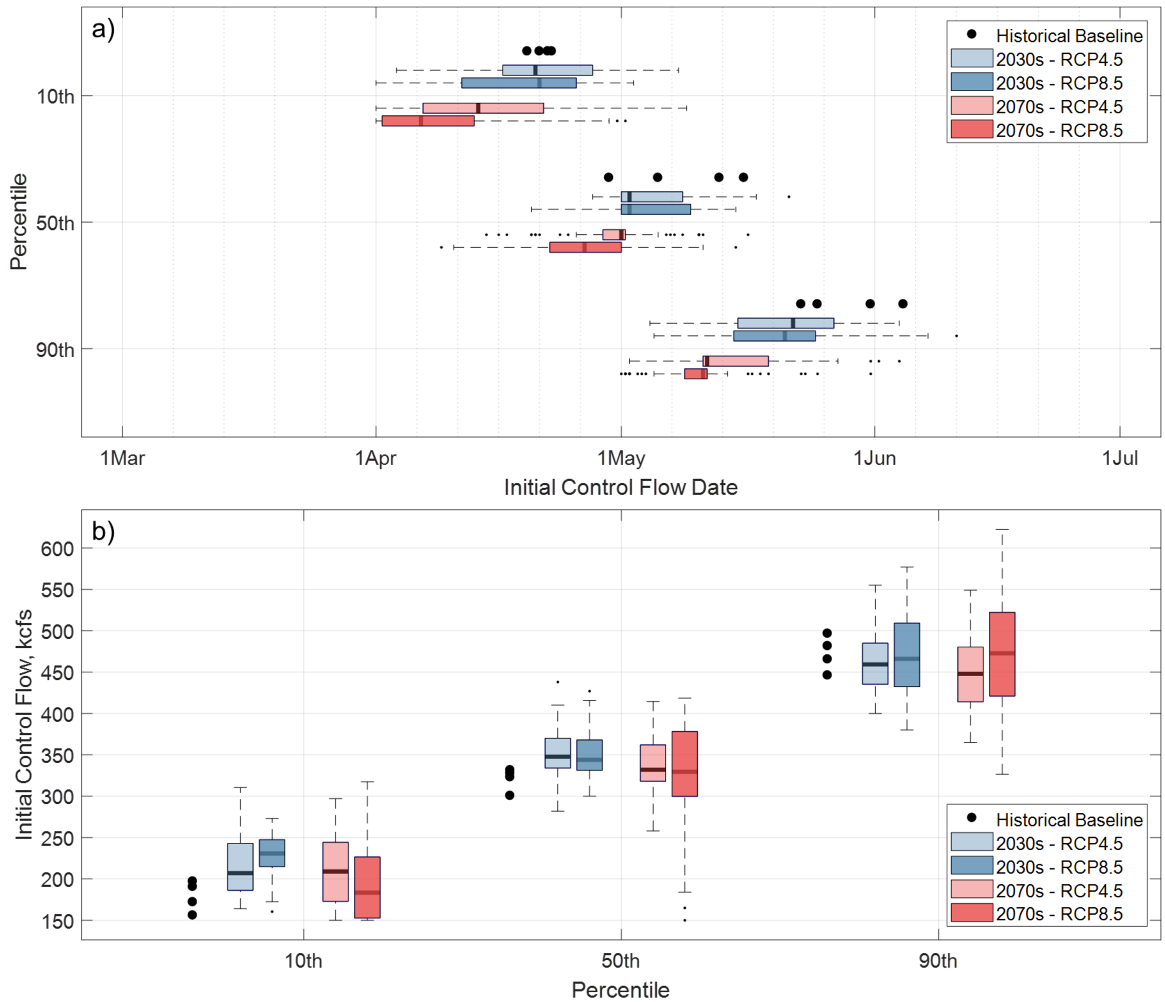

Figure 60. Modeled historical and future system (*a*) date of initiation of refill (initial control flow date) and (*b*) initial control flow target for the Columbia River at The Dalles.

8.2.2 Winter

The primary objective of winter flood system operations is to reduce downstream flows and reduce peak flood stages in the Lower Columbia River from November to March. Lower Columbia River peak flood stage is measured at Vancouver, Washington. FCRPS winter operations are activated and informed with near-term forecasts. These forecasts predict out about one to five days of the stage at Vancouver, which is a function of regulated outflows at Bonneville Dam; regulated flows on the Willamette River at Willamette Falls, Oregon; and local inflow downstream of these points. The Willamette Valley Project is a system of 13 dams operated by USACE Portland District for various authorities, including FRM. During winter, Willamette Valley reservoirs are drafted with fixed guide curves to provide flood space to make damaging floods manageable at downstream control points on the Willamette River. The Willamette Valley Project is not designed or optimized to provide targeted flood control at Portland/Vancouver. Nonetheless, there is a storage effect from the Willamette Valley projects during winter operations.

The winter Columbia FRM operation in ResSim is modeled using a tiered approach based on event severity. An increasing number of projects activate winter operations as higher-severity events are forecasted (**Table 5**). The tiers are groups of reservoirs that collectively operate for system winter operations. The winter FRM operation in the WAT-ResSim model are based on the flood regulation operations implemented during a flood event in February 1996. The operation was designed to minimize flooding at Portland/Vancouver by operating the Columbia River System projects to reduce flow on the main stem of the Columbia River. This is achieved by combining one or more of the following: (1) short-term pre-event drafting of the lower four projects on the Lower Columbia, (2) halting winter drafts to pass inflows at storage projects, and (3) reducing outflow to a minimum rate to store inflows until the event is over. The implementation of these winter operations in the model is somewhat uncertain as most are not formally described in water control manuals. For complete modeling details, see Appendix A.

Figure 61 displays the average number of days per year that the modeled historical and future operational tiers are activated. This is the average across each 30-year epoch; it should not be interpreted that the winter operations are activated every year. The projections indicate that the number of days that reservoirs are operated for winter operations significantly increases in both the 2030s and 2070s for all tiers with the largest increases in Tier 1. This indicates that projects will suspend other operations to be operated to minimize flooding on the Lower Columbia River in the winter more frequently in the future than historically.

Table 5. Methods used for regulated flow return intervals.

Operational Tier	Forecasted Vancouver Stage (feet CRD*)	Projects with Active Winter FRM Operations
1	≥16, <17	Bonneville Dam, The Dalles, John Day, McNary
2	≥17, <20	Tier 1, Grand Coulee, Albeni Falls, Dworshak
3	≥20	Tiers 1–2, Libby, Hungry Horse, Seli'š Ksanka Qlispe', Arrow, Duncan

* Columbia River Datum

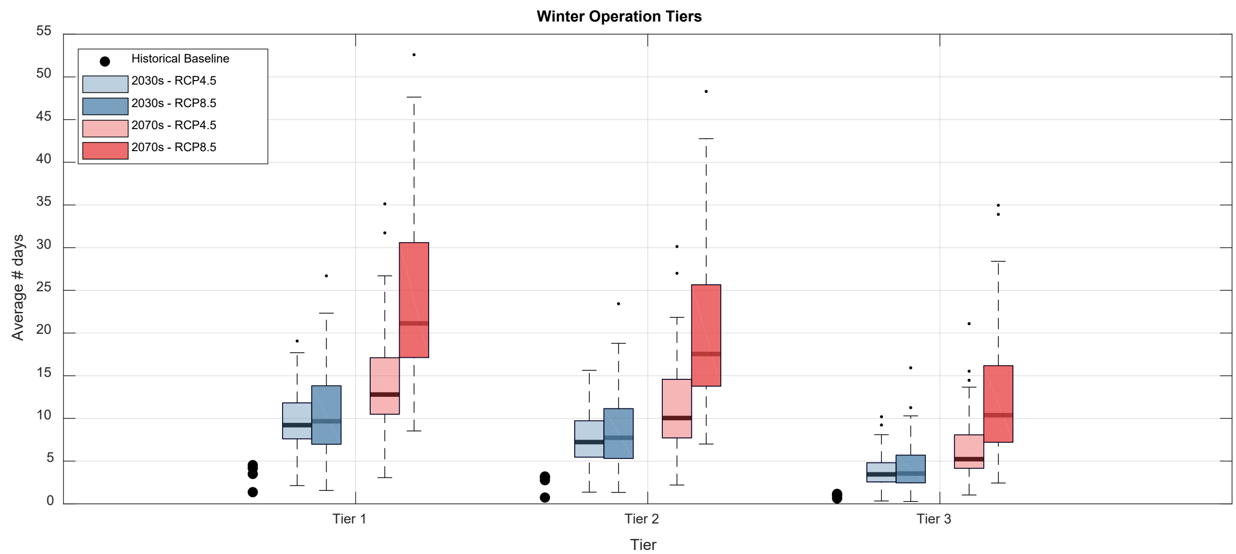

Figure 61. Average number of days per year where winter operations were modeled to be active in each operational tier for historical and future epochs.

8.3 Peak Flow Frequency

Flood frequency evaluation is a combination of two important components: peak streamflow probabilities and flood stage thresholds. The focus in this section is the peak streamflow magnitude and probability for regulated flow. The approach to estimating the peak streamflow and the associated probabilities varies slightly depending on the type of flow data being used. This section describes the general procedures for regulated flow frequency.

Determining the unregulated peak flow frequency is an established procedure that requires extracting peak flows during a predetermined period (e.g., annual, monthly, seasonally, etc.) and fitting an analytical statistical distribution to those data. The most common distribution to use for annual peak maximum streamflows is a three-parameter Pearson distribution, often referred to as a Pearson type 3 distribution. When using the log transform of the input flow values, this distribution is called log-Pearson type 3. For unregulated flows, this analytical distribution can be used to describe the range of potential peak flows possible at a specific location and assign those to probabilities.

Performing a flow frequency analysis on regulated flows is often approached differently. This is due to the varying relative influence that storage projects have on peak streamflows across the probability distribution. For example, in some regulated systems, regulation of low to median peak events results in annual peak flows being substantially less than what would have occurred naturally, whereas the low-frequency extreme events may be nearly the same magnitude whether regulated or unregulated. Conversely, flood regulation systems may not reduce unregulated peak events until reaching damaging levels of inflow. This external influence on the flows complicates fitting analytical distributions for all probabilities because the necessary assumption of all data being independent and identically distributed is not satisfied. Depending on the system and relative degree of reservoir regulation, during wetter hydrologic conditions, the regulated outflow from storage projects can trend toward matching natural peak flows. This is especially true for very rare events that result in the reservoir storage filling quickly.

Although the impact of regulation varies by location within the watershed, we chose to focus on changes in flow frequency at The Dalles for this study. This study summarizes the 25, 10, 2, and 1 percent chance exceedance probabilities (4-, 10-, 50-, and 100-year return period) at each location. We estimated peak flow quantiles using an analytical distribution (Pearson type 3), following the same procedure that is typically used for unregulated peak flows. The Columbia River is heavily regulated, but reservoirs have a sliding scale flow objective at The Dalles based on the forecast and current reservoir elevations. Therefore, the regulated flood frequency curve does not have any sharp discontinuities, despite the large regulation effects. We would also note that the method used in our analysis was developed only to demonstrate the relative differences in peak flows between epochs. These results should not be used for any current flow frequency estimates.

The summary plot for The Dalles shows the range of flow values for each peak flow probability. This range includes peak flow estimates for that specific probability of the 80 projections within an individual RCP. Our study separated the flow frequency into two seasons (winter and spring) to capture seasonal changes in peak events and to describe which season drives the annual maximum. The months included for the winter and spring seasons are October–March and April–July, respectively. The peak flow values this analysis used are based on a 31-day centered moving average (CMA) time series. USACE chose to present 31-day duration annual peaks because (1) peak flows of long duration are more likely to stress flood storage and operations, (2) consistent peak flow duration would be presented throughout, and (3) the development of daily hydrologic projections results in highly variable daily peak flows, which mask changes from the baseline hydrology; therefore longer duration peak flows were used to ensure that any change from the baseline would be detectable. Note that analysis of long-duration peak flows may not be the most appropriate for smaller headwater locations or short-duration rainfall-driven events.

Figure 62 summarizes the relative winter and spring shifts in the distribution of outflows at The Dalles Dam and the lower Columbia River reach through Bonneville Dam. Winter and spring flows are likely to increase in the future. Our results indicate the largest increases are for winter peak flows; however, the highest flows annually will continue to occur in the spring.

The variability and increase of flows are relatively moderate in the 2030s. However, there are noticeable increases in magnitude as well as variability by the 2070s. The increases in winter peak flows are of significance for winter flood reduction. For example, the CMA 50-year peak flow is over 500 kcfs by the end of the 2070s. This supports the conclusion that winter flood risk for The Dalles is increasing under the majority of future hydrology projections.

In contrast to the winter flows, the regulated spring peak flows do not indicate a significant shift in the medians of the ensembles of projections at any return period in the 2030s. However, projections do indicate potential increases in peak flows in the 2070s under RCP8.5. Overall, our results show winter peak flow median change to be increasing based on future projections and is most pronounced in the 2070s under RCP8.5. A summary of flood risk changes below Bonneville Dam is described in Section 8.5.

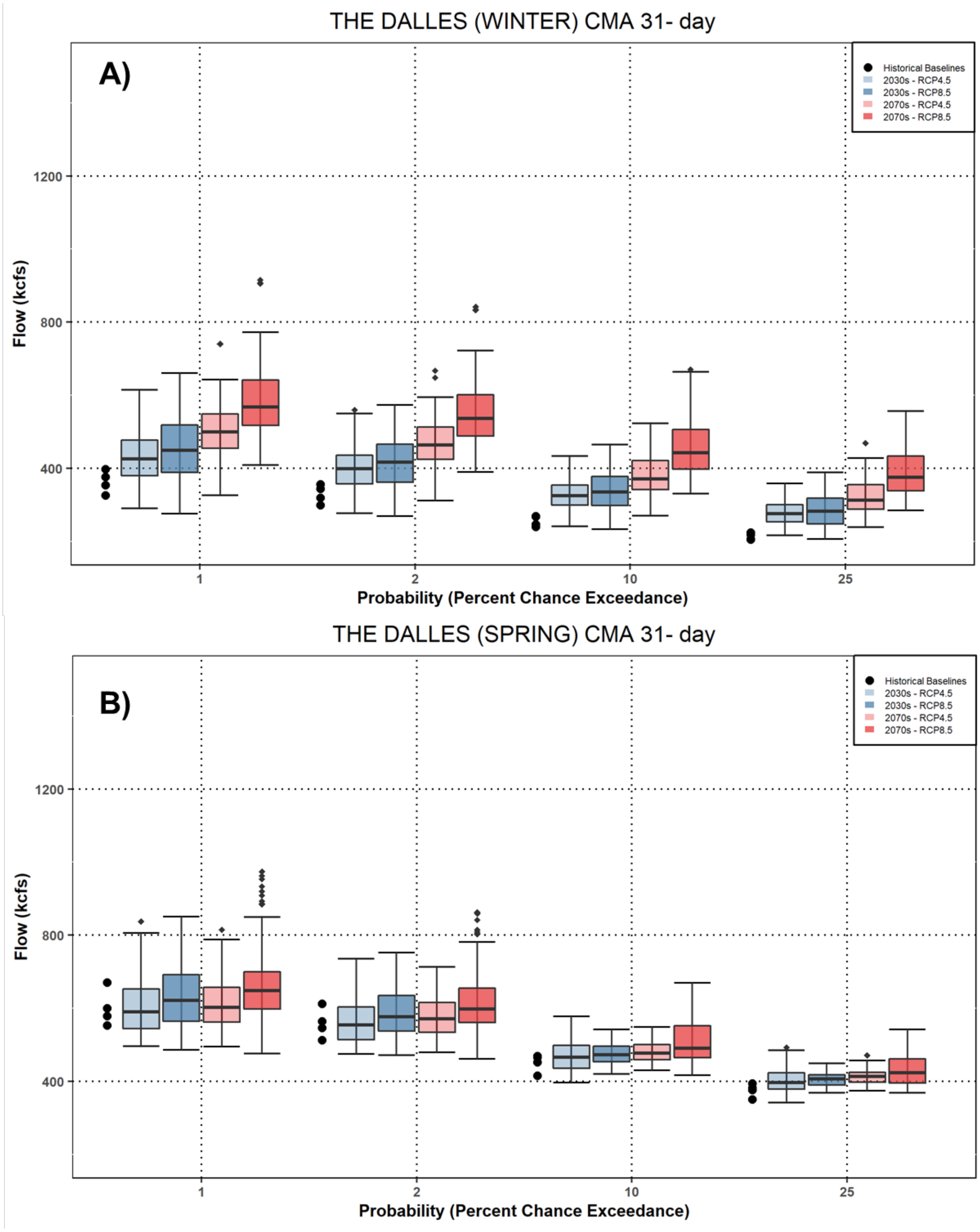

Figure 62. Flow frequency analysis for 31-day duration annual peak outflow of The Dalles Dam for (*a*) winter and (*b*) spring.

8.4 Local Flood Risk

FRM operations include system-level flood control operating targets (flow of the Columbia River at The Dalles) as well as local flood constraints. Local flood risk thresholds are usually defined at gaged points in the river (called control points) that are representative of local areas sensitive to damage. The thresholds are typically defined in terms of peak flow rates or water-surface elevation (stage). Operationally, many storage projects adjust outflow to aid in maintaining flow or stage at these control points below these thresholds to reduce major damages from flooding.

To evaluate potential changes in local flood risk, years where the defined local flood threshold was exceeded were summed in each projection. This was done by month and categorized by winter and spring. The presentation of the spread of the ensemble for each period and emissions scenario follows that of other metrics where the metric was calculated for each individual projection and the spread of the values across all projection is statistically described with a boxplot (Section 1.6.5). Modeled historical reference cases are presented as discrete points (black circles) in each of the figures.

8.4.1 Bonners Ferry, Idaho

Bonners Ferry, Idaho, located on the Kootenai River, is prone to flooding. The stage of the Kootenai River at Bonners Ferry is influenced by outflows of Libby Dam, local inflow, and backwater effects of Kootenay Lake located downstream. The defined flood stage threshold for Bonners Ferry is 1764.8 feet. The projections indicate that the flood risk in the 2030s could be similar to historical levels (**Figure 63**). For the 2070s, the projections show increased flood risk in spring. The majority of RCP8.5 projections show increased occurrences of exceeding the flood stage in May and June. This is linked with projected increased peak outflows from Libby Dam during spring (Sections 7.3.2).

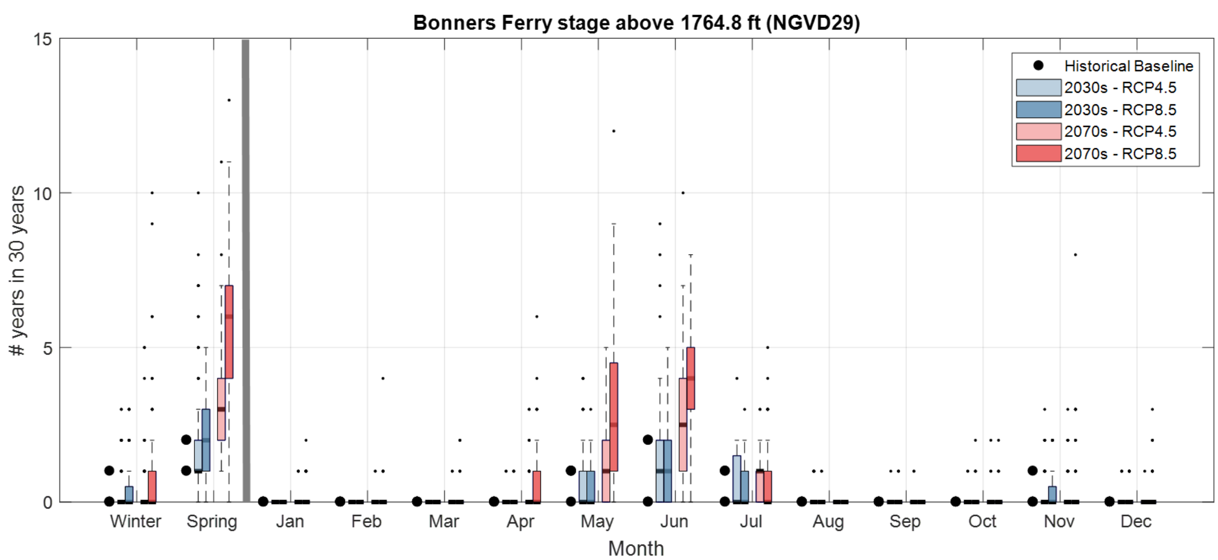

Figure 63. The frequency (number of years in the 30-year epoch) where the stage of the Kootenai River at Bonners Ferry, Idaho, was projected to exceed a threshold of 1764.8 feet NGVD29 (National Geodetic Vertical Datum of 1929).

8.4.2 Kootenay Lake, BC

Kootenay Lake is located in eastern BC on the Kootenai River. Inflows to Kootenay Lake are composed of outflow from Libby and Duncan Dams and the local unregulated tributaries of the Lardeau, Yaak, Goat, and Moyie Rivers, among others. The elevation of the lake is often controlled by a natural channel constriction at Grohman Narrows that limits outflow. The analysis used a water-surface elevation of 1,755 feet NGVD29 as the flood stage threshold.

The projections indicate that the frequency of exceeding this threshold is likely to be similar to historical levels for the 2030s (**Figure 64**). During the 2070s, the projections indicate potential increases in occurrences of exceeding the threshold in spring, May–July. The strongest signal of increased occurrences is for June under RCP8.5.

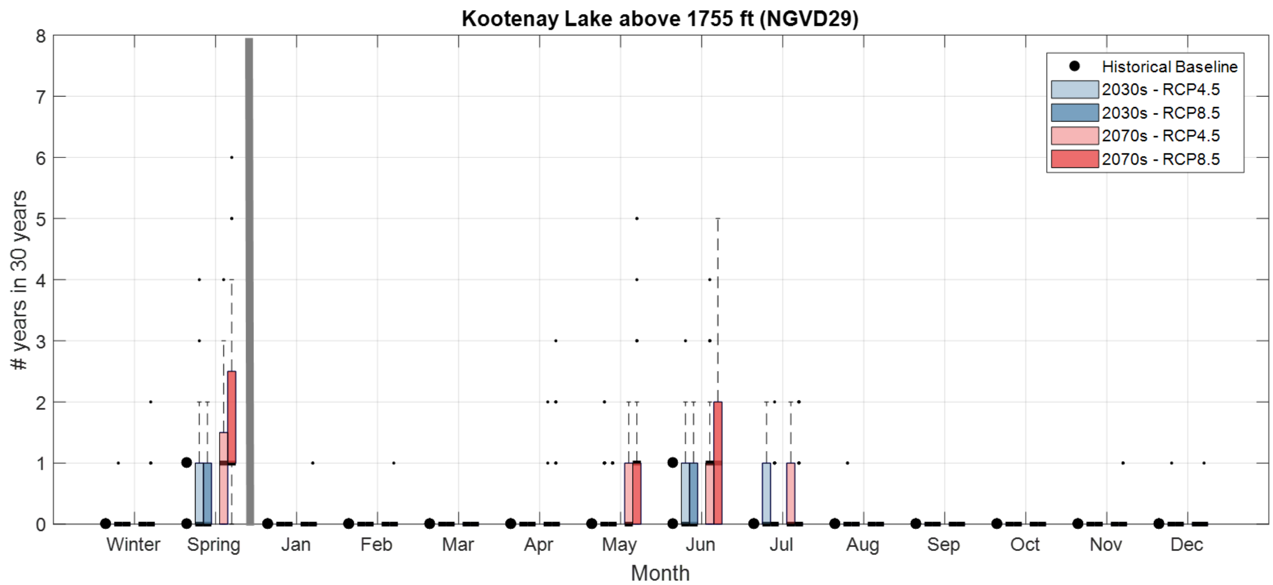

Figure 64. The frequency (number of years in the 30-year epoch) where the surface elevation of Kootenay Lake was projected to exceed a threshold of 1,755 feet NGVD29.

8.4.3 Columbia Falls, Montana

Flows of the Flathead River at Columbia Falls are a product of outflows from Hungry Horse Dam and local inflow from the middle and north forks of the Flathead River. Historically, unregulated local flow has been a large contributor to flooding. The threshold used to describe flooding at Columbia Falls depends on the elevation of Flathead Lake (downstream); 13 feet river stage (approximately 44 kcfs) when the lake elevation is greater than 2,892 feet NGVD and 14 feet river stage (approximately 51 kcfs) when it is below 2,892 feet NGVD. Outflow from Hungry Horse Dam is controlled to aid in maintaining downstream flow below this threshold when possible.

Flood risk increases in both seasons under both RCPs and future periods (**Figure 65**). Increased forecast error may accentuate local FRM variability at this site. The projected increase in occurrences of exceeding the flood flow threshold is largest for spring months in the 2070s where nearly all projections show some increase in occurrences. This can be linked to projected increases in unregulated tributary inflow (Section 7.4.1) and outflow from Hungry Horse Dam (Sections 7.4.2) during these months.

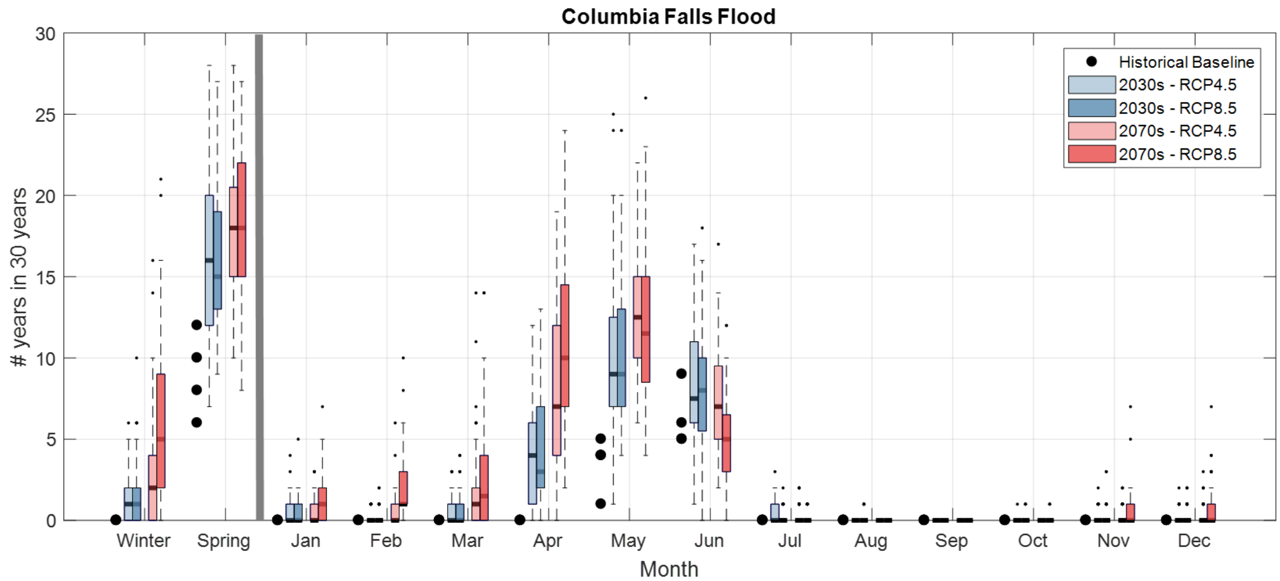

Figure 65. The frequency (number of years in the 30-year epoch) where the projected flow of the Flathead River at Columbia Falls exceeds the flood threshold.

8.4.4 Albeni Falls Dam and Lake Pend Oreille

Albeni Falls Dam is located in the Pend Oreille basin and is located downstream from the confluence of the Priest River with Lake Pend Oreille. Albeni Falls Dam controls the flow of the Pend Oreille River during seasonal periods with lower flows; however, it often has limited influence on flow during periods of high flow (spring freshet) when the dam undergoes a free-flow operation. When the dam is in control of outflow, outflows are regulated to stay below 95 kcfs when possible for downstream flood considerations. Flood risk also exists upstream of the dam on Lake Pend Oreille. Shoreline flood damages are possible when the lake exceeds the elevation of 2,365.5 feet NGVD29.

For the 2030s and 2070s, the projections point to increasing occurrences of exceeding the downstream flood threshold in April–June (**Figure 66a**). The occurrences shift to earlier in this period as time progresses and more warming is occurring (2070s, RCP8.5). The majority of the projections indicate a net increase in occurrences for spring. The projections also indicate potential increases in winter months (December–March) under the RCP8.5 emissions scenario. The potential for exceeding flood stage upstream on Lake Pend Oreille shifts earlier in the year with more occurrences in April and May. The ensemble medians indicate similar amounts as historical conditions for spring; however, there is a significant range of uncertainty under RCP8.5 in the 2070s (**Figure 66b**).

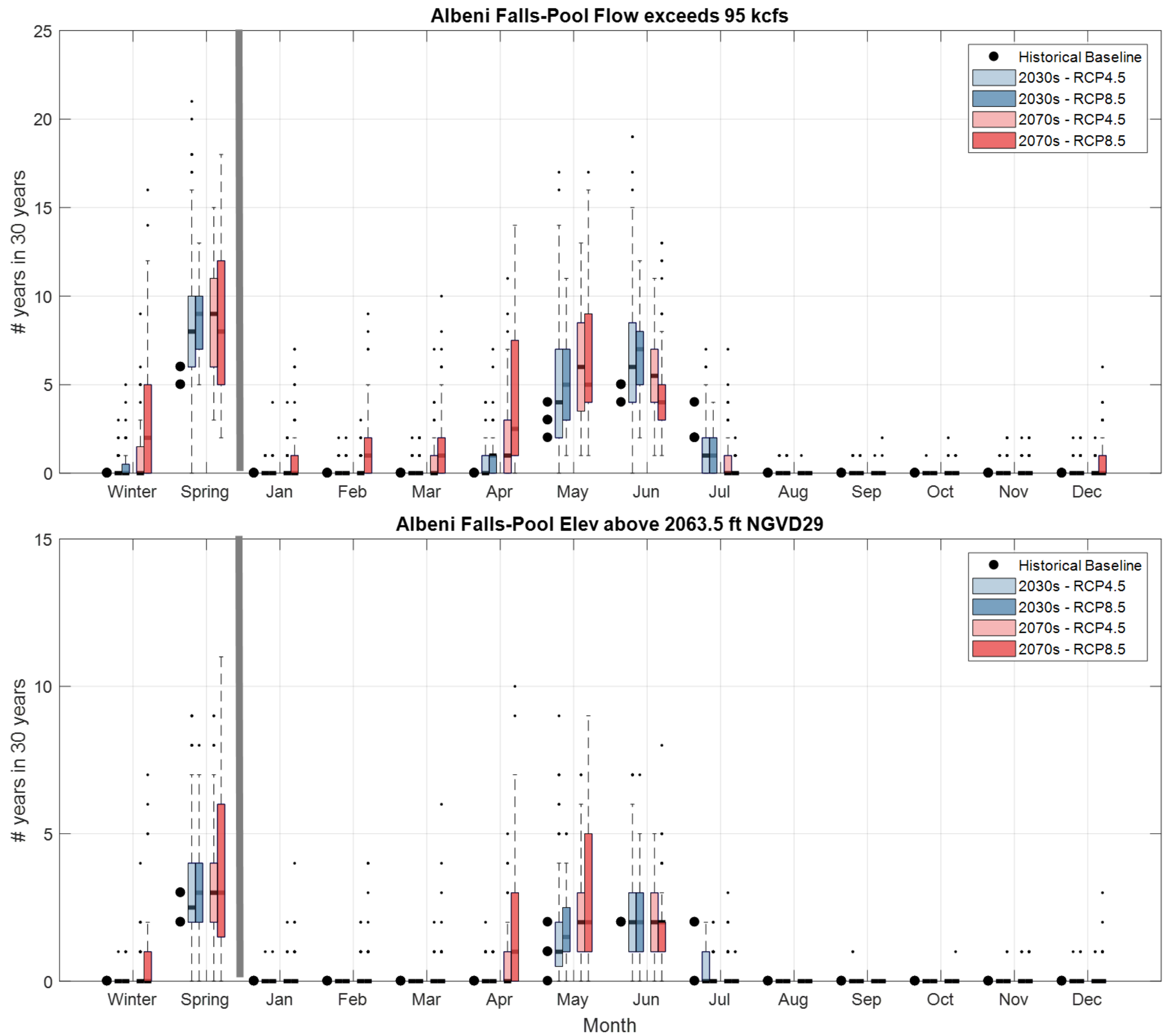

Figure 66. The frequency (number of years in the 30-year epoch) where the projected (*a*) outflows of Albeni Falls Dam exceeds the flood threshold of 95 kcfs and (*b*) elevation of Lake Pend Oreille exceed 2,063.5 feet NGVD29.

8.4.5 Spalding, Idaho

Spalding, Idaho, is located on the Clearwater River above its confluence with the Snake River, downstream of Dworshak Dam. The threshold flow value at Spalding of 105,000 cfs is based on regulation objectives for Lewiston, Idaho. Dworshak is operated to reduce flows at this location, ramping to minimum outflows to offset high flows from the unregulated portion of the Clearwater River. There were no events in the modeled historical baselines that exceeded this threshold (**Figure 67**). Some projections (less than 50 percent) indicate occurrences of exceeding the threshold during the winter season under RCP8.5 in the 2070s; however, there is not strong consensus for increased risk. For the spring period, some projections include more events that exceed the threshold; and when taken as a seasonal composite indicate a potential increase in flood risk for both epochs with the strongest consensus shown for the 2070s under RCP8.5.

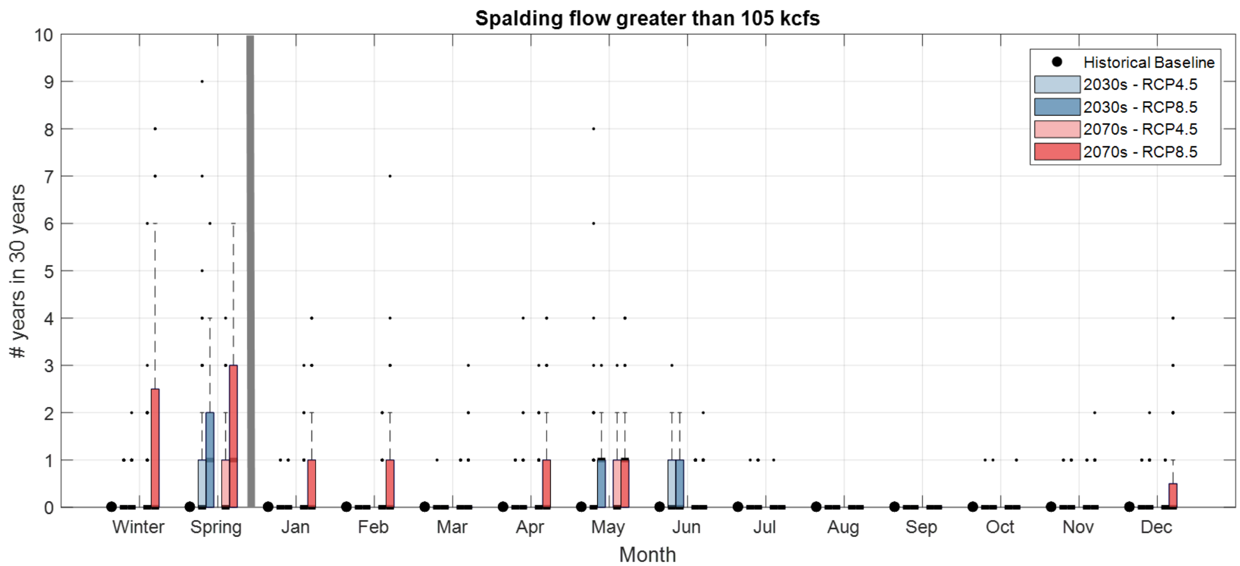

Figure 67. The frequency (number of years in the 30-year epoch) where the projected flow of the Clearwater River at Spalding, Idaho, exceeds the flood threshold of 105 kcfs.

8.5 Lower Columbia Basin Flood Risk

Historically, high river stage in the Lower Columbia River is most frequently created by the Columbia River Basin peak spring (freshet) flows, occurring May through early July. The historic floods of May–June 1894 and 1948 are primary examples of snowmelt-driven events for which rainfall intensified. However, some of the extreme historic flood stages have occurred in the winter (December–March). These are driven by a high influx of moisture, warmth, and wind into the northwest via atmospheric river storms. These storms result in high flows on the Willamette, Lower Snake, and Lower Columbia Rivers, creating high flood stages at Vancouver/Portland. The February 1996 event is the most recent large winter system-wide flood event. The precipitation for this event was centered within the basins downstream of Grand Coulee Dam while most of the contributing snowmelt was from the Cascade Mountains in Oregon and southern Washington as well as the Blue Mountains in eastern Oregon. Therefore, high flows resulted on the Willamette River and were coincident with high winter flows on the Columbia River. This event created the highest water-surface elevations in the Lower Columbia since implementation of the full Columbia River hydroregulation management.

A stage gage on the Columbia River at Vancouver is used as an index of flood severity in the Lower Columbia River. The Vancouver gage is located at river mile 106.1 and is operated collaboratively by the National Oceanic and Atmospheric Administration (NOAA), the National Weather Service, and the U.S. Geological Survey (gage 14144700). The reported elevations at the Vancouver gage are in Columbia River Datum (CRD). **Table 6** lists the flood categories assigned to specific stage measurements by the National Weather Service.

Table 6. National Weather Service flood ratings for the Columbia River gage near Vancouver, Washington.

Flood Category	Stage (feet, CRD)
Major Flood	25
Moderate Flood	20
Flood	16
Action	15
Lower	1

The river hydraulics at the Vancouver gage are complex due to the backwater effects of the flow contributions of the Willamette River. ResSim simulates the Vancouver stage using a polynomial regression equation. This equation is a function of outflow from Bonneville Dam; flow of the Willamette River at Willamette Falls, Oregon; and local inflow between these two points and the Portland/Vancouver area. This regression-based approach was trained using HEC-RAS hydrodynamical model simulations. The regression approach was used to increase computational efficiency for modeling the large ensemble of projections.

The Willamette River boundary time series were applied as cumulative unregulated daily flows at Willamette Falls. Cumulative 2010L depletions were applied to make this an MFL inflow. Use of an unregulated boundary inflow was required due to the limited daily time step regulation modeling for this basin. Regulation by Willamette Valley projects has the greatest impact on flood risk reduction at local flood control points and at Salem, Oregon, itself. Regulation has less effect on Willamette River inflows at Willamette Falls, Oregon, further downstream. That being said, there could be a difference when comparing scenarios using regulated versus unregulated Willamette inflows. However, for the RMJOC study, the general conclusions of seasonal changes in flood risk are unlikely to change. Appendix A of this report further addresses how Willamette inflow were applied for RMJOC-II hydroregulation modeling.

The projections indicate increasing extreme winter flows on the main stem of the Columbia River (Section 7.1.2). This is clearly depicted in the 90th percentile outflows of The Dalles Dam during December–March where the interquartile range of the ensemble spread exceeds the historical baseline levels for both periods and emissions scenarios. Further compounding these increases, the projections indicate increasing high winter flows from the Willamette River during December–March, with the largest increases in January and February (Section 1.6.5). Events that affect both the Columbia and Willamette Rivers will likely exacerbate high flood stages of the Lower Columbia River near the Willamette/Columbia River confluence, leading to future increase in overall flood risk of the Portland and Vancouver metropolitan areas.

Future projections point to more frequent flood stage exceedances of the National Weather Service flood severity levels (**Table 6**). This is expressed as the number of years within a 30-year epoch, where a projection simulation has a modeled Vancouver stage that exceeds the threshold. This is composited monthly and seasonally to depict shifts in flood seasonality.

The Columbia River exceeded the “flood” level designation (16 feet CRD) in both winter and spring in the historical baselines (**Figure 68a**). The spring season had more occurrences. The future projections indicate an increase in years where this threshold is exceeded during

December–March. The interquartile range of the projection spread for January and February and for the winter season is above historical levels. In addition, 50 percent of projections include winter floods that exceed 16 feet in 17 or more years in the 2030s. The projections indicate minor changes for exceedance in the spring for the 2030s. A shift toward increasing occurrences earlier in the freshet period and less in July resulted in no significant changes in the net occurrences for the spring season.

In the 2070s, projections show further amplification of the increasing occurrences in winter months. Under RCP4.5, 50 percent of the projections have 20 or more years in the 30-year epoch that exceed the 16 feet threshold in winter. Under RCP8.5, this increases to 23 or more years that exceed the 16 feet threshold. In the 2070s, the projections point to springtime high-water increases for April and May. This is particularly true for RCP8.5 in the 2070s, where the median spring exceedance of 16 feet occurs in 13 out of 30 years.

There is a similar but less extreme pattern for moderate-severity flood stage with a 20 feet threshold (**Figure 68b**). For major floods (greater than 25 feet), the predominant increases occur in the winter (**Figure 68c**). Half of the projections indicate that major flood stage could be exceeded in five or more years within the 2070s epoch under RCP8.5. This is a substantial increase compared to the baseline projections.

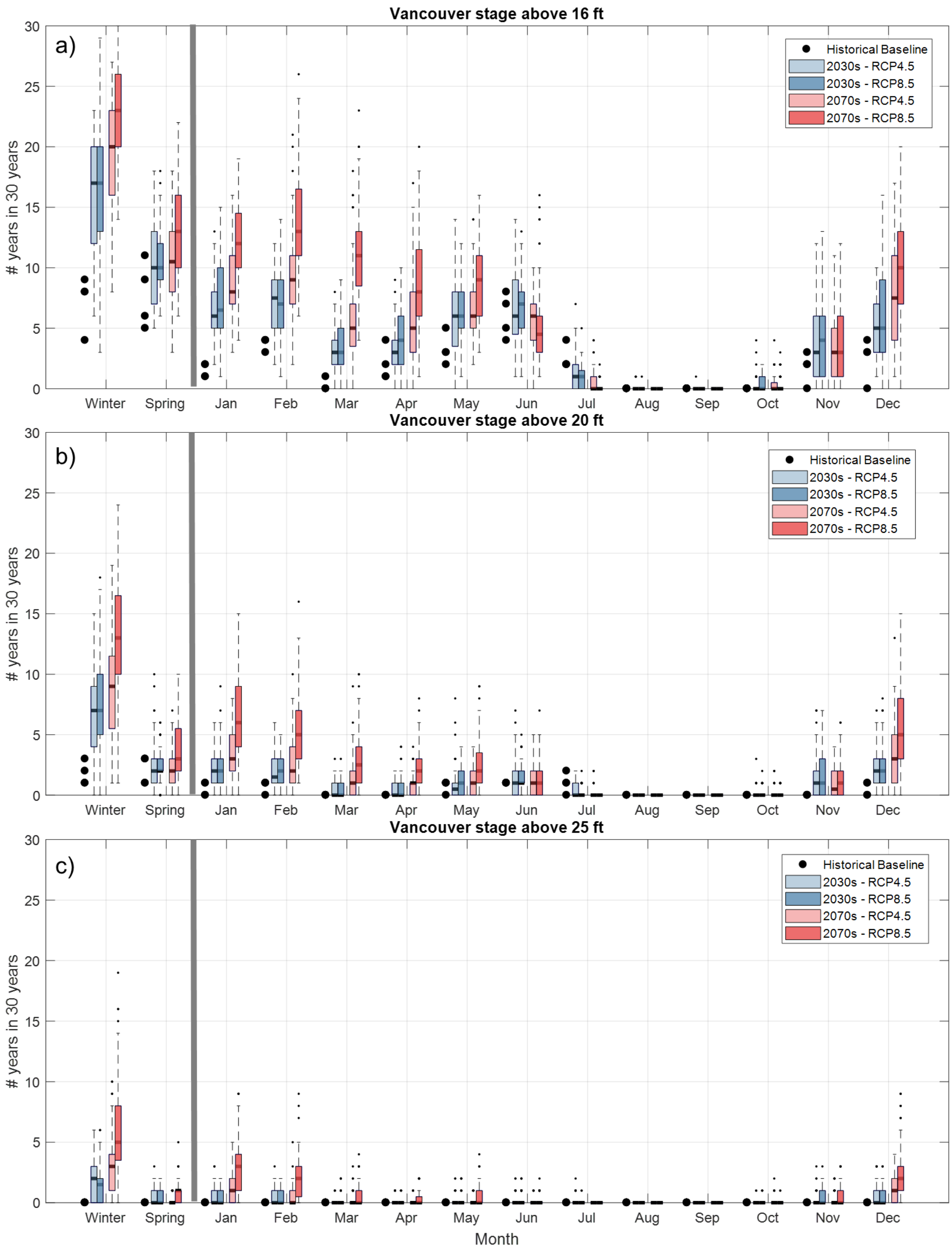

Figure 68. The frequency (number of years in the 30-year epoch) of which the stage of the Columbia River near Vancouver, Washington, was projected to exceed a defined flood severity thresholds of (*a*) 16 feet CRD, (*b*) 20 feet CRD, and (*c*) 25 feet CRD.

The evaluation of the projections in exceeding flood stage classifications demonstrates a marked increase in future flood risk, particularly in the winter season. The projections also indicate increasing spring flood risk at Vancouver in the 2070s, albeit less than the winter increases. To further describe mechanisms driving this flood risk, USACE evaluated the top five winter and spring events affecting the lower Columbia for each projection and epoch. Also analyzed were inflow from the Willamette River and outflow from Bonneville Dam associated with each event (**Figure 69**).

The top spring flood events are projected to be of similar magnitude to those of the historical baseline period for both emissions scenarios in the 2030s (**Figure 69b, d**) and under RCP4.5 in the 2070s (**Figure 69b**). In contrast, projections for the 2070s under RCP8.5 indicate potential increases in spring flood risk (**Figure 69d**). There is strong consensus among projections for increased magnitude of winter flood events (**Figure 69f, h**). The projections show progressive increases through the epochs with the largest increases for the 2070s under RCP8.5, where the median difference of these largest winter event from those of the historical periods is 8.7 feet. However, it should be noted that few moderate and no major flood events were modeled in the historical baseline period (**Figure 69b, c**).

The analyses of these events with the highest Vancouver stage provide further support for potential increases in winter flood risk. These analyses also identify the predominant driver of increasing winter high-stage events. There is increasing winter contribution from the Willamette and Columbia, but larger relative change from the Columbia River (**Figure 69**; **Table 7**). For example, in the 2070s under RCP8.5, the median change for the Willamette inflow is 39 percent whereas the Columbia main stem is 151 percent.

Table 7. Median projected changes for the average of top five winter flood events in the Lower Columbia River.

	Change in Stage (feet)		Willamette Flow (%)		Columbia Flow (%)	
Epoch	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**
2030s	4.5	4.8	29	29	36	44
2070s	6	8.7	40	39	72	151

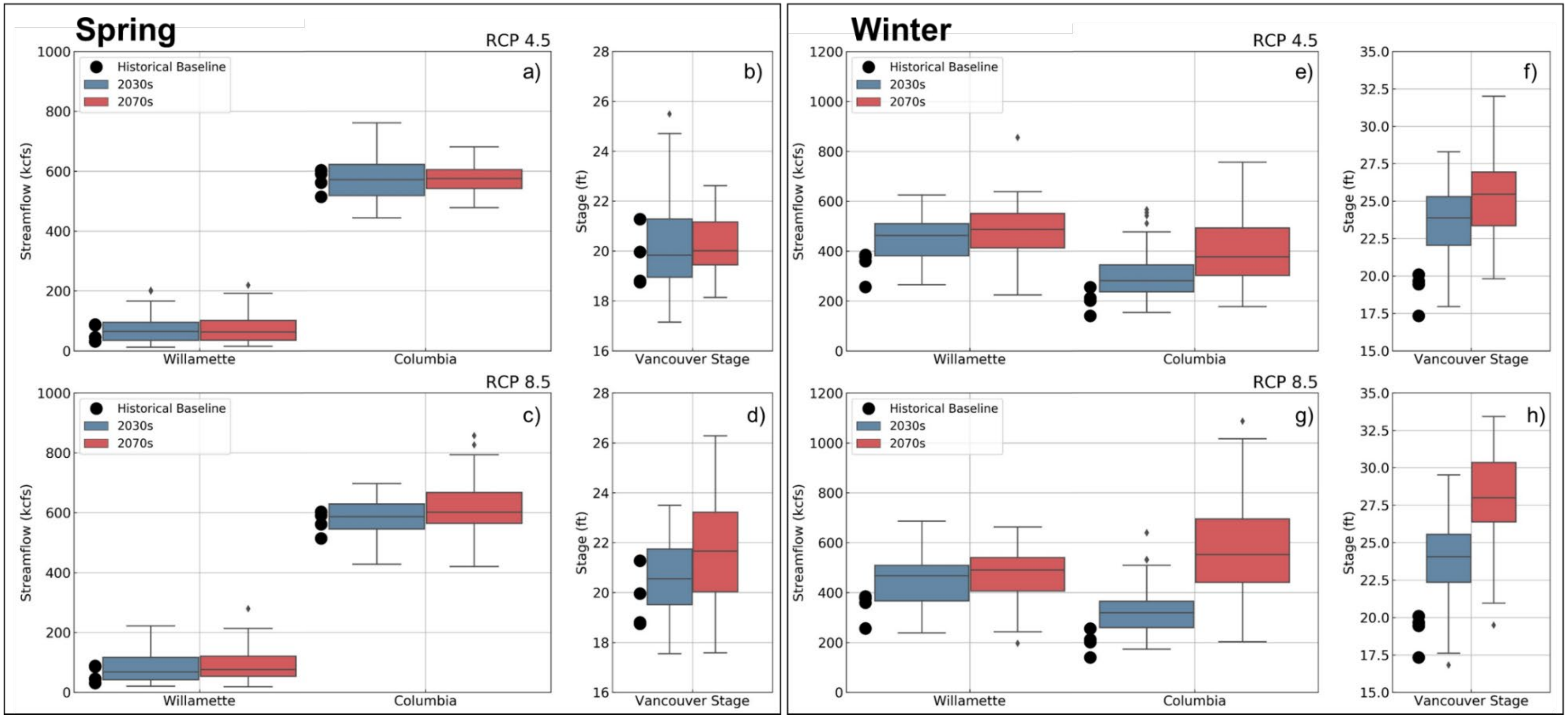

Figure 69. Peak stage and mean daily flow corresponding to the average top five winter and spring flood events from each 30-year projection

8.6 Reservoir Model Sensitivity Analyses

Several components of the WAT-ResSim implementation of operations and inputs could have a great influence on projected future flood risk. USACE explored two of these components with model sensitivity experiments to identify and quantify the influence on the projected changes to flood risk.

8.6.1 Water Supply Forecast Error

One of the sources of operational uncertainty during annual reservoir cycling is related to differences between predicted and observed runoff volumes. This difference, termed *forecast error*, is important when evaluating the metrics outlined in this section. Water supply forecasts determine reservoir draft and refill patterns, thus the skill or error in the prediction can have a large influence on meeting the objectives of the reservoir system. For example, underforecast situations can adversely impact FRM, whereas overforecasts can adversely impact refill and water supply for irrigation and summer flow augmentation. To help evaluate the impact forecast error has on the flood risk results of our modeling, USACE used the WAT-ResSim model to create regulated streamflows that have zero difference between predicted and actual streamflow volume for each projection. These simulations are the *perfect forecast* results. These results allow for quantification of any differences in hydroregulation results simply due to forecast error.

One of the key metrics for system flood risk is the flow frequency at The Dalles. USACE quantified the effects of forecast error on peak flows for specific probabilities by using the perfect forecast simulations. Based on the operating rules in the WAT-ResSim model, the largest differences using perfect forecast volume was expected to be in the spring peak flows. This is because the available system reservoir storage drafted prior to the freshet is based on the predicted forecast volume for spring flows at The Dalles. Therefore, when the runoff volume is known with certainty, flood operations should result in the most efficient possible regulation for that specific freshet volume and peak. **Figure 70** shows the results for spring (April–August) peak flows at The Dalles. The effects of forecast error are displayed as a difference between perfect forecast results and those using RMJOC-II forecasts with uncertainty included. The latter simulations are those that include errors as described in Chapter 5.0.

Results for the spring peak 31-day duration flows indicate minimal change for the 10 and 25 percent annual chance exceedance. The lower probabilities show a decrease in the peak flows compared to simulations using the RMJOC-II forecasts discussed in Chapter 5.0. This result is expected since water supply forecasts often underpredict high-flow events. Although the distribution of percent differences for all probabilities reflects an overall decrease in peak flow using perfect forecasts (as would be expected), there are projections that result in slightly higher peak 31-day flows at The Dalles. This situation likely is a result of the diversity of hydrograph shapes included in each hydrologic projection. For example, even if the seasonal volume is known perfectly, the concentration of flow may cause high reservoir outflows because the system reservoir storage fills very quickly. Projections with a slightly higher flow could also be the result from advantageous outcomes of forecast error (when overforecasted).

The magnitude of regulated spring peaks is projected to increase through time with more warming. For example, the highest change in peak flows at The Dalles is for the 2070s under RCP8.5 (Sections 7.12). In contrast, the relative influence of forecast error decreases in the 2070s, and the difference between using perfect forecasts and forecasts with errors is less when comparing the 2030s and 2070s epochs. This further reinforces the attribution of this increase in flood magnitude to changes related to runoff characteristics, such as seasonal timing, as opposed to forecast error. The results indicate that changes in forecast error may have varying impacts on regulated peak flows simulated under current operating criteria.

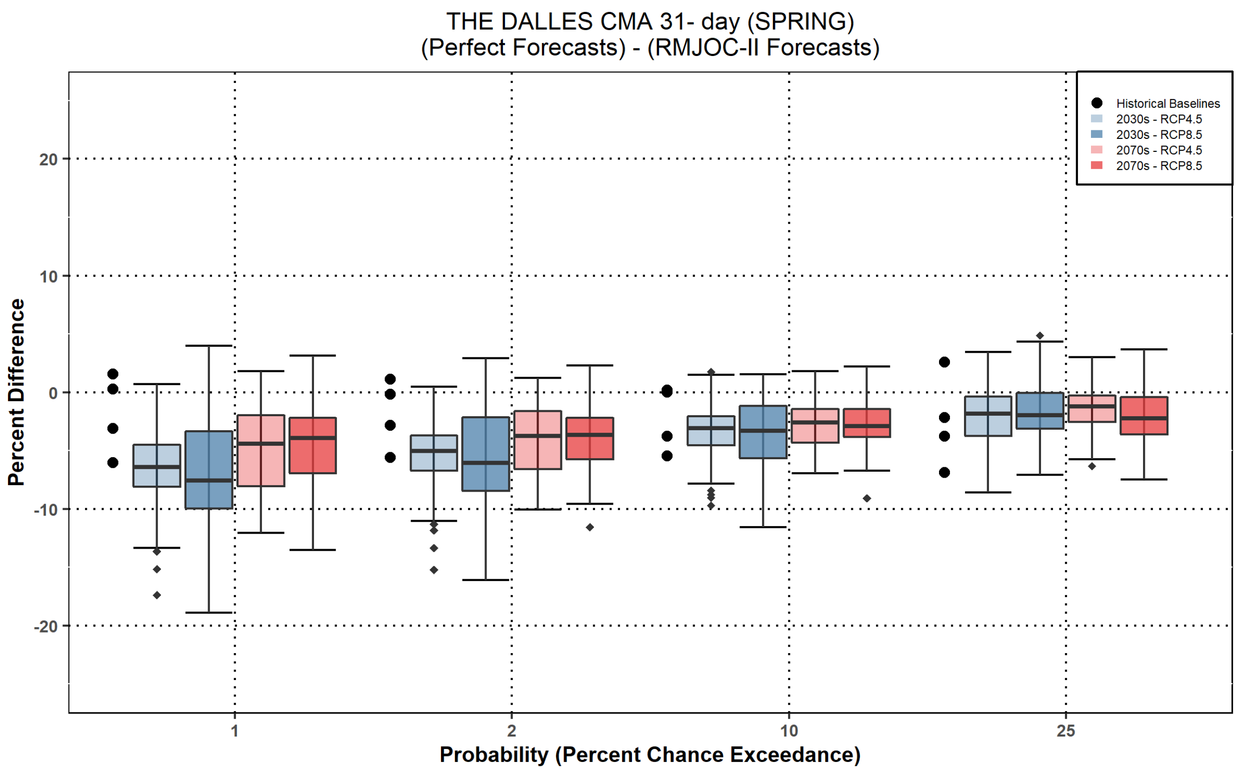

Figure 70. The difference between the spring 31-day duration peak flow frequencies of the Columbia River at The Dalles simulated with perfect water supply forecasts (no forecast error) and water supply forecasts described in Chapter 5.0 (RMJOC-II forecasts). The percent difference indicates the relative amount that the estimated flow magnitude at the 4 quantiles would change in the absence of forecast error.

8.6.2 Winter Operations

The WAT-ResSim model can be configured to turn on and off hydroregulation operation sets, including simulated winter flood risk operations. USACE used this functionality to perform sensitivity analyses of the effects for both winter and spring peak flows. Winter operating rules were included in the WAT-ResSim modeling of projections presented throughout this report. The implementation of winter FRM operations in ResSim is somewhat uncertain given that the operation is not formally codified in water control manuals. This is a primary reason for performing the winter operations sensitivity analysis.

For comparison, this analysis repeated all of the modeling runs without the winter operations. The sensitivity analysis quantifies the degree to which the implemented winter operations reduces winter peaks. The winter draft for spring FRM objectives is interrupted by operations for winter events. This analysis also quantifies the effects of winter operations on spring flood risk.

Figure 71a–c below shows the difference (delta) between simulations with winter operations enabled (“Winter Ops”) and without winter flood operations (“No Winter Ops”). A positive delta indicates “No Winter Ops” had more years where flood thresholds (16, 20, and 25 feet CRD) were exceeded. As expected, for November–March, the delta is positive. Winter flood operations are specifically targeted to reduce peak stages in the Lower Columbia River during the November–March season. One conclusion from the comparison was that winter operations do not appear to negatively impact spring flood risk in the lower Columbia River (April–July) significantly. Only a small number of projections had years with negative delta values in the spring (“Winter Ops” simulations produced spring stage exceedances), and these were limited to the lower thresholds in the 2070s under RCP8.5. Winter operations could impact spring operations in the 2070s because the snowmelt timing of many of the projections shifts toward early spring and late winter and more winter events require storage. This results in less time for the reservoir system to reset after a winter event. This was a compounding effect, as these two seasons merge.

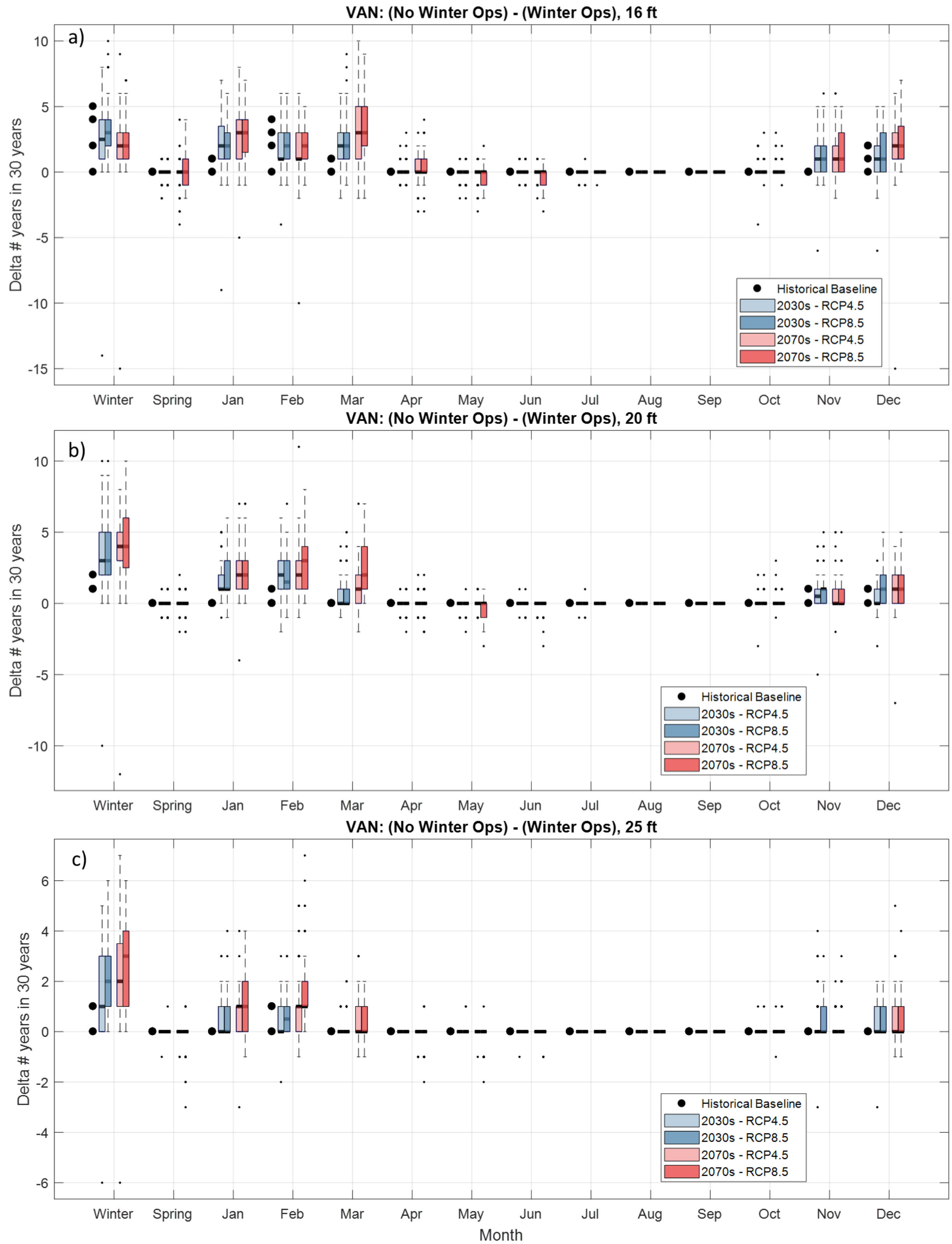

Figure 71. The difference (delta) of the number of years where the flood threshold stage of (*a*) 16 feet, (*b*) 20 feet, and (*c*) 25 feet was exceeded. The difference is presented as the number of occurrences from the "No Winter Ops" model simulation minus the "Winter Ops" model simulation.

The effect of modeled winter operations is also apparent in regulated flow frequency estimates (**Figure 72**). Without winter operations, the ensemble median 31-day duration peak flow frequency estimates are 1–10 percent higher. Given the short duration of these events, it is likely that these results would be more pronounced for shorter durations of analysis. With respect to spring regulated flow frequency, winter operations do have an increasing influence on flow frequency estimates at the 1 and 2 percent AEP quantiles by the 2070s (**Figure 72**). However, the relative difference is generally less than 5 percent. Moreover, this increase does not appear to contribute to increased occurrences of exceeding moderate or major flood stage (**Figure 71**).

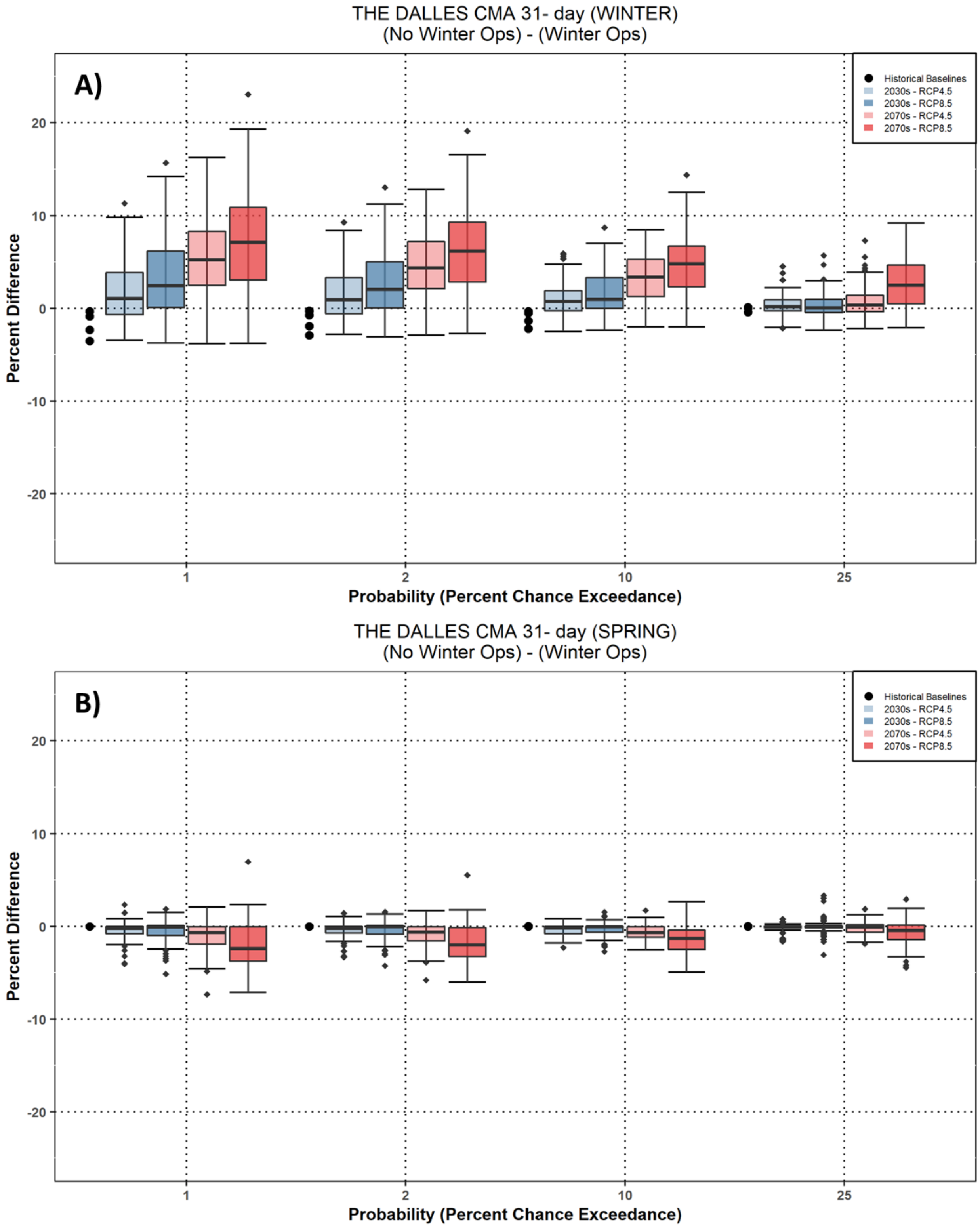

Figure 72. The Dalles winter and spring 31-day peak flow differences by excluding winter operations.

8.7 Summary

USACE modeled and analyzed system and local flood risk operations for historical (WYs 1976–2005), 2030s (WYs 2020–2049), and 2070s (WYs 2060–2079) periods. Key contributors to potential changes to flood risk were investigated, including unregulated runoff volumes and regulated flows, using the WAT-ResSim model simulations that represent present-day operations. The primary focus of the flood risk analyses centered on two key seasonal hydroregulation operational windows: spring (April–August) and winter (November–March).

Future projections point to a potential overall increase in flood risk in the Columbia River Basin for both spring and winter, with the largest increases for winter. These changes in flood risk are attributable to increasing runoff volumes and the spatial distribution of those volumes. Furthermore, the identified shifts in projected runoff volume timing and variability in the spring could stress the effectiveness of the current hydroregulation operations which were developed based on historically observed patterns of spring snowmelt timing and duration.

Spring is likely to continue to produce the greatest flood volumes at The Dalles, but the freshet was projected to peak earlier (about a month). The magnitude of unregulated flow peaks is projected to be higher compared to historical baselines. Regulated high flows increase at The Dalles (Section 7.12). However, the changes in flow relative to the historical baseline are greater than unregulated changes in the spring months in the 2070s under RCP8.5. This suggests increased future flood risk is driven by hydrologic characteristics of the climate-affected streamflow regime (e.g., timing, rate of snowmelt, and basin hydrological response) that are inconsistent with hydrological assumptions used to design system operations. To segregate the influence of water supply forecast skill on these results, a sensitivity analysis using perfect forecasts (Section 8.6.1) was performed. This analysis suggested that with time, the influence of forecast error to increased spring flood peaks decreases and that other hydrological changes such as seasonal timing drive the performance of system operations.

The greatest potential change in future flood risk identified in these projections is from increased winter flooding. Projected increases in Columbia River flows in the winter are attributed to increased winter precipitation, precipitation occurring as rainfall in larger areas of the basin, potentially larger atmospheric river events, wetter antecedent conditions prior to flood events, and earlier snowmelt. The Willamette River winter volumes are projected to likely increase from more intense precipitation and less snowfall.

Water control manuals do not formally define winter flood operations for the system because of the low frequency of these events over the historical period. A modeling sensitivity was conducted to quantify the significance of these operations as implemented in the WAT-ResSim model. The analysis showed that winter operations reduce peak stages in the Lower Columbia River with minimal adverse influences on spring flood operations.

9.0 Hydropower

BPA markets wholesale electrical power from 31 federal hydroelectric projects in the Northwest, one nonfederal nuclear plant, and several small nonfederal power plants. The dams are operated by USACE and Reclamation. BPA operates and maintains about three-fourths of the high voltage transmission lines in its service territory, which includes Oregon, Washington, Idaho, western Montana, and small parts of eastern Montana, California, Nevada, Utah, and Wyoming. It provides about 28 percent of the electric power used in the Northwest and over 50 percent of the capacity. Regionally, the hydropower (federal and nonfederal) system produces up to 75 percent of the energy used in the Northwest in a year, with the majority of the hydropower generated by the projects on the Columbia River. The Columbia River Basin produces more hydropower than any other region in North America.

The BPA hydropower assessment of climate change impacts focuses on the Columbia River component of the FCRPS. This encompasses hydropower generated from U.S. projects above Bonneville Dam, which compose 14 of the 31 federal hydroelectric projects in the FCRPS (see **Figures 1** and **9**). This includes the headwater projects, Libby, Hungry Horse, Albeni Falls, and Dworshak; the Mid-Columbia projects, Grand Coulee and Chief Joseph; the four Lower Snake projects, Lower Granite, Little Goose, Lower Monumental, and Ice Harbor; and, the four Lower Columbia projects, McNary, John Day, The Dalles, and Bonneville. The federal projects in the FCRPS below Bonneville Dam were not modeled. The operation of these projects were set to a 30-year median generation value and treated as a fixed resource in the HYDSIM modeling of the historic baselines, and for the 2030s and 2070s epochs. The non-federal projects on Columbia River above Bonneville Dam were modeled with no adaptive modifications to their operations due to the climate change flows. The non-federal hydropower projects located below Bonneville Dam were not modeled and were also set to a 30-year median generation value and treated as a fixed resource in the climate change modeling. How climate change may influence these non-federal projects was beyond the scope of this study. The main variable of interest is how climate change may impact the federal projects on the Columbia River above Bonneville Dam and it was determined that using this modeling design would not affect the overall findings of the RMJOC-II study.

Changes in basin hydrology, combined with increasing uncertainty of forecasting the volume and distribution of the runoff, can significantly affect the operation of the FCRPS, potentially resulting in both economic and reliability issues. This study analyzed impacts to generation, spill, and operational flexibility for a subset of 19 scenarios out of the 160 climate change projections and the 4 historic baseline scenarios. The selection of these scenarios is described in Sections 4.2 and 9.2 and in RMJOC-II Part I (RMJOC 2018). The intent of the modeling was to test the operation of the FCRPS with climate change hydrology without adaptation of loads, resources, and project operating criteria and to determine critical areas of the operation that will need to be addressed in the future.

9.1 Modeling Approach

This study used the HYDSIM hydroregulation model for the hydropower analysis and evaluation. As described in Section 3.4.4, HYDSIM is a deterministic model that regulates each project to meet hydropower, FRM, and fishery objectives. **Figure 73** shows the HYDSIM modeling approach and its interaction with the ResSim model for the FRM information.

Key inputs to the modeling process were the MFL climate change hydrology for the 19 scenarios described in Chapter 5.0 and the climate change water supply forecasts described in Chapter 6.0. These inputs were used to generate operating rule curves for FRM and energy production and to determine the timing and magnitude of meeting fishery objectives as defined in Chapter 3. These were the only changes to the modeling inputs. All other input data were taken from the Columbia River Treaty 2022 Assured Operating Plan (AOP) and the 2018 Detailed Operating Plan (DOP). This included the critical rule curves, the operating criteria, and physical limitations for the operation of Canadian projects and the U.S. projects in the FCRPS. All the HYDSIM Treaty Storage Regulation (TSR) studies used the residual hydro load defined in the 2022 AOP, while the hydro residual load from the 2016 rate case study was used for the HYDSIM operational modeling (OPER). Defining a series of climate change load sequences and applying them to AOP and TSR studies in preparation of running OPER studies was beyond the scope and resources of the RMJOC analysis.

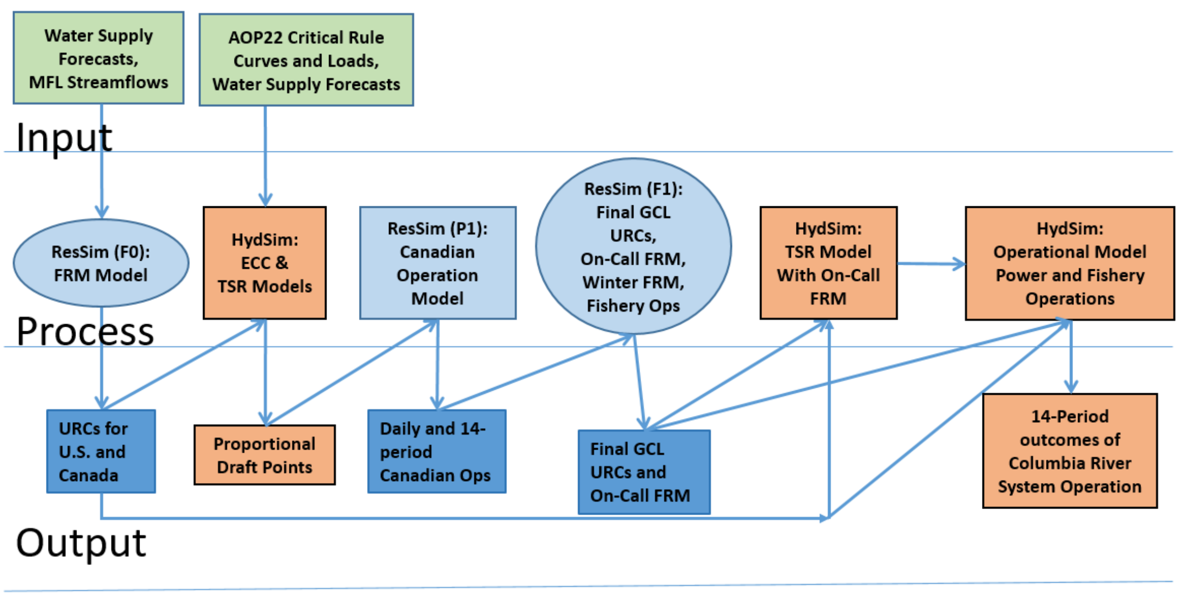

Figure 73. HYDSIM modeling approach for modeling the 19 climate change scenarios.

9.1.1 Operating Rule Curves for HYDSIM Modeling

Rule curves represent reservoir levels for each of the 14 periods in the water year. The 14 periods are all months other than April and August, which are split into two half-periods to model the variability in streamflows during the normal initiation of reservoir refill and the transition to summer operations. Rule curves help to coordinate the operation of reservoirs under various water conditions. Different types of rule curves depict different operating objectives. The FRM objective is reflected in the Upper Rule Curves (URCs). The desire to refill each spring is addressed by the Energy Content Curves (ECCs). The Critical Rule Curves (CRCs) define reservoir operations under proportional draft in low water years. The rule curves used for HYDSIM hydroregulation studies are defined as follows:

URCs define the upper storage limit at a reservoir to minimize the risk of flooding. As shown in **Figure 73**, USACE calculated the URCs for all 19 scenarios for the HYDSIM modeling by using the water supply forecasts described in Chapter 6.0 and with the FRM procedures described in Chapter 8.0. Only the URCs calculated for spring runoff were used in the HYDSIM 14-period modeling. The ResSim modeling sequence addresses winter FRM operations but in a process that makes it difficult to define a composite URC that reflects winter and spring FRM for HYDSIM modeling. This approach would also be an adaptive process that is outside the current process for developing URCs for HYDSIM modeling and is a future effort that is described in Chapter 11.0.

ECCs are used to determine certain PNCA rights and obligations. Additionally, reservoir owners may use them to guide reservoir operations. ECCs define reservoir operations that provide a high probability of refill by the end of the operating year. Drafting a reservoir below ECC decreases the probability of refill and is only done to meet firm load. A Base Energy Content Curve (BECC) is calculated for all storage projects and is the same for every water year. For those projects where the BECC does not go empty during the year, a Variable Energy Content Curve (VECC) is calculated from January to July as a function of water supply forecasts at the project and at The Dalles Dam. As shown in **Figure 73**, BPA calculates the VECCs using the water supply forecasts described in Chapter 6.0, the URCs from USACE, and the streamflows from the historic baselines and the 19 climate change scenarios.

CRCs define the reservoir operation that will draft the reservoir from full to empty over the number of years in the critical period to make most efficient use of available water. The CRCs were not modified using the climate change scenarios. They are from AOP 2022 and are based on the 2010L Modified flows.

9.1.2 Treaty Storage Regulation Modeling

These rule curves help guide reservoir operations in the TSR modeling step that is required to determine the regulation of the Canadian Treaty projects that is shown in **Figure 73**. The critical output of the TSR for the RMJOC-II hydroregulations is the resultant contribution to the flow at the U.S.-Canadian border. As described above, the rule curves for FRM and VECCs were developed with the climate change water supply forecasts and streamflows. No other adaptations were made to the procedures for the TSR. This includes CRCs and the Mica-Arrow balancing guidelines. All procedure and operating guidelines and limits were from the Columbia River Treaty AOP 2022. More information on this subject is available in the *Columbia River Treaty Entity Agreement on the Principles and Procedures for Preparing and Implementing Hydroelectric Operating Plans for Operation of Canadian Treaty Storage* (CRTOC 2003).

9.1.3 HYDSIM Operational Modeling

As **Figure 73** shows, the final step in the HYDSIM modeling process is the OPER model. The OPER models the FCRPS to meet the operating rule curves for FRM, energy production, fishery objectives, and other uses such as irrigation pumping at Grand Coulee. **Figure 10** in Chapter 3.0

shows the seasonal operations of the major U.S. projects for these purposes. The Canadian flow at the U.S.-Canadian border that was defined from the TSR is modified when possible to include the operation of 1.0 Maf of Canadian treaty storage for flow augmentation and 0.5 Maf of non-treaty storage for fishery purposes in the lower Columbia River. The following sections in this chapter address the results of HYDSIM modeling for power production, spill, and operational flexibility. The results for meeting the fishery objectives are shown in Chapter 10.0, “Hydroregulation Results for Ecosystem, Irrigation, and Navigation.”

9.2 Climate Change Streamflow Scenarios for HYDSIM Modeling

The 19 streamflow projections used in HYDSIM modeling were selected from the available 172 streamflow projections as described in Section 4.2 and in Chapter 8 of the RMJOC-II Part I report (RMJOC 2018). These selections were made from the RCP8.5 ensemble only; therefore any reference to the future epochs, 2030s and 2070s, in this section is with regards to RCP8.5. The RCP8.5 projections were chosen over the RCP4.5 due to their higher carbon emissions to stress the HYDSIM operation modeling of the FCRPS. **Figures 74** and **75** compare the total annual runoff volume at The Dalles of the 19 streamflow scenarios relative to all 80 RCP8.5 streamflow scenarios in both the 2030s and 2070s. For comparison purposes, the median annual flow of the 80-year modified flow data for 1929–2008 is about 133 Maf, which is surpassed in each climate change scenarios for each epoch, the 2030s and 2070s. Because of this selection process, the distribution of results based on this subset may not exactly match the distribution of results based on the full ensemble of streamflow projections. Also, note that the graphical representation of model results differs slightly between the 160-member ensemble and the 19-member subset. For model results based on the 19-member subset, data were pooled prior to creating box plots, and therefore the data points in these charts reflect all 570 water years. For the 160-member ensemble, the box plots were created based on the 10th percentile, median, or 90th percentile metrics of each ensemble member. In other words, these plots are based on the distribution of 160 statistical metrics with each value representing an ensemble member.

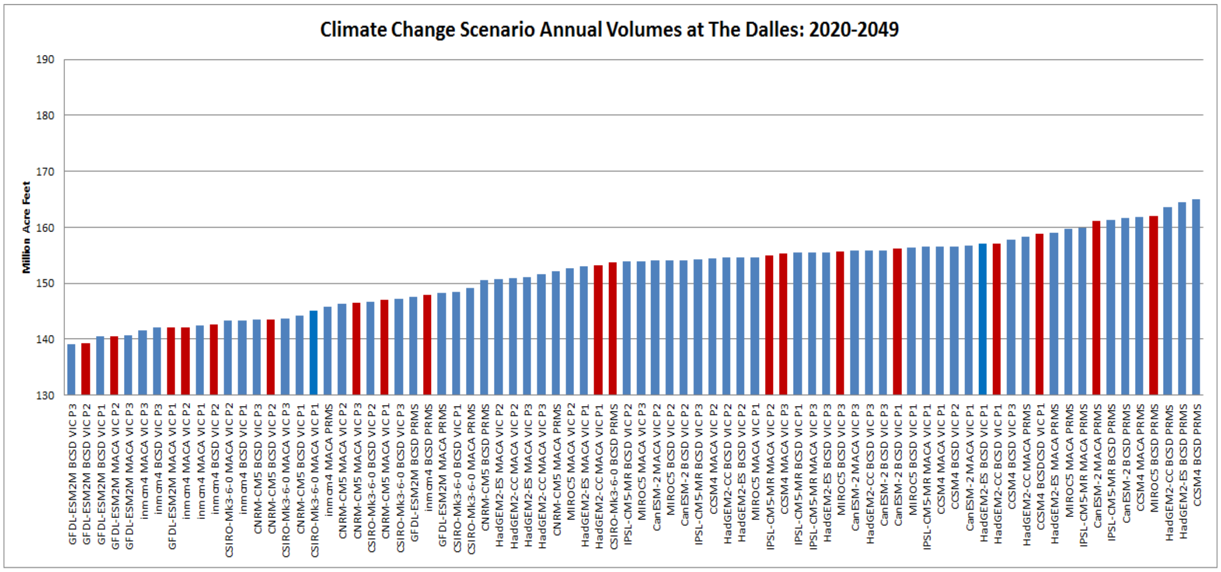

Figure 74. Average annual volumes at The Dalles, Oregon, for the 2030s (WY 2020–2049) for each of the 80 scenarios using RCP8.5, the 10 GCMs used for this study, and statistical downscaling (BCSD and MACA). Red scenarios are the 19 selected using the iterative technique described in RMJOC-II Part I.

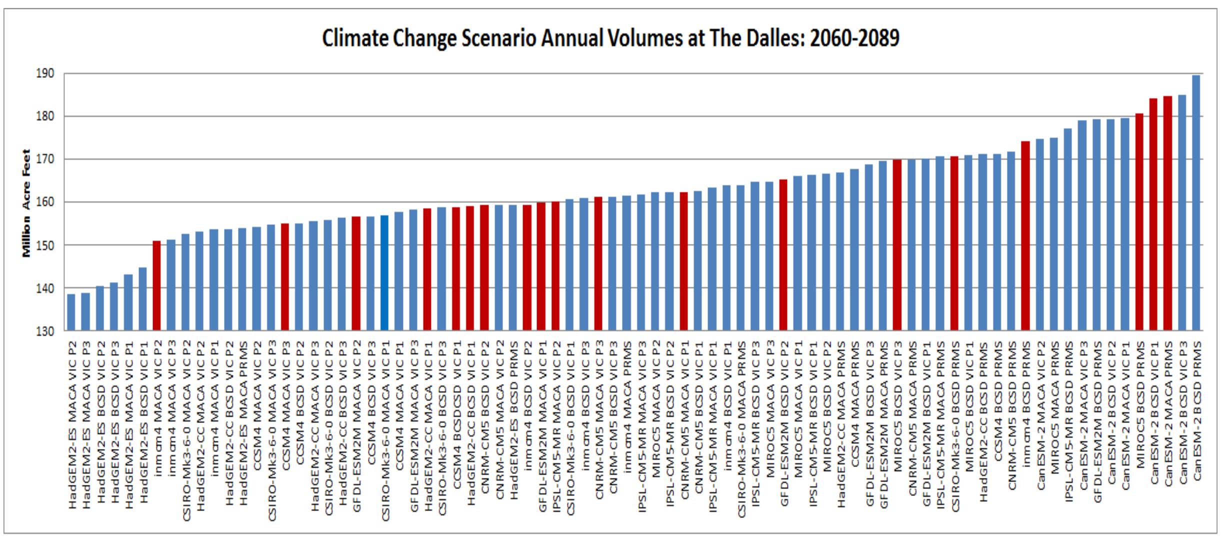

Figure 75. Same as Figure 74, except for the 2070s (WY 2060–2089).

9.2.1 Seasonal Comparison

The two key seasonal periods for hydroregulation modeling are January–July and April–August. They are used to determine the operating rules curves as described in Section 9.1.1. The January–July period is used for developing the energy rule curves while the April–August period is the principle seasonal period to define both the FRM rule curves and the parameters for the system operation during the spring refill. **Figure 76** shows the distribution of the medians of the January–July period with respect to the annual runoff for the 19 climate change projections and the four historical baselines. What is striking is the consistency and general trend of the increasing January–July volumes with the annual runoff through both the 2030s and 2070s.

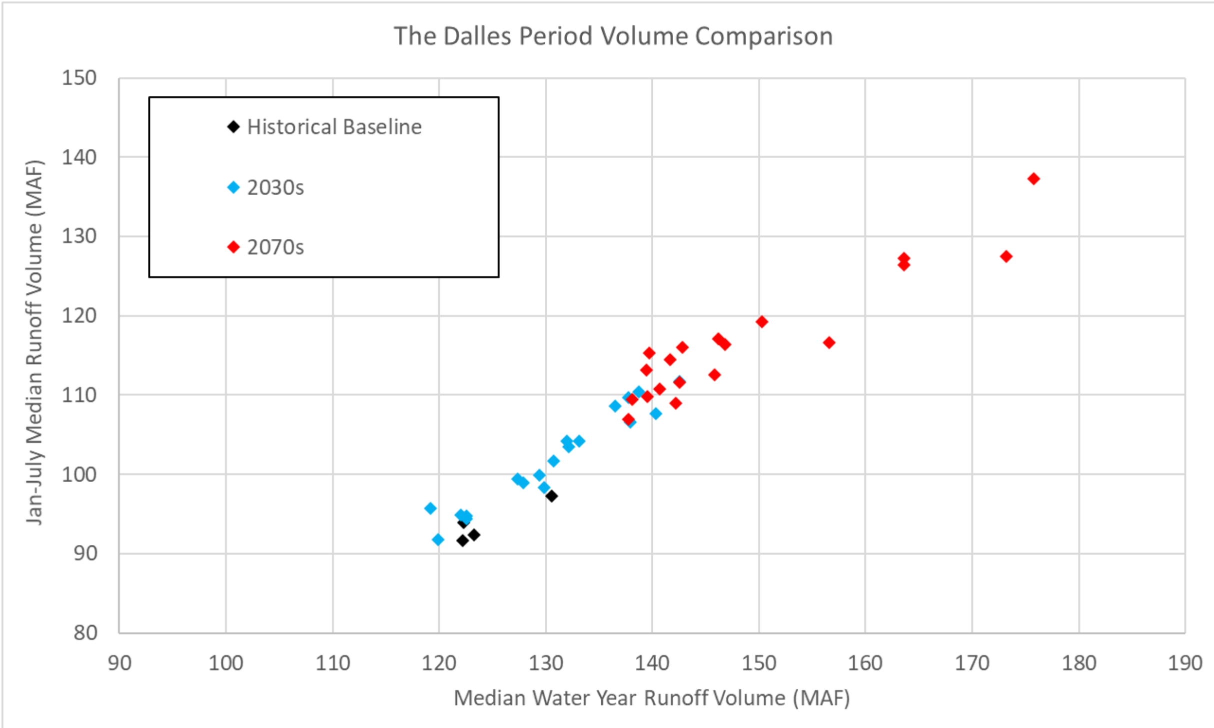

Figure 76. Comparison of the annual volume runoff at The Dalles, Oregon, to the January-July seasonal period. The data shows the medians from the 19 scenarios for the 2030s and 2070s and the medians from the four historical baselines.

On the other hand, the distribution and trends of the relationship between the annual medians and the April–August periods (**Figure 77**) is not as consistent and linear in appearance. For the 2030s, the April–August median volumes show either a general loss of volume, up to 10 Maf, or a similar level of volume as compared to the historical baselines. For the 2070s, **Figure 77** shows a general dispersion of annual volumes as the amount increases. In most of the projections, the April–August volumes are similar or much less than the historical baselines. The general trend is for the April–August volumes to decrease as the annual volumes increase.

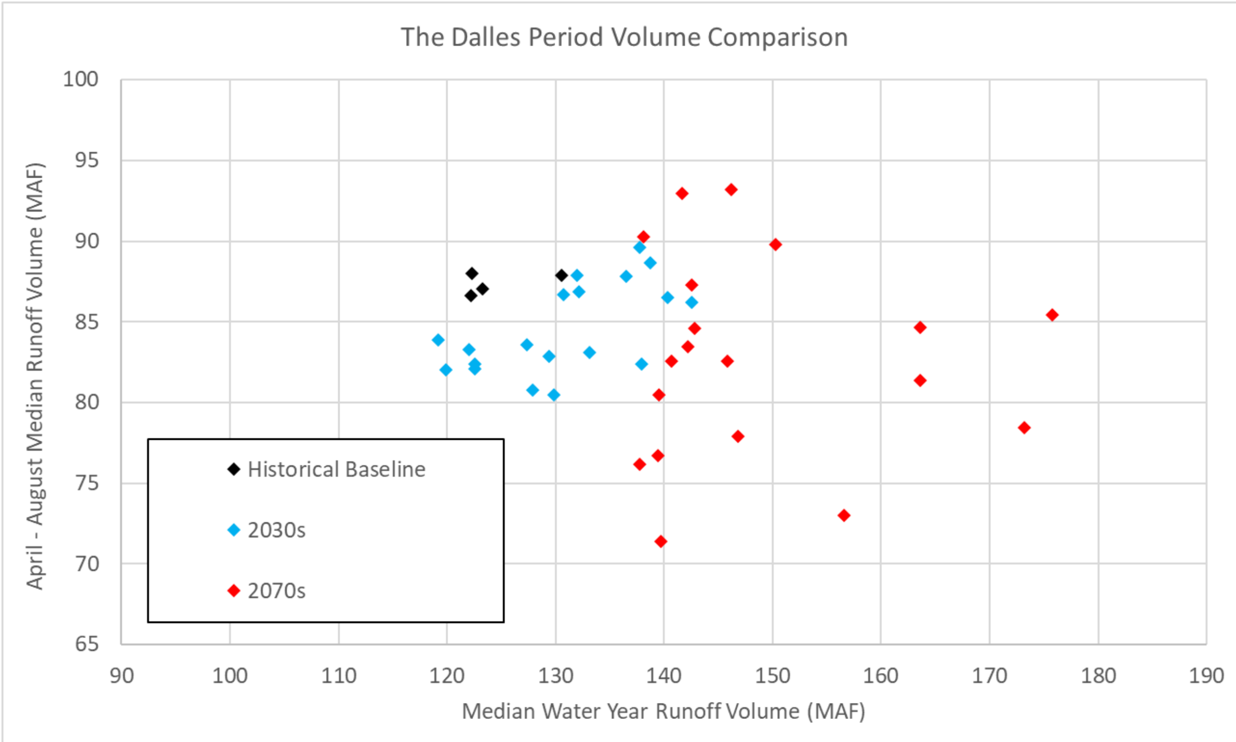

Figure 77. Comparison of the annual volume runoff at The Dalles, Oregon, to the April–August seasonal period. The data shows the medians from the 19 scenarios for the 2030s and 2070s and the medians from the four historical baselines.

9.2.2 Historical Baseline Streamflows used in HYDSIM Modeling

The hydropower analysis uses the four historical baselines to determine the possible impact of the 19 climate change projections. The baseline cases consist of simulated historical streamflows using the Livneh et al. (2013) representation of gridded temperature and precipitation for 1976–2005 (see Chapters 4.0 and 5.0). **Figure 78** shows a composite of the four historic baseline data for The Dalles along with 80-year 2010L Modified flows data for 1929–2008 and a 30-year subset (1979–2008) of this data.

The 80-year 2010L modified flows set is a very common input to many regional hydroregulation studies as well as to BPA power modeling. The 80-year dataset of daily unregulated flows is modified to represent a current level of irrigation and evaporation and is compiled into a 14-period dataset (monthly with two split months, April and August) of volumes designed specifically for hydropower modeling. Typical hydropower planning studies that use the 80-year 2010L Modified flows set are BPA Rate Case studies; Columbia River Treaty studies, such as the Assured Operating Plan and TSR; and Pacific Northwest Coordination Agreement studies. As **Figure 78** shows, the comparison of the 80-year 2010L modified flows and the 30-year subset are reasonably similar to the historical baseline flows. However, a direct comparison of modified flow-based planning studies with the climate change modeling should be done with caution due to the differences in derivation of the 80-year 2010L Modified flows as compared to the four historical baselines. To conclude, the results in this study represent a delta between the historical baseline and the 2030 and 2070 periods of the selected climate change scenarios, not a direct comparison to the 80 year 2010 Level Modified flow data (Section 4.1).

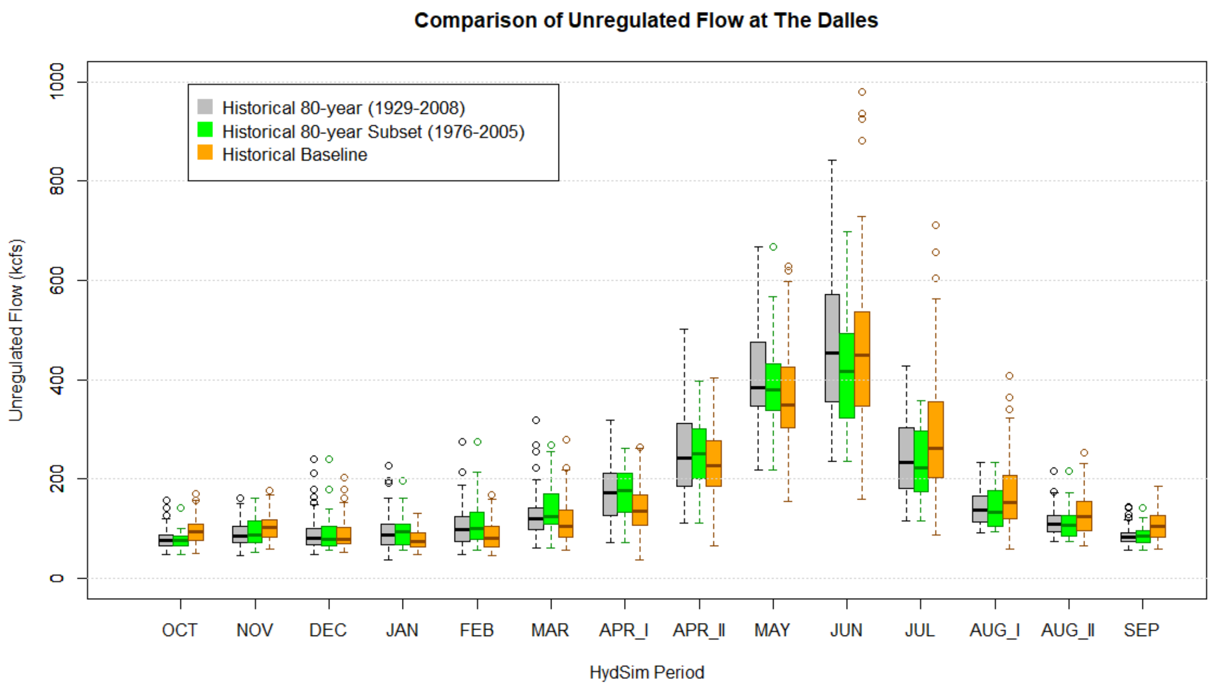

Figure 78. The Dalles: Comparison of the (1) 80-year 2010L Modified flows, (2) the 30-year subset of the 80-year 2010L Modified flows set corresponding to the same period used in the historical baseline, and the (3) 30-year simulated climate change historical baseline.

9.3 General Regulation Results of the Operational HYDSIM Modeling

The following section describes the general reservoir regulation results of the HYDSIM operational modeling for the subset of 19 climate change projections and the 4 historical baselines. The results are shown for only the regulated flows in the Upper Columbia, the Mid-Columbia at Grand Coulee, the Snake River at Lower Granite, and the Lower Columbia at The Dalles. These results provide a general overview of the regulated flows from the HYDSIM modeling. They show the general shift to higher winter flows and correspondingly lower flows in the summer and early fall. The regulated results from the 14-period HYDSIM modeling are similar to the daily ResSim modeling results, which can be found in Chapter 7.0. The results from the ResSim modeling of the 160 climate change scenarios and the four historical baselines can be used to complement the HYDSIM modeling results.

Figure 79 shows the distribution of regulated flows at the U.S.-Canada border resulting from HYDSIM operational modeling. These flows are a combination of regulation on the Kootenay, Pend Oreille, and Upper Columbia portions of the basin (see Sections 2.2 and 2.3). This includes the federal projects (Libby on the Kootenai River, Hungry Horse, and Albeni Falls on the Pend Oreille River) and the Canadian projects (Mica, Arrow, and Duncan). The results suggest an increase in border flows during the 2030s and 2070s relative to the historical baseline during the winter and early spring months. During the summer months, July–September, the flow in the 2030s and 2070s is much lower than the historical baseline. In addition, the early fall months of October and November also show a drop in regulated flows. These observations are consistent with the shift in runoff that can be observed in the natural flows.

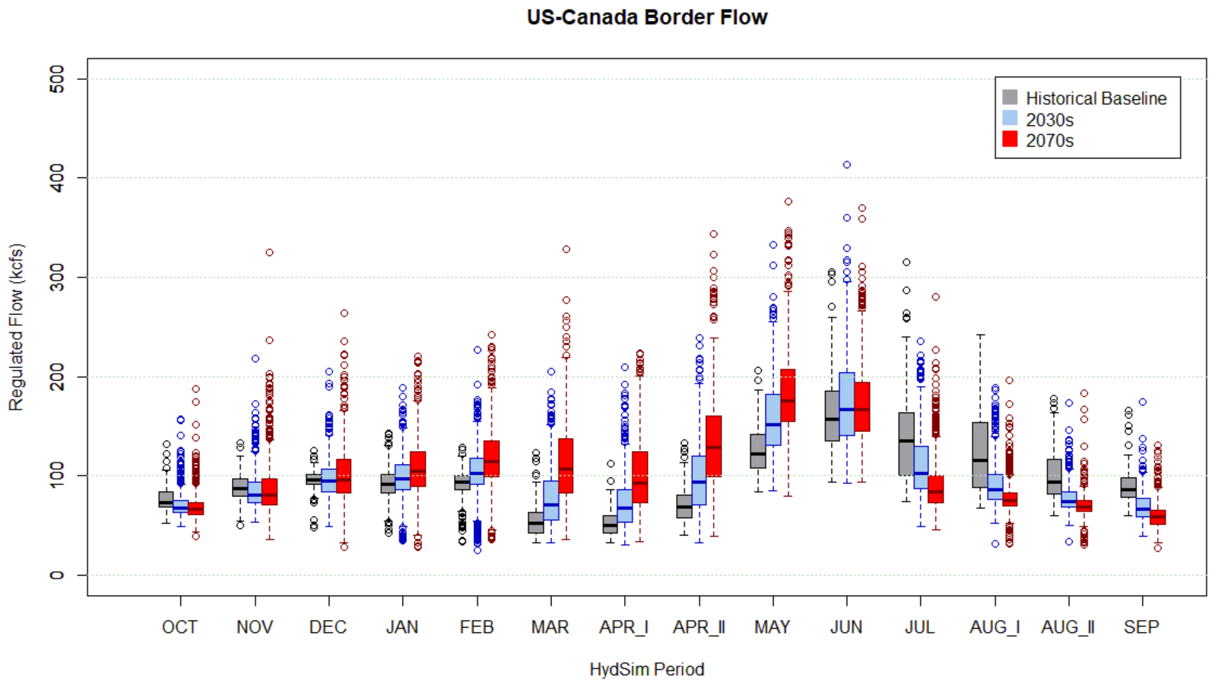

Figure 79. Distribution of period-average regulated flow at the U.S.-Canada border based on HYDSIM power modeling. Distributions in the 2030 and 2070s are based on the 19 GCMs selected by RMJOC-II.

Figure 80 shows the regulated inflows for Grand Coulee for the subset of 19 HYDSIM scenarios. Grand Coulee is in the Mid-Columbia and its inflows consist primarily of the flow at the U.S.-Canadian border and the Spokane River (see Sections 2.3 and 2.4). As shown in **Figure 79** for the flow at the border, **Figure 80** also depicts higher inflows in the winter months, January–March, and spring months, April and May, for both the 2030s and 2070s relative to the historic baseline. June appears to be a transition month of little change; however, inflows in the summer months, July–September, considerably decrease in the 2030s and 2070s relative to the baseline. This decrease in flows extends into the early fall months of October and November. The decrease in summer and early fall flows is driven by natural climate change flows and by the operations at upstream reservoirs. Chapter 7.0 provides more detail on the operation of the specific projects above Grand Coulee.

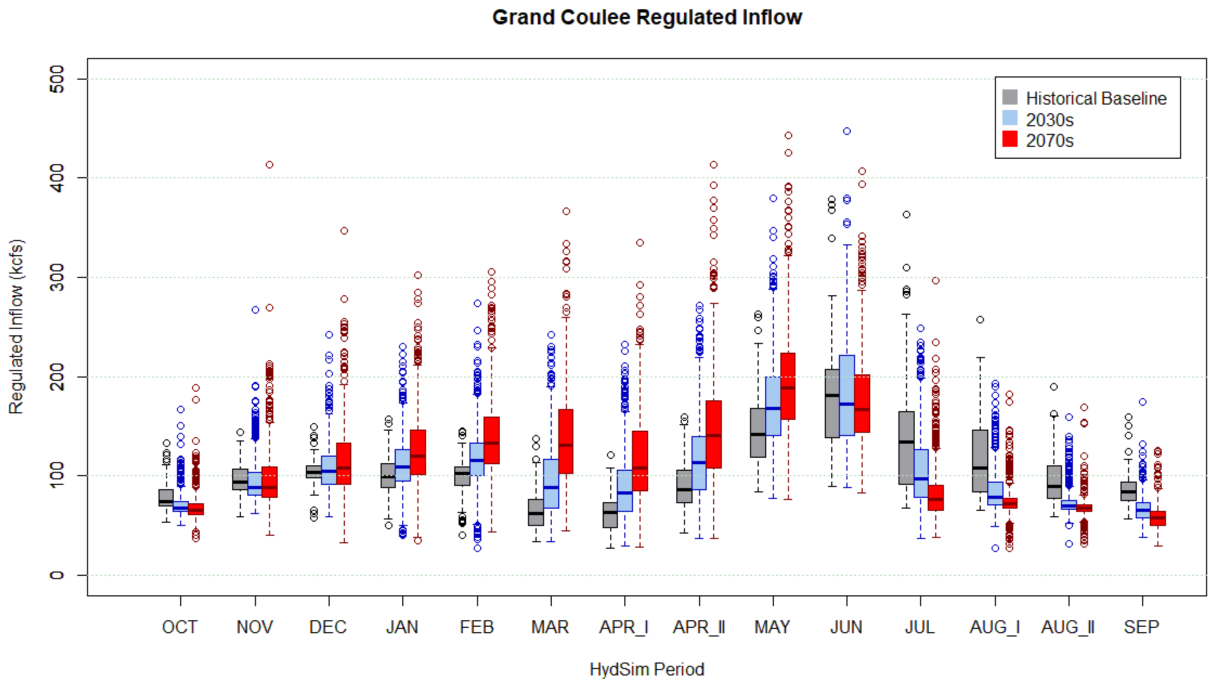

Figure 80. Grand Coulee period-average regulated inflow from HYDSIM power modeling. Distributions in the 2030s and 2070s are based on the 19 GCMs selected by RMJOC-II.

Figure 81 shows the regulated inflows for Lower Granite for the subset of 19 HYDSIM scenarios relative to the historical baseline. Lower Granite is in the Lower Snake basin. Inflows include the flow from the Clearwater River that is regulated by Dworshak Dam and the regulated flows from Brownlee Dam. The Brownlee inflows used in the HYDSIM modeling are from the Reclamation MODSIM modeling of the Upper Snake River, which is highly regulated by a multitude of reservoirs and dams (see Sections 2.5 and 3.4.1). Similar to the flow at the border and at Grand Coulee, **Figure 81** also depicts higher inflows in the winter months, in this case December–March, and spring months, April and May, for both the 2030s and 2070s relative to the historic baseline. June appears to be a transition month of little change although the flows drop in the 2070s. However, inflows in the summer month of July show a slight decrease in the 2030s and 2070s relative to the baseline. This decrease appears short lived as the flows for the remainder of summer and fall, August–November, show little change in the 2030s and 2070s as compared to the historical baseline. Chapter 7.0 provides more detail on the operation of the specific projects, such as Dworshak on the Clearwater and Brownlee on the Snake.

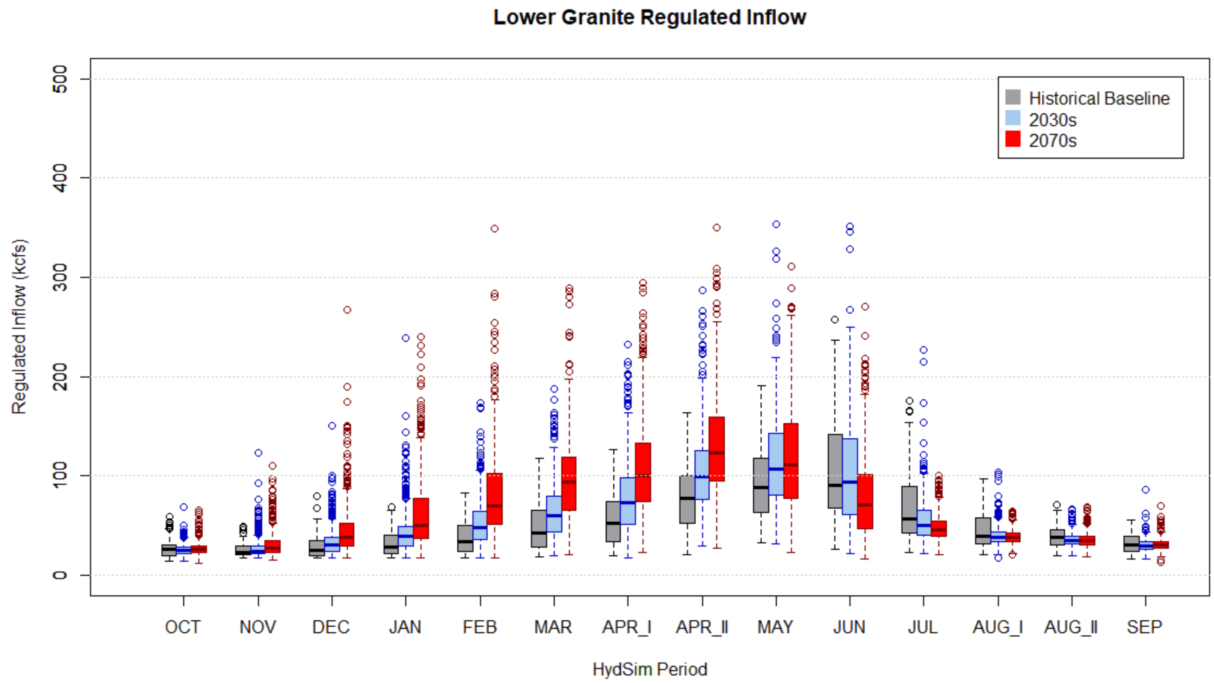

Figure 81. Distribution of Lower Granite inflow results from HYDSIM power modeling. The 2030s and 2070s results are based on the 19 RMJOC-II scenarios.

Figure 82 shows the regulated inflows for The Dalles for the subset of 19 HYDSIM scenarios relative to the historical baseline. The Dalles Dam is in the Lower Columbia River. Its inflows consist of the flow from the Mid-Columbia and Snake River basins (see Section 2.6). The Dalles is the primary stream-gaging site for the Columbia River and is integral to the hydrosystem design and operation. Similar to the regulated flows previously shown, **Figure 82** also depicts higher inflows in the winter months, December–March, and spring months, April and May, for both the 2030s and 2070s relative to the historic baseline. June appears to be a transition month of little change although the flows drop in the 2070s. However, inflows in the summer months of July–September show a pronounced decrease in the 2030s and 2070s relative to the baseline. The fall months of October and November appear to be transition months where the flows are relatively similar in the 2030s but begin to slightly increase for the 2070s in November.

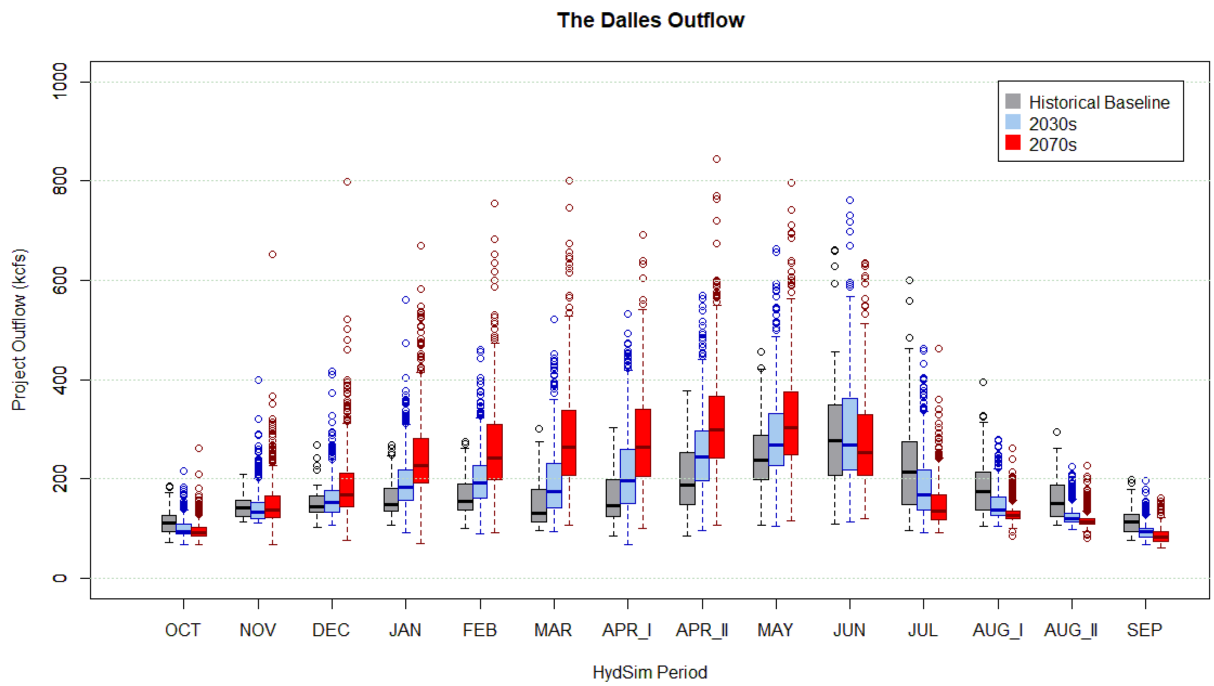

Figure 82. Distribution of The Dalles outflow results from HYDSIM power modeling. The 2030s and 2070s results are based on the 19 RMJOC-II scenarios.

To summarize the general distribution of regulated flows from the HYDSM operational modeling of the subset of 19 climate change projections, the flows increase consistently through the winter months throughout the basin and suffer decreasing flows in the summer months and, to some extent depending on location, into the early fall months. Decreasing flows in the summer months appear to be more pronounced in the portion of the basin above the U.S.-Canadian border, while the regulated flows in the Snake River basin do not drop as significantly. These outcomes are highly dependent on the modeling assumptions for reservoir regulation and the nonadaptive approach to the operating criteria and procedures.

9.4 Hydropower Results of the HYDSIM Operational Modeling

The primary output of the HYDSIM OPER modeling is hydropower for the Columbia River hydrosystem and specifically for the FCRPS. The OPER modeling is driven by the available hydrology, seasonal water supply volumes, and the operating criteria and limitations that determine the drafting and refilling of the storage reservoirs. The OPER model is driven mostly by non-power requirements. The influence of load demand is reflected in earlier modeling steps that define the AOP and TSR regulation of the Canadian reservoirs that determines the flow at the U.S.-Canadian border (see **Figure 79**). The OPER model runs to maximize power production while meeting FRM requirements and the variety of fishery objectives for both resident and anadromous fish. The modeling also accounts for other purposes, such as recreation, navigation, and irrigation. The generation numbers below reflect changes in streamflow projections for the subset of 19 climate change scenarios and their associated water supply forecasts for the 2030s and 2070s epochs.

9.4.1 Federal Generation Results

Figure 83 shows the distribution of generation at the 14 federal hydrogeneration projects that were the focus of the operational modeling. This includes Libby, Hungry Horse, Albeni Falls, Dworshak, Grand Coulee, Chief Joseph, Lower Granite, Little Goose, Lower Monumental, Ice Harbor, McNary, John Day, The Dalles, and Bonneville. Relative to the historic baseline, this figure shows an increase in generation during the winter and early spring in the 2030s and 2070s and a reduction in generation during the summer and early fall.

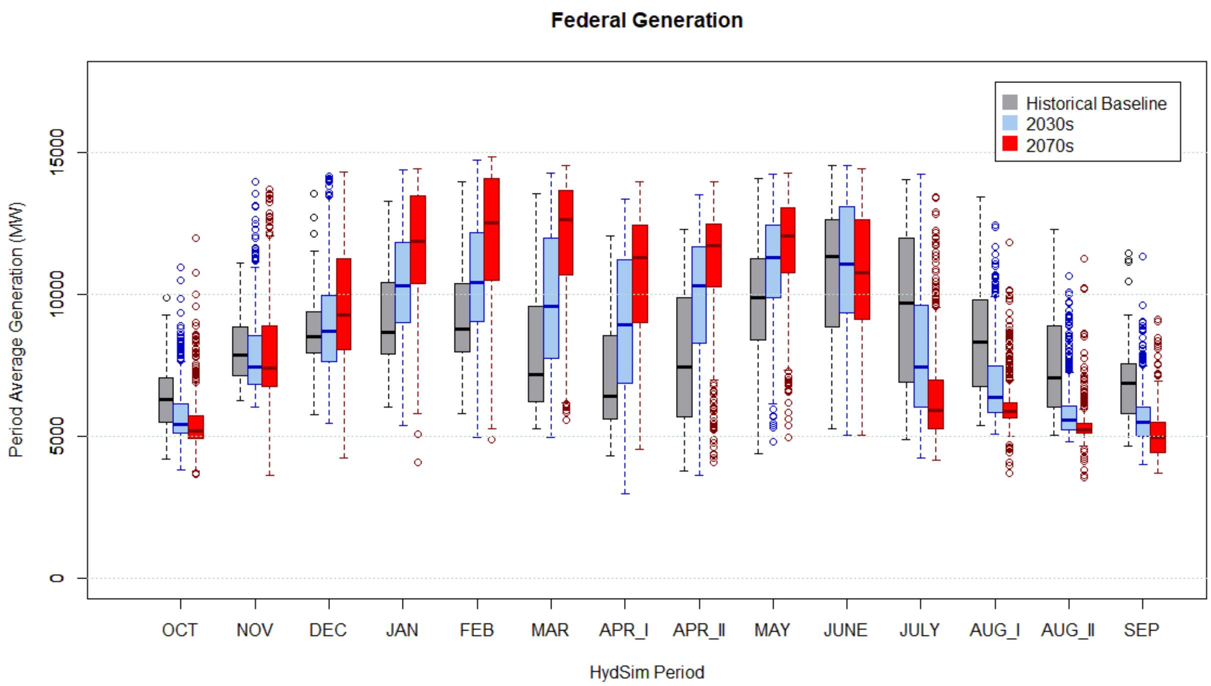

Figure 83. Combined generation of the 14 federal hydrogeneration projects in the Columbia River Basin. Distribution in the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling.

This trend closely mirrors what we see in the regulated flows at Grand Coulee (**Figure 80**), Lower Granite (**Figure 81**), and The Dalles (**Figure 82**). Federal generation increases substantially during the winter months, December–March, for both the 2030s and 2070s. This increase continues into the spring months of April and May before tapering off in June for both epochs. The generation outlook changes in the summer and into the fall; for all months, July–October, there is a significant drop in federal generation. **Table 8** shows the 14-period generation values for the 10th, 50th, and 90th percentile results for the historical baseline and the 2030s and 2070s. For the winter months, generation increases in the range of about 500 MW to over 4,000 MW, depending on the selected month and probability level compared. The maximum drop in generation occurs in July where the P50 results show that over 3,000 MW are lost by the 2070s. The annual generation values show that much of the seasonal shift in generation is balanced out with a much lower average MW gain. For the P50 results of the subset of 19 climate change scenarios, the annual average generation increases by about 480 MW for the 2030s and by about 840 MW for the 2070s. The annual change in average generation for the P10 results is slightly less, with an increase of about 120 MW for the 2030s and about 370 MW for the 2070s. For the P90 results, it increased about 420 MW for the 2030s and for the 2070s.

Table 8. Combined generation of the 14 federal hydro projects in the Columbia River Basin.*

Federal Period-Average Generation (MW)

		OCT	NOV	DEC	JAN	FEB	MAR	APR I	APR II	MAY	JUN	JUL	AUG I	AUG II	SEP	Annual
Historical Baseline	P10	5124	6776	7369	7050	7429	5820	5092	4694	6564	7981	5899	6107	5679	5506	6351
	P50	6324	7773	8571	8524	8881	7026	6269	7335	9753	11089	9715	8337	6969	6829	8240
	P90	7776	9536	10065	11101	11504	11441	9613	11112	11806	13402	13498	11472	9990	8379	10797
2030s	P10	4855	6590	6977	7439	7245	6403	5680	6275	8723	8101	5443	5634	5076	4583	6469
	P50	5720	7913	8972	10323	10508	9844	8977	9764	10963	11023	8094	6890	5879	5656	8719
	P90	7101	10099	11128	13198	13705	13515	12350	12456	13132	13890	11765	8816	6933	6965	11214
2070s	P10	4457	6506	7314	8833	8726	8456	6960	8257	9138	7847	4854	5469	4984	4187	6919
	P50	5448	8015	9717	11661	12009	11892	10570	11074	11639	10717	6483	6058	5374	5067	9081
	P90	6807	10696	13073	14083	14502	13940	12925	13077	13661	13721	9215	6763	5742	5958	11221

* The 10th percentile, 50th percentile, and 90th percentile of each distribution is shown. The distribution of the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling.

9.4.2 U.S. System Generation

U.S. system generation in the HYDSIM operational modeling includes generation produced at 58 hydroelectric plants in the Columbia River Basin, both federal and nonfederal. The U.S. system generation includes the 14 federal projects discussed in Section 9.4.1 along with the the non-federal projects above Bonneville Dam and the federal and non-federal projects in the tributaries below the Bonneville Dam. For the projects on the tributaries below Bonneville Dam, no operational data existed for the subset of 19 HYDSIM climate change projections that is needed for the TSR and OPER modeling. To overcome this limitation, the 30-year median generation values from AOP 2022 were used as a fixed resource for the TSR and OPER modeling for the historical baselines and the 2030 and 2070 epochs.

The impact of operational modeling of U.S system for the subset of 19 HYDSIM climate change projections is similar to the federal hydrogeneration shown in Section 9.4.1. **Figure 84** shows the distribution of the U.S. system generation for the 2030s and 2070s. Relative to the historic baseline, this figure shows an increase in generation during the winter and early spring in the 2030s and 2070s and a reduction in generation during the summer and early fall. This trend closely mirrors what we see in the regulated flows at Grand Coulee (**Figure 80**), Lower Granite (**Figure 81**), and The Dalles (**Figure 82**).

U.S. system generation increases substantially during the winter months, December–March, for both the 2030s and 2070s. This increase continues into the spring months of April and May before tapering off in June for both epochs. The generation outlook changes in the summer and into the fall as for all months, July–October, there is a significant drop in U.S System generation. **Table 9** shows the 14-period generation values for the P10, P50, and P90 results for the historical baseline and the 2030s and 2070s. For the winter months, generation increases in the range of about 500 MW to over 7,000 MW, depending on the selected month and probability level compared. The maximum drop in generation occurs in July where the P50 results show that over 5,000 MW are lost by the 2070s. The annual generation values show that much of the seasonal shift in generation is balanced out with a much lower average megawatt gain. For the P50 results of the subset of 19 climate change scenarios, the annual average generation increases by about 660 MW for the 2030s and by about 1,110 MW for the 2070s. The annual change in average generation for the P10 results is slightly less, with an increase of about 230 MW for the 2030s and about 790 MW for the 2070s. For the P90 results, it is increased about 740 MW for the 2030s and about 660 MW for the 2070s. The non-federal generation represents about 30 percent of the annual average generation for the U.S. system. As stated previously, the operation of these projects above Bonneville Dam were not adapted to climate change flows and the projects below Bonneville Dam were set to a 30-year median generation value and treated as a fixed resource in the HYDSIM modeling. How climate change may influence many of these projects was beyond the scope of the RMJOC-II study.

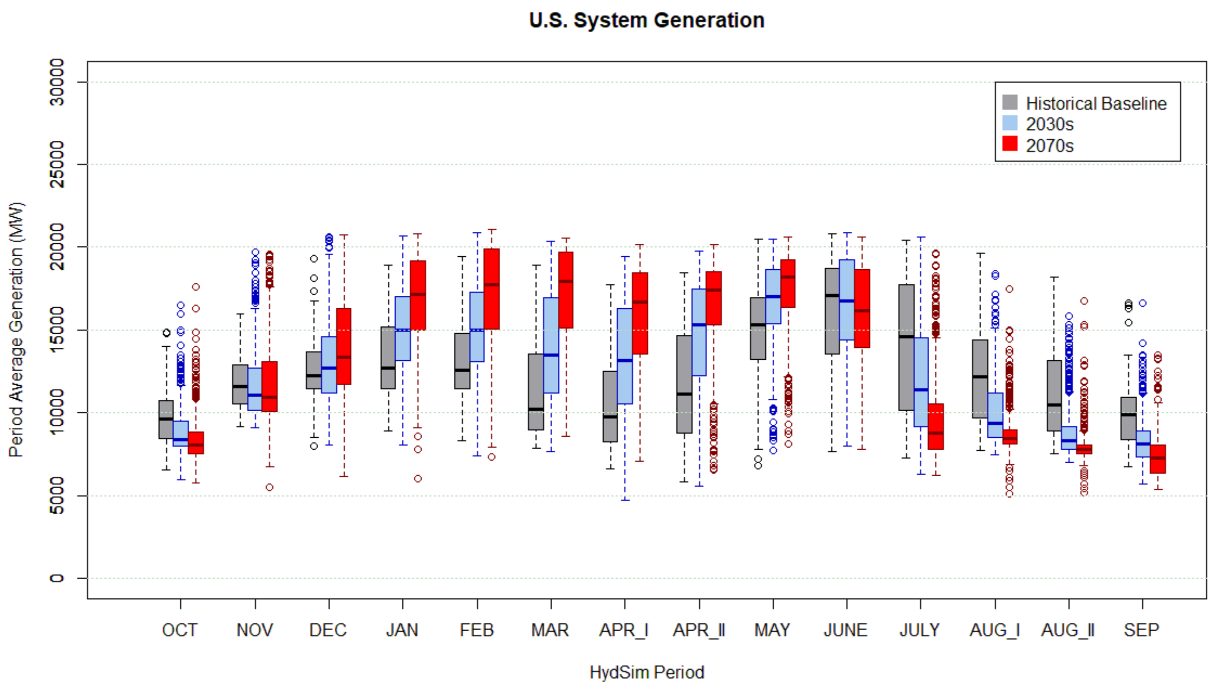

Figure 84. Combined generation of all U.S. system hydrogeneration projects. Distribution in the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling.

Table 9. Combined generation of all U.S. system hydro projects in the Columbia River Basin.*

US System Period-Average Generation (MW)

		OCT	NOV	DEC	JAN	FEB	MAR	APR I	APR II	MAY	JUN	JUL	AUG I	AUG II	SEP	Annual
Historical Baseline	P10	7835	10122	10612	10282	10745	8471	7424	7086	10091	12202	8959	8923	8336	7707	9399
	P50	9664	11469	12302	12705	12561	9945	9583	10961	15143	16543	14823	12229	10527	9901	12223
	P90	11819	14179	14407	16101	16433	15747	13681	16247	17845	19517	19719	16749	14461	12286	15715
2030s	P10	7538	9870	10321	10966	10768	9358	8590	9044	12949	12301	8128	8160	7534	6721	9625
	P50	8857	11744	13084	14979	15036	14019	13308	14616	16610	16512	12137	10135	8813	8308	12878
	P90	10781	15112	16334	18711	19247	19406	18264	18445	19336	19996	17665	13594	11090	10393	16454
2070s	P10	6929	9663	10773	12752	12230	12007	10505	12216	13836	12162	7151	7795	7323	6008	10191
	P50	8404	11876	14101	16842	17104	16987	15678	16498	17444	16025	9638	8787	7977	7370	13331
	P90	10336	15812	18925	20274	20644	20093	19024	19196	19856	19850	13735	10225	8646	8813	16378

* The 10th percentile, 50th percentile, and 90th percentile of each distribution is shown. The distribution of the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling.

As the prior sections show, both the federal and U.S. system generation patterns are similar to the regulated flow, where increased winter and spring flow results in more hydropower and lower summer and early fall flows reduces generation as compared to the historical baseline.

However, another factor in the distribution of seasonal generation is the required spill in the spring and summer for anadromous fish passage that is specified in the 2019 Biological Opinion (NOAA 2019). The following section describes the results of the HYDSIM operational modeling for fish passage spill for the projects in the Lower Snake and Lower Columbia along with the spill in the federal system.

9.5 Spill Results from HYDSIM Operational Modeling

Spill is outflow from reservoirs that does not pass through turbines. The HYDSIM operational model spills water for a number of reasons. These include forced spill that requires releasing outflows up and beyond the turbine capacity of the project to meet reservoir operating limits and regulated spill to meet anadromous fish passage spill. The regulated spill for fish passage has a spring spill period that starts in early April and lasts through the first half of June followed by a summer spill period that starts in the second half of June and last through August. The spill requirements are for the Lower Snake and Lower Columbia projects, and the requirements are specified in the 2019 Biological Opinion (NOAA 2019) and the 2019 Fish Passage Plan (USACE 2019). The fish spill requirements are given a higher priority than generation. The one exception in the HYDSIM operational model is when project flows become so low that fish spill requirements cannot be met while still supporting a project minimum turbine flow. In this situation, the project will maintain the minimum turbine flow and simply spill as much as possible in an effort to achieve the fish spill requirements. In addition, the operational model includes the spill from dam leakage and navigational lockage in the Lower Snake and Lower Columbia projects. This magnitude of spill is often very small compared to fish spill requirements.

The HYDSIM operational model does not spill due to lack of market conditions, which is a common occurrence at the peak of spring runoff. Lack-of-market spill occurs when there is an excess of water that must be passed through the project, but due to a lack of market to deliver the surplus energy, the water is spilled. The HYDSIM operational model does not run to meet this type of market load but rather runs to meet operational objectives such as FRM and fishery requirements. Modeling the lack-of-market spill requires running additional models to determine market depth and the price of energy on a daily step. This is beyond the scope of the RMJOC-II project and is considered a future effort as described in Chapter 11.0.

9.5.1 Federal System Spill

Figure 85 shows the combined spill at the 14 federal projects in the Columbia River system. The combined spill is the summed spill for the 14 federal projects in thousands of cubic feet per second (kcfs) for each of the 14-periods in the HYDSIM modeling for the 2030s and 2070s as compared to the historical baseline. It is the combination of spill from headwater projects, such as Libby and Dworshak, and from the federal projects in the Mid-Columbia, Lower Snake, and Lower Columbia. It includes spill due to regulated outflows exceeding turbine capacity, called turbine capacity in the figures, and spill required for fish passage in the spring and summer for the Lower Snake and Lower Columbia projects.

The combined spill in the federal system increases substantially during the winter months, January–March, for both the 2030s and 2070s. This increase continues into the spring months of April and May before tapering off in June for both epochs. The spill outlook changes in the summer, July–August, as the spill drops slightly for each month due to lower regulated flows in the summer throughout most of the basin (see Section 9.3). **Table 10** shows the 14-period spill results for the P10, P50, and P90 probabilities for the historical baseline and the 2030s and 2070s. The annual average combined spill values show that much of the seasonal shift in spill is balanced out with a general overall increase. For the P50 results of the subset of 19 climate change scenarios, the annual average combined spill decreases by about 285 kcfs for the 2030s and increases by about 42,000 kcfs for the 2070s. The annual change in average spill for the P10 results shows an increase of about 6,500 kcfs for the 2030s and about 5,500 kcfs for the 2070s. For the P90 results, the increase is about 79,000 kcfs for the 2030s and about 281,000 kcfs for the 2070s.

The following two sections describe the changes in spill for exceeding turbine capacity and the spill for meeting fish passage requirements for the 2030s and 2070s. The total amount of the accumulated spill for turbine capacity and fishery spill compares with the total spill shown here for the federal system.

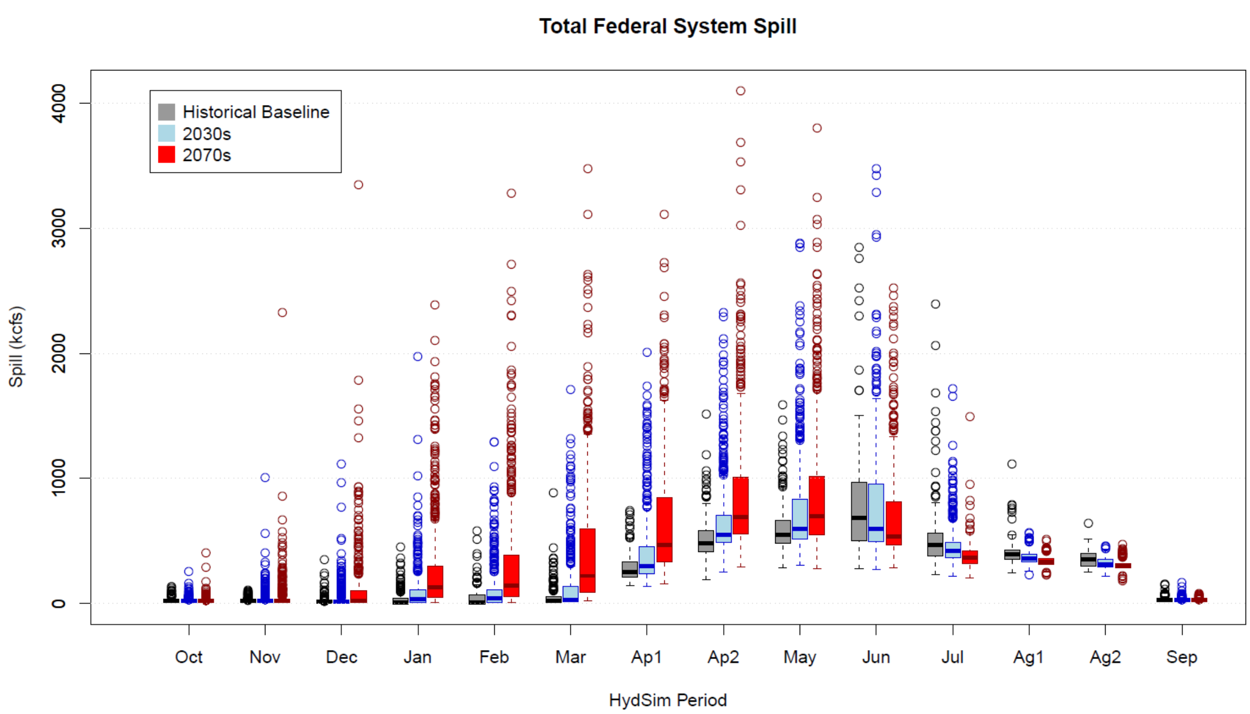

Figure 85. Total combined perod-average spill in the federal system. Distribution in the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling.

Table 10. Total combined spill in the federal system in the Columbia River Basin.*

(Total Combined Period-Average Spill in kcfs)

		OCT	NOV	DEC	JAN	FEB	MAR	APR I	APR II	MAY	JUN	JUL	AUG I	AUG II	SEP	Annual
Historical Baseline	P10	23,991	23,446	14,373	9,812	9,875	23,311	184,764	332,374	432,645	427,906	341,643	324,503	282,404	24,402	158,559
	P50	24,457	23,446	14,373	9,921	10,466	23,518	253,624	483,833	548,807	684,821	468,672	391,714	356,530	29,335	215,874
	P90	57,316	46,310	34,323	128,359	140,541	170,709	454,013	708,220	929,344	1,258,894	749,062	483,015	439,352	60,368	385,457
2030s	P10	23,991	23,446	14,373	9,812	9,875	23,311	203,756	410,835	464,092	444,067	328,887	314,835	279,520	24,736	164,979
	P50	24,286	23,446	14,373	33,865	42,465	32,243	300,662	550,066	597,001	595,420	423,410	361,386	316,124	28,599	215,589
	P90	42,649	84,570	94,406	215,070	259,407	324,107	741,795	1,047,180	1,212,801	1,410,322	586,525	430,592	386,655	38,990	464,249
2070s	P10	23,991	23,446	14,373	9,812	9,875	24,740	249,315	487,166	469,866	413,876	292,326	302,523	269,976	24,381	164,060
	P50	23,991	23,446	21,989	131,011	141,582	222,053	469,558	692,424	698,101	537,907	365,426	334,957	298,226	26,923	257,942
	P90	39,702	118,343	269,989	726,570	860,470	1,107,483	1,244,348	1,486,754	1,500,229	1,142,234	479,565	389,774	349,311	30,836	666,071

* The 10th percentile, 50th percentile, and 90th percentile of each distribution is shown. The distribution of the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling.

9.5.2 Turbine Capacity Spill in the Federal System

Figure 86 shows the combined spill due to exceeding turbine capacity at the 14 projects in the federal system. The combined spill in the federal system increases substantially during the winter months, January–March, for both the 2030s and 2070s. This increase continues into the spring months of April and May before tapering off in June for both epochs. The spill outlook changes in the summer, July–August, as the spill drops slightly for each month due to lower regulated flows in the summer throughout most of the basin (see Section 9.3). **Table 11** shows the 14-period turbine capacity spill results for the P10, P50, and P90 probabilities for the historical baseline and the 2030s and 2070s. The annual spill values show that much of the seasonal shift in spill is balanced out with a much lower average overall increase. For the P50 results of the subset of 19 climate change scenarios, the annual average spill increases by about 3,100 kcfs for the 2030s and by about 47,400 kcfs for the 2070s. The annual change in average spill for the P10 results is slightly less, with an increase of about 100 kcfs for the 2030s and a decrease of about 50 kcfs for the 2070s. For the P90 results, the annual average change is about 80,400 kcfs for the 2030s and about 288,200 kcfs for the 2070s.

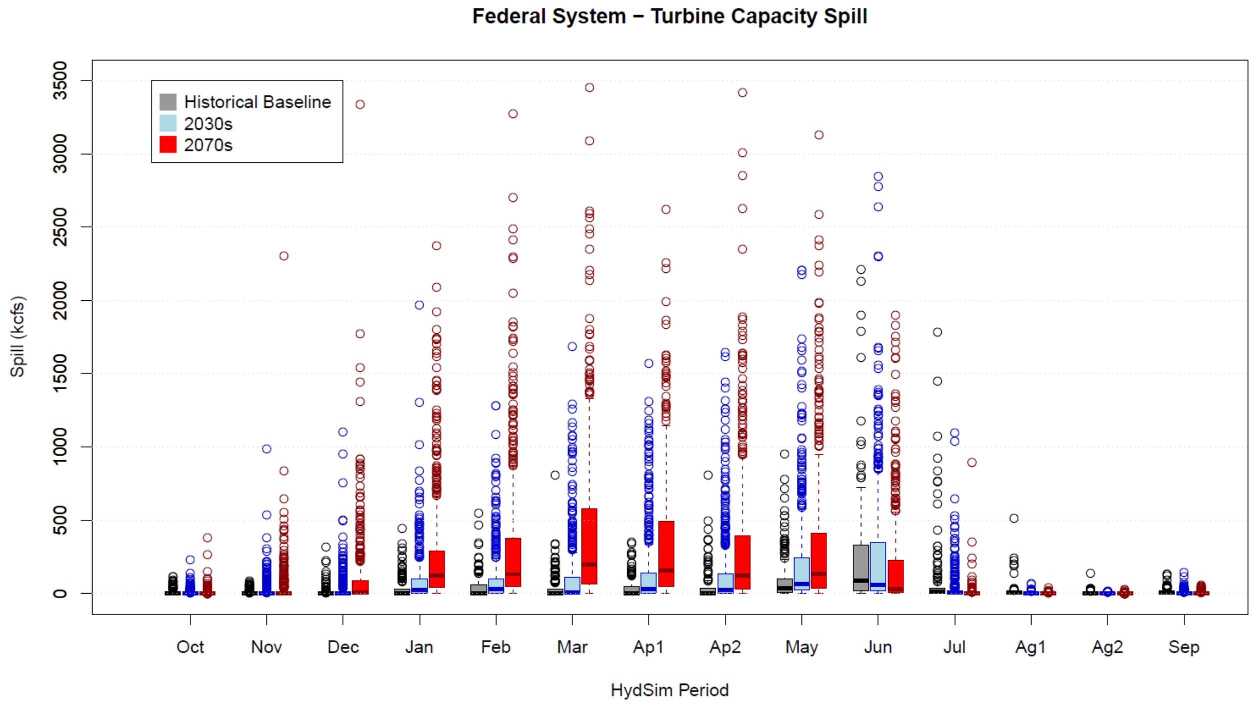

Figure 86. Combined period-average turbine capacity spill in the federal system. Distribution in the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling.

Table 11. Total combined turbine capacity spill in the federal system in the Columbia River Basin.*

(Total Combined Period-Average Spill in kcfs)

		OCT	NOV	DEC	JAN	FEB	MAR	APR I	APR II	MAY	JUN	JUL	AUG I	AUG II	SEP	Annual
Historical Baseline	P10	21,970	21,740	13,870	9,290	9,300	22,040	26,330	26,510	28,702	33,633	27,702	27,819	26,480	22,121	22,045
	P50	22,436	21,740	13,870	9,399	9,891	22,247	31,447	30,326	61,288	160,900	39,584	34,397	30,110	27,054	37,585
	P90	55,295	44,604	33,820	127,837	139,966	169,438	175,194	171,458	364,934	666,473	193,876	53,092	38,864	58,087	172,343
2030s	P10	21,970	21,740	13,870	9,290	9,300	22,040	26,330	26,510	33,049	30,495	27,414	27,432	26,480	22,455	22,143
	P50	22,265	21,740	13,870	33,343	41,890	30,972	56,031	53,715	93,524	87,575	33,382	31,533	27,919	26,318	40,702
	P90	40,628	82,864	93,903	214,548	258,832	322,836	424,334	449,380	620,595	821,856	78,648	39,529	34,903	36,709	252,752
2070s	P10	21,970	21,740	13,870	9,290	9,300	23,469	26,330	31,134	31,647	27,097	27,151	27,153	26,480	22,100	21,993
	P50	21,970	21,740	21,486	130,489	141,007	220,782	183,226	149,923	161,215	56,988	27,997	28,097	26,480	24,642	84,953
	P90	37,681	116,637	269,486	726,048	859,895	1,106,212	883,533	866,372	889,588	574,085	39,014	34,229	30,242	28,555	460,575

* The 10th percentile, 50th percentile, and 90th percentile of each distribution is shown. The distribution of the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling.

9.5.3 Spill for Fish Passage

Figure 87 shows the combined spill due to meeting the fish passage requirements at the four federal projects in the Lower Snake River and the four federal projects in the Lower Columbia River. The combined fish passage spill increases during the spring months, April and May, for both the 2030s and 2070s. The spill outlook changes, however, in the summer, June–August, as the spill drops for each month for both the 2030s and 2070s. This is due to lower regulated flows in the summer throughout most of the basin (see Section 9.3). **Table 12** shows the 14-period fish passage spill results for the P10, P50, and P90 probabilities for the historical baseline and the 2030s and 2070s. The annual average fish passage spill values show that much of the seasonal shift in spill is balanced out with a much lower average overall difference. For the P50 results of the subset of 19 climate change scenarios, the annual average spill decreases by about 2,500 kcfs for the 2030s and by about 5,200 kcfs for the 2070s. The annual change in average spill for the P10 results is slightly less, with an increase of about 5,700 kcfs for the 2030s and about 5,200 kcfs for the 2070s. For the P90 results, the annual change decreases by about 1,200 kcfs for the 2030s and about 5,900 kcfs for the 2070s.

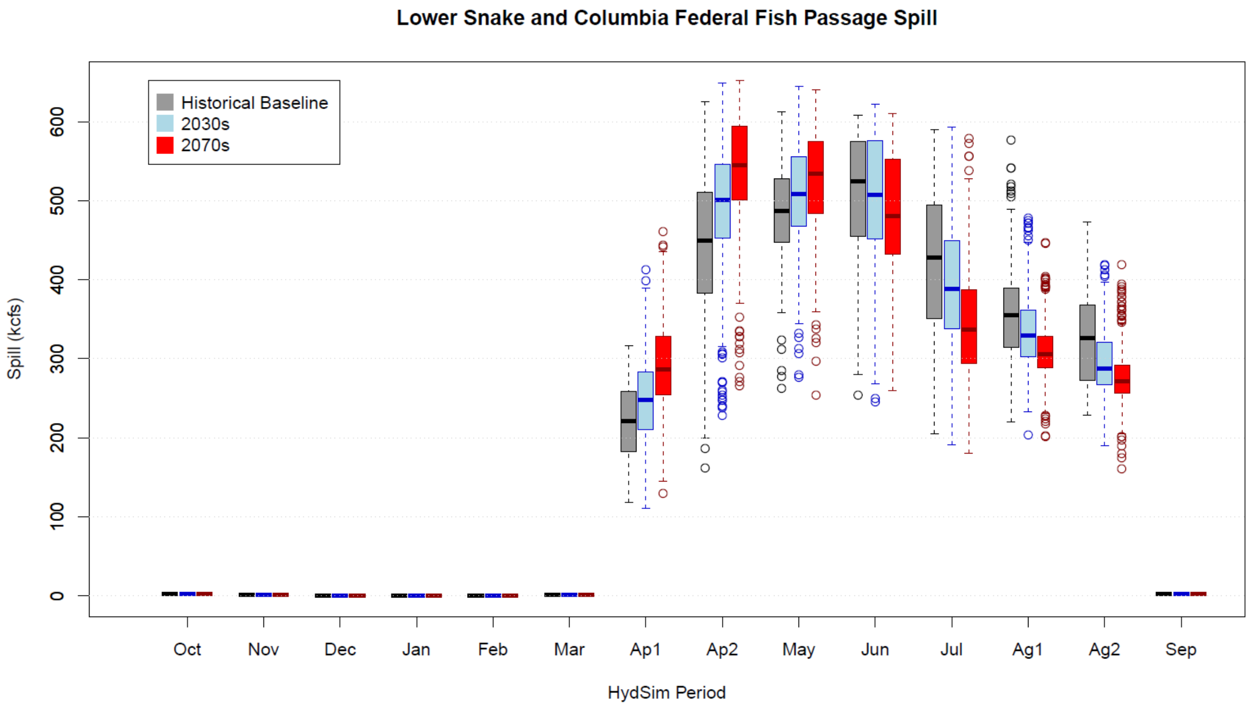

Figure 87. Combined period-average spill for fish passage in the federal system. Distribution in the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling.

Table 12. Total combined spill for fish passage at the Lower Snake and Lower Columbia Federal Projects.*

(Total Combined Period-Average Spill in kcfs)

		OCT	NOV	DEC	JAN	FEB	MAR	APR I	APR II	MAY	JUN	JUL	AUG I	AUG II	SEP	Annual
Historical Baseline	P10	2,021	1,706	503	522	575	1,271	158,434	305,864	402,891	395,123	313,982	295,382	255,709	2,281	136,435
	P50	2,021	1,706	503	522	575	1,271	221,392	449,219	486,960	524,372	428,373	355,431	326,390	2,281	177,930
	P90	2,021	1,706	503	522	575	1,271	280,781	543,409	565,777	590,685	552,118	434,618	399,567	2,281	213,334
2030s	P10	2,021	1,706	503	522	575	1,271	177,426	380,772	429,257	411,763	298,889	287,125	253,040	2,281	142,159
	P50	2,021	1,706	503	522	575	1,271	248,314	500,681	508,631	507,624	388,427	329,314	287,968	2,281	175,467
	P90	2,021	1,706	503	522	575	1,271	318,952	594,304	589,125	594,303	512,215	393,249	353,555	2,281	212,169
2070s	P10	2,021	1,706	503	522	575	1,271	215,464	454,847	439,548	385,267	264,955	274,163	243,496	2,281	141,630
	P50	2,021	1,706	503	522	575	1,271	286,098	544,978	534,266	480,407	337,291	306,144	271,387	2,281	172,760
	P90	2,021	1,706	503	522	575	1,271	360,359	625,509	608,762	588,129	441,753	357,147	320,292	2,281	207,391

* The 10th percentile, 50th percentile, and 90th percentile of each distribution is shown. The distribution of the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling.

9.5.4 Spill at Grand Coulee, Lower Granite, and The Dalles

The following figures show the change in total spill at a few key projects in the federal system. **Figure 88** shows the spill at Grand Coulee, which is from flows exceeding turbine capacity. The project does not have fish spill or navigational spill requirements. Relative to the historic baseline, there is an increase in spill in the 2030s and 2070s for the winter through spring months, January–June. However, the distributional spread is more pronounced for the 2070s. The increased spill is due to changes in the regulated inflow to the project (see Section 9.3).

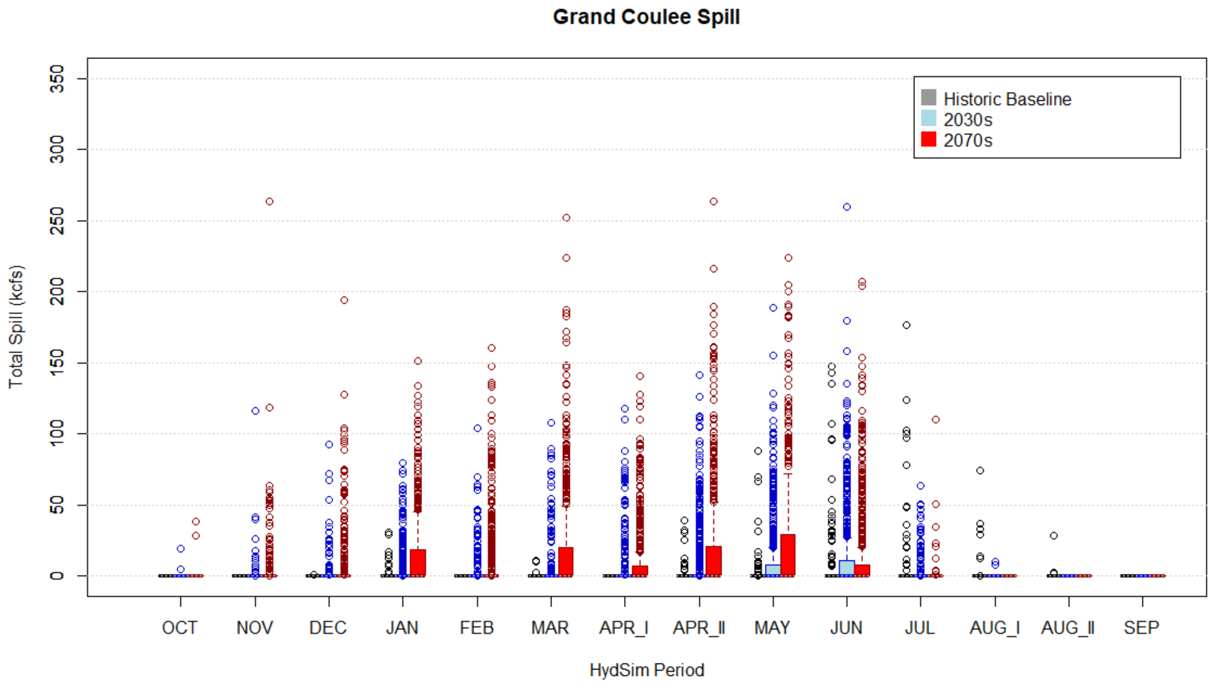

Figure 88. Grand Coulee period-average total spill from HYDSIM power modeling. Distributions in the 2030s and 2070s are based on the 19 GCMs selected by RMJOC-II.

Figures 89 and **90** show the distribution of spill results for Lower Granite and The Dalles. Lower Granite is representative of the Lower Snake River projects that spill for fish passage in the spring and summer, while The Dalles is representative of the Lower Columbia projects that also spill for fish passage. The spill depicted also represents spill from flows exceeding turbine capacity in addition to navigational spill. Both Lower Granite and The Dalles show spill increasing during the winter months and into the spring, March–May for Lower Granite and December–May for The Dalles, in the 2030s and 2070s relative to the historic baseline. Both projects show a reduction of spill during June that appears to be a transition to decreasing spill. For Lower Granite, the depiction of the spill for the rest of the summer does not show much of a trend for both the 2030s and 2070s. However, the spill for the summer months, July–August, shows a continuing drop relative to the historic baseline.

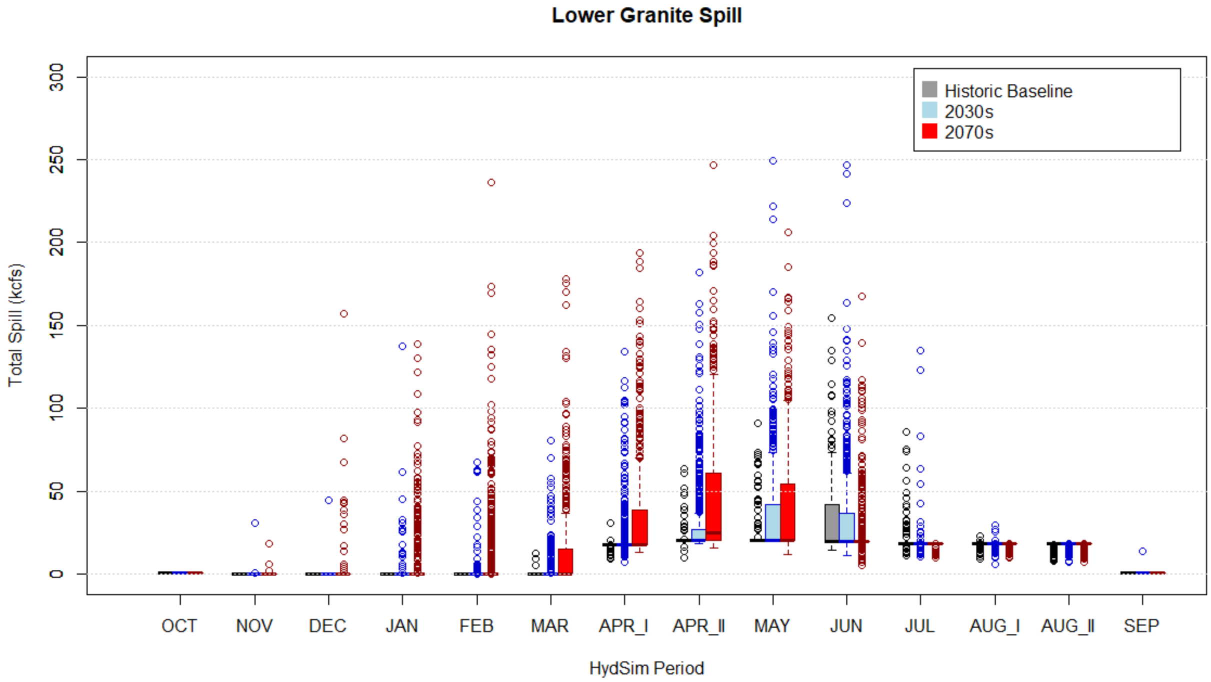

Figure 89. Lower Granite period-average total spill from HYDSIM power modeling. Distributions in the 2030s and 2070s are based on the 19 GCMs selected by RMJOC-II.

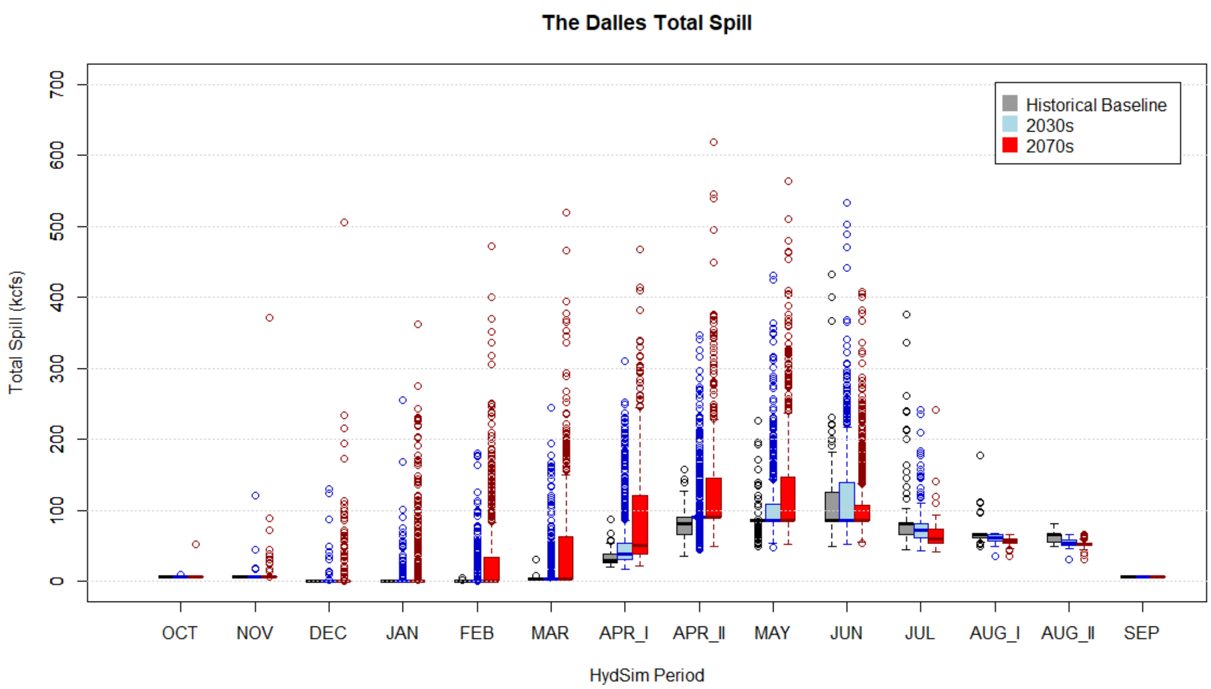

Figure 90. The Dalles period-average total spill from HYDSIM power modeling. Distributions in the 2030s and 2070s are based on the 19 GCMs selected by RMJOC-II.

9.6 Operational Flexibility at Grand Coulee

The bulk of the hydroelectric power production on the federal system occurs downstream of Grand Coulee. Most of the downstream projects have minimal storage and are defined as run-of-river projects. These projects include the four Lower Snake projects (Lower Granite, Little Goose, Lower Monumental, and Ice Harbor) and the four Lower Columbia projects (McNary, John Day, The Dalles, and Bonneville). Chief Joseph in the Mid-Columbia, which has some storage capability, is also operated in the manner of a run-of-river project. Operating these projects to meet hourly load and to manage market activity for surplus or deficit energy conditions relies heavily on the operation of Grand Coulee. The storage and turbine capacity of Grand Coulee provides the ability to manage flows through the Lower Columbia projects to maximize generation on an hourly to daily timescale while meeting other operational objectives, such as FRM, fishery objectives, and Lower Columbia flows required for navigation (see **Figure 10** in Chapter 3.0).

Grand Coulee is operated in the fall months to provide sufficient flow to support the spawning of anadromous fish in the Mid-Columbia below Priest Rapids and in the Lower Columbia below Bonneville. This operation establishes minimum flows that are required to be maintained until the emergence of the fish in the spring. Grand Coulee is also required to provide storage space for FRM from January through April and to maintain an 85 percent probability of reaching the April 10 elevation objective. This requirement intends to provide as much water as possible for fishery during the spring runoff while meeting FRM objectives. These operating requirements limit the use and flexibility of Grand Coulee for power purposes. To define the operating limits during the winter, a variable draft limit curve (VDL) is calculated that allows drafting Grand Coulee below its FRM requirements while meeting the 85 percent criteria of reaching the required elevation on April 10.

During the spring runoff, Grand Coulee plays a major role in controlling flows for FRM and is operated to refill by the end of June or early July. During the summer months, Grand Coulee provides summer flow augmentation for fishery objectives and operates to an elevation of 1,278 to 1,280 feet by August 31 based on the water supply forecast. For the months of September into the early fall, Grand Coulee operates for Lake Roosevelt resident fish, power, maintaining fish flows below Priest Rapids Dam, and ensuring sufficient flows in the lower Columbia for navigation. The desired end of September elevation is between 1,283 and 1,288 feet, and the end of October is 1,288 feet. This provides desired lake levels for resident fish, sufficient water for power flexibility in the fall and winter, and maintains fish flows below Priest Rapids and Bonneville in November.

The following sections describe the impacts to Grand Coulee operation and its operational flexibility for power purposes for the subset of 19 climate change scenarios.

9.6.1 Grand Coulee Regulation Results

Figure 80 in Section 9.3 shows the regulated inflows for Grand Coulee for the subset of 19 HYDSIM scenarios. Higher inflows are projected for the winter months, January–March, and spring months, April and May, for both the 2030s and 2070s relative to the historic baseline. June appears to be a transition month of little change. However, inflows in the summer months, July–September, show a considerable decrease in the 2030s and 2070s relative to the baseline. This decrease in flows extend into the early fall months of October and November.

Figure 91 shows the distribution of Grand Coulee elevation results for the subset of 19 HYDSIM scenarios. Compared to the historic baseline, the results from the 2030s and 2070s shows deeper drafts during January and February but little or no change for March. April appears to be a transition month where the first half of April shows no change in the 2030s but higher pool levels in the 2070s. The second half of April and May show higher pool levels in both the 2030s and 2070s. Pool levels are projected to drop lower in September for both the 2030s and 2070s as compared to the historical baseline as the reservoir may need to be drafted to support minimum navigation flows below Bonneville Dam.

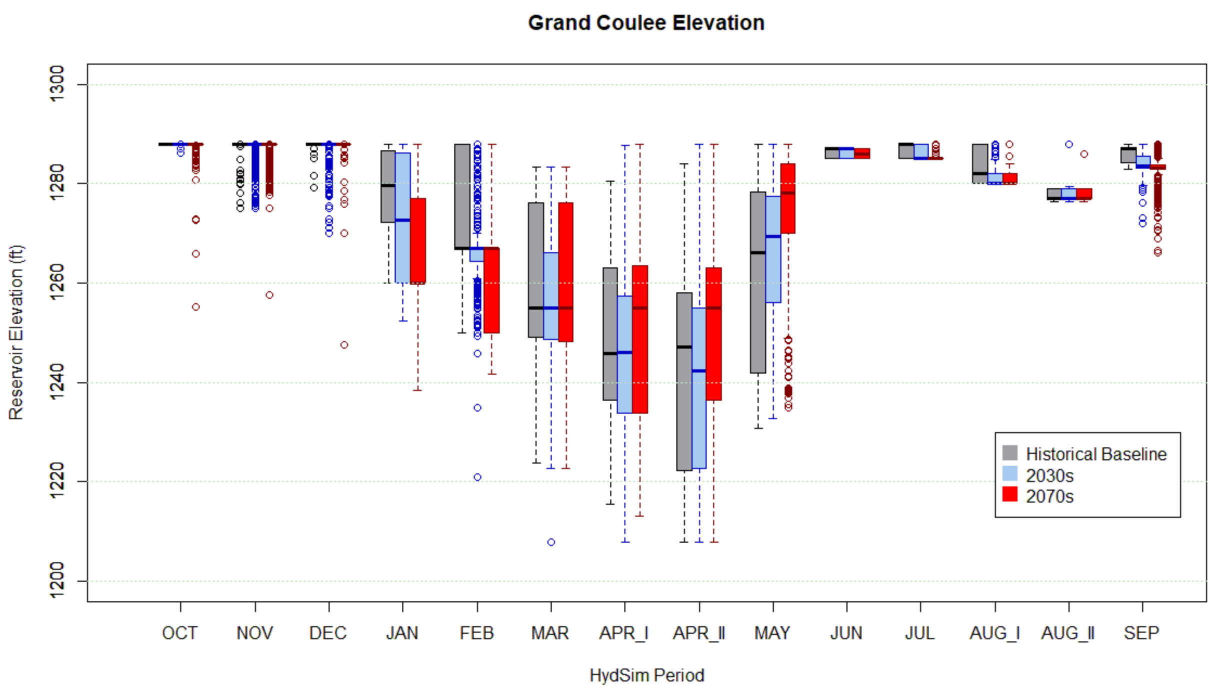

Figure 91. Distribution of Grand Coulee elevation results from HYDSIM power modeling. The 2030s and 2070s results are based on the 19 RMJOC-II scenarios.

Figure 92 shows the distribution of Grand Coulee outflow results for the subset of 19 HYDSIM climate change scenarios as compared to the historical baseline. Higher outflows are projected for the winter and spring months, January–June, and a decrease for the summer and fall, July–November, for both the 2030s and 2070s. December appears to be a transition month with little change in the 2030s and 2070s.

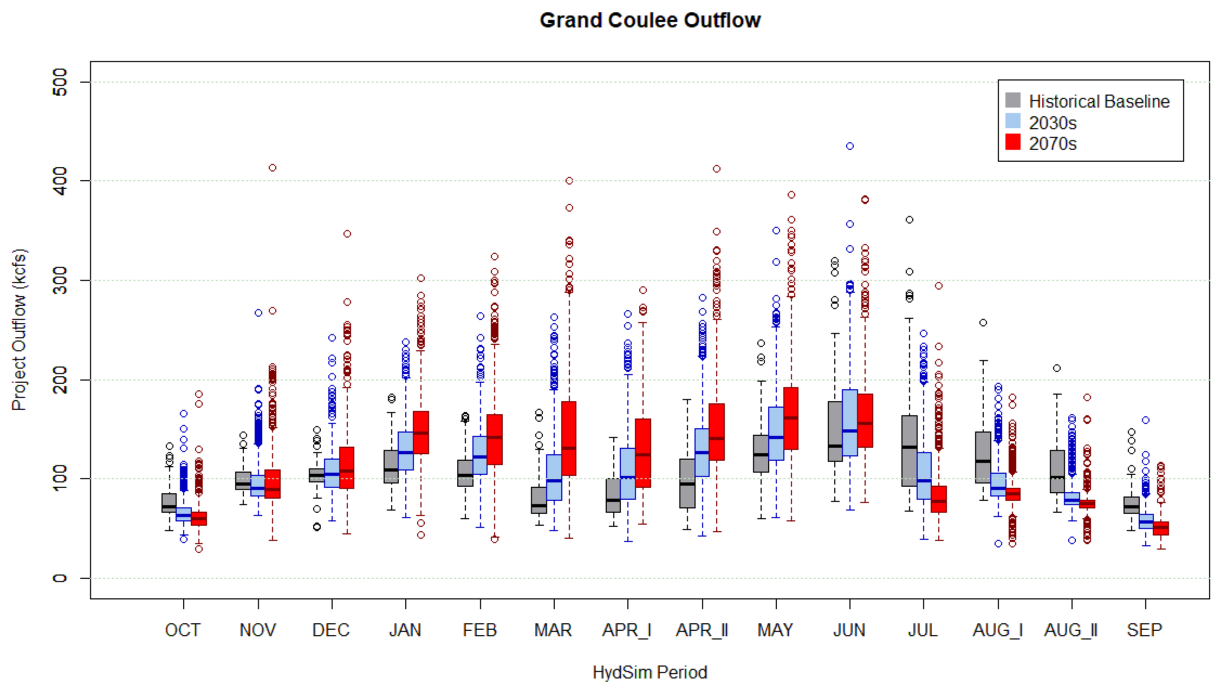

Figure 92. Distribution of Grand Coulee outflow results from HYDSIM power modeling. The 2030s and 2070s results are based on the 19 RMJOC-II scenarios.

9.6.2 Grand Coulee Variable Draft Limits

As previously described, the VDL at Grand Coulee is a reservoir elevation that provides a lower limit to power flexibility in the winter months. The VDL is calculated to ensure an 85 percent chance of meeting both Vernita Bar minimum protection flows as well as the April 10 elevation objective. The absolute minimum VDL elevations are set at 1,260 feet in January; 1,250 feet in February; and 1,240 feet in March. Deeper drafts are often observed, but these are driven by flood control or downstream fish flow objectives and not power production.

The VDL content calculation for the HYDSIM modeling is

$$\textit{VDL Content} = \textit{April 10 Content} - (\textit{P15 Inflow Volume})_{Date\text{–}April10} + (\textit{Outflow Objective})_{Date\text{–}April10},$$

where the *April 10 Content* is the interpolation between the April 15 and March 30 FRM requirements, the *P15 Inflow Volume* is the 15th percentile of the distribution of regulated inflow into Grand Coulee plus incremental flows between Grand Coulee and Priest Rapids, and the *Outflow Objective* is the regulated outflow from Grand Coulee required to meet fish flow objectives at Vernita Bar below Priest Rapids Dam.

Exceedance frequency graphs for the January, February, and March VDLs are shown in **Figures 93**, **94**, and **95**, respectively. Relative to the historical baseline, these figures show decreasing VDL elevations for all three months for both the 2030s and the 2070s for the subset of 19 HYDSIM climate change projections. **Figure 93** shows that reaching the minimum January VDL elevation of 1,260 feet increases by over 20 percent for the 2030s and over 40 percent for the 2070s as compared to the historical baseline. This trend of increasing likelihood of deeper VDL drafts exists for elevations above the 1,260 limit. **Figure 94** shows that reaching the February

VDL elevation limit of 1,250 feet increases by over 40 percent for the 2030s and by about 80 percent for the 2070s as compared to the historical baseline. This trend also stays consistent for the VDL elevations above 1,250 feet. **Figure 95** shows that reaching the March minimum VDL elevation of 1,240 increases by about 10 percent for the 2030s and by about 30 percent for the 2070s as compared to the historical baseline. Similar to January and February, this trend of deeper VDL drafts stays consistent for higher-elevation drafts.

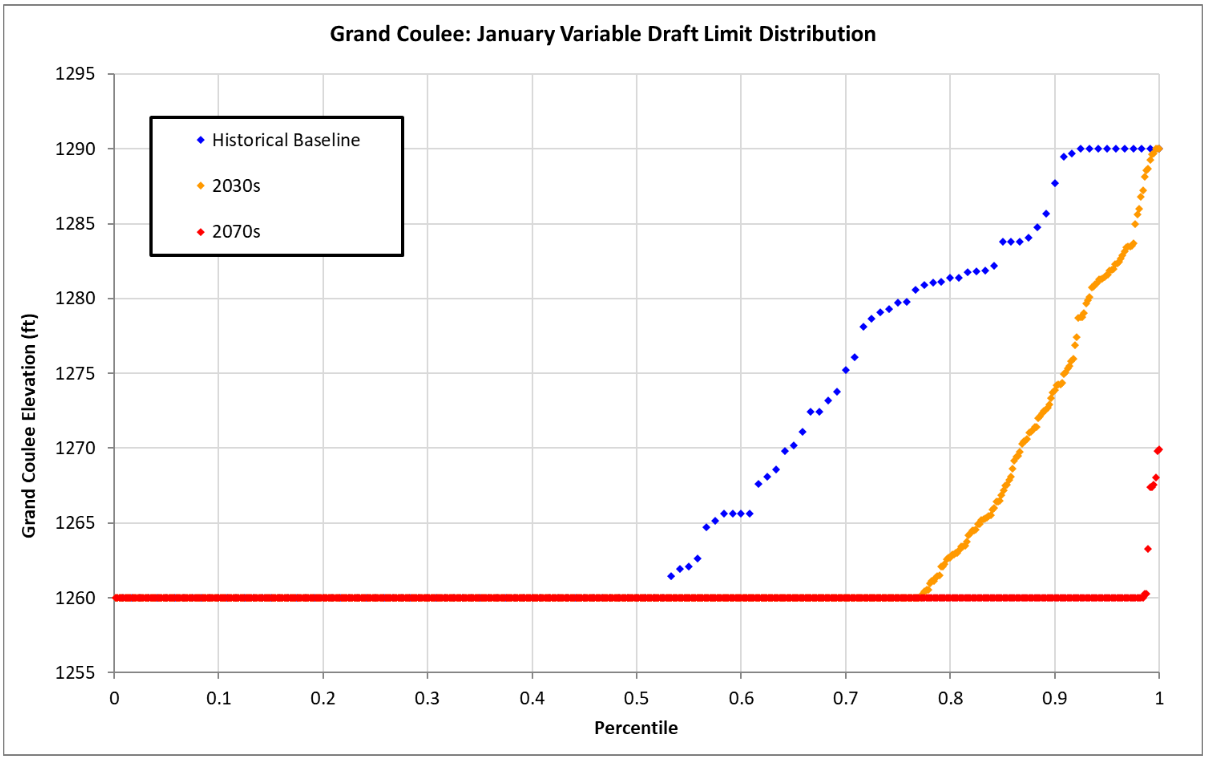

Figure 93. Distribution of January VDLs at Grand Coulee based on HYDSIM power modeling. Distributions in the 2030s and 2070s are based on the 19 RMJOC-II GCM streamflow sets. Each data point represents individual water years in the historical baseline, 2030s, and 2070s. The historical baseline consists of 120 data points while the 2030s and 2070s each consist of 570 data points.

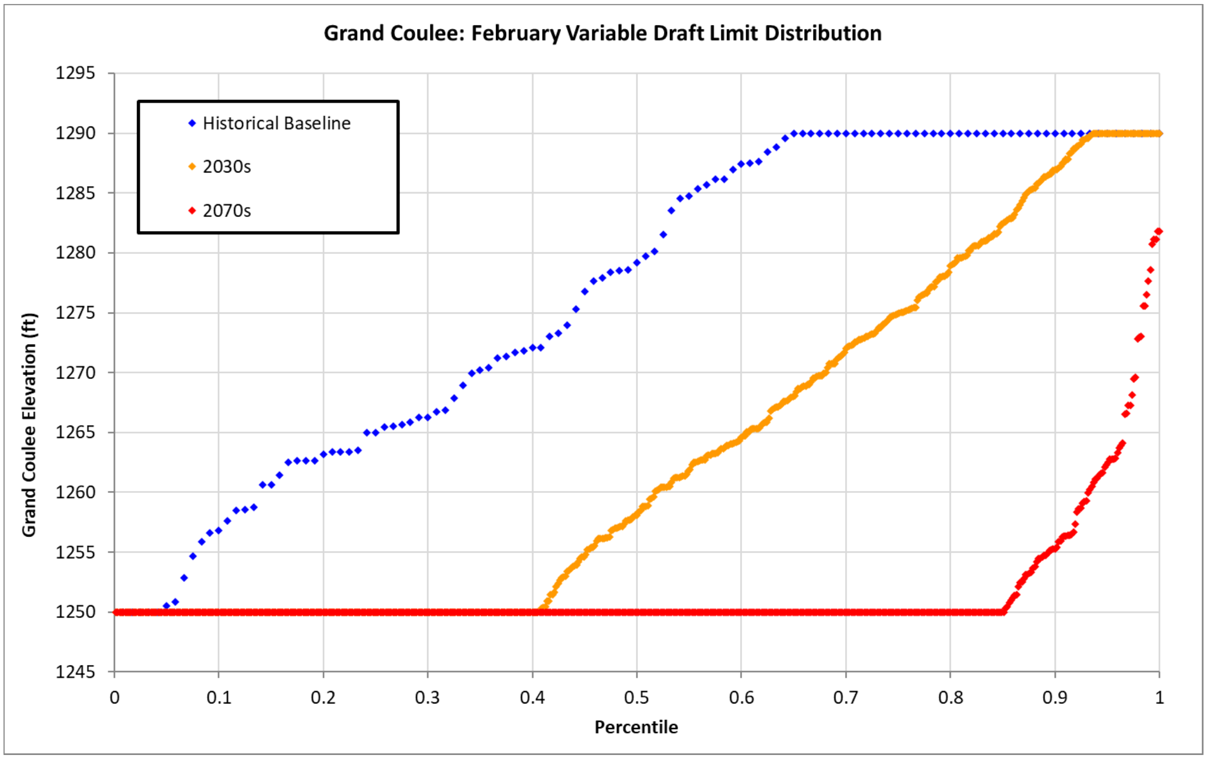

Figure 94. Distribution of February VDLs at Grand Coulee based on HYDSIM power modeling. Distributions in the 2030s and 2070s are based on the 19 RMJOC-II GCM streamflow sets. Each data point represents individual water years in the historical baseline, 2030s, and 2070s. The historical baseline consists of 120 data points while the 2030s and 2070s each consist of 570 data points.

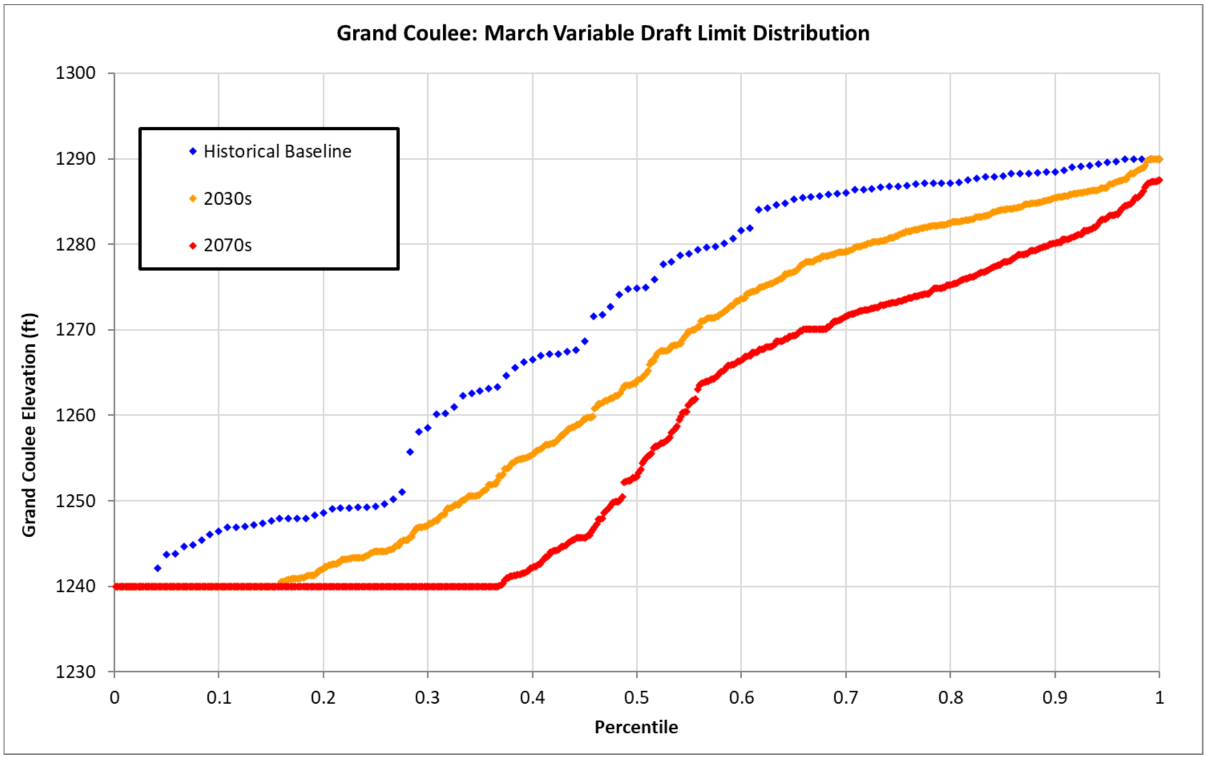

Figure 95. Distribution of March VDLs at Grand Coulee based on HYDSIM power modeling. Distributions in the 2030s and 2070s are based on the 19 RMJOC-II GCM streamflow sets. Each data point represents individual water years in the historical baseline, 2030s, and 2070s. The historical baseline consists of 120 data points while the 2030s and 2070s each consist of 570 data points.

The lower VDLs at Grand Coulee result from a combination of higher regulated inflows (**Figure 80** in Section 9.3), deeper drafts necessary for FRM (**Figure 96**), and slightly lower minimum outflow objectives for Vernita Bar (**Table 15** in Chapter 10.0). **Figure 80** shows that the regulated inflows to Grand Coulee increases for the winter months, January–March, for the 2030s and 2070s as compared to the historical baseline. Correspondingly, **Figure 96** shows the trend for deeper April 10 FRM requirements for much of the Grand Coulee pool range. While the upper and lower end of this distribution are relatively similar, the middle portion of the distribution shows a lowering trend in the April 10 elevation objectives for the 2030s and 2070s as compared to the historical baseline. **Table 15** shows the distribution of Vernita Bar minimum fishery flows for the various streamflow datasets. The data shows the trend of establishing lower minimum flow requirements for Vernita Bar for the 2030s and 2070s as compared to the historical baseline. The combination of these three factors leads to the lower VDLs for the 2030s and 2070s.

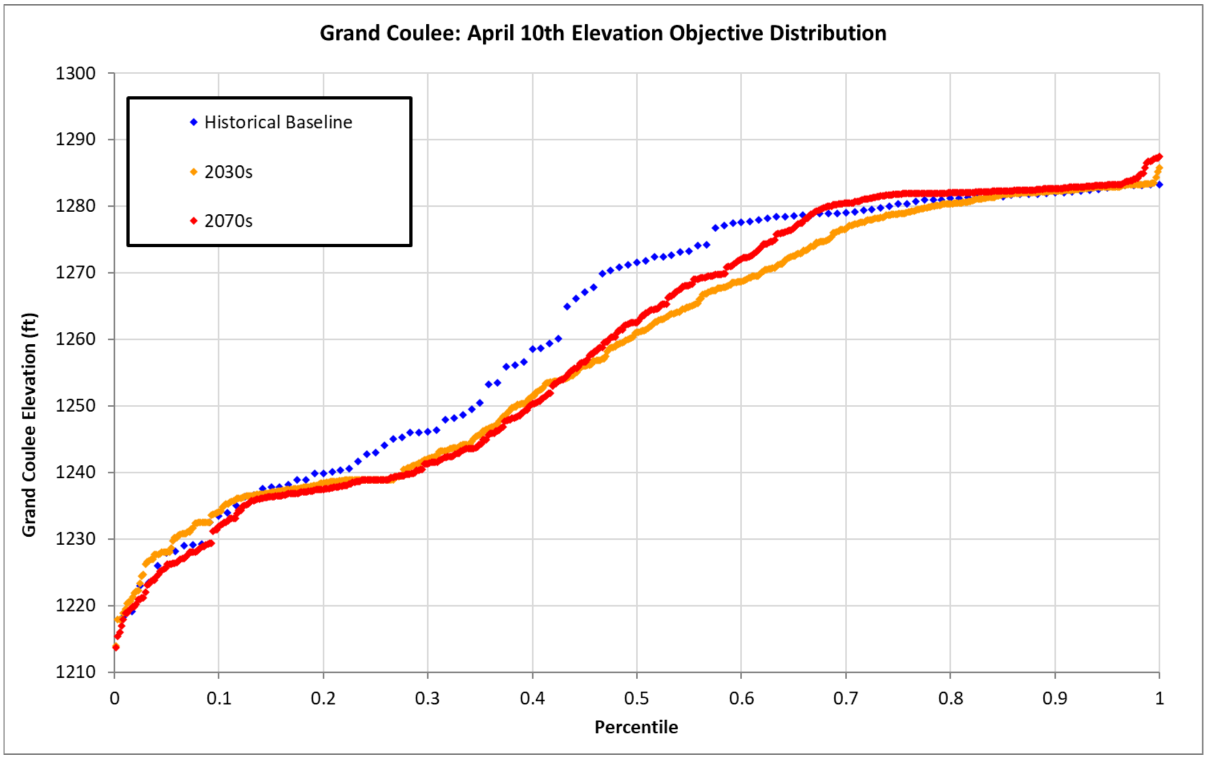

Figure 96. Distribution of Grand Coulee April 10 FRM elevation objective used in HYDSIM power modeling. The 2030s and 2070s results are based on the 19 RMJOC-II scenarios. Each data point represents individual water years in the historical baseline, 2030s, and 2070s. The historical baseline consists of 120 data points while the 2030s and 2070s each consist of 570 data points.

The decrease in the VDL elevations as shown in this section for the 2030s and 2070s as compared to the historical baseline increases the operating range of Grand Coulee for hydropower production. This increased operating range during the winter months provides more operational flexibility to manage the flows through the Lower Columbia projects to maximize generation on an hourly to daily timescale while meeting the operational objectives for other purposes.

9.6.3 Impact of Minimum Flows on Operational Flexibility

While power operations and flexibility on the U.S. system are limited much of the year due to FRM and fishery requirements, the late summer and early fall does provide some operational flexibility to maximize generation. The end of September elevation target at Grand Coulee is modeled as a range between 1,283 and 1,288 feet; and the end of October target is 1,288 feet. These modeling objectives are designed to preserve storage in Grand Coulee for fall and winter power reliability and for fall fishery operations at Vernita Bar below Priest Rapids and below Bonneville (see **Figure 10** in Chapter 3.0). The flexibility during this period is a balance between power operations, supporting fishery flows below Priest Rapids, and supporting minimum flows in the lower Columbia. For the Hydsim modeling, the minimum flow is 70 kcfs at Bonneville Dam.

Figure 97 compares to the historical baseline the September end-of-month elevations at Grand Coulee for the 2030s and 2070s. About 3 percent of the years fail to maintain 1,283 feet in the

2030s, which increases to about 16 percent of years failing to meet the 1,283-foot elevation objective in the 2070s.

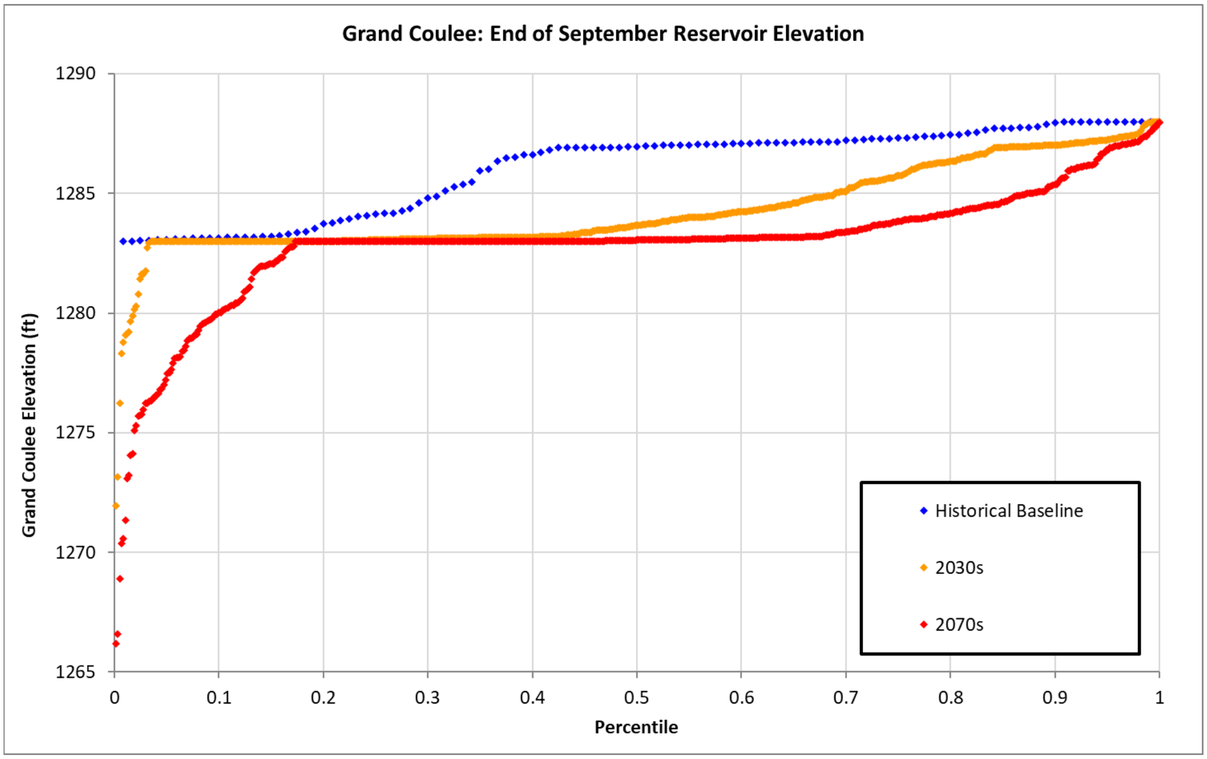

Figure 97. Distribution of end-of-September GCL elevations from HYDSIM power modeling. Distribution in the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling. Each data point represents individual water years in the historical baseline, 2030s, and 2070s. The historical baseline consists of 120 data points while the 2030s and 2070s each consist of 570 data points.

Figure 98 compares to the historical baseline the October end-of-month elevations at Grand Coulee for the 2030s and 2070s. By October, the project often recovers back to the target of 1,288 feet but for a small occurrence of drafting below 1,288 feet, by about 1 percent in the 2030s and about 5 percent in the 2070s, with a few years ending much deeper. Drafting below 1,288 feet would likely impact the operational flexibility to meet power objectives and to prepare for meeting fishery flow objectives below Bonneville in the fall and winter.

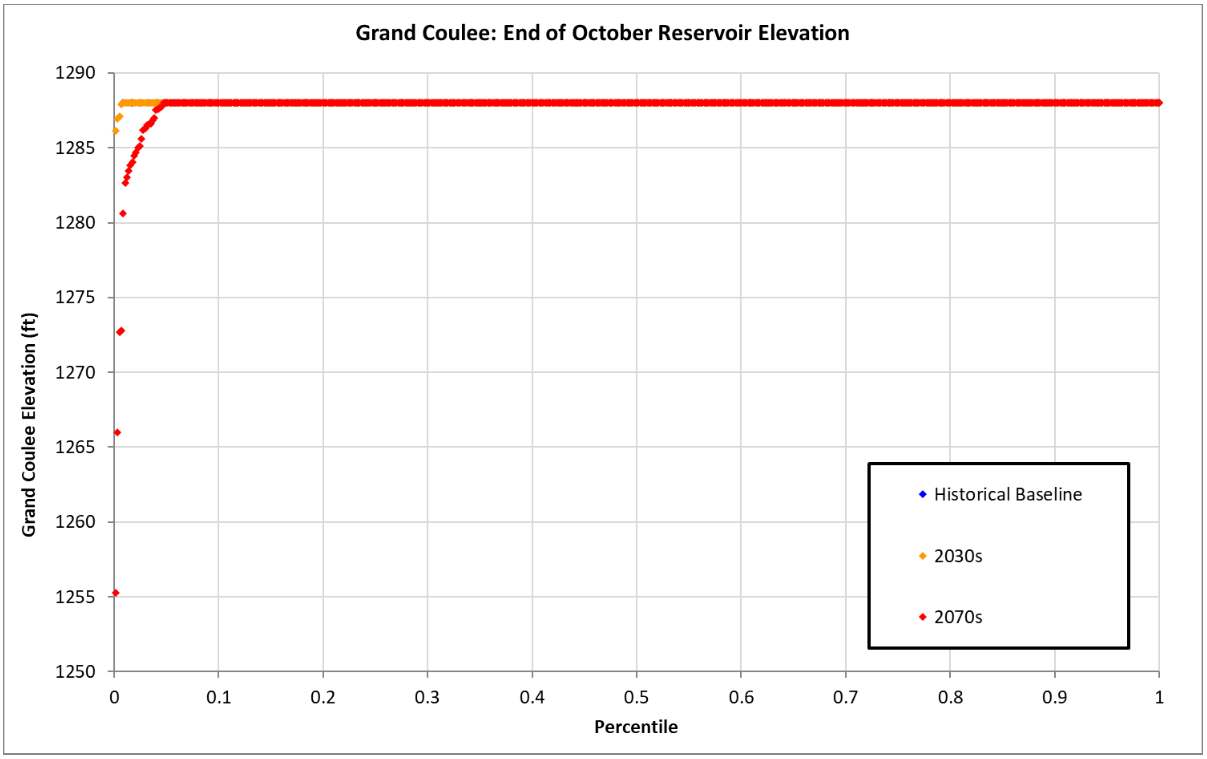

Figure 98. Distribution of end-of-October elevations from HYDSIM power modeling. Distribution in the 2030s and 2070s is based on the 19 RMJOC-II streamflow scenarios used for power modeling. Each data point represents individual water years in the historical baseline, 2030s, and 2070s. The historical baseline consists of 120 data points while the 2030s and 2070s each consist of 570 data points.

For both September and October, Grand Coulee is drafted below the elevation targets to maintain the minimum flow of 70 kcfs at Bonneville Dam in the lower Columbia in the HYDSIM modeling of the subset of 19 climate change projections. Section 10.4 further analyzes the impacts to maintaining minimum flows in the Lower Columbia, specifically for maintaining navigation flows in the ResSim modeling of the 160 projections.

9.7 Summary

The results of the HYDSIM operational modeling of the subset of 19 climate change scenarios and the four historical baselines show an increase in generation for the U.S. and federal system for the winter and spring months for both the 2030s and the 2070s. However, generation is projected to decrease in the summer and early fall. This is due to the general shift in hydrology that increases winter and spring runoff and lowers summer and fall flows.

Compared to the historical baseline, spill follows a similar pattern and is projected to increase in the winter and spring while decreasing in the summer for both the 2030s and 2070s. Fish passage spill increases for April and May but declines in the summer, June–August, for both the 2030s and 2070s.

The operational flexibility at Grand Coulee to manage the flows through the Lower Columbia projects to maximize generation also increases in the winter, January–March. This can be attributed to a combination of increased regulated inflows to Grand Coulee, deeper draft requirements for FRM, and the modeling trend to establish lower minimum fishery flows at Vernita Bar below Priest Rapids Dam. The operational flexibility at Grand Coulee decreases in late summer and fall for both the 2030s and 2070s as compared to the historical baseline. Grand Coulee drafts below the end-of-September modeling target to help sustain minimum flows in the lower Columbia River. This also occurs in October but to a lesser degree.

The following chapter discusses the results of both the ResSim modeling of the 160 climate change scenarios and the modeling of the subset of 19 HYDSIM scenarios for meeting the fishery flow objectives and performing required maintenance at Grand Coulee and the impacts to irrigation and navigation.

10.0 Hydroregulation Results for Ecosystem, Irrigation, and Navigation Objectives

The hydro projects in the Columbia River Basin are regulated to meet multiple objectives. In addition to FRM and hydropower, these objectives may include ecosystem, irrigation, navigation, recreation, water quality, and project maintenance and construction. The hydroregulation modeling process and operational rules used to meet these objectives have evolved over time as new operational measures have been introduced to improve the multiuse management of the Columbia River system. As stated in previous chapters, the operating procedures and rules have not been modified for the climate change projections. The climate change streamflows and water supply forecasts were used with the current operating criteria and procedures without adaptation.

The following sections describe the impact of climate change on some of the nonpower and non-FRM objectives. As these objectives are numerous, this chapter presents the objectives that have the largest impact on the overall system. See **Figures 1** and **9** in Chapters 1.0 and 2.0 for key project and site locations. It does not discuss many of the objectives that are specific to a single project. Both Hydsim and WAT-ResSim simulate operations targeting fish, ecosystem, water supply, and navigation operations. This chapter leverages the output of both models to discuss the projected effects of climate-affected hydrology.

10.1 Fish and Ecosystem objectives

The Columbia River system is operated to meet many fish objectives for both resident and anadromous fish. Section 3.2.1 details the basis for fish operations discussed in this section. Reservoir operations to meet these objectives normally consist of operating reservoir levels to provide water for resident fish or anadromous fish passage, minimum outflows for downstream fish habitat, and flows sufficient to meet lower river flow targets for fish passage (see **Figure 10** in Chapter 3.0). This section presents the effects of climate change on some of these fish objectives. Specifically, the following sections address the potential effects on providing flow augmentation from headwater reservoirs, meeting the flow objectives at Lower Granite and McNary for anadromous fish passage, and providing flows for spawning and rearing of Chinook salmon at Vernita Bar in the Mid-Columbia region and chum salmon below Bonneville Dam in the lower Columbia.

10.1.1 Flow Augmentation from Headwater Reservoirs

Stored water is released for flow augmentation following refill (June and July) through September. Lake Pend Oreille drafts in mid to late September from the summer operating range. Libby and Hungry Horse target being 10 to 20 feet from full at the end of September while providing stable flows to protect bull trout and other downstream resident fish. Dworshak Dam targets drafting 80 feet from full by the end of September unless modified per an agreement with the Nez Perce Tribe.

Based on the hydrologic projections, Inflow to Lake Koocanusa is projected to decrease during August and September. Minimum outflows to maintain flows downstream for Bull Trout result in projected decreases in reservoir elevation and storage for this period (see **Figures 36** and **30** in Section 7.3). The median of the 10th percentile elevation for 2070s RCP8.5 is approximately

10 feet deeper than the historical baselines. The projections for Hungry Horse (see **Figures 32** and **33** in Section 7.4) and Dworshak (see **Figures 41** and **42** in Section 7.7) reservoirs indicate a lesser effect. The modeled operations of the reservoir target the summer draft targets, which, in turn, result in projected decreases in reservoir outflow. The projections do not indicate decreased outflow from Albeni Falls in September (see **Figures 35** and **36** in Section 7.5) or any effects on meeting the September draft requirements.

Flow augmentation water is provided from multiple sources in the Upper Snake River above Brownlee: Reclamation's uncontracted storage space, powerhead reserve space, annual storage rentals, acquired natural flow rights, and leased natural flow rights. Reclamation's minimum target from the Upper Snake is 427,000 acre-feet (though there may not be enough water to meet that target in dry years) and can be as much as 487,000 acre-feet. Increased refill reliability on the Upper Snake due to increased runoff would lead to continued reliability of meeting Reclamation's flow augmentation commitments.

10.1.2 Lower Snake River—Spring and Summer Biological Guidelines

The Lower Snake River has both summer and spring flow objectives intended to benefit salmon and steelhead migration. These seasonal average flow objectives measured at Lower Granite Dam vary according to runoff volume forecasts and are as follows:

- 85 to 100 kcfs from April 3 to June 20
- 50 to 55 kcfs from June 21 to August 31

For the April 3 to June 20 flow objective planning period, the April final runoff volume forecast at Lower Granite Dam for April to July determines the spring flow objective at Lower Granite Dam. When the forecast is less than 16 Maf, the flow objective will be 85 kcfs. If the forecast is between 16 and 20 Maf, the flow objective will be linearly interpolated between 85 and 100 kcfs. If the forecast is greater than 20 Maf, the flow objective will be 100 kcfs. The flow objective is measured as the season average of the discharge at Lower Granite between the planning dates of April 3 to June 20. These flow objectives are biological guidelines and will likely not be met throughout the entire migration season in all years. This is because the flow in the Snake River depends primarily on the volume and shape of the natural runoff, while the augmentation volumes available are small in comparison to the overall objective. Flow in the Snake River during this period is supported by drafting Dworshak Dam and flow augmentation water from the Upper Snake River. Dworshak storage is released from the April 10 elevation to the April 30 flood risk elevation at a rate that does not exceed the Idaho's TDG water quality standards (110 percent TDG) at the project.

For the summer flow objective planning period, June 21 to August 31, the June final runoff volume forecast at Lower Granite Dam for April to July determines the summer flow objective at Lower Granite Dam. When the forecast is less than 16 Maf, the flow objective will be 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. The summer flow objective is measured as the season average of the discharge at Lower Granite between the planning dates of June 21 to August 31. The summer flow in the Snake

River is augmented by the release of stored water upstream of Lower Granite Dam. The Summer flow objectives are biological guidelines and will likely not be met throughout the entire migration season in all years. This is because there is a limited amount of stored water available for flow augmentation, and the natural shape of the runoff generally produces decreasing streamflows from July to the end of August.

During the spring flow objective period (April 3–June 20), WAT-ResSim modeling indicates regulated flow at Lower Granite is below the spring biological flow guideline about 40 percent of the time for the historical baselines (**Figure 99a**). Regulated flows during this period in the 2030s and 2070s are generally greater than the historical baseline, and the number of years that fall below the threshold decreases to about 30 percent.

During the summer flow objective period (June 21–August 31), the regulated flows drop below the biological guideline 40–60 percent of the time historically, depending on which historical baseline is considered (**Figure 99**b). Summer flows at lower quantiles (less than 30 percent nonexceedance probability) are projected to be similar to historical levels, whereas flows at higher quantiles (greater than 70 percent nonexceedance probability) are projected to be less than historical levels. For the 2030s, the majority of the ensembles project that flows will fall below the range of biological guideline minimums at the 60 percent nonexceedance probability. This occurrence is projected to increase to approximately 70–80 percent of the time by the end of the 2070s, depending on the emissions scenario (**Figure 99b**).

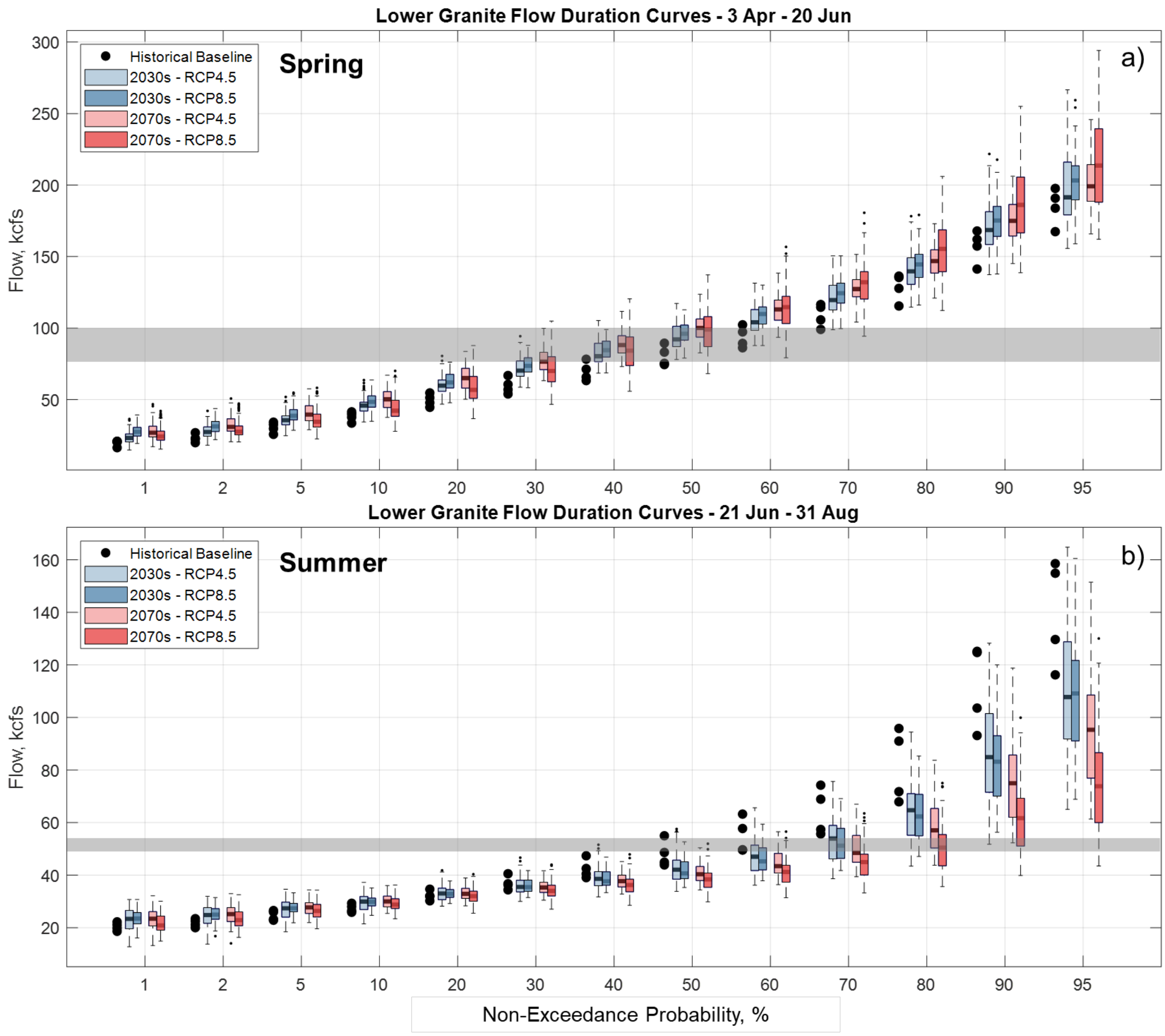

Figure 99. Modeled historical and future flow duration quantiles of flow of the Snake River at Lower Granite Dam for the (*a*) spring and (*b*) summer period. The areas shaded in gray indicate variable minimum flow specified by biological guidelines for water management.

10.1.3 Lower Columbia—Spring and Summer Biological Guidelines

For the lower Columbia River, the seasonal biological guidelines describing flow objectives at McNary Dam vary according to water volume forecasts and are as follows:

- 220 to 260 kcfs from April 10 to June 30
- 200 kcfs from July 1 to August 31

The flow objective at McNary Dam for the spring flow objective planning period, April 10 to June 30, depends on the runoff volume forecast at The Dalles Dam for April to August issued on the first of April. When the forecast is less than 80 Maf, the flow objective will be 220 kcfs. If the forecast is between 80 Maf and 92 Maf, the flow objective will be linearly interpolated between 220 kcfs and 260 kcfs. If the forecast is greater than 92 Maf the flow objective will be 260 kcfs. The spring flow objective is measured as the season average discharge at McNary Dam between the planning dates of April 10 to June 30. The flow objective is a biological guideline and will not be met throughout the migration season in all years due to variability in volume and shape of the natural runoff.

The summer flow objective at McNary Dam is 200 kcfs. It is measured as the season average of the discharge at McNary Dam between the planning dates of July 1 to August 31. The flow in the summer at McNary is augmented by the release of stored water upstream of McNary Dam. The summer flow objective cannot be met in all years as there is a limited amount of stored water available for flow augmentation, and the natural shape of the runoff generally produces decreasing streamflows from July to the end of August.

During the spring flow objective period (April 10–June 30), ResSim modeling indicates that regulated flow at McNary is below the spring biological flow guideline about 40 percent of the time for the historical baselines (**Figure 100a**). Regulated flows during this period in the 2030s and 2070s are generally greater than the historical baseline, and the number of years that fall below the threshold decreases to about 30 percent.

During the summer flow objective period (July 1–August 31), ResSim modeling indicates that regulated flow at McNary Dam will decrease (**Figure 100b**). Historical baseline flows are below the summer biological guideline about 60–70 percent of the time. This is projected to increase to about 80 percent of the time in the 2030s and to about 90–95 percent of the time for the 2070s.

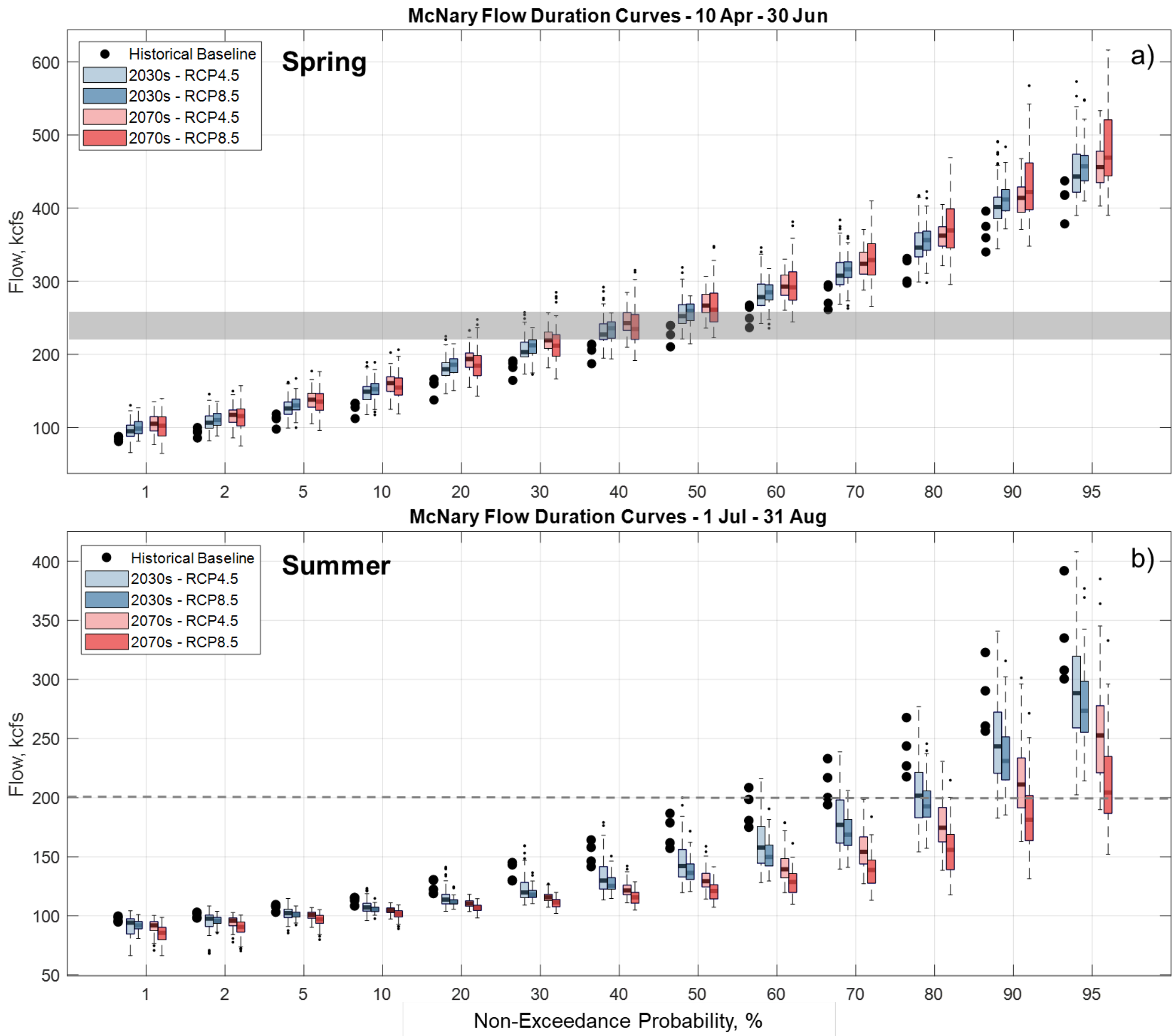

Figure 100. Modeled historical and future flow duration quantiles of the Columbia River at McNary Dam for (*a*) April 10–June 30 and (*b*) July 1–August 31.

10.1.4 Operations for Chum

The RMJOC-II hydroregulation modeling includes operations supporting chum spawning and incubation below Bonneville Dam. For modeling purposes, the chum-spawning period is November and December, and the incubation period is January–March. During the spawning period, Bonneville must have a minimum 11.5-foot tailwater level to provide adequate spawning habitat. Chum spawning is surveyed throughout the spawning period, and a minimum tailwater elevation is established for the incubation period based on the location of redds. During the spawning period, daytime tailwater elevations in excess of 13 feet increase the likelihood of chum spawning at higher tailwater elevations and therefore increase the chances that a protection level during the incubation period will be higher than 11.5 feet. A higher protection level can result in a higher probability that Grand Coulee will run out of storage to protect the redds, and the chum must be abandoned to preserve storage for spring fish needs. As a result, the ideal operation keeps the Bonneville tailwater elevation low enough to set an

11.5-foot protection level during the incubation period. The project is often reverse load factored with high powerhouse turbine flows at night to avoid high powerhouse flows during the daytime hours when fish are more likely to spawn.

Modeled operations cannot replicate the actual process used in the real-time chum operations. The flow required to maintain an 11.5-foot tailwater is highly variable and depends on Willamette River flow, local flows into the Portland Harbor and the Lower Columbia below Bonneville Dam, wind speed and direction, and tides. Furthermore, the analyses did not include the effects of sea level change in the lower river. This may affect actual operations. Real-time operation estimates the chum flow at an hourly resolution while 14-period modeling uses a simpler method that calculates the required chum flow on a month average basis as a function of the Willamette flow as measured at Salem. Both the real-time and operational modeling methods are empirical and based on observed data. The climate change modeling used the unregulated Willamette flows since regulated Willamette flows were unavailable.

For modeling purposes, the chum incubation is abandoned when reservoir levels at Grand Coulee decrease to a specific threshold. This threshold is set using the higher of either 10 feet below the VDL or the minimum VDL, which varies by month. The VDL operations described in Chapter 9.0 provide flexibility for hydropower operations at Grand Coulee. The minimum VDL for January is 1,260 feet; for February, 1,250 feet; and for March, 1,240 feet. Chum incubation is not abandoned if Grand Coulee drafts below these targets for FRM. In actual operation, the decision to abandon chum is much less straightforward. The Technical Management Team makes the decision, and regional fish managers can debate and discuss the option. Abandoning chum incubation flows can jeopardize chum while continuing to support chum may jeopardize fish during April–June.

Table 13 shows the percentage of years that set a chum protection level higher than 11.5 feet Bonneville tailwater. These results are based on the 19 HYDSIM projections used for power modeling. This table shows a large increase in the number of years that set a higher protection level by the 2070s. This is consistent with the trends observed in Chapter 7.0 that show an increase in future regulated flow during November and December.

Table 13. Percentages of WYs with a chum protection level greater than Bonneville tailwater of 11.5 feet.*

Period	Years with chum protection above 11.5 feet
Historical Baseline	25.8%
2030s	36.5%
2070s	55.1%

* The historical baseline is the four simulated historic streamflows using the Livneh et al. (2013) representation of gridded temperature and precipitation for 1976–2005.

Table 14 shows the percentage of years in which the chum operation is abandoned during the incubation period. These results, also based on the 19 HYDSIM RMJOC-II scenarios used for power modeling, show a decreased likelihood of abandoning chum in the 2030s and 2070s. The increase in winter inflow helps to meet the chum requirements even in the 2070s when more than half of the years set a chum protection level higher than 11.5 feet. This increase in winter flows may help ameliorate the current trade-off between chum protection and spring migration.

Table 14. Percentages of WYs that abandon chum during the incubation period.*

Period	Years that abandoned chum
Historical Baseline	18.3%
2030s	7.4%
2070s	0.9%

* The historical baseline is the four simulated historic streamflows using the Livneh et al. (2013) representation of gridded temperature and precipitation for 1976–2005.

10.1.5 Vernita Bar

Vernita Bar is a historically productive spawning site for fall Chinook salmon in the Mid-Columbia River region directly below Priest Rapids Dam (see Chapter 2.0 for basin description). The spawning site is uniquely impacted by the operation of Grand Coulee, Chief Joseph, and the five Mid-Columbia PUD dams. In 2004, the Mid-Columbia PUDs, BPA, NOAA, Washington Department of Fish and Wildlife, and Colville Tribes signed the Hanford Reach Fall Chinook Protection Program Agreement (HRFCPPA). The purpose of this agreement is to protect fall Chinook salmon in the Hanford Reach of the Columbia River by providing minimum flows to meet biological objectives. Project operations specified in the HRFCPPA cover the spawning, pre-hatch, post-hatch, emergence, and rearing periods. The RMJOC-II hydroregulation modeling of Vernita Bar is as follows:

- From June to November, the minimum flow at Priest Rapids is 36 kcfs.
- From December to May, the Vernita Bar minimum flow varies by water year between a minimum of 50 kcfs and a maximum of 70 kcfs. This minimum flow is empirically estimated by multiplying the higher of the month average October or November Wanapum outflow by 0.68 and rounding to the nearest 5 kcfs (the determination of minimum flow in actual operation is based on a redd survey).
- Grand Coulee will draft as necessary to support these minimum flows.

Figure 101 shows the distribution of Priest Rapids outflow using the results of the 14-period power modeling with the 19 HYDSIM subset projections. These results show the distributions for all of the water years modeled within the 19 projections subset.

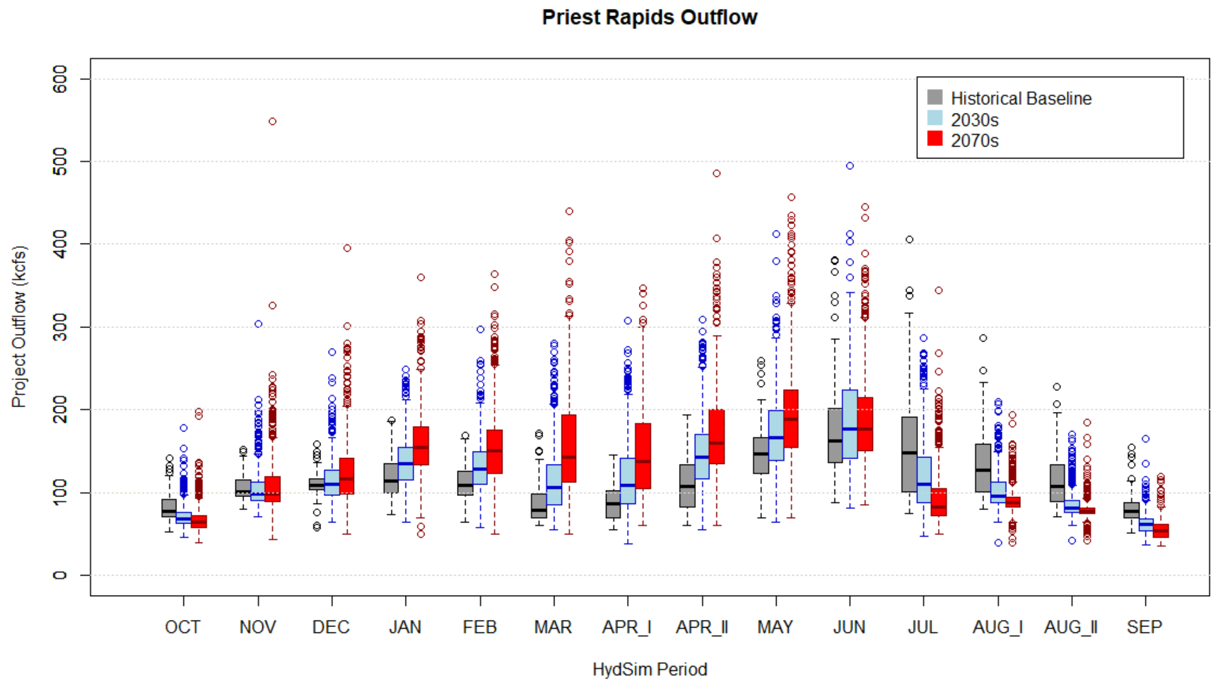

Figure 101. Priest Rapids period-average regulated outflow from HYDSIM power modeling. Distributions in the 2030s and 2070s are based on the 19 GCMs selected by RMJOC-II. The historical baseline is the median and distribution of the four simulated historic streamflows using the Livneh et al. (2013) representation of gridded temperature and precipitation for the 1976–2005 period.

During October, the flows show a slight decrease in the future relative to the historical baseline. For November, the flows appear relatively consistent between the future and the historic baseline. As a result, we would not expect much difference in Vernita Bar minimum flows given the calculation methodology outlined above. **Table 15** shows the distribution of Vernita Bar minimum flows. These data do not show any strong trends for the future.

Table 15. Percentage of occurrence of various Vernita Bar minimum flow objectives (kcfs) for the 2030s and 2070s compared to various historical datasets.*

	Vernita Bar Min Flow (kcfs)				
Period	**50**	**55**	**60**	**65**	**70**
Historical Baseline	0%	2%	11%	29%	58%
2030s	1%	8%	21%	24%	46%
2070s	3%	9%	19%	20%	49%

* The 2030 and 2070 results are based on the 19 RMJOC-II scenarios. The historical baseline is the four simulated historical streamflows using the Livneh et al. (2013) representation of gridded temperature and precipitation for 1976–2005.

Figure 101 shows that future outflow from Priest Rapids increases relative the historical baseline in December–May. In theory, this would make it easier to meet the minimum Vernita Bar flows. **Table 16** shows the percentage of WYs that are limited by the Vernita Bar minimum flow and verifies that the Vernita Bar minimum becomes less of an operational driver in the future as flows in the winter and early spring increase.

Table 16. Percentage of WYs in HYDSIM power modeling that are binding on Vernita Bar minimum flow in January–April.*

Period	Years that are limited by Vernita Bar minimum flow
Historical Baseline	42.5%
2030s	14.4%
2070s	5.6%

* The 2030 and 2070 results are based on the 19 RMJOC-II scenarios. The historical baseline is the four simulated historic streamflows using the Livneh et al. (2013) representation of gridded temperature and precipitation for 1976–2005.

10.2 Irrigation Deliveries

Changes in the hydroclimate could effect irrigation in both the tributary basins and on the main stem of the Columbia River. In the tributary basins, natural flow is limited; and there is often not enough to satisfy all users' needs, which is why many Reclamation storage projects are in the tributary basins. As runoff patterns and volumes change due to shifts in the hydroclimate, the timing and amount of natural flow available could change, which could increase the reliance on storage projects. This study did not fully analyze future irrigated agriculture cropping patterns as the focus was on the main stem of the Columbia River.

Irrigation was modeled differently in the tributary basins and the main stem of the Columbia. For the Deschutes, Upper Snake, and Yakima, irrigation demand was modeled at the 2010 Level Modified Flows level (defined in Chapters 4.0 and 5.0) and was satisfied based on available water supply from both natural flow and stored water. For the main stem, the Modified Flow-like process was used (see Chapters 4.0 and 5.0) to modify climate change streamflows to represent the current levels of irrigation. The only exception to this is pumping from Lake Roosevelt to Banks Lake for the Columbia Basin project, which was explicitly simulated in both ResSim and HYDSIM.

10.2.1 Tributary Water Deliveries

In the tributary basins, water is supplied using both natural flow and stored water. Natural flow is the natural or unregulated runoff in the system. Many of the projections indicate lower summer and late summer unregulated flows, particularly in the tributaries where water supply is already limited. **Figure 102** shows the shift in deliveries of natural flow and stored water for the Northside Canal on the Upper Snake River, a representative water user in the basin. Note that deliveries of live flow decrease for all projections sets and deliveries of stored water increase.

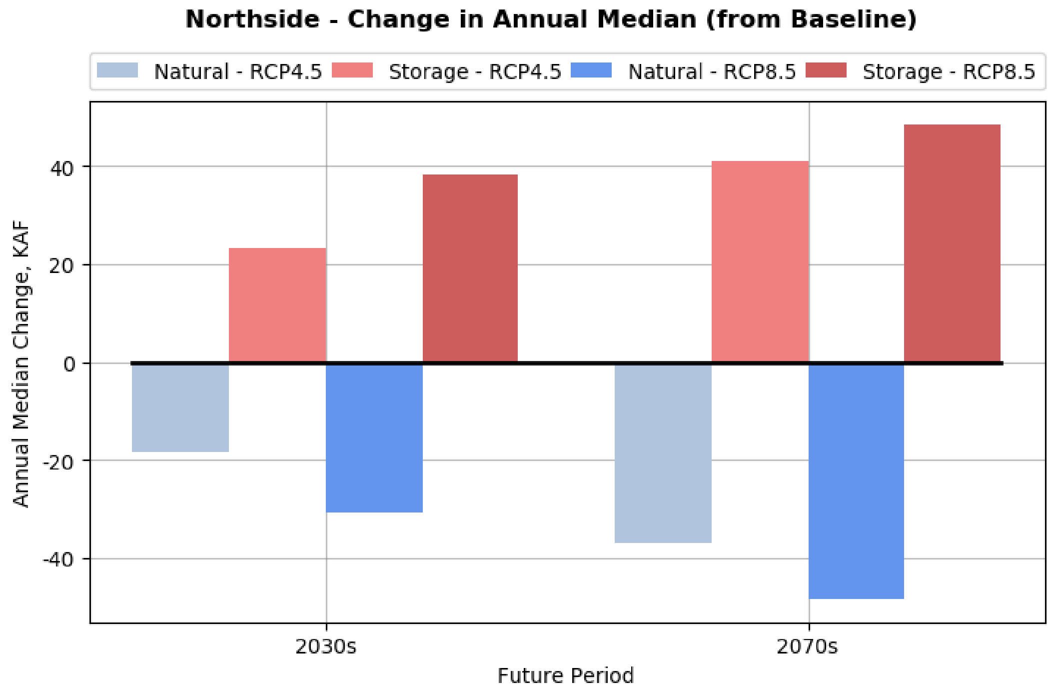

Figure 102. Projected change in annual median natural flow and storage flow delivered to Northside Canal as compared to baseline conditions.

10.2.1 Lake Roosevelt Pumping

The annual net pumping at Grand Coulee is 3.3 Maf. Pumping to the Columbia Basin Project occurs at the John Keys Pumping Plant, which consists of six pumps and six pump generators. The John Keys Pumping Plant pumping capacity is dependent on the pool elevation of Lake Roosevelt; the capacity decreases with lower pool elevation. The pump generators cannot pump water if the elevation in Lake Roosevelt is below 1,240 feet. However, the pumps can generally continue to pump below 1,240 with additional planning, allowing irrigation demand to be met. **Figure 103** shows the frequency at which the elevation of Lake Roosevelt is below 1,240 feet. In most cases, the projections indicate that this will occur as often or less frequently than in the historical baselines, which indicates that climate change will not likely impact pumping for the Columbia Basin project. Because of projected decreases in summer inflows, pumping will likely have a greater influence on in-stream flows during summer months.

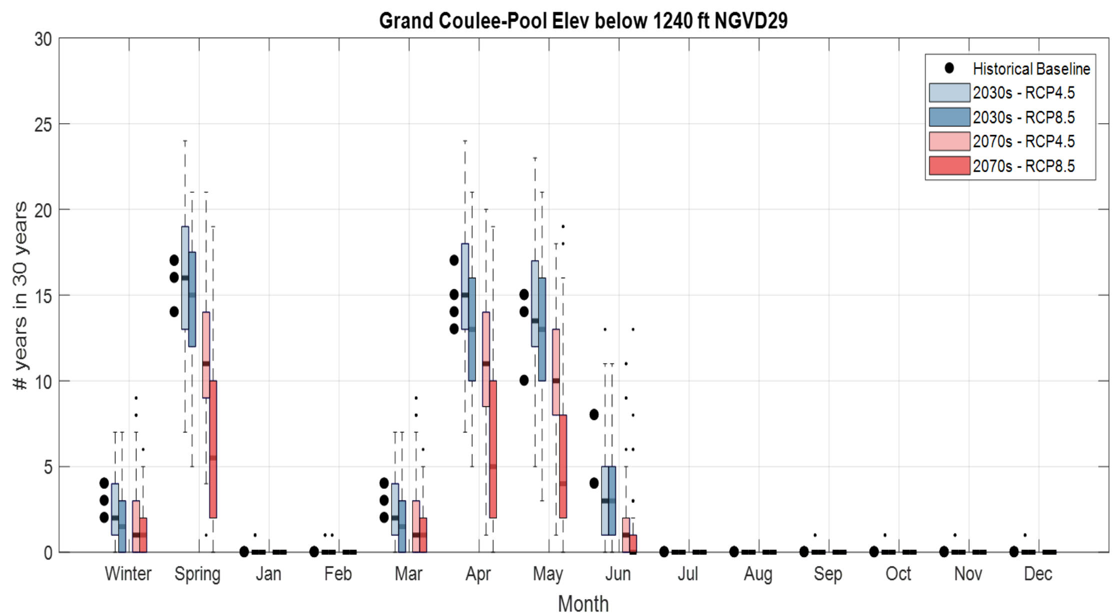

Figure 103. Modeled Grand Coulee-Pool historical and future number of WYs in a 30-year period where the pool falls below 1,240 feet per 30-year epoch.

10.2.2 Interruptible Water Rights

On the main stem, the majority of the water delivered is natural flow, and there has historically been sufficient supply. The State of Washington has designated a group of main stem water rights as "interruptible," and they are not allowed to divert if the system is in a water-short condition. A water-short condition is determined if the March official water supply forecast for April to September runoff at The Dalles falls below 60 Maf.

Figure 104 shows the frequency of The Dalles forecast below 60 Maf under projected future climate conditions. Overall, the number of years that this occurs is low, even in the most extreme set of models (RCP8.5, 2070s). Generally, the median is around zero to one year, which is similar to the historical baseline.

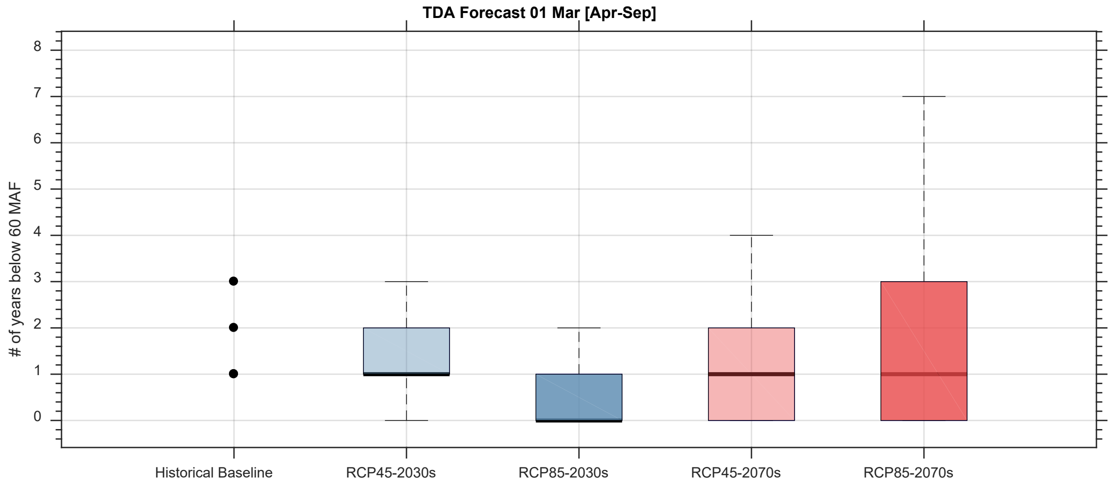

Figure 104. Modeled historical and future March 1 (April to September) forecasts for The Dalles and the number of water years out of each 30-year epoch, 2030s and 2070s, that are below 60 Maf.

10.3 Grand Coulee Drum Gate Maintenance

Drum gate maintenance at Grand Coulee typically occurs between March 15 and May 15. The drum gates are an important dam safety feature and must be maintained at a satisfactory level. To accomplish the maintenance, the reservoir must be at or below an elevation of 1,255 feet NGVD29 for eight weeks. To meet this elevation requirement, the reservoir typically needs to draft deeper than flood control guidance in February and March. To avoid exceeding draft rate limits, the end of February should have a maximum elevation of 1,267 feet in a drum gate year. FRM often drafts the reservoir deeper than the drum gate requirements in April. If FRM and VDLs are higher than 1,255 feet, the reservoir is given an operating range between 1,250 and 1,255 feet.

The decision to do drum gate maintenance is made in early February of every year and can be deferred in dry years. If the February water supply forecast predicts an April 30 FRM draft deeper than 1,255 feet, Reclamation elects to do drum gate maintenance. If drum gate maintenance was deferred in the previous year, the April 30 FRM threshold is raised to 1,265 feet. The goal is to achieve a minimum frequency of one time in a three-year period, two times in a five-year period, and three times in a seven-year period. Drum gate maintenance will be forced regardless of water supply forecasts if the frequency requirements are in danger of not being met. For example, if drum gate maintenance was deferred two years in a row due to low water supply forecasts, the third year will automatically be a drum gate year regardless of water supply.

The WAT-ResSim model abandons drum gate maintenance operation if the pool rises above the maximum pool required for maintenance. This occurs when the reservoir is needed to store inflow to reduce peak flood stage at Vancouver during winter flood events. If the elevation of Lake Roosevelt is not at or below 1,255 feet for a continuous period of eight weeks, the drum gate maintenance operation is abandoned; it does not meet the criteria for a successful operation. The subset of 19 HYDSIM projections did not include winter flood control; and therefore, the drum gate maintenance was not abandoned to control downstream flows during the winter and early spring as frequently. The RMJOC team determined that the ResSim modeling that included the climate change impacts of winter FRM operations provided a more reasonable projection of impacts to the drum gate maintenance operation.

Figure 105 compares the drum gate operations as modeled by ResSim. In the historical baseline, drum gate operations are attempted in 60 to 70 percent of the years modeled. In the 2030s, the operation will likely be attempted more frequently because storage of inflow to reduce the peaks of stage of the Lower Columbia River leads to more years where the operation is abandoned. However, through increased attempts of the operation, the amount of successful operations within the 30-year epoch is projected to be similar to historical conditions.

In the 2070s, winter flood events affecting the Lower Columbia River are projected to increase substantially (Section 9.4). Grand Coulee is projected to store inflow during winter events more frequently, leading to the operation being abandoned and fewer years where the operation was successfully completed during the 30-year period than occurred historically. For the 2070s, particularly under RCP8.5, increased winter flood events challenge the ability to maintain a similar frequency of maintenance than was modeled for the historical period. In the ResSim model, operations for winter flood events are given higher priority than drum gate operations regardless of flood severity; and as a result, the minimum drum gate frequency is not always met. Given the importance of drum gate maintenance for dam safety, other considerations may inform abandonment of the operations in future conditions where the hydrology challenges the frequency of maintenance.

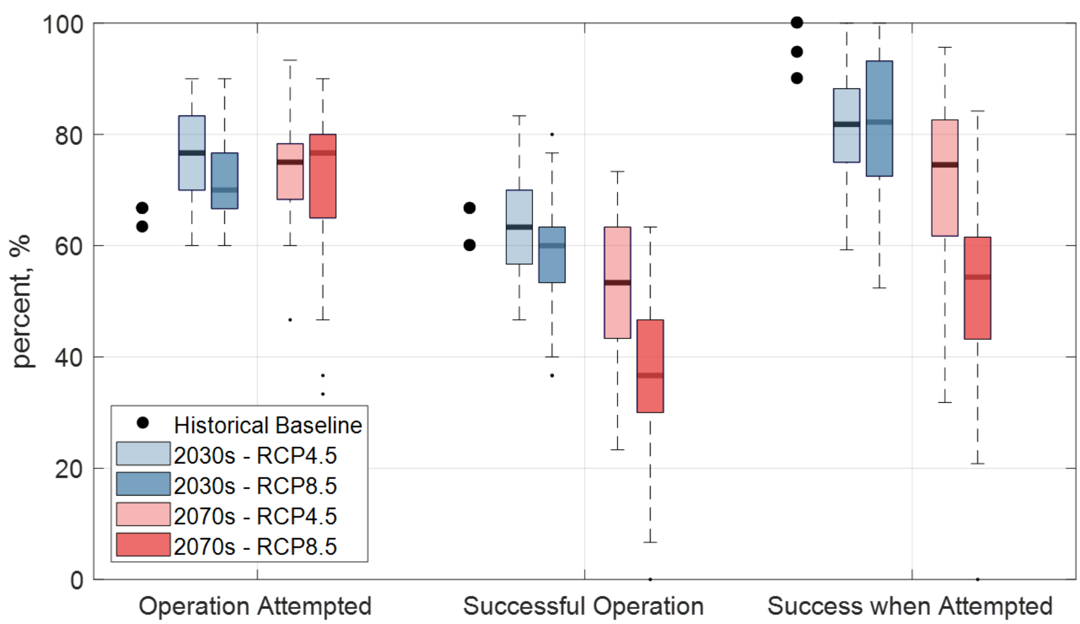

Figure 105. The percent of years within each 30-year epoch where the drum gate maintenance operation was attempted at Grand Coulee ("Operation Attempted"), the percent of years during a 30-year period where a successful operation was completed ("Successful Operation"), and the percent of attempts that were successful within a 30-year period ("Success when attempted").

10.4 Navigation

The following analyses summarize projected impacts to navigation in the Lower Columbia River, in the Lower Snake River, and for river ferry operations on Lake Roosevelt. The Columbia-Snake Navigation System is the federally authorized navigation channel and stretches 470 miles. It follows the navigable reaches of the Lower Snake River beginning near Lewiston, Idaho, and Clarkston, Washington, to its confluence with the Columbia River near Pasco, Washington, and then down another 330 miles on the Columbia River to its confluence with the Pacific Ocean near Astoria, Oregon. The Columbia-Snake Navigation System consists of three primary segments:

1. A 43-foot deep-draft segment between the Pacific Ocean and Portland, Oregon / Vancouver, Washington (RM106)
2. A 17-foot segment of the Columbia River between Portland/Vancouver and The Dalles, Oregon
3. A 14-foot shallow draft section of the Columbia River, which stretches from The Dalles, Oregon, to Pasco, Washington, to the Snake River RM140 at Lewiston, Idaho, and Clarkston, Washington (River ferry transportation includes a ferry that crosses Lake Roosevelt between Inchelium and Gifford, Washington.)

10.4.1 Lower Columbia and Snake Navigation

High or low flow can adversely impact navigation of the Columbia-Snake Navigation System channel. Extremely high or low river flows increase costs for commercial navigation activities when compared with normal flow conditions. Low- and high-flow conditions may require changes in tow configuration, loading, or the number of barge trips required. For example, during low-flow conditions, decreased channel depths may cause draft restrictions that affect operating costs by requiring light loading or other adjustments to account for limitations in channel depth.

In the Lower Snake River, flows less than 15 kcfs adversely affect navigation. Brownlee Dam outflows water during summer (July–September) to maintain a minimum flow of 13,000 cfs below the confluence of the Salmon River with the main stem of the Snake River (below Lime Point, approximately 80 miles upstream from Lower Granite Dam). The minimum flow at Brownlee decreases to 8,800 cfs in October. In the historical baselines, flow in the Lower Snake River, modeled at Lower Granite Dam, met or was below the threshold of 15 kcfs less than 2 percent of the time during the low-flow periods (**Figure 106**). The medians of the ensembles of future projections indicate that this low-flow condition could occur less frequently than historically.

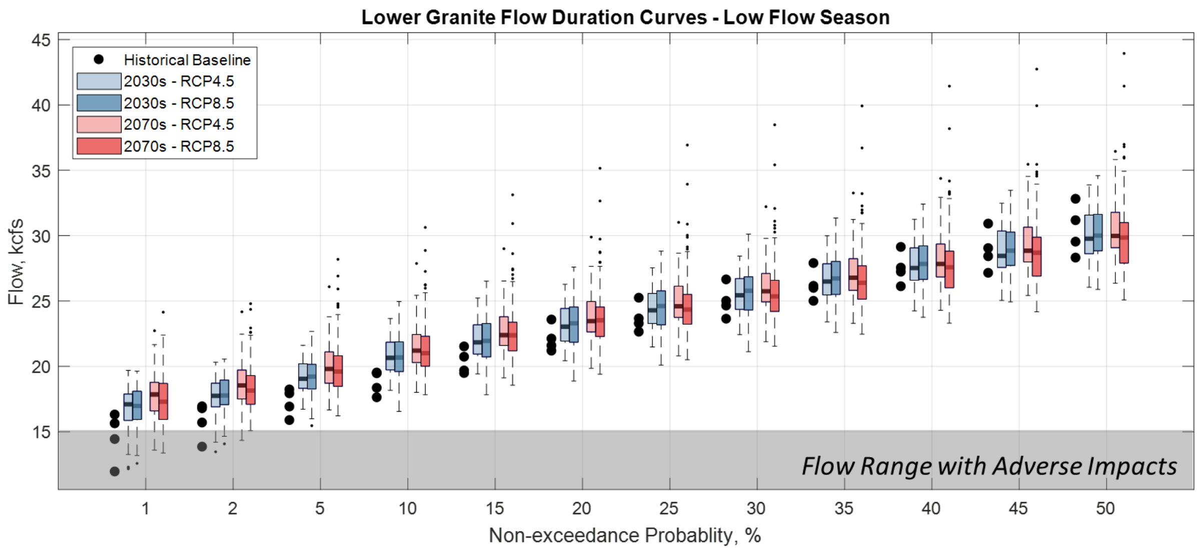

Figure 106. Modeled historical and future flow duration quantiles of outflow from Lower Granite Dam during the low-flow season (August–October). For clarity, only the lower 50 percent of flow quantiles are shown.

During the low-flow conditions, storage from Grand Coulee is released in the WAT-ResSim model to maintain a minimum flow out of Bonneville Dam of 70–100 kcfs. The targeted minimum flow is based on inflows to Lake Roosevelt. Outflows at Bonneville Dam below 80 kcfs adversely impact navigation in the lower river. Over the historical baseline period, flows met or dropped below this threshold approximately 5 percent of the time during the low-flow period of August–October (**Figure 107**). The median of the ensembles of projections indicate that this could increase to approximately 10 percent of the time in the 2030s. In the 2070s, the medians of projections indicate meeting this threshold approximately 15 percent of the time for RCP4.5 and 20–25 percent of the time under RCP8.5. The regulated system is projected to maintain a minimum of 70 kcfs during the low-flow season for all projections through the release of water stored at Grand Coulee.

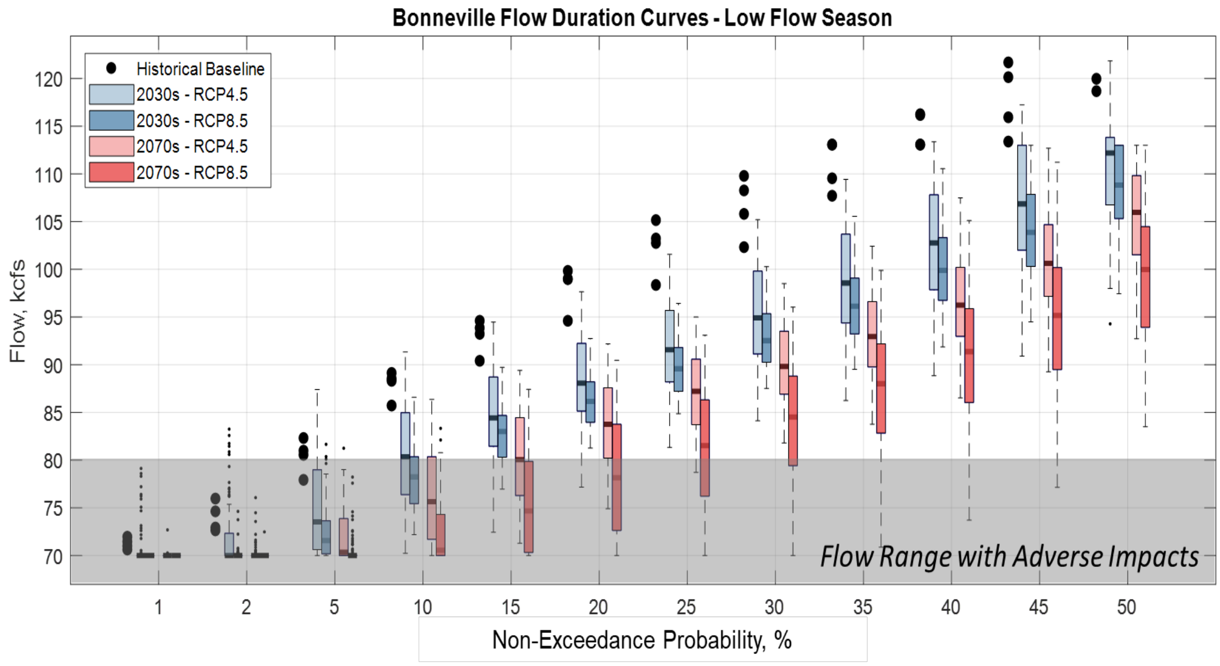

Figure 107. Modeled historical and future flow duration quantiles of outflow from Bonneville Dam during the low-flow season (August–October). For clarity, only the lower 50 percent of flow quantiles are shown. Navigation is adversely impacted when flows fall below 80 kcfs (*gray shading*).

10.4.2 Lake Roosevelt: Inchelium Ferry Operation

The Inchelium Ferry, operated by the Confederated Tribe of the Colville Reservation, provides vehicular and passenger ferry service across Lake Roosevelt between Inchelium and Gifford, Washington. The ferry is important to commuters, schoolchildren, emergency services, Tribe members, and tourists. When the ferry is inoperable, alternate routes include a 70-mile detour to the nearest bridge. Ferry service is most typically interrupted when the elevation of Lake Roosevelt falls below 1,229 NGVD29. This occurs during the spring of wet years (high runoff volume forecast) where flood risk requirements draft Lake Roosevelt deep in anticipation of high spring flow.

In the baseline historical runs, the number of years that Lake Roosevelt pool elevation was less than 1,229 feet was 6–12 years out of 30 years. For the 2030s, the interquartile ranges of the ensemble of projections indicate that the lake could be drafted below this elevation 8–13 years during the 30-year period (Error! Reference source not found.). The timing of when it is drafted below these elevation shifts, with decreasing occurrences in June and increased occurrences in April. Occurrences of the elevation of the pool falling below the ferry operational threshold are projected to be less than historical during the 2070s as inflow volume decreases and shifts to earlier in the year, reducing flood draft requirements. The largest reduction in occurrences is modeled under RCP8.5. The average number of days that the pool elevation fell below the ferry operational threshold was 7 to 16 days per year in the historical baseline (**Figure 108**). The duration that the lake could be drafted below this elevation was 5 to 13 days per year during the 2030s and 3 to 7 days per year during the 2070s under RCP4.5, and larger reduction in occurrences is projected under RCP8.5.

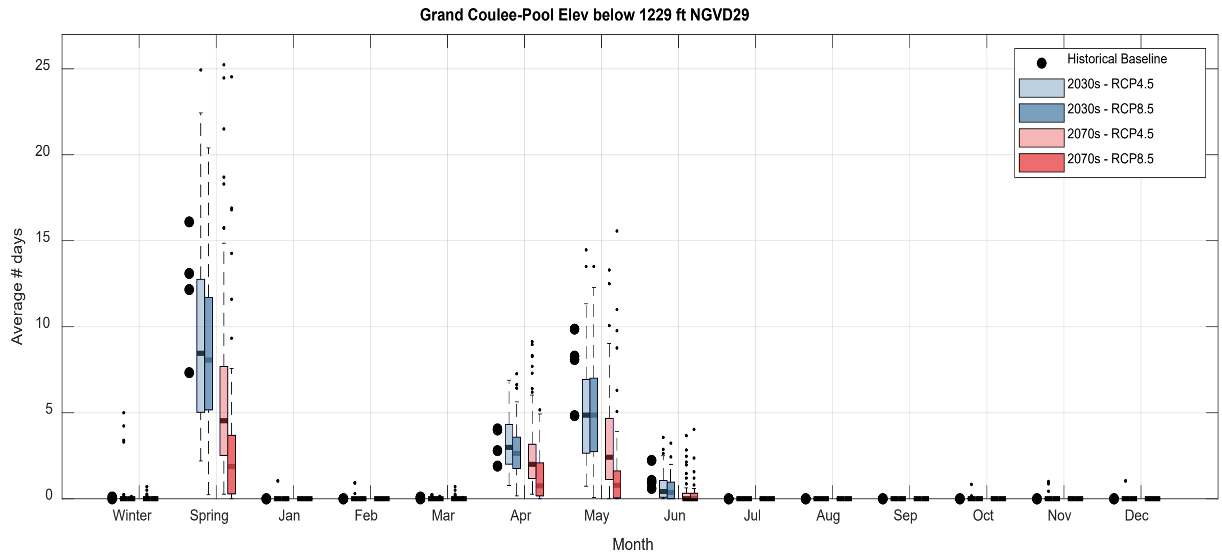

Figure 108. Average number of days in which the elevation of Lake Roosevelt was modeled to fall below the elevation of 1,229 feet, at which the Inchelium Ferry cannot operate.

10.5 Summary

Overall, meeting biological, maintenance, and navigation objectives will likely be more complex in the future. This is driven by changes in projected hydrology to increasingly wetter winters, above average and more variable springs, and drier summers. Flow augmentation operations and meeting minimum biological flow targets will most likely be more difficult in the summer low-flow period. Projected higher spring volumes will generally make it easier to meet future biological objectives overlapping those months.

Effects for future irrigation are less clear because we did not adjust underlying depletions and assumptions dynamically for climatic change in the RMJOC modeling. The most prominent diversion in the RMJOC modeling is the annual pumping at Grand Coulee and Lake Roosevelt. The future ensemble runs show that on average, Grand Coulee–Lake Roosevelt pumping was not materially impacted.

A projected increase in the frequency of winter flood events in the Lower Columbia River could interfere with completing drum gate maintenance at Grand Coulee at the same frequency at which it was completed historically. Water stored during these events interrupts maintenance.

Projected changes in summer low flows indicate potential negative effects on navigation in the Columbia River.

Modeling results showed an increase in frequency of flows below the threshold of 80 kcfs at Bonneville Dam, whereas flows were maintained above a more critical threshold of 70 kcfs through release of stored water at Grand Coulee. The frequency of the Lower Snake River flows falling below 15 kcfs (e.g., outflow from Lower Granite Dam) were generally comparable to historical baselines.

11.0 Discussion

This section focuses on connecting the work presented in preceding chapters with recommendations for future development, considerations for adaptive management and planning decision-making, and recommendations for usage of the RMJOC-II datasets. The discussions below reflect multidiscipline objectives and interests. They also reflect lessons learned from this effort and what may benefit resilient and flexible Columbia River reservoir system management under uncertain future conditions.

11.1 Recommended Future Work

The focus of the RMJOC modeling effort was to determine how climate change might affect the Columbia River system and the objectives it serves under current operating criteria. The results presented in this report are the culmination of a large multiagency modeling effort. Through the modeling and data analysis processes, the RMJOC team identified gaps in knowledge and areas of high uncertainty. Below, we use the results presented in the preceding chapters to recommend directions and themes for future development of modeling and data products. These recommendations cover three main topics: development of future hydrologic projections, reservoir modeling assumptions, and impact assessment.

11.1.1 Development of Hydrological Projections

The following sections describe possible work to develop new hydrological projections that could be used in future climate assessment analyses.

11.1.1.1 Process Based Downscaling

Chapter 8.0 describes potential increases in winter flood risk. Future development of meteorological projections could focus on more refined modeling of the mechanisms of the storms that drive winter flooding. A primary focus of winter flooding is short duration, intense precipitation events typically associated with atmospheric rivers. Future efforts should include downscaling techniques that provide better resolution of these physical processes. Dynamical or hybrid statistical-dynamical downscaling approaches are preferred because these methods provide an increased representation of physical processes over what can be achieved by statistical methods. These refined approaches for modeling atmospheric processes will aid in further detailed characterization of winter flood events affecting the reservoir system. However, this area of research is still very active, and improved downscaling methods may not be limited to only these two options. As discussed in RMJOC-II Part I, hybrid-dynamical downscaling was briefly explored early in this project; but the results were not included in the final 160 projections of streamflow.

11.1.1.2 Hydrologic Model Applications and Bias Correction

Hydrologic models are used to translate projections of future weather to projections of streamflow. Hydrological model performance can vary greatly based on the complexity of the hydrological system being simulated, the objective metrics used in calibration, and the quality of the observationally derived data used in the calibration routine. Given rapid advancements in technology, computational resources, and underlying datasets, there are ample opportunities for improvement in simulating hydrological processes. For example, the Columbia River Basin includes regions where surface and subsurface flow interactions play a pronounced role in streamflow patterns. Improved representation of groundwater processes and use of more recent analyses of irrigation withdrawals and returns will be beneficial for future work.

Increased computational efficiency is likely to improve parameter selection routines and quantification of parameter uncertainty. The overarching direction of these improvements is to reduce reliance on postprocessing through bias correction. UW statistically adjusted model streamflow data to remove systematic biases. Bias correction is a necessary step for using hydrological model data in reservoir modeling. Reservoir models include many operations that are triggered based on specific flow thresholds. Systematic biases in inflows can lead to different operational responses, thus bias correction reduces these systematic biases and limits the resulting artifacts in modeled reservoir operations.

RMJOC-II Part I evaluated several bias correction techniques. The BMORPH technique developed for this study provided more realistic hydrograph shapes but lead to some differences in low-flow conditions in specific areas (Snake River Basin) as compared to previous methods. In addition, bias correction assumes that hydrologic model biases are stationary. This may be a false assumption, depending on the physical process linked to the bias and how that process responds to climate change. Furthermore, UW applied bias correction on each streamflow time series independently. This can lead to mass conservation issues when calculating local inflow volumes between two stream locations. Given the importance of bias correction, and the potential for it to introduce other artifacts, future research should expand, evaluate, and improve these methods.

11.1.2 Reservoir Modeling

The reservoir modeling conducted for RMJOC-II highlights several areas where enhancements could improve these models for evaluating reservoir systems under future climate-affected hydrology. The following sections describe areas where future development efforts could improve reservoir modeling.

11.1.2.1 Reduce Dependence on Historical Data in Reservoir Models

Reservoir models are commonly developed and applied for planning purposes focused on historical or current conditions. Given the historical focus for initial development of these models, the model logic that represents operations often includes hardcoded hydrological parameters. For instance, some operations may use a historically based average seasonal volume or a date-based operational trigger derived from historical hydrology. This study updated some of these hydrological parameters to reflect future conditions (e.g., forecast error hedges and cross-validated standard error of water supply forecasts). However, others embedded deeper in the model logic were not updated. Further development efforts should include removing these hydrological parameters from the operational logic and including them as input variables. This would allow more flexibility in updating hydrological variables to reflect future hydrological conditions in the modeling.

11.1.2.2 Treaty Modeling

The operation of treaty projects for all streamflow scenarios in this study is based on rule curves developed as part of the 2022 Assured Operation Plan. Replicating the AOP process for each streamflow set would be very resource intensive and was beyond the scope of this study. Future work focusing on how treaty operation may respond to climate-driven changes in generation and load could improve expectations of flow at the U.S.-Canada border. This would also improve the understanding of how to ameliorate any impacts of climate change and provide insight into the adequacy of our critical-period planning.

11.1.2.3 Energy Demand (Load)

BPA conducted a preliminary look at the response of energy demand to climate change temperatures but it was not incorporated into HYDSIM power modeling. This would have required extensive work to incorporate scenarios of climate change load projections into new AOPs and TSR models and the associated operating criteria for each load projection. This was beyond the scope of this RMJOC modeling effort.

In the historical period, peak heating-demand season in the Pacific Northwest is from November through April, with peak cooling demand from June through August. Loads are projected to decrease in the 2030s in October–February (mostly due to warmer temperatures). However, the largest load changes, and largest spread between model projections, are in July and August, with increases projected for the 2030s and the 2070s. Not only is this driven by warmer temperatures themselves but also the longer duration of higher summer temperatures compounded by increasing air conditioning penetration.

While the effects of load changes were not incorporated in the HYDSIM hydropower generation modeling, they may affect the outcome of the modeling given the potential large seasonal changes. One critical question surrounding load changes is how much of the regional load will the hydrogeneration projects on the Columbia River be required to serve. This requires a more robust look at regional load changes and projections of future generation resources. Combined modeling of future climate and demand changes will be necessary to fully understand the range of conditions that could be problematic for the hydropower system.

11.1.2.4 Lack-of-Market Spill

The hydroelectric projects in this study are a part of the Western Interconnection Bulk Power System, which includes 14 western U.S. states, two Canadian provinces, and northern Baja Mexico. Generation from the Columbia River hydroelectric projects is often used to serve load outside of the Columbia Basin.

All generation must be used to serve load. If there is no need for additional generation and no interconnected utility is willing or able to purchase the generation to meet load, then turbine flows on the federal hydroelectric system must be reduced. If turbine flows cannot be reduced, then the flow must the spilled past unloaded turbines and is referred to as lack-of-market spill.

Lack-of-market spill on the federal hydrosystem typically occurs during times of high flow and low load and at projects that are unable to store the reduction of flow in the reservoir. This is most often experienced at run-of-river projects during the spring months but could occur anytime given the right conditions.

To estimate lack-of-market spill, This study used HYDSIM modeling results as input to another model known as AURORA. This model provides a regional balancing of loads and resources and can be used to estimate market price and to identify periods where the federal hydrosystem will experience lack-of-market spill. AURORA requires regional load and energy resource projections for the subset of 19 climate change scenarios across the Western Interconnection Bulk Power System and requires daily shaping of the 14-period HYDSIM flows. The development of this data was beyond the scope of the RMJOC effort as this would require temperature projections that extend well beyond the Columbia Basin and that were not available for this study. As a result, this model could not be used to provide insight into the lack-of-market spill exposure of the federal hydrosystem for the climate change streamflow sets.

The HYDSIM modeling of the subset of 19 climate change scenarios showed increased regulated flows in the winter and spring months, including increased potential generation and spill, for the 2030s and the 2070s. Additional modeling is needed to determine if this generation is marketable and does not result in lack-of-market spill. This analysis will require determining climate-related load, depth of market, and energy pricing for hourly to daily time steps and the use of additional modeling applications.

11.1.2.5 Improved Coordination between Regional Modeling Tools

Water management agencies and stakeholders in the Columbia River Basin use a range of modeling tools and approaches for resource assessment and decision-making. With respect to reservoir modeling, each of the RMJOC action agencies use a different reservoir model. The overarching water management objectives in each of these models are consistent; however, each model is tailored to the resources that are most relevant for the missions of each agency. This can lead to some model differences. For instance, ResSim includes a representation of system winter flood operations that are primarily short-term daily events and are not easily represented in the monthly Hydsim and MODSIM models. These differences are minimal historically but could increase as the hydrology of the basin changes. While a single model to meet everyone’s interests may not be possible, model development should continue to collaboratively promote consistency as hydrological conditions change. There are also potential benefits for linking these modeling tools to other applications in the basin. For instance, we did not link the regulated flow datasets to water quality or fish modeling. As regional tools and technologies advance, linking and integrating broader applications should be a priority.

11.1.2.6 Climate Change Assessment

The preceding chapters in this report provide a high-level overview of the potential effects of climate-affected hydrology on the regulated hydrology and water management objectives of the Columbia River reservoir system. RMJOC agencies will further analyze and identify operational vulnerabilities and attribute those to specific hydrological drivers. These detailed project-specific analyses will be the starting point for developing operational adaptive mechanisms.

As climate science and computing technology evolves, the amount of information available to inform future planning will continue to grow. This study advanced the use and integration of ensemble-based projections in application-based assessments of climate change for water resource systems. Additionally, we developed a method for selecting subsets of ensembles. These advances provide a leading example for impact assessment. However, further development of incorporating large ensembles of data into the more quantitative aspects of long-term planning and engineering design is warranted.

11.2 Adaptive Management Considerations

Adaptive management is a decision-making process tailored to planning for uncertain future conditions. The goal of adaptive management is to allow flexibility in responding to conditions as they are monitored through time. Current reservoir system operations may include a degree of flexibility (e.g., collaborative determination of operations based on current basin conditions) and some may lack flexibility (e.g., fixed seasonal flood control and refill reservoir guide curves, fixed monthly water supply forecasts). Developing operations and mechanisms that are flexible to future conditions is the cornerstone of adaptive management. Developing and evaluating these potential mechanisms was not in the scope of the RMJOC-II study. However, the data generated and lessons of the RMJOC-II hydroregulation studies are a precursor for this process. These discussions will aid in carrying forward RMJOC-II efforts to lead long-term planning and decision-making toward resilient and flexible management of the Columbia River reservoir system in the face of a changing hydroclimate.

The projections in this report describe a range of potential future conditions and vulnerabilities. The projections are not used to precisely forecast the future, but to understand what potential future conditions the system is most vulnerable to. These vulnerabilities can be analyzed to establish indicators to systematically monitor those conditions. Thresholds in monitored indicators can be established to guide implementation of adaptive management mechanisms. These indicators are likely to include, but are not limited to, trends in timing of the spring freshet, magnitudes of low flows, and intensity of winter flood events.

The following sections briefly discuss a few examples of adaptive management opportunities in the Columbia River Basin.

11.2.1 Water Supply Forecasting for Seasonal Reservoirs

The majority of storage reservoirs in the Columbia River Basin have seasonal operations that are based on spring runoff forecasts. The system currently has some existing flexibility to respond to changes in runoff volume and timing. However, this flexibility is limited; if the shape of the spring freshet and timing drastically deviate from the historical patterns, the operating assumptions based on historical hydrological conditions may no longer be appropriate.

The variability of the spring snowmelt runoff could increase with changes in basin states, higher temperatures, and potential increased precipitation. Currently, runoff volume forecasts are made at the beginning of the month to set end-of-the-month elevation targets. Grand Coulee and Brownlee are exceptions as these projects use ensemble streamflow prediction (ESP) for water supply forecasts that are updated daily. For the remaining projects, developing and adding capabilities for within-month forecast procedures and establishing reservoir operating targets would increase flexibility in responding to conditions that vary at sub-month timeframes. This could benefit system operations in current conditions by reducing lagged responses from end-of-month targets. More frequent forecast updates would also reduce requirements for justifying in-season deviations from reservoir draft targets.

Under transient conditions, the historical data that water supply forecasts are based on will require a high level of scrutiny. Currently, statistical forecasts use training data from approximately 30 years prior to the time of development. In contrast, ESP forecasts use historical meteorological forcing data. This method can be advantageous for determining reservoir storage requirements because the historical meteorological datasets include a wide range of variability. However, data earlier in the record may no longer represent current climate, particularly with respect to air temperature. As the climate changes, the ESP datasets and forecasts will also need more frequent updates.

A collaborative international workgroup, the Columbia River Treaty Hydrometeorological Committee, serves as a forum for the exchange of ideas to advance the science of water supply forecasting. The group also reviews and approves new forecast procedures developed for application in the basin. As water supply forecasting is challenged by loss of snowpack and as new modeling and observation technologies are developed, this committee could serve as a mechanism to advance adaptation strategies.

11.2.2 Flood Risk Management

One of the most pronounced projected hydrological changes is a shift in timing of the spring freshet, occurring earlier than historically. The current FRM draft and refill operations of storage reservoirs were developed based on a range of historical conditions. For most reservoirs, the runoff volume for April to August guides operations. The projections indicate that a significant proportion of the freshet volume will eventually run off before this period, and the runoff volumes later in the period (July–August) will be smaller and less relevant for guiding reservoir draft and refill. This disconnect between assumed timing in operations and earlier runoff could limit storage available for FRM and challenge refill objectives later in the season. Two potential operational strategies to adapt spring FRM operations to these changing conditions are apparent. First, the timing of the maximum draft could be shifted to earlier in the season. Second, the period used for runoff volume forecasting could be changed reflect the period that contains the snowmelt freshet. For instance, this could be shifted to March–April for future conditions.

Draft targets and refill operations that guide filling reservoir storage may also need to be reformulated to account for changes to hydrological response. Several hydrological changes may affect refill aside from timing and volume changes. First, with wetter and warmer winters, basin states (increased soil moisture and snowpack ripeness) could lead to a flashier runoff response than historically. These basin conditions may require deeper drafts and more rapid refill even if total seasonal volumes remain similar.

11.2.3 Flow Augmentation for Fish and Habitat Management

The drafting of storage reservoirs to augment downstream flows during the summer is largely based on fixed-elevation targets implemented to reflect typical augmentation patterns of current operations. In different climate conditions, the timing of these drafts would likely be altered to manage downstream conditions that reflect when the flow augmentation may be needed. Seasonal augmentation operations may need to be reformulated to be more beneficial based on climate-impacted hydrology and potential biological adaptation (e.g., earlier fish migrations). Adjustments to the forecast period and draft and refill timing for FRM purposes (Section 11.2.2) could also enhance spring flows.

11.3 Data Usage and Considerations

This report and accompanying datasets are available for use in long-term planning activities of regional stakeholders. The RMJOC-II products provide an important source of information for considering the effects of potential future hydrological conditions. The modeling analyses and conclusions documented in this report may be synthesized and applied to provide a foundation to support other applications and long-term planning decisions in the region.

The RMJOC-II project developed 160 different projections of unregulated and regulated streamflow in the Columbia River Basin. Development of hydrological datasets that project future conditions include many data and modeling assumptions that may introduce artifacts that contribute to inherent differences from historical observationally derived datasets. Thus, the RMJOC agencies recommend several considerations for working with the datasets described in RMJOC-II Parts 1 and 2:

- *Event-based analyses*: When using climate change projections, the focus should not be placed on individual events or individual projections. Utilizing ensemble-based analyses or analyses of a representative subset of an ensemble allows greater confidence in the assessed outcomes from future projections. This is achieved by describing the relative agreement among projections for the subject evaluation. Furthermore, the spread of projections is indicative of the amount of uncertainty in the future condition.
- *Spatial scale of analysis*: The RMJOC hydroregulation analyses utilized spatially and temporally downscaled input data. The methods applied to develop the hydrological projections started with coarse-scale processes (e.g., global climate models simulating global weather patterns) that were progressively processed to a finer resolution more relevant for impact assessments at the river-basin scale. The global climate model output was downscaled to a finer spatial resolution through the use of statistical downscaling. Hydrological models translated the finer-scale modeled weather patterns to streamflow time series. While the aggregate of these processes at the basin and major tributary scale is thought to be robust, some fidelity of physical processes may be lacking at small spatial scales. More refined modeling may be required to capture finer-scale localized processes (e.g., groundwater flow and microclimatology). Hydrological model calibration and statistical bias correction were applied to represent local conditions; however, some artifacts of the chain of modeling and adjustments may be evident in the data of small local drainage areas.

- *Historical comparisons*: Throughout this report, we provide comparative analyses against historical modeled base cases. We should reiterate the rationale behind this. Comparing future projections to modeled historical conditions reduces the influence of modeling biases on the interpreted climate change signal in the period-based comparisons. For this reason, we do not recommend comparing the future projections developed as part of this study to historically observed data.

Further resources and recommendations for incorporating climate change information are available:

- Vano, Julie A., Jeffrey R. Arnold, Bart Nijssen, Martyn P. Clark, Andrew W. Wood, Ethan D. Gutmann, Nans Addor, Joseph Hamman, and Flavio Lehner. 2018. "DOs and DON'Ts for using climate change information for water resource planning and management: guidelines for study design." *Climate Services* 12: 1–13.
- U.S. Army Corps of Engineers. 2018. *Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects*. USACE Engineering and Construction Bulletin 2018-14. Washington, DC: U.S. Army Corps of Engineers. https://www.wbdg.org/ffc/dod/engineering-and-construction-bulletins-ecb/usace-ecb-2018-14.

11.4 Summary

This section focused on connecting the work presented in preceding chapters with directions for future adaptive management planning and decision-making. The recommendations outline how the RMJOC-II work could be used as a foundation and springboard for future work.

12.0 Summary and Significant Findings

In 2013, RMJOC commissioned a research team from the UW and OSU to develop a set of natural streamflow datasets derived from the latest CMIP5 GCM projections. In 2018, the description of the process and approach for the development of these climate change datasets, as well as the resulting products, were documented in RMJOC-II Part I: *Hydroclimate Projections and Analyses*. Part I concluded that temperatures have warmed about 1.5°F since the 1970s and are expected to warm another 1°F to 4°F through the 2030s. They are then projected to warm 3°F to 6°F and 4°F to 10°F for the RCP4.5 and RCP8.5 emissions scenarios, respectively. Precipitation is projected to increase in the winter and decrease in the summer. By the 2030s, higher average fall and winter flows, earlier peak spring runoff, and longer periods of low summer flows are very likely. These patterns are projected to continue through the 2070s, with further amplification associated with the higher RCP8.5 emissions scenario. RMJOC-II Part I work produced 160 scenarios of temperatures, precipitation, and natural streamflows representing both the RCP4.5 and RCP8.5 emission projections, along with four historical baselines. A representative subset of 19 RCP8.5 scenarios was selected for hydropower modeling.

Given this information, the next step in the RMJOC-II study was to use the 160-scenario dataset of temperature, precipitation, and natural streamflow projections with a variety of reservoir operation models to evaluate the resilience and vulnerabilities of the Columbia River system. The models were applied with no modifications to procedures and modeling process and reflect the current operational state of the Columbia River system. Therefore, no adaptive management was performed to modify operational criteria, rule curves, or operating procedures to improve or ameliorate the operational issues found from the climate change modeling.

The technical steps included creating monthly water supply forecasts, modifying the natural streamflows to reflect the current level of irrigation, and simulating the reservoir operations throughout the Columbia River. A variety of models was used for reservoir modeling of the full set of 160 climate change scenarios. Reclamation modeled the Upper Snake and Deschutes Rivers with its monthly MODSIM model and used their daily RiverWare model for the Yakima River. USACE modeled the Columbia River system using its daily ResSim model, and BPA modeled the subset of 19 projections with its 14-period HYDSIM model. Each of these models are designed for specific purposes of irrigation, FRM, hydropower, and fish objectives.

This study evaluated two future epochs and a historical baseline period. These epochs represent 30-year periods, centered on the reference decade. Therefore, the 2030s period was defined as October 1, 2019, through September 30, 2049. Similarly, the 2070s is defined for WYs 2060 through 2089. The baseline 30-year period represents historical conditions for WYs 1976 through 2005. The RMJOC agencies assessed potential changes in future conditions through comparative analyses between simulated pool elevations and regulated river flows and stages of future projections and historical baselines (Chapter 4.0). The RMJOC-II reservoir modeling datasets are a suite of modeled data, presented at monthly time steps.

Overall, the RMJOC-II modeling and datasets identify potential consequences of climate change on meeting objectives of the Columbia River reservoir system under current operating criteria.

These analyses set the foundation for future work in identifying operational mechanisms and approaches to adaptively manage system operations to ameliorate potential negative consequences of climate change. A summary of this report's significant findings is outlined below.

12.1 Flood Risk Management Conclusions

- The spring snowmelt runoff is projected to peak at The Dalles earlier for the 2030s and about a month earlier for the 2070s (RMJOC-II Part I). Winter precipitation is projected to increase and, due to warming temperatures, to result in increased rainfall runoff instead of contributing to the snowpack. The future projections indicate a potential overall increase in flood risk in the Columbia River Basin for both spring (April–August) and winter (November–March) under current operating criteria.
- Regulated spring high-flow events for the Columbia River as measured at The Dalles, Oregon, and in the Lower Columbia River are projected to be similar in the 2030s and to increase modestly in the 2070s (Section 8.1). Modeling outcomes of spring runoff also show increased flood risk at other locations in the Columbia Basin. Bonners Ferry on the Kootenai River below Libby Dam, Columbia Falls on the Flathead River below Hungry Horse Dam, and Spalding on the Clearwater River below Dworshak show increasing flood risk in the 2030s and 2070s.
- The greatest projected adverse change in future flood risk is higher winter flow volumes affecting the Lower Columbia River. For the 2030s and 2070s, the risk of flooding increases (refer to Section 8.5). Projected increases in winter flood risk is primarily linked to increasing regulated flows from the Columbia main stem. Projected increases in inflow from the Willamette River during winter events further exacerbates this increase in flooding due to the backwater effect exhibited above its confluence with the Columbia River.
- Increasing flood risk can be partially attributed to hydrological changes that differ from the historical hydrological characteristics for which the system was designed. That is, the current system operations for FRM are not designed for the projected future hydroclimate of the basin.

12.2 Hydropower Conclusions

- Projected increases in regulated streamflow during the winter and early spring increases the potential for hydropower generation for both the federal and U.S. systems. Modeling results from the subset of 19 climate change projections show that between November and May, the monthly generation could substantially increase in both the 2030s and 2070s.
- Projected decreases in regulated streamflow from June to October result in less future generation in both the federal and U.S. systems as compared to the historic baselines. During these months, modeling results from the subset of 19 climate change projections show that generation could decrease significantly in both the 2030s and the 2070s.
- The annual average generation for both the federal and U.S. systems are projected to increase in the 2030s and 2070s as compared to the historical baselines. Depending on the

probabilities compared, the federal system is projected to increase by as much as 500 MW for the 2030s and 850 MW for the 2070s. Although not fully modeled, the U.S. system shows a potential maximum increase of about 750 MW for the 2030s and 1100 MW for the 2070s. Future studies will need to be conducted to determine if future load demand, market conditions, and adaptive reservoir management practices will allow for these generation benefits to be realized and to ameliorate the projected critical decrease in generation in the summer and fall.

- Spill in the federal system increases substantially during the winter months, January–March, for both the 2030s and 2070s in the subset of 19 climate change projections. This increase continues into the spring months of April and May before tapering off in June for both epochs. The spill outlook changes in the summer, July–August, as the spill drops slightly for each month due to lower regulated flows in the summer throughout most of the basin. The annual combined spill values show that much of the seasonal shift in spill is balanced out with a general overall yearly increase.
- Projected increases in regulated streamflow during the winter and early spring in the subset of 19 climate change projections improves the operational flexibility for hydropower operations at Grand Coulee for both the 2030s and 2070s. The increased flexibility comes from a combination of increased regulated inflows to Grand Coulee and a modeling trend showing less constrained fishery flow operations at Vernita Bar below Priest Rapids Dam and below Bonneville Dam for chum protection. The increased regulated streamflows result in lower VDLs and a greater likelihood that Grand Coulee could be drafted earlier in the winter while still meeting the April 10 elevation requirement for fish habitat purposes.
- The operational flexibility at Grand Coulee decreases in late summer and fall for both the 2030s and 2070s as compared with the historical baseline. By the 2070s, hydropower modeling of the subset of 19 projections suggests that Grand Coulee could draft below the end of September modeling target to help sustain minimum flows in the lower Columbia River in about 17 percent of the years. This limits the ability to use storage in the reservoir to manage regional power needs. This situation never occurs in the historic baseline and only occurs 3 percent of the time during the 2030s. This also occurs in October but to a much lesser degree.

12.3 Biological, Navigation, and Other Nonpower Use Conclusions

- Flow augmentation operations and meeting biological (minimum) flow targets will likely be more difficult in the summertime (low-flow period).
- The projections indicate more frequent reduced late summer flows, which could increase reliance on stored water, particularly in the tributary basins. The projections also indicate that water delivery to the Columbia Basin project via pumps from Lake Roosevelt to Banks Lake could become more reliable due to higher elevations in Lake Roosevelt.
- Fish passage spill at the federal projects in the Lower Snake and Lower Columbia increases during the spring months, April and May, for both the 2030s and 2070s in the subset of 19 HYDSIM climate change projections. The spill outlook changes, however, in the summer,

June–August, as the spill drops for each month for both the 2030s and 2070s. This is due to lower regulated flows in the summer throughout most of the basin.

- The maintenance of drum gates at Grand Coulee requires low-pool elevations for extended periods in winter. The projections indicate that this operation could be challenged by an increase in system-wide winter events where inflows are stored in Lake Roosevelt to lessen flood peaks in the Lower Columbia River. In the 2070s, the frequency of successful future maintenance operations is less than the current required frequency.
- When Bonneville Dam outflow falls below 80 kcfs, navigation is adversely affected. The projections indicate an increased likelihood of flows below this threshold during August–October. Water stored in Lake Roosevelt is project to be released more frequently to maintain minimum outflows at Bonneville Dam, impacting fall storage for resident fish, power operations, and operations to support chum.
- Increased streamflow in November–April increases the ability to provide the minimum flow requirements for chum spawning below Bonneville Dam.
- Increased streamflow in November–April also lowers the likelihood that the April 10 elevation target will be missed in order to draft Grand Coulee to support minimum flows at Vernita Bar.

12.4 Closing Statement

Continued warming will alter the hydrology of the Columbia River Basin and affect the management of its water resource infrastructure. Meeting flood, power, biological, and other key objectives will become more complex and challenging in the future. As the hydrological regime changes, current modeling processes and reservoir operating criteria will need to be re-formulated to better serve the purposes of the system. This study highlights the need for regional stakeholders to understand system vulnerabilities and strongly endorses adopting an adaptive management approach as the best framework for addressing future uncertainty in meeting water management objectives.

The datasets and tools described in RMJOC-II Parts One and Two provide foundational elements for developing long-term adaptive management strategies. Some adaptive measures to enhance resilience of the system may be straightforward, while others will require more complex and holistic solutions. For example changing draft and refill patterns to better reflect spring snow melt timing may be a straightforward adaptation strategy. Measures to mitigate the effects of potential increases in winter extremes, increased summer power demand and decreased flow, or buffering low flow conditions may be more challenging. Multifaceted solutions to these emerging challenges may span many sectors of resource management and planning.

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Climate and Hydrology Datasets for RMJOC Long-Term Planning Studies: Second Edition (RMJOC-II)

Part II: Columbia River Reservoir Regulation and Operations—Modeling and Analyses

APPENDIX A
COLUMBIA RIVER SYSTEM HEC-WAT AND HEC-RESSIM MODELING DOCUMENTATION

PREFACE

This technical appendix documents the Columbia River System hydroregulation modeling approach, executed using Watershed Analysis Tool (HEC-WAT) and Reservoir System Simulation (HEC-ResSim) software from the U.S. Army Corps of Engineers Hydrologic Engineering Center. The combined use of these software is referred to as WAT-ResSim. This technical appendix documents key modeling input, assumptions, and operations implemented specifically for the RMJOC-II study. Furthermore, it provides additional details for key elements relevant to reservoir modeling with climate-impacted hydrology. For full documentation of the Columbia River System HEC-WAT and HEC-ResSim Model, refer to the corresponding technical appendix for Columbia River System Operations Environmental Impact Statement (crso.info).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

ANN	artificial neural network
ANN-TSR	simplified treaty storage regulation modeling using ANNs
AOP	Assured Operating Plan
AR	atmospheric river
BPA	Bonneville Power Administration
cfs	cubic feet per second
CRD	Columbia River Datum
DOP	Detailed Operating Plan
FRM	flood risk management
HEC	Hydrologic Engineering Center
HEC-ResSim	HEC Reservoir System Simulation
HEC-WAT	HEC Watershed Analysis Tool
kaf	thousand acre-feet
kcfs	thousand cubic feet per second
NGVD29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRNI	No Regulation No Irrigation
NSE	Nash Sutcliffe Efficiency
NTDE	National Tidal Datum Epoch
PRMS	Precipitation Runoff Modeling System
Reclamation	Bureau of Reclamation
RMJOC-II	Second River Management Joint Operating Committee Climate Change Study
RSLC	relative sea level change
SKQ	Seli’š Ksanka Qlispe’
TSR	Treaty Storage Regulation
USACE	U.S. Army Corps of Engineers
UW	University of Washington

A.1 INTRODUCTION

This technical appendix documents the Columbia River System hydroregulation modeling approach, executed using Watershed Analysis Tool (HEC-WAT) and Reservoir System Simulation (HEC-ResSim) software from the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC). This technical appendix documents the second River Management Joint Operating Committee climate change study (RMJOC-II). The U.S. Army Corps of Engineers (USACE), the Bureau of Reclamation (Reclamation), and Bonneville Power Administration (BPA) prepared the second report of the RMJOC-II study to present the results of reservoir modeling and evaluations of the resilience and preparedness of the Columbia River system in response to projections of future climate-impacted hydrology.

A.2 PURPOSE OF TECHNICAL APPENDIX

This appendix describes the hydroregulation modeling approach used to characterize physical water conditions (river flows, reservoir releases, and elevations) in the Columbia River System and to inform subsequent modeling and impact analyses that depend on physical water conditions. USACE employed an automated, rules-based modeling approach to reflect operations at multiple projects in the Columbia River Basin.

A.3 WAT-RESIM OPERATIONS ALTERNATIVE

The Columbia River and many of its tributaries are managed for multiple purposes, including hydropower, flood risk management (FRM), ecosystem function, irrigation, recreation, water supply, and navigation. In practice, modelers perform various types of hydroregulation modeling in support of short-term and long-term decision-making. Short-term model applications often involve user-specified “hand regulation” to override general rules, which is appropriate when a high amount of real-time information is available to the modeler. In contrast, long-term planning studies benefit from a rules-based hydroregulation modeling approach, as described in this appendix. The rules-based approach consistently applies operational rules that govern over a wide range of hydrologic conditions. Many years of observed and synthetic data are run through the model to determine the range of expected results from a particular alternative.

In this chapter, we provide a high-level overview of the alternative used for the RMJOC-II WAT-ResSim modeling. This reservoir operations alternative is referred to as the No Action Alternative. It was developed for the reservoir modeling of the Columbia River Systems Operation Environmental Impact Statement. Complete details of the model operations and assumptions can be found in the Columbia River System Operations Environmental Impact Statement documentation. We did not model the preferred alternative from the Columbia River System Operations Draft Environmental Impact Statement because it was developed after this work had started. However, the conclusions from this climate change assessment would be unlikely to change if the preferred alternative was modeled.

We provide a detailed description of the representation of winter FRM operations in the alternative. These modeled winter operations have an increasing influence on the model simulations when the hydrological projections include increased winter flood activity. Details of the winter FRM operation were inspired and loosely based on the flood regulation operations implemented during the flood event in February 1996. These operations are not formally documented in water control manuals (aside from John Day Dam), and there is uncertainty around winter FRM reservoir operations.

A.3.1 No Action Alternative

The No Action Alternative describes the operation, maintenance, and configuration of the Columbia River System, from September 30, 2016, the date the Notice of Intent to complete the Columbia River System Operations Environmental Impact Statement was published in the Federal Register. The No Action Alternative considers what would happen if the Columbia River System continued to be operated, maintained, and configured with no operational changes. The No Action Alternative assumes the Columbia River System will continue to be operated for all congressionally authorized purposes, requiring a balancing of operations across the Columbia River Basin. Information described in the No Action Alternative is drawn from a number of documents, including the Fish Operations Plan (USACE 2016a), Fish Passage Plan (USACE 2016b), biological opinions from National Marine Fisheries Service (NMFS) and the

United States Fish and Wildlife Service (USFWS)(NMFS 2008; USFWS 2006), Water Management Plans (USACE 1992), and other sources.

A.3.2 Winter Operations

The Portland, Oregon, and Vancouver, Washington, area can flood during both winter (November–March) and late spring (May–June). Large winter flood events in the Pacific Northwest are caused by atmospheric rivers (ARs). ARs are enhanced water-vapor plumes in the atmosphere sourced from tropical latitudes and transported by extratropical cyclones. ARs last only a few days but deliver a substantial amount of precipitation and higher temperatures over their duration. High rainfall rates during these events, often augmented by low-elevation snowmelt, can cause flooding. Flood stage categories for the Columbia River at the Vancouver gage are established by the National Weather Service.[1]

Most of the Columbia River System storage is well upstream of the Portland and Vancouver area, and a majority of the heavy AR rainfall occurs in the drainage basin below major storage projects. However, the Columbia River Basin can offer some storage to reduce flood impacts to Portland and Vancouver. During the largest ARs, there is often a substantial amount of rainfall that lands east of the Cascades and into the lower Snake River Basin. During the winter event in February 1996, the projects on the Columbia River System provided support to the lower reaches through regulation over the week of the storm. This operation consisted of 12 large projects in the basin, including a pre-event drafting and storage in the 4 projects on the lower Columbia River and storage at Arrow to limit outflows to the natural lake outflow.

In the WAT-ResSim model, Columbia River Basin system-wide winter FRM operations are implemented in a tiered framework; each operational tier is determined by the severity of forecasted stage at the Vancouver gage. This mimics real-time operations, where operators use a forecast developed by the National Weather Service Northwest River Forecast Center. The River Forecast Center produces a 10-day forecast of streamflow; however, operational decisions for short-duration winter events typically rely only on forecasts within a 5-day window due to high uncertainty and lower skill in the 5- to 10-day range. The WAT-ResSim model uses a method to generate a 5-day forecasted stage similar to the operational forecast product.

The modeled forecast routine in WAT-ResSim uses a regression-based method of estimating stage from the inflow from the Willamette River and Columbia River main stem. To estimate the 5-day forecasted regulated flow out of Bonneville Dam, this calculation uses a simplified representation of regulation in the Columbia River System. The WAT-ResSim uses this simple projection of Bonneville Dam outflow and known quantities for the other inputs of the Vancouver stage estimation method for the forecasts of Vancouver stage. This simple projection uses generic operating rules for regulation from the headwaters down to Bonneville

[1] The datum at the Vancouver station is 1.82 feet (a stage reading of 0 is 1.82 feet above sea level, or more specifically NGVD29).

Dam. The projection of operations and regulated flow occurs for the length of the forecast window, and the starting pool elevations at all projects are the previous day's elevation. The operations at the most upstream reservoir are modeled for the whole forecast horizon, then the flows are routed downstream to the next reservoir to adjust the flows. This process is carried through until flows are routed all the way down to Bonneville Dam. This method allows for the use of short-term forecast inflows when projecting reservoir operations and downstream flows. The use of forecasted inflows with error is not currently implemented in the model—the future inflows are assumed to be known with perfect foresight. Incorporating short-term forecast error could have a large influence on operations at headwater projects. However, this has less of an influence on the flows out of Bonneville Dam because much of the system's operations of large storage projects are based on the spring FRM objectives, which are less affected by short-term forecasts.

The simplified model projection simulates all reservoirs, ensuring that the forecasted flows are realistic and incorporate the at-site project limits. The model uses the following reservoirs in forecasting the Vancouver stage: Mica, Arrow, Duncan, Libby, Corra Linn, Hungry Horse, Seli'š Ksanka Qlispe' (SKQ), Albeni Falls, Grand Coulee, Brownlee, and Dworshak.

The severity of forecasted events is described using different levels, called tiers. The 1- to 5-day forecast of the stage of the Columbia River near Vancouver is used to determine the event tier level. Table A-1 lists the tier levels and corresponding Vancouver stage triggers. The modeled Vancouver stage is used to determine the Operations Status, which is either Status 1 (Pre-Event), Status 2 (Near Peak), or Status 3 (Recession).

Table A-1. Flood severity tiers and operational response (status) based on the Vancouver stage used in the No Action Alternative of the WAT-ResSim model.

	Vancouver Stage			
Tier	**Tier Trigger (forecast)**	**Status 1, Pre-Event (current, ft CRD)**	**Status 2, Near Peak (current, ft CRD)**	**Status 3, Recession (current, ft CRD)**
Tier 1	≥16, <17	<16	≥16	≤15
Tier 2	≥17, <20	<17	≥17	≤16
Tier 3	≥20	<20	≥20	≤17

Note: CRD = Columbia River Datum.

The tier of the forecasted event determines which projects will operate for FRM. For a Tier 1 event, lower Columbia River projects, including Bonneville Dam, John Day, McNary, and The Dalles, operate for winter FRM. During Tier 2 events, Grand Coulee, Albeni Falls, and Dworshak are added. During the most severe events, Tier 3, projects in the upper basin are added to the FRM operations: Libby Dam, Hungry Horse, SKQ, Arrow, and Duncan (Table A-2). FRM operations are divided into three categories that are referred to as statuses in the model nomenclature. The first status (Status 1) is pre-event, where the river is forecasted to exceed flood stage within the 5-day forecast window, and the current stage is still below flood stage. In Status 1, some of the projects will draft to create flood storage. The second status (Status 2) is near the peak of the event, and active projects store water. The final status (Status 3) occurs after the flood peak has occurred, flow is receding, and the projects draft to their normal operating elevations. Table A-2 lists the ranges of Vancouver stage that define each of these statuses. The following sections summarize the specific operations for each of the projects with winter FRM operations.

Table A-2. Projects with winter flood risk management operations for event Tiers 1 to 3.

Tier	Projects with FRM Operations
1	Bonneville Dam, The Dalles, John Day, and McNary
2	Tier 1, Grand Coulee, Albeni Falls, and Dworshak
3	Tiers 1 and 2, Libby, Hungry Horse, SKQ, Arrow, and Duncan

A.3.2.1 Lower Columbia River Dams

The Tier 1 projects operate for winter FRM during events at any tier level. During Status 1, pre-event, these projects draft to their respective minimum pool elevations. The draft is constrained to keep the stage at Vancouver at or below 16 feet CRD. During Status 2, these projects fill available storage, distributing the fill evenly over the number of days where Vancouver stage is projected to be in the Status 2 range. Once Status 3 is triggered, these projects draft over the course of 7 days the water stored during the event that is above the normal operating pool. This modeled operation provides a total of 921 kaf (thousand acre-feet) of flood storage space (John Day, 534 kaf; Bonneville Dam, 149 kaf; McNary, 185 kaf; and The Dalles, 53 kaf).

A.3.2.2 Grand Coulee

Grand Coulee operates for winter FRM during Tier 2 and 3 events when there is space available. During Status 1, the project passes inflow until 3 days before Status 2. Next, during the 3 days prior to and during Status 2, the project fills the storage space available (to full pool), distributed evenly over this period. This impounds water during the peak of the flood to mitigate flooding on the Columbia River main stem. Once Status 3 is initiated, the project drafts the water stored during the event that is above the spring FRM requirement. The post-event draft is constrained by the variable maximum draft rates specified for the project. The travel time from Grand Coulee to Vancouver is approximately 1 to 1.5 days.

A.3.2.3 Albeni Falls

Albeni Falls operates for winter FRM during Tier 2 and 3 events. During Status 1, the project passes inflow. During Status 2, when inflow is less than 50,000 cfs (cubic feet per second), the project releases 10,000 cfs. If inflow is greater than 50,000 cfs, outflow is equal to the maximum release of the powerhouse (17,000 to 27,000 cfs). During these events, Lake Pend Oreille can be filled to an elevation of 2061 feet (NGVD 29) at which time outflow is set to inflow. Once Status 3 is triggered, the project drafts the water stored during the event that is above the spring FRM requirement. This draft is constrained by the physical limits of the river channel between the lake and the dam. The travel time from Albeni Falls to Grand Coulee is approximately 1 day.

A.3.2.4 Dworshak

Dworshak operates for winter FRM during Tier 2 and 3 events. This project does not have winter FRM operations during Status 1 because the travel time is too long to ensure evacuated storage can pass through the system before the winter storm. During Status 2, the project limits outflows to the minimum outflow requirement. Once Status 3 is triggered, the project drafts at the maximum allowable outflow rate the water stored during the event that is above the spring FRM requirement. The travel time from Dworshak to Vancouver is approximately 1 to 2 days.

A.3.2.5 Libby

Libby operates for winter FRM during Tier 3 events. During Status 1 and 2, release is limited to 4,000 cfs (minimum flow). Once Status 3 is initiated, the water stored during the event that is above the spring FRM requirement is drafted. This draft is limited by ramping rates and the maximum capacity of the powerhouse (12,000 to 28,000 cfs).

A.3.2.6 Hungry Horse

Hungry Horse operates for winter FRM during Tier 3 events. During Status 1 and 2, release is limited to the maximum of at-site minimum release or the Columbia Falls minimum. Once Status 3 is initiated, the water stored during the event that is above the spring FRM requirement is drafted evenly over the course of 7 days.

A.3.2.7 Seli'š Ksanka Qlispe'

SKQ operates for winter FRM during Tier 3 events. During Status 1 and 2, release is limited to the minimum of powerhouse capacity (13,500 cfs) and inflow. Once Status 3 is initiated, the water stored during the event that is above the spring FRM requirement is drafted. This draft is limited by the physical constraints of the channel between the dam and the upstream lake.

A.3.2.8 Arrow

Arrow operates for winter FRM during Tier 3 events. If Vancouver stage is projected to be over 20 feet in the next 3 days, the project attempts to reduce releases to natural inflow. A ramping rate of 15,000 cfs per day is applied, and releases are not permitted to drop below a minimum flow of 15,000 cfs. This ramp down in releases continues through Status 2. Once Status 3 is triggered, the project drafts over the course of 7 days the water stored during the event that is above the spring FRM requirement.

A.3.2.9 Duncan

Duncan operates for winter FRM during Tier 3 events. If Vancouver stage is projected to be over 20 feet in the next 3 days, the project releases the maximum of inflow and the minimum release (100 cfs). This release logic continues through Status 2. Once Status 3 is triggered, the project drafts over the course of 3 days the water stored during the event.

A.3.2.10 Willamette

A time series of flow at Willamette Falls is used as a boundary condition, and the CRS Model has no knowledge of the internal states (reservoir pool conditions or flows) beyond the Willamette inflow at Willamette Falls just upstream of Portland. Further description of the inflow time series used for Willamette Falls is provided in Chapter A.4.

A.4 WILLAMETTE RIVER

The Willamette River inflow is a boundary condition into the HEC-ResSim model. The Willamette River inflows are applied at the "Willamette Falls" HEC-ResSim junction node. This node is located upstream of the Clackamas River confluence at Oregon City, Oregon.

The inflow dataset developed for RMJOC hydroregulation purposes was developed from University of Washington (UW) cumulative unregulated (natural) flows at Willamette Falls. USACE applied the 2010 level cumulative depletion to the UW flows to create the Willamette Falls inflow datasets.

The Willamette River boundary time series used in this report is not the product of reservoir modeling; the effects of upstream regulation are not represented in the inflow time series. USACE flood risk management for the Willamette River reservoir regulation uses Salem, Oregon, as a control point. Real-time and Willamette Valley planning studies are informed by a Portland District ResSim model of the Willamette Valley. This model uses subdaily time series (e.g., 6 hour) for the most accurate simulations of flood levels. This is a reflection of the shorter travel times in the Valley relative to those typically found in downstream reaches of the Columbia River. The implication for the RMJOC hydroregulation studies is that the Willamette River simulations, run at the daily time step, will likely not be as accurate as equivalent real-time or planning study models run at a subdaily resolution. Furthermore, the performance of the RMJOC-II hydrological models in the Willamette Basin was much lower than the rest of the basin; and the river routing network was too coarse to accurately represent some upland areas. Valley projects have higher impact for flood risk reduction at local control points and at Salem, Oregon, the main Willamette Valley regulation point for FRM. Willamette Valley FRM regulation has less effect for inflows at Portland, Oregon (Willamette Falls). However, the general conclusions of this study are unlikely to change.

This limitation was not a decisive constraint for the RMJOC hydroregulation analyses. To verify this determination, the RMJOC ResSim development team made a preliminary verification using unregulated flows. They found that the unregulated input time series resulted in an annual peak flow frequency that is similar to the regulated peak flow frequency for the hydrology model that was used for initial study planning, VIC_P1. Figure A-1 shows Willamette Falls Annual Maximum Flow-Frequency curves for the four historical cases modeled with a different hydrology model, an observationally derived No Regulation No Irrigation (NRNI) unregulated dataset, and a historical reservoir model-based regulated dataset. As was found initially, the VIC_P1 distribution matches the regulated base case well. However, the historical distributions of the three other hydrological models tend to produce higher annual maximum flows that more closely match the natural flow frequency distribution.

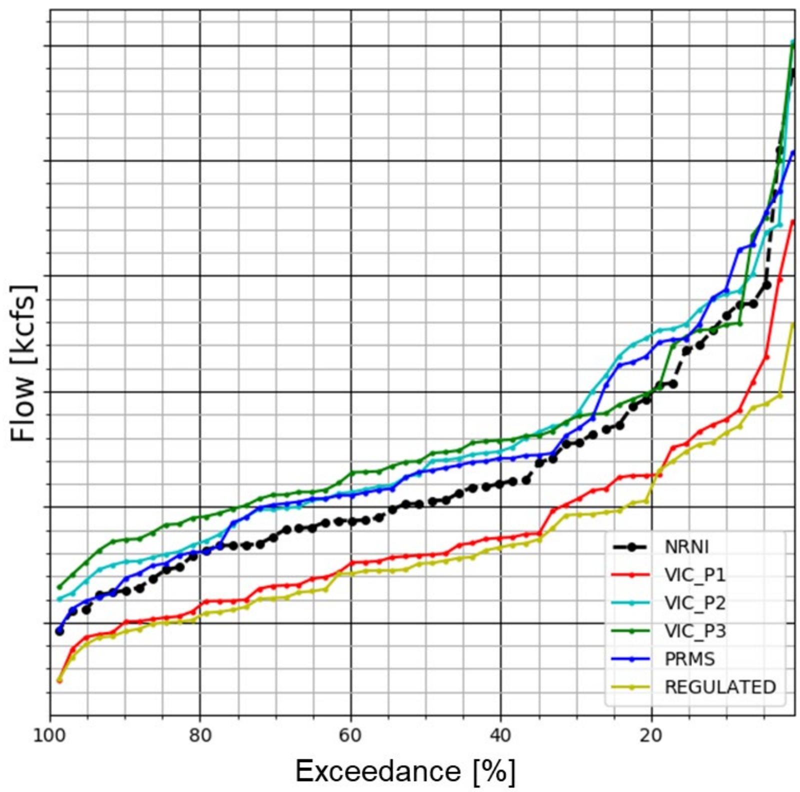

Figure A-1. Annual daily mean peak flow frequency of the Willamette River at Willamette Falls using a naturalized observation-based dataset (NRNI), historical flows from a current-condition Willamette Valley reservoir model, and unregulated historical flows from the four RMJOC-II hydrological models (VIC_P1, VIC_P2, VIC_P3, and PRMS).

The implication for using VIC_P2, VIC_P3, and PRMS (Precipitation Runoff Modeling System) unregulated Willamette Falls flow is that Willamette River peak flows may be higher than a regulated peak flow, for which VIC_P1 was comparable. Winter peak stages in the Lower Columbia are affected by inflow from the Willamette River. To characterize how this may manifest itself in some of the results presented in Chapter 8, we explicitly denote each model in the flood threshold exceedance analysis for the Columbia River at Vancouver, Washington, for the historical baselines (Figure A-2). The largest effect of this boundary condition assumption is observed in the exceedances of the lowest threshold, 16 feet (Figure A-2a). The historical baseline of VIC_P1 has half the number of winter events that exceed 16 feet. The largest differences are in November and December. The differences between models is less evident for the 20 foot stage threshold (Figure A-2b), and no differences are noted for the 25 foot threshold (Figure A-2c).

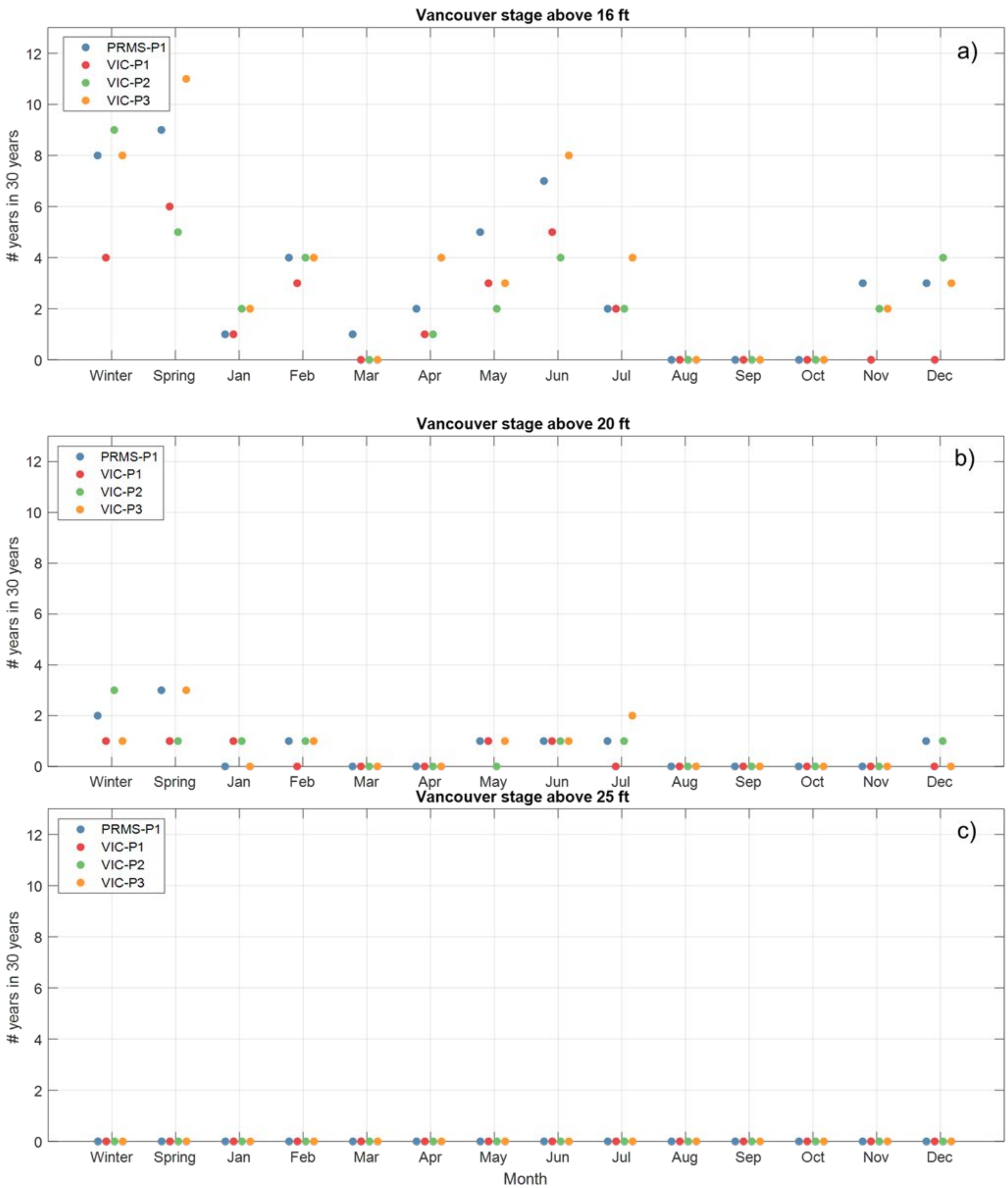

Figure A-2. Flood stage exceedance analysis of the Lower Columbia River at Vancouver, Washington, for the historical baseline models.

Stage in the lower Columbia River is a function of regulated flows on the Columbia River and the Willamette River at Willamette Falls. As summarized in Section 8.5, Vancouver stage increases in the future (2030s and 2070s) are most strongly linked to increases in flow from the Columbia River during winter flood events. Therefore, the impact of potentially using higher Willamette flows is less influential on the projected relative changes in winter flood events for the lower Columbia River. However, understanding the effects of the treatment of the Willamette River boundary inflow is important for interpreting modeled winter events for the Lower Columbia River.

A.5 SEA LEVEL RISE

Sea level rise has an effect on water surface elevations of the Lower Columbia River below Bonneville Dam. The WAT-ResSim modeling analyses did not consider sea level rise. The model focused on system operations and does not include a sea level boundary condition in any of its algorithms. Chapter 8 presents projections of flood stages in the Lower Columbia River. While we did not include the effects of sea level rise in the projections, previous analyses have demonstrated that its effects on peak stages of flood events are minor (Wherry et al. 2019). While sea level rise was not a focus of the report, we present and discuss potential effects of sea level rise in this section.

Sea level rise is closely linked to increasing global temperatures. Global mean sea level has risen by about 7 to 8 inches since 1900 and is very likely to rise by another 0.5 to 1.3 feet by 2050 (USGCRP 2017). Locally affected future sea level is referred to as relative sea level change (RSLC). RSLC reflects integrated global effects plus local changes of geologic or oceanographic origin. In the Pacific Northwest, the RSLC is likely to be less than the global average (USGCRP 2017). The RLSC has the potential to affect river water surface elevation as far inland as the extent of the tidal influence. Tidal effects in the Columbia River extend upriver to Bonneville Dam (River Mile 145).

Corps policy guidance applies a scenario-based approach to evaluate the impacts of RSLC. This scenario approach bounds a range of RSLC using three plausible scenarios. Each of the three scenarios is based on the latest actionable science from the International Panel on Climate Change, National Oceanic and Atmospheric Administration (NOAA), and National Research Council (NRC). The RSLC scenarios are specific for a given coastal location and are generated for each NOAA tide station that meets quality control protocol requirements (Corps 2013). The low, intermediate, and high scenarios for NOAA tide gauges can be obtained using the Corps online sea level calculator at http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html.

Figure A-3 shows the three RSLC scenarios applicable for Astoria/Tongue Point, Oregon, NOAA Tidal Station 9439040. Corps projections for the future RSLC are based on a start date of 1992, which corresponds to the midpoint of the present National Tidal Datum Epoch[2] of 1983 to 2001.

The “USACE Low” scenario for future RSLC is extrapolated from the observed historical rate derived from NOAA tide gages. For 2050, the USACE Low scenario projection for Astoria is −0.05 feet using 2020 as the base year. The value is negative due to the regional rate of landmass uplift being greater than the sea level rise.

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[2] The National Tidal Datum Epoch is “the specific 19-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values for tidal datums. It is necessary for standardization because of periodic and apparent secular trends in sea level. The present NTDE is 1983 through 2001 and is actively considered for revision every 20–25 years” (NOAA 2019).

The "USACE Intermediate" scenario focuses its projection primarily on thermal expansion of the ocean and is computed from the modified NRC Curve I, considering both the most recent IPCC projections and modified NRC projections. For 2050, the USACE Intermediate scenario projection for Astoria is 0.15 feet using 2020 as the base year.

The "USACE High" scenario accounts for the thermal expansion of the ocean and accommodates for a potential rapid loss of ice from Antarctica and Greenland. It is estimated using the modified NRC Curve III. For 2050, the USACE High scenario projection for Astoria is 1.05 feet using 2020 as the base year.

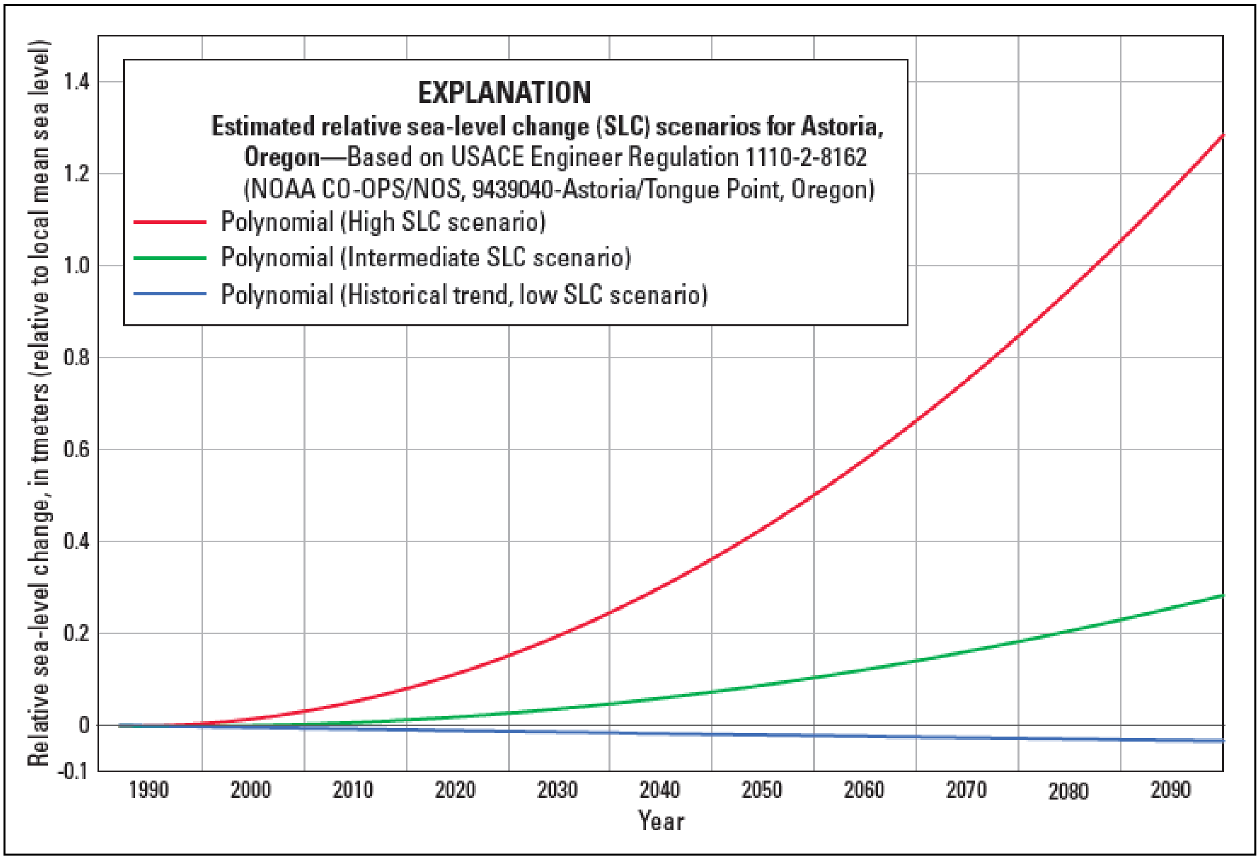

Figure A-3. Estimated Sea Level Change Scenarios at Astoria, Oregon. (Note: Figure taken from Wherry et al. 2019).

The surcharge effect of RLSC on river water surface elevation dissipates upriver from the mouth of the Columbia River at the Pacific Ocean (River Mile 0). This surcharge can also vary with flow conditions, whereas low-flow conditions will be affected more. At Woodland Islands, Washington, located in the lower Columbia River (River Mile 86), stage surcharge is estimated to be 0.5, 0.15, and 0.0 feet for the High, Intermediate, and Low RLSC scenarios, respectively (Corps 2019). During extreme high-flow conditions of the Columbia River near Vancouver, Washington (River Mile 106.5), 1 meter (3.3 feet) of RLSC results in a difference in peak river stage of approximately 0.5 foot (Wherry et al. 2019).

A.6 TREATY STORAGE REGULATION

Reservoir modeling of the Columbia River reservoir system is commonly conducted through a multiagency coordinated effort (Chapter 3). USACE WAT-ResSim modeling typically uses time series flow inputs from Reclamation for the Yakima, Deschutes, and Upper Snake River tributaries. BPA provides proportional draft points used as input for the simulation of the Treaty Storage Regulation (TSR) operations of three Canadian treaty dams, Mica, Arrow Lakes, and Duncan. Time series of PDPs are an intermediate product of Hydsim modeling. USBR produced reservoir modeling simulations for all of the 160 projections (Chapter 4). BPA modeled a subset of 22 RCP 8.5 projections with Hydsim. Nineteen of these projections are presented in the body of this report (Chapter 9). BPA modeled three additional projections in early phases of testing and dataset development. This resulted in a total of 22 projections simulated using Hydsim. BPA's decision to only model a subset of projections was attributed to the heavy resource and time requirements of using the largely manual Hydsim modeling framework.

USACE policy prioritizes evaluation of all potential future conditions. Modeling all 160 projections required an alternate modeling approach to remove the dependence on Hydsim simulations for input data. USACE does not have access to the source code or documentation that describes model algorithms of the BPA Hydsim model, thus could not recreate them in a similar modeling framework. Using the Hydsim simulations of the subset of projections, USACE developed a methodology to simulate TSR operations with reservoir outflow and storage that closely mimic those simulated by the Hydsim model. This modeling routine is not intended to replace Hydsim modeling, and the RMJOC-II study does not apply it to hydropower-specific analyses.

The following sections describe (1) the general development of the approach, (2) how the method was trained and validated, and (3) validation of the approach in TSR operations and full system WAT-ResSim modeling.

A.6.1 Simplified method of TSR Modeling

The objective for the development of a TSR modeling routine was to create a model algorithm capable of simulating outflow and storage of Canadian reservoirs that would closely resemble the patterns of storage and outflow in the TSR output of the Hydsim model. The Hydsim model output for 22 projections and two future periods (2030s and 2070s) was available to train and test this new methodology. We used a total of 1,320 years of Hydsim simulation of future projections for the basis of this development.

The new modeling algorithm simulates reservoir storage and outflow patterns that closely reflect the full simulation of operations using Hydsim. Inputs available to this modeling algorithm are hydrological variables (local inflow, unregulated cumulative flows, and water supply forecasts) and system-state variables (reservoir content at a previous time step).

A.6.1.1 Artificial Neural Network Model Development

Given recent advances in machine learning technologies and applications for reservoir modeling (e.g., Ehsani et al. 2016), USACE determined that the development and use of Artificial Neural Networks (ANN) for predictive regression would provide a viable platform for TSR modeling. We used the TensorFlow software package in the Python scripting environment (https://www.tensorflow.org/). Tensorflow is one of the most widely used machine learning packages in engineering and research.

The general structure of a neural network consists of an input layer, hidden layers, and an output layer. For this application, the input layer consists of a set of hydrological and reservoir system variables that are correlated with TSR operations. Hidden layers consist of elements called neurons, or nodes. Each element of an input layer is connected to each neuron. Neurons include activation functions that respond to the data fed to them and, in turn, pass data onto the next element in the network. There are numerous activation functions to choose from. We used the rectified linear unit, one of the most commonly used activation functions. Finally, in our application, the output layer consists of reservoir outflows. The elements of each layer are linked to the next layer through connections. Each connection includes a “weight,” which is used to determine the relative importance of the connections between elements. The weights and bias terms of connections and parameters of activation functions of neurons are determined through iterative training algorithms (calibration) of the network.

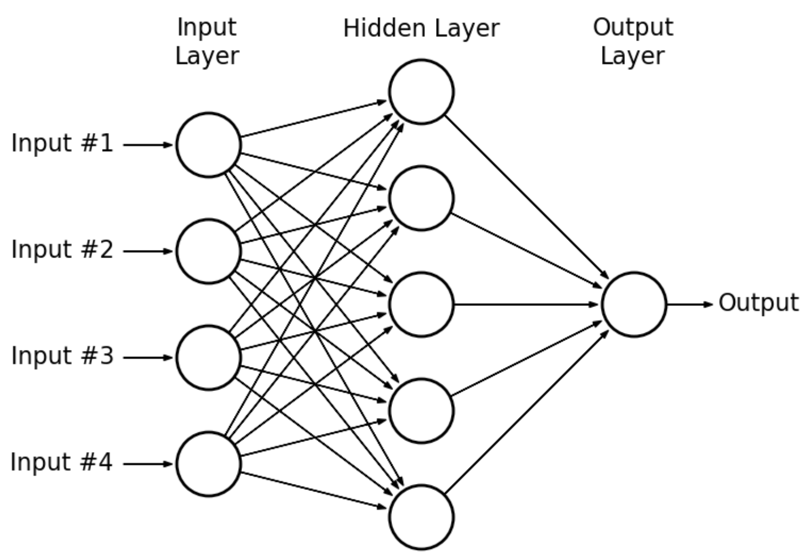

Figure A-4. Conceptual diagram of neural network elements and flow of information in a simple feed forward network (Eindhoven University of Technology 2017).

We evaluated a set of potential covariates to be included as input to the ANNs. First, we tested the correlation between potential covariates and the targeted output, reservoir outflow (A-5). This correlation analysis highlighted variables to be included, and screened ones out that lacked correlation with the target output variables. We used the period of record Columbia River System Operations No Action Alternative TSR reservoir model output from the Columbia River

System Operations Environmental Impact Statement modeling dataset for this correlation analysis.

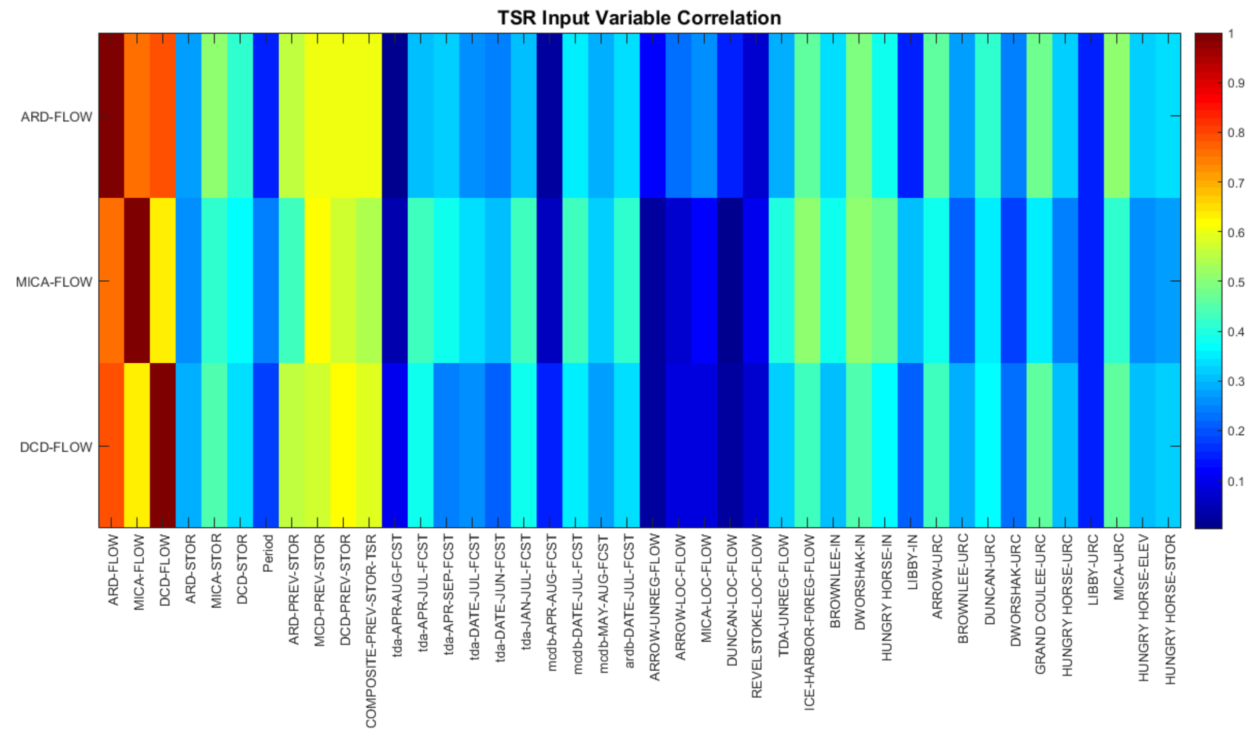

Figure A-5. Correlation between outflow of Arrow Lakes (ARD), Mica Dam (MICA), and Duncan Dam (DCD) with hydrological and system variables.

We found that storage in the Canadian reservoirs at the previous time step, seasonal water supply forecasts, and unregulated cumulative flow for large basin tributaries have the strongest correlations with TSR outflow of Canadian reservoirs. We eliminated other variables with lower correlations from the list of inputs to limit unnecessary network complexity that could introduce spurious effects in the training of the network. We did not test correlations between the input variables, which may be high in some cases. However, the selection of input variables was found to produce reasonable results, and only limited effort was placed on narrowing the number of input variables. We selected a total of 16 inputs to use in the development of the ANNs (Table A-3).

Table A-3. Input variables used for ANN TSR outflow prediction.

Reservoir Storage	Water Supply Forecasts	Inflow Hydrology
Arrow Lakes	The Dalles, April–August	Arrow Cumulative Unregulated Flow
Mica	The Dalles, April–July	Arrow Lakes Local Flow
Duncan	The Dalles, DATE–July	Mica Inflow
Total Canadian	The Dalles, January–July	Duncan Inflow
	Mica, May–August	Revelstoke Local Flow
		The Dalles unregulated cumulative flow
		Ice Harbor Unregulated Flow

We developed a separate ANN model for each reservoir and period. TSR modeling includes 14 periods, a monthly time step with the exception of April and August being split into two periods. This totals 42 models to be applied for TSR simulation. Initially, we tested a simpler approach where each reservoir had a single ANN and the period was used as an input parameter; however, this simpler approach had less predictive skill (Figure A-6). Each of the 42 ANN models consist of an input layer of 16 elements, one hidden layer including 45 neurons, and an output layer of one element (reservoir outflow). The ANNs were applied in a "feed forward" framework; the information flows from left to right as opposed to allowing data from flow "backwards" within the network.

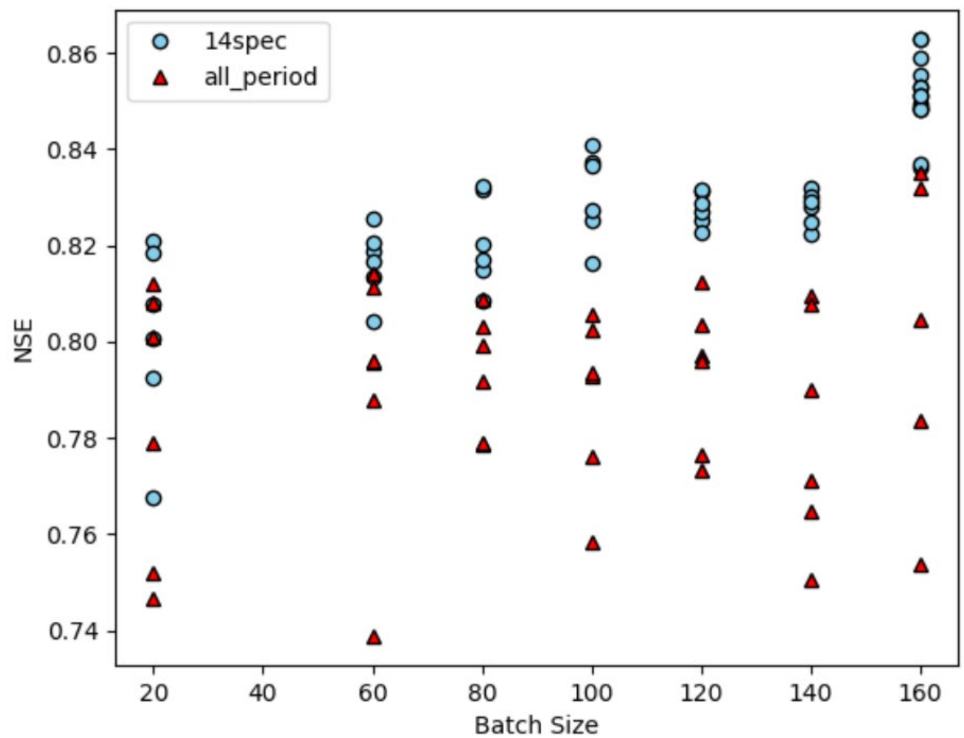

Figure A-6. Results of initial testing demonstrating the performance (Nash Sutcliffe Efficiency, NSE) using a single ANN trained for and applied for all periods (*all_period, red triangle*) and using 14 networks trained specifically for each period (14*spec, blue circle).* These results are for prediction of outflows from Arrow Lakes. Performance was also evaluated against a range of the batch-size network parameter.

A.6.1.2 Artificial Neural Network Training and Testing

The calibration or training procedure of ANNs involves iteratively adjusting the parameters of the network connections and neurons to improve the skill in reproducing a set of training data. The method that we applied can be best described in a sequence of processes:

1) Training Data Preparation: Divide data sample into a set used for training and calibration and a set used to apply and validate the calibrated model. BPA provided 1,320 years of Hydsim simulations. We developed period-specific models, thus there were 1,320 data points available for each model. We randomly divided 80% of the

data into a set to be used for model training, reserving the remaining 20% of the data to be used for independent validation. The random shuffling avoids weighting the training and validation to a sequence of years or projections for which the original dataset was organized by. This also provides better accounting for uncertainty in the selection of the training data as the subsetting in each iteration of training.

2) Transform Training Data: Compose the input and output variable of different units of different magnitudes. To avoid false numerical weighting associated with units, we transformed all training and validation data to be [−1,1] based on the minimum and maximum of the respective variables in the training dataset.

3) Train Network: Apply an iterative numerical procedure to calibrate or train network parameters. A cost function is used to measure the difference from network predictions and training targets. We used the mean squared error (average squared difference between prediction and targets) as the cost function. An optimization routine called the Adaptive Moment Estimation calculates "gradients." The direction in the weights and biases have to be changed to minimize the cost function in the iterative training procedure.

   We applied a training procedure called "mini-batch." This method splits the training dataset into small batches of random samples of the training set. A sampled batch of data flows through the network to the output later. Then, the model compares the predictions against the targets and updates the network parameters using the ADAM routine. After updating the network parameters, the next batch is sampled, and the process repeats itself. The procedure continues until all batches have been fed through the network. A full sweep through all batches is called an epoch. The process repeats itself by randomly selecting a different initial batch, continuing the iterative adjustment of network parameters until reaching a prescribed number of epochs.

4) Network Evaluation: After each network completes the training procedure described in step 3, the test data, data that were not used in training, are used to validate the network. The test data were input to the network, and the output is compared against the corresponding test data targets to evaluate model performance.

Further details on developing predictive neural network models using TensorFlow can be found in Heinz (2017). The method described above was derived from this approach.

A.6.1.3 Artificial Neural Network Validation

As described in the previous subsection, the final step of the training of the ANNs is a validation using data that were not used in the training. We compared the ANN predictions of outflows from Arrow Lakes, Mica, and Duncan against Hydsim simulations. We used Nash Sutcliffe

Efficiency (NSE) values and percent exceedance curve comparisons to assess ANN prediction skill.

The outflows of the ANNs closely match those of Hydsim (Figure A-7). In general, NSE values in this study are greater than 0.85; however, the comparisons do display some lower performance for some periods and locations. The outflow of Arrow Lakes for April 1–15 (Apr1) has an NSE value of 0.58, and the Hydsim simulations show more variability in lower flows than the ANN predictions. Similarly, the ANN and Hydsim outflows of Duncan Dam compare less well during the March and Apr1 period. These periods can have more variability as the operations shift between draft- and refill-based objectives. The distribution of outflows of Mica Dam simulated by Hydsim displays distinct abrupt changes. The ANN-based outflows reconstruct this general shape of the frequency curve but are smoother across the abrupt transitions. The Hydsim abrupt shape changes reflects explicit operational constraints. For instance, an operation may set a constant outflow and not deviate from that single value until a system or forecast threshold is exceeded. The ANN does not include these explicit threshold-based formulations of operations. However, we imposed additional operational constraints in the full implementation of the ANNs in the modeling, as described in the next section. These were not imposed in the initial training and validation step.

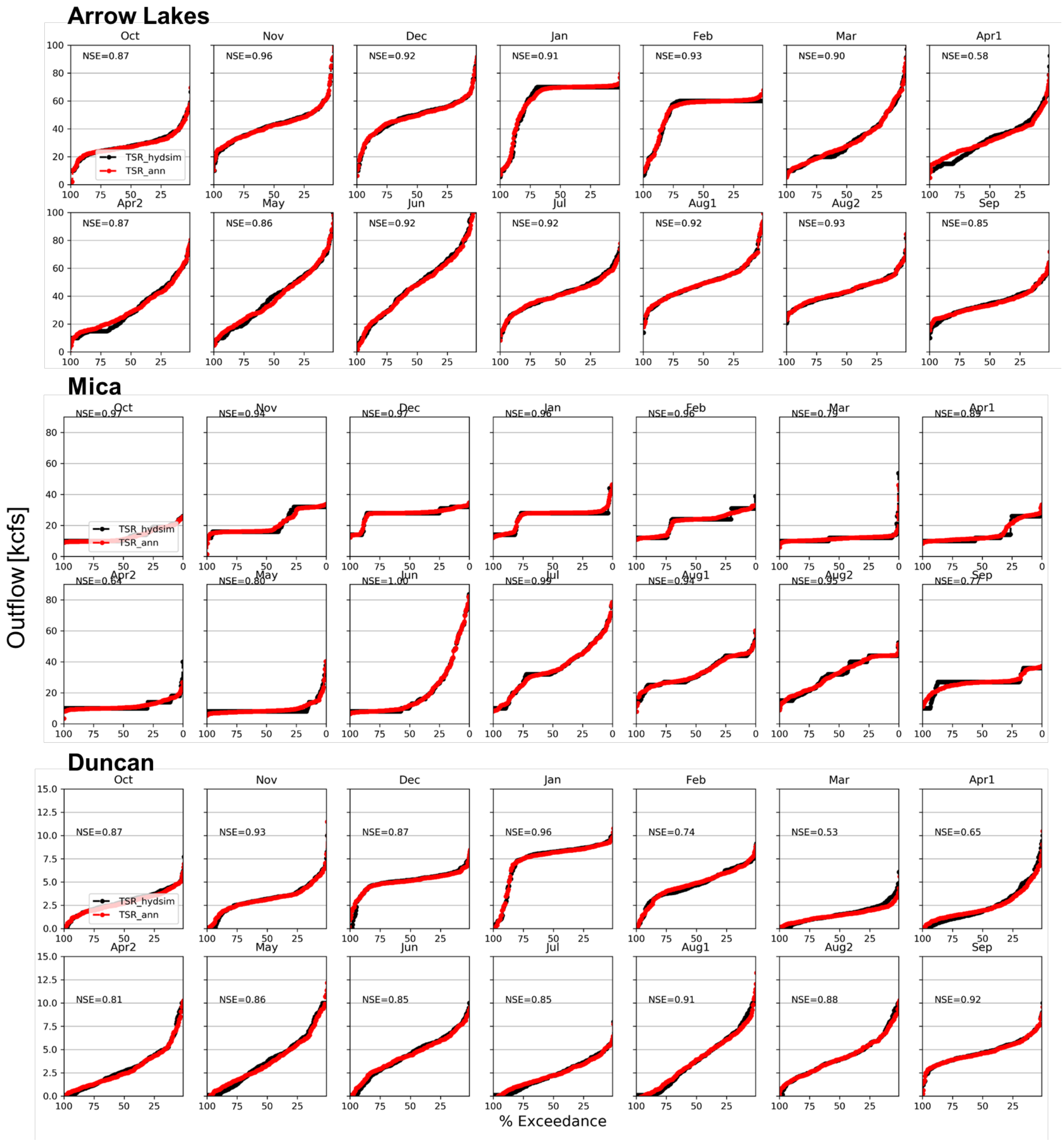

Figure A-7 . Comparison of reservoir outflow predicted by the trained Neural Networks (TSR_ann) and simulated by Hydsim (TSR_hydsim). These comparisons represent data that were not used in the training of the networks.

A.6.2 ANN-TSR ResSim Implementation

The training and validation processes produced an ANN for each period and location (42 ANNs). Implementation of these ANNs differs from how they were trained and validated. The largest distinction is that Hydsim data are not available for all of the projections for which the method will be applied. The training and validation processes used Hydsim-simulated reservoir storage from the previous time step to keep consistency for point-to-point comparisons with Hydsim. In the full ANN-TSR simulation, the ANN-TSR simulated reservoir contents from the previous time step were used as input.

In the full implementation, the ANN models are applied sequentially to each time step in the simulation, and the storage of the reservoirs is calculated based on the simulated outflows. The ANN model sequence starts with the simulation of Mica Dam. Next, Arrow Lakes outflow is simulated, and the outflow of Mica is used to calculate storage change at Arrow Lakes. The simulation of Duncan Dam outflow for the time step is then conducted. The reservoir storage simulated by the ANN implementation is used as input for ANN models at the next time step.

Additionally, in the full implementation, we applied several layers of constraints. First, the predicted outflows were checked to see if they exceeded the seasonally varying minimum or maximum flow constraints described in the Assured Operating Plan (AOP 2022) and the 2019 Detailed Operating Plan (DOP) that are used in the Hydsim TSR modeling. Similarly, the storage content resulting from the predicted outflow is checked to ensure it does not violate constraints defined in operating plans or physical constraints of the reservoir pools. If these outflow or storage constraints are violated, outflow is adjusted to maintain storage and outflow within operating constraints. Figure A-8 demonstrates the general flow and processing of information in this approach.

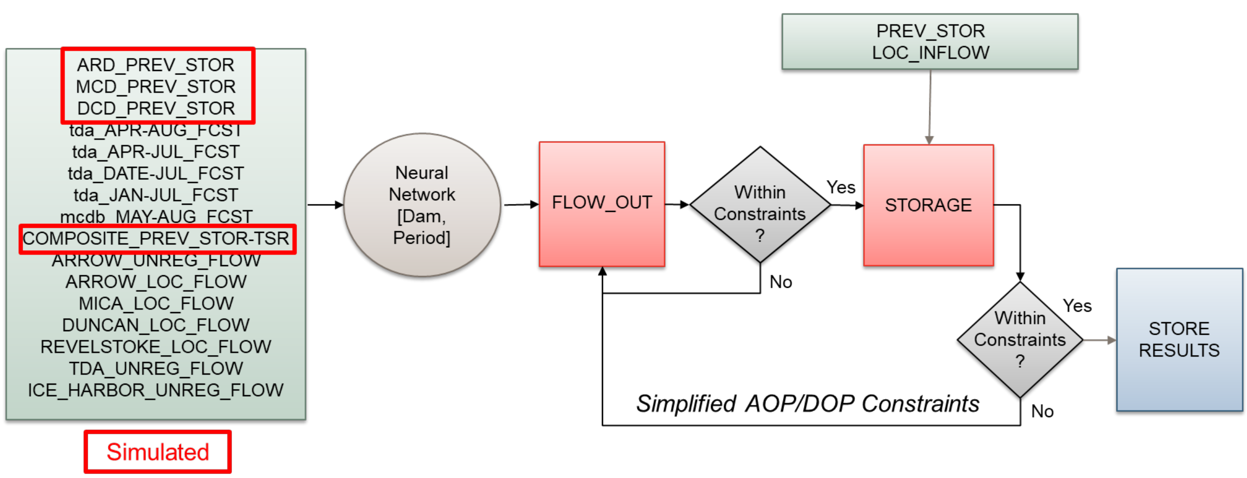

Figure A-8. Sequence of implementation of ANN models in predicting TSR reservoir outflow and storage.

Figures A-9 and A-10 show an example of the full implementation of this approach for a single projection, CanESM2_RCP85_BCSD_VIC_P1. Figure A-9 shows the time series of outflow and storage of Arrow Lakes simulated by the ANN-TSR and Hydsim modeling approaches. For the same projection, the summary statistics are shown in Figure A-10. There is strong agreement between the two approaches for median and extreme (5th and 95th percentiles) statistical composites.

In the full implementation, the two approaches are expected to deviate to some extent with respect to point-to-point comparisons. For example, if the ANN-TSR simulation leads to different reservoir storage value than Hydsim, this difference would carry through to the next time step where that storage value is used as input. For this reason, in evaluation of the full implementation and implementation in ResSim, we focus on comparing statistical properties with less emphasis on point-to-point comparisons.

We use violin plots to visually compare the ANN and Hydsim simulations across all 22 projections (Figures A-11, A-12, and A-13). The full set of 1,320 years of simulation is used to define the statistical distribution for each of the 14 periods. Overall, the distributions of TSR outflows and storage for the three projects compare well. However, some differences are noted. During March and April, there are differences in distributional shape at all three projects. This was noted in the training and validation discussion (Section A.6.1) and is attributed with more operations in these periods being more variable as reservoirs can either be drafting or refilling, depending on the water year.

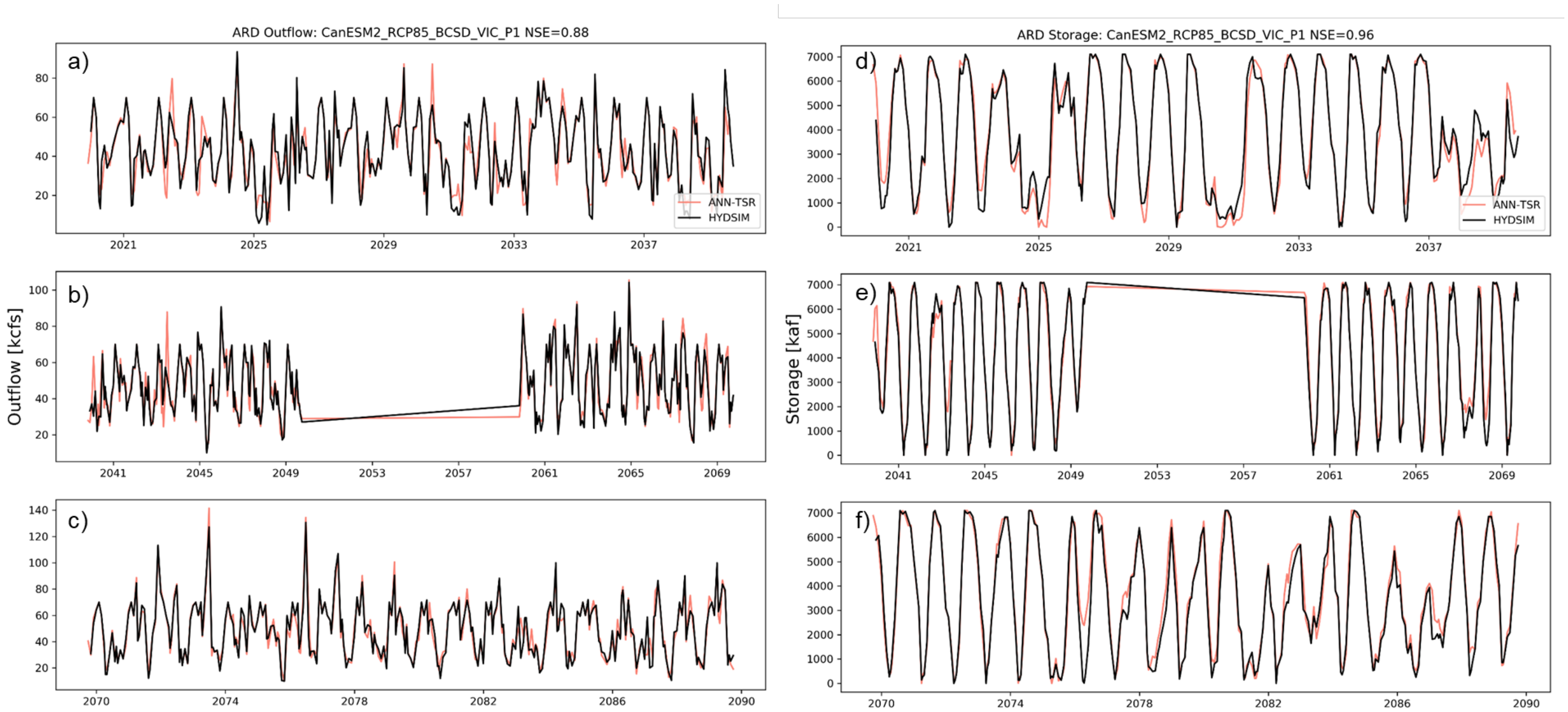

Figure A-9. Comparison of time series of TSR outflow and storage of Arrow Lakes reservoir simulation by the ANN-based model (ANN-TSR) and Hydsim. This example shows a single projection (CanESM2_RCP85_BCSD_VIC_P1). We did not model water years 2050–2059.

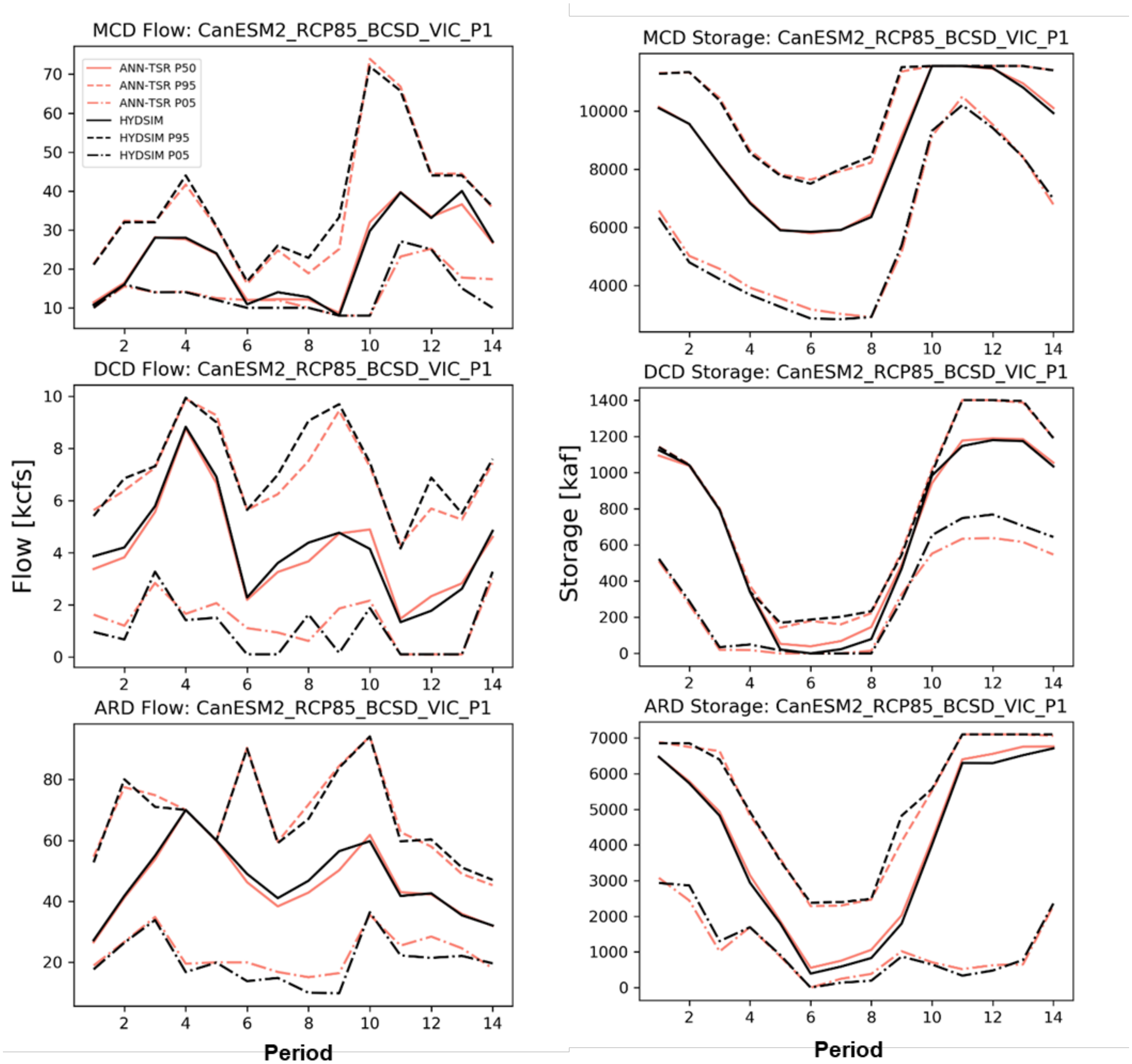

Figure A-10. Comparison of statistical summaries of TSR outflow and storage of Mica Dam (MCD), Duncan Dam (DCD), and Arrow Lakes (ARD) reservoir simulation by the ANN-based model (ANN-TSR) and Hydsim. This example shows a single projection (CanESM2_RCP85_BCSD_VIC_P1).

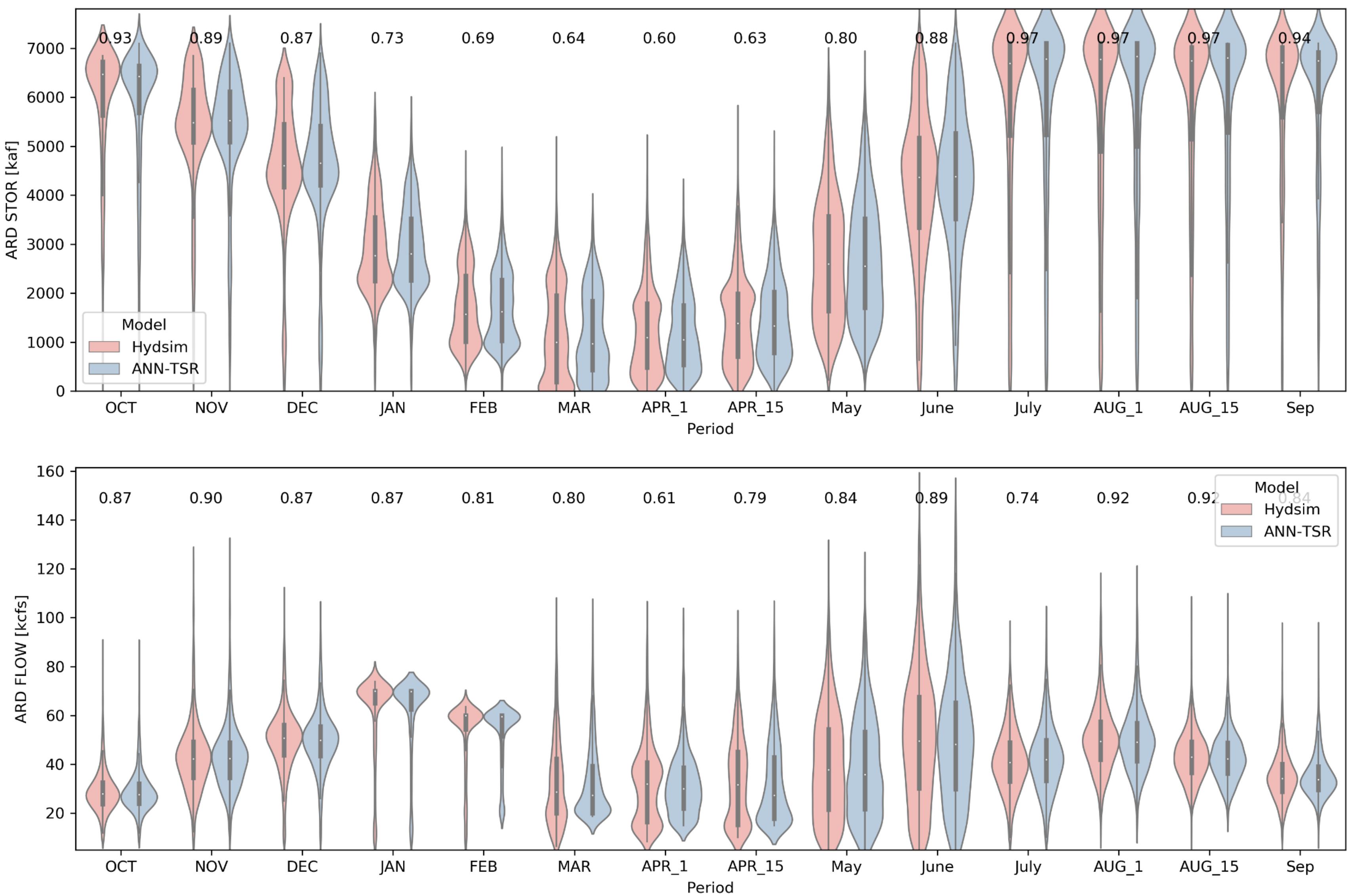

Figure A-11. Violin plots demonstrating the distribution of TSR outflow and storage of Arrow Lakes reservoir simulation by the ANN-based model (ANN-TSR) and Hydsim. The NSE comparison metric for each period is denoted at the top of the panels.

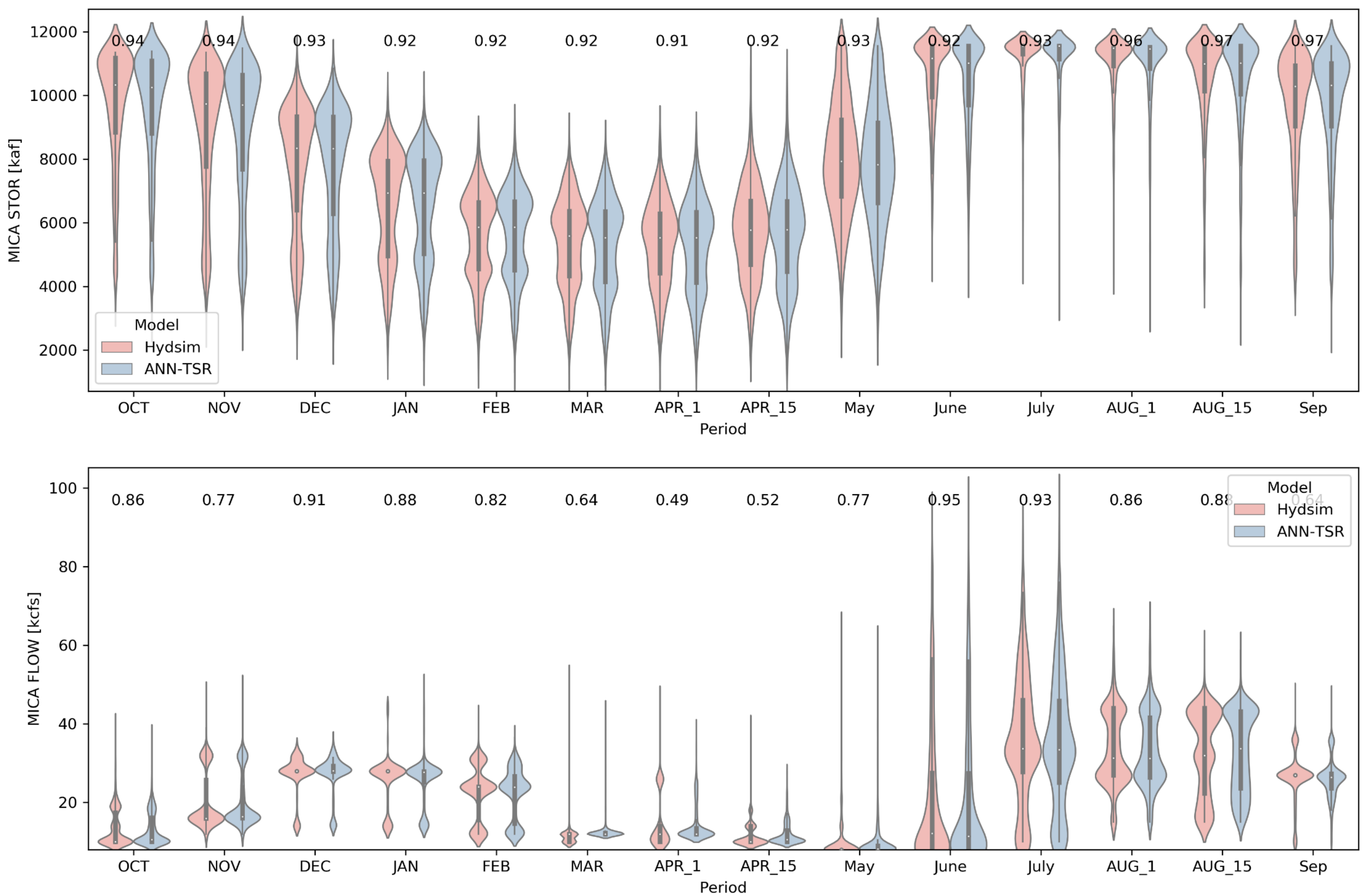

Figure A-12. **Violin plots demonstrating the distribution of TSR outflow and storage of the Mica Dam / Lake Kinabasket simulation by the ANN-based model (ANN-TSR) and Hydsim. The NSE comparison metric for each period is denoted at the top of the panels.**

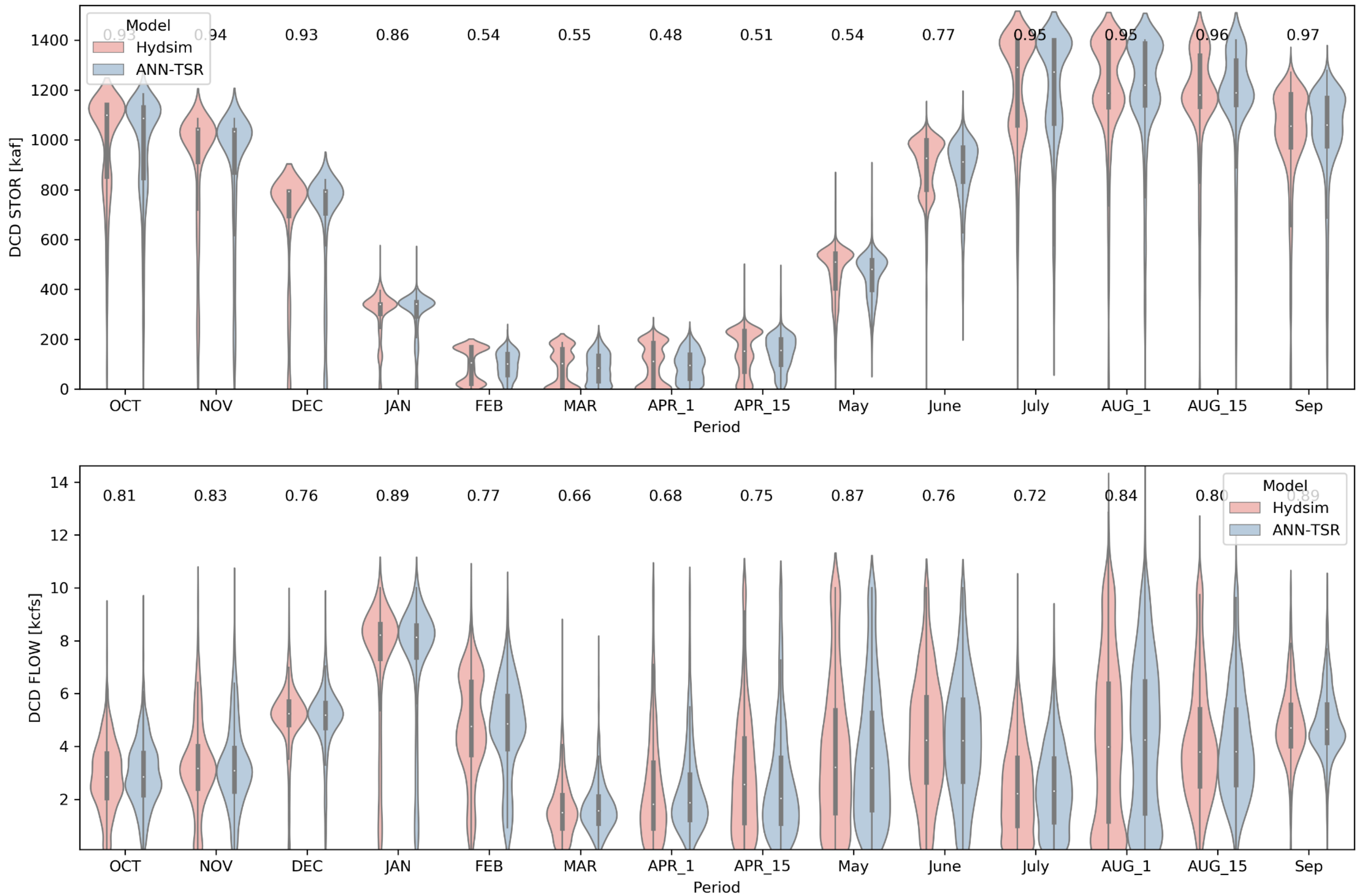

Figure A-13. Violin plots demonstrating the distribution of TSR outflow and storage of Duncan reservoir simulation by the ANN-based model (ANN-TSR) and Hydsim. The NSE comparison metric for each period is denoted at the top of the panels.

A.6.3 ANN-TSR in Full Columbia River Reservoir System WAT-ResSim Modeling

Modeling TSR operations is an intermediate step that is nested within the WAT-ResSim compute workflow. Several reservoir model operations are simulated after the TSR step. For the final stage of evaluating the ANN method for TSR operations, we analyzed the flow resulting from full WAT-ResSim simulations. The projections presented in the body of this report are from the results of the full WAT-ResSim simulations.

To facilitate this analysis, we ran WAT-ResSim simulations that included TSR outflows that BPA simulated with Hydsim. These are compared against the WAT-ResSim simulations using ANN-simulated TSR outflows. These analyses directly compare the end product of WAT-ResSim modeling (regulated flow and reservoir storage), not the intermediate products of TSR modeling, as was done in Sections A.6.1and A.6.2.

Figures A-14, A-15, and A-16 compare statistical descriptors of outflow from Arrow Lakes, Grand Coulee Dam, and The Dalles Dam. These locations depict the influence of the modeling approaches on flows throughout the system. These figures statistically describe each projection and epoch outflow for the 10th, 50th, and 90th percentiles of each month. We did this for each of the modeling techniques to compare the modeled flow patterns.

Outflow of Arrow Lakes is most sensitive to the TSR model formulations (Figure A-14). For median conditions (50th percentile), the resulting outflow from each method is in close agreement. There are larger differences between modeling approaches for the extreme statistical composites. Generally, these differences are small and do not include systematic patterns; however, there are some features worth noting. For the projections with the highest November outflows, the ANN-TSR WAT-ResSim approach leads to smaller outflow than Hydsim. Differences between modeling approaches are more variable for the low-flow statistic (10th percentile). This is the greatest for January and February where the range in 10th percentile flows is greatest between projections.

The differences between model approaches dissipates downstream of Arrow Lakes. Outflows from Grand Coulee between the two methods very similar, with the exception of several individual projections (Figure A-15). For example, two projections show the ANN-TSR WAT-ResSim approach having higher August outflows than the Hydsim approach. These two are also evident in the comparisons of 10th percentile August outflows at Arrow Lakes. These are two data points among a set of 44 (22 projections, 2 epochs) and thus do not present a high level of concern for the general results of the modeling approach.

There are minor differences in outflow from The Dalles Dam between the two approaches (Figure A-16). At this downstream location, the differences from TSR approaches are overshadowed by other system operations, and the magnitude of the differences are small relative to the total cumulative flow.

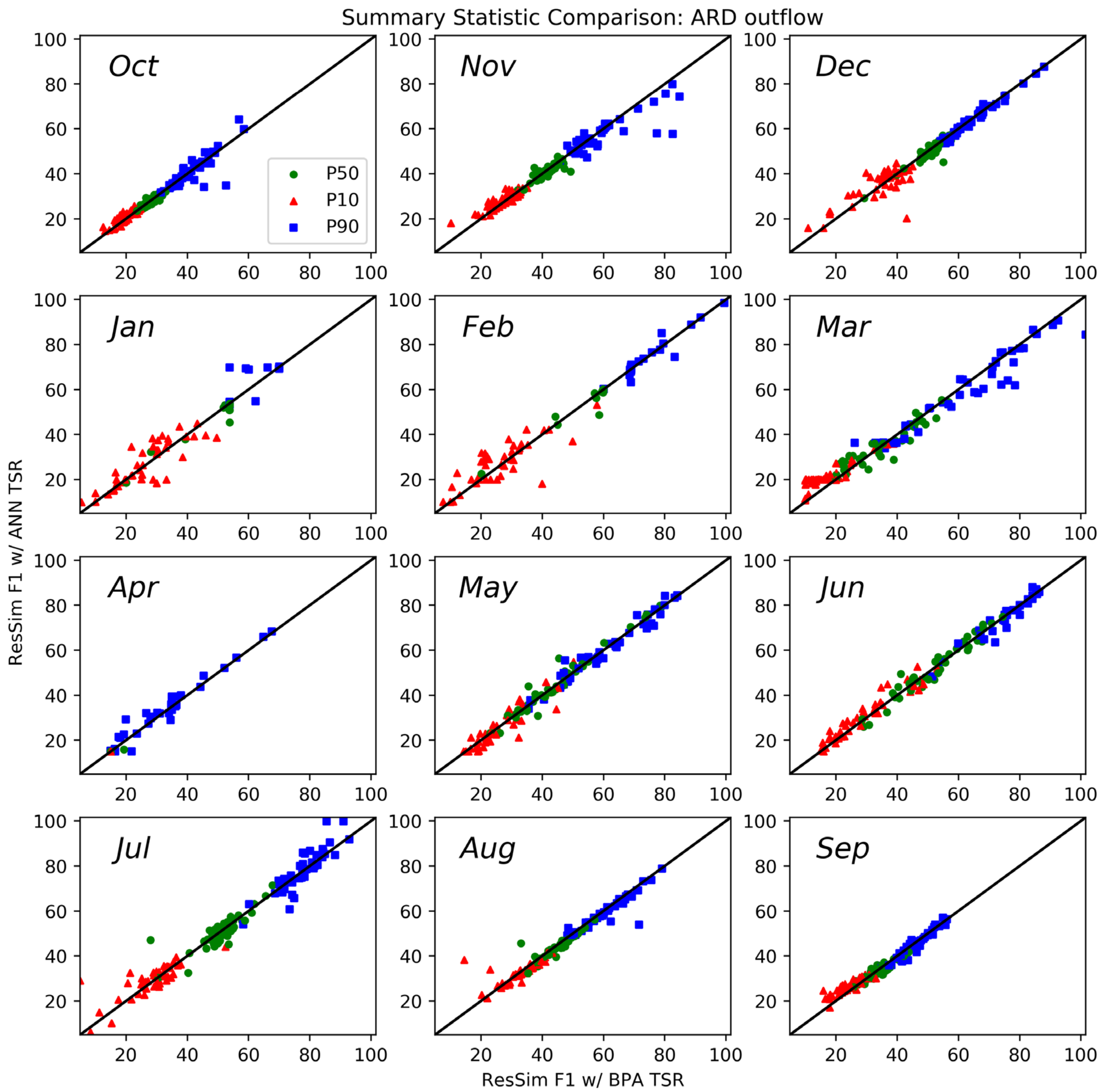

Figure A-14. Comparison of regulated outflow of Arrow Lakes Reservoir (ARD) using the WAT-ResSim model with artificial neural network Treaty Storage Regulation inputs (ResSim F1 w/ ANN TSR) to the results of the WAT-ResSim model using Hydsim Treaty Storage Regulation input (ResSim F1 w/ BPA TSR). The metric of comparison is statistical composites (10th, 50th, and 90th percentiles) calculated for each epoch (2030s and 2070s) in each projection. The black line represents a 1:1 relationship.

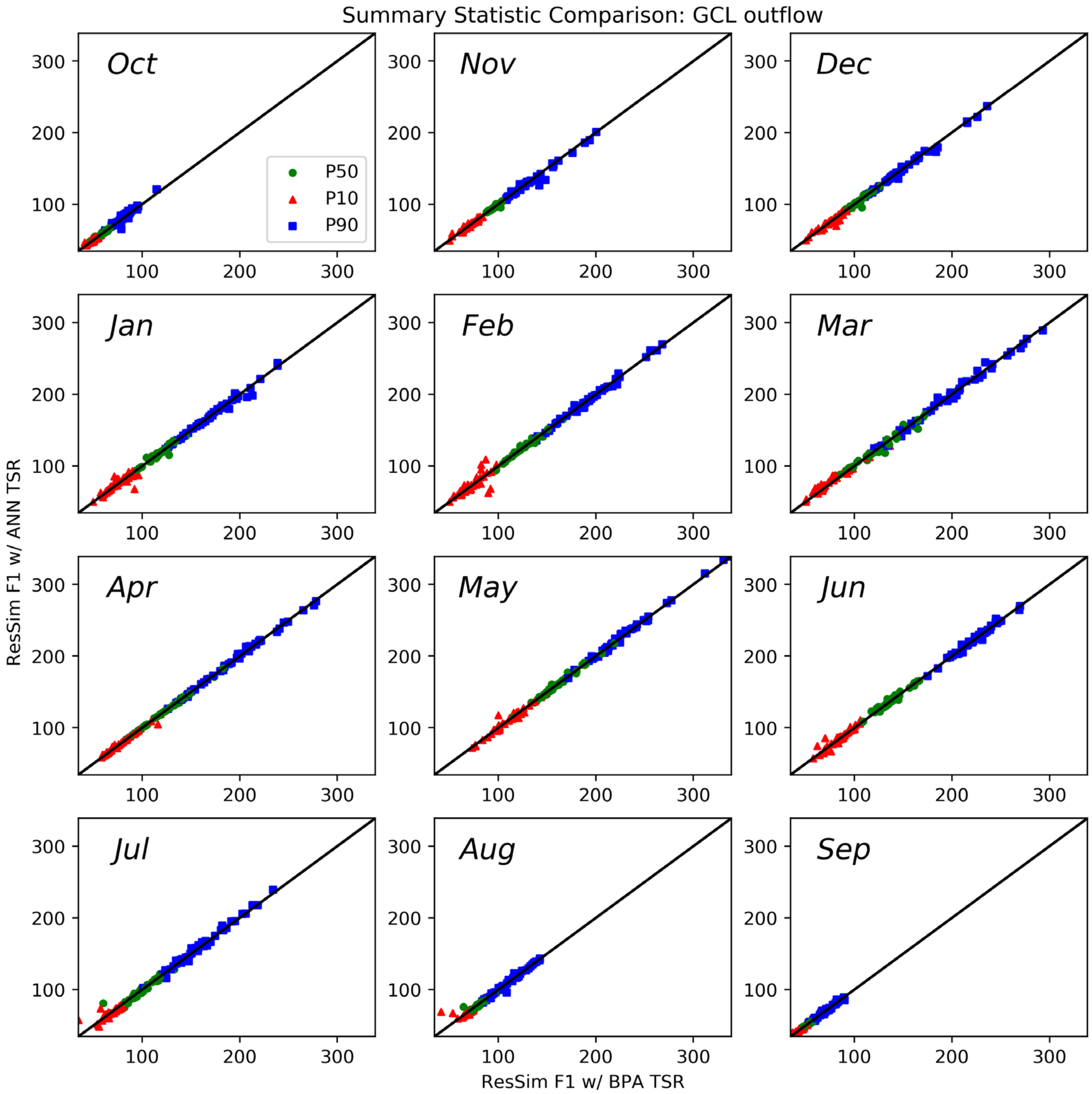

Figure A-15. **Comparison of regulated outflow of Grand Coulee Dam (GCL) using the WAT-ResSim model with artificial neural network Treaty Storage Regulation inputs (ResSim F1 w/ ANN TSR) to the results of the WAT-ResSim model using Hydsim Treaty Storage Regulation input (ResSim F1 w/ BPA TSR). The metric of comparison is statistical composites (10th, 50th, and 90th percentiles) calculated for each epoch (2030s and 2070s) in each projection. The black line represents a 1:1 relationship.**

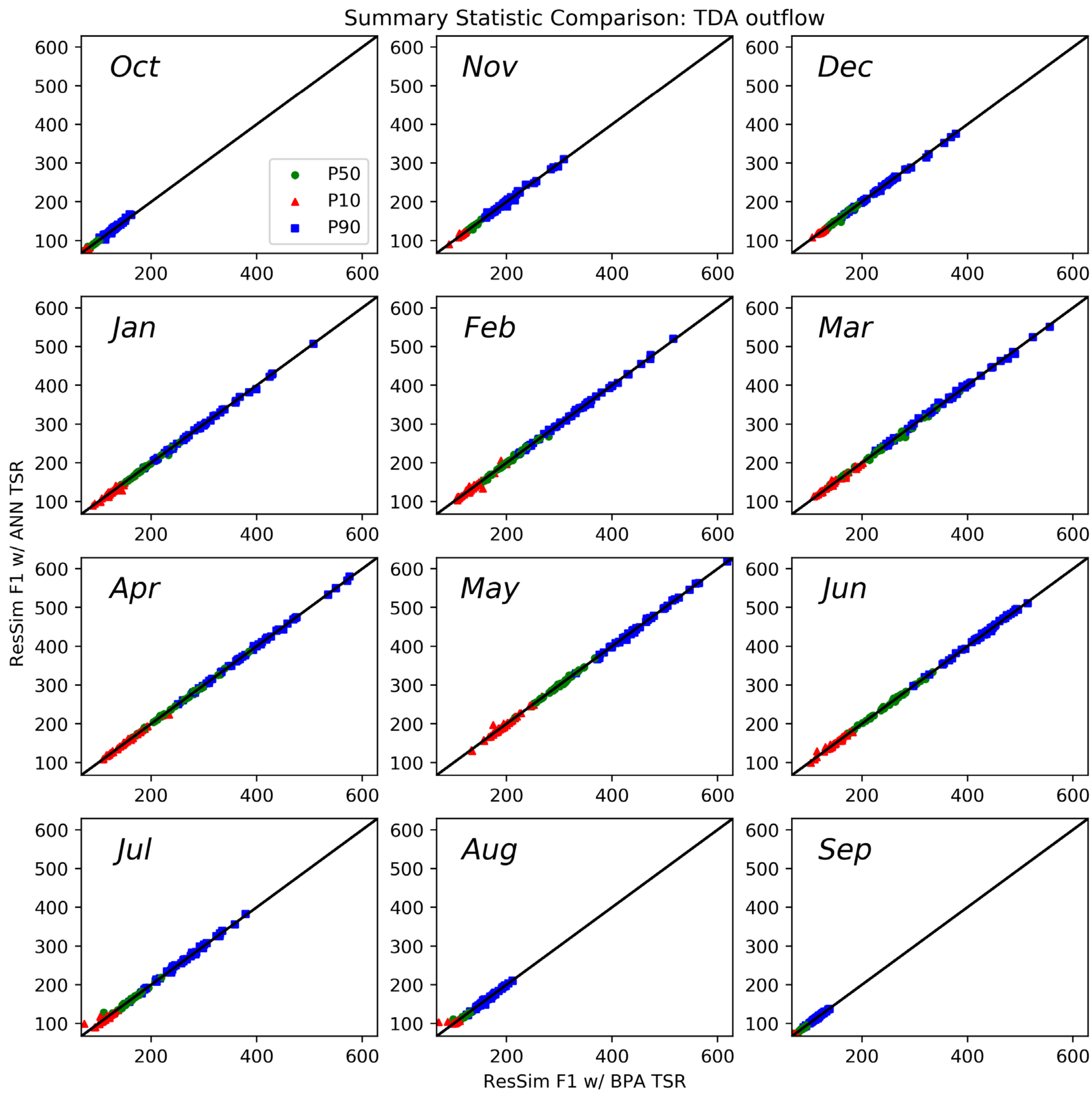

Figure A-16. **Comparison of regulated outflow of The Dalles dam (TDA) using the WAT-ResSim model with artificial neural network Treaty Storage Regulation inputs (ResSim F1 w/ ANN TSR) to the results of the WAT-ResSim model using Hydsim Treaty Storage Regulation input (ResSim F1 w/ BPA TSR). The metric of comparison is statistical composites (10th, 50th, and 90th percentiles) calculated for each epoch (2030s and 2070s) in each projection. The black line represents a 1:1 relationship.**

A.7 VERTICAL DATUM SHIFT

Table A-4 shows the datum adjustment from NGVD29 to NAVD88 for all dams and CCPs within the model. Datum conversion values were calculated using Corpscon6 (a coordinate conversion software developed by the Corps). The latitude and longitude of the point to be converted (e.g., top of dam) was obtained from the project's background information. If this information was not available, the midpoint of the dam was estimated using ArcGIS and aerial photography, and latitude and longitude values were extracted for use in Corpscon.

Table A-4. Vertical Datum Adjustment.

Dam or CCP Name	Datum Adjustment (feet)
Albeni Falls	3.9
American Falls	3.3
Anderson Ranch	3.4
Arrow	4.3
Arrowrock	3.4
Bonneville	3.3
Boundary	4.0
Box Canyon	4.0
Brilliant	4.2
Brownlee	3.3
Bumping Lake	3.9
Cabinet Gorge	3.9
Cascade	3.6
Chelan	3.9
Chief Joseph Dam	4.0
Cle Elum	3.9
Corra Linn	4.3
Deadwood	4.0
Duncan	4.3
Dworshak	3.3
Grand Coulee	3.9
Hells Canyon	3.6
Hungry Horse	3.9
Ice Harbor	3.4
Jackson Lake	4.3
John Day	3.2
Kachess	3.9
Keechelus	4.0
Kootenay Canal Projects	4.2
Libby	3.9
Little Falls	3.8
Little Goose	3.2
Long Lake Dam/Lake Spokane	3.8

Dam or CCP Name	Datum Adjustment (feet)
Lower Bonnington	4.2
Lower Granite	3.4
Lower Monumental	3.3
Lucky Peak	3.3
McNary	3.3
Mica	4.7
Monroe Street	3.8
Nine Mile	3.8
Noxon Rapids	3.9
Owyhee	3.3
Oxbow	3.4
Palisades	4.0
Pelton	3.6
Pelton ReReg	3.5
Post Falls – Lake Cœur d'Alene	3.8
Priest Lake	4.0
Priest Rapids	3.5
Revelstoke	4.5
Rock Island	3.7
Rocky Reach	3.8
Round Butte	3.6
Seven Mile	4.1
SKQ	3.6
Slocan	4.2
The Dalles	3.3
Thompson Falls	3.8
Tieton	3.8
Upper Bonnington	4.2
Upper Falls	3.8
Wanapum	3.5
Waneta	4.0
Wells	4.0

The Columbia River Datum (CRD) is a plane of reference from which river stage is measured on the Columbia River from the lower Columbia River up to Bonneville Dam, and on the Willamette River up to Willamette Falls. Equals 1.82 feet above mean sea level (equivalent to NGVD) at Vancouver, Washington.

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