RECLAMATION
Managing Water in the West

Crooked River Pilot Study

Analysis of resource impacts from operational changes due to various runoff volume forecast methods, future climate scenarios, and alternative operations

Crooked River Basin, Oregon

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region
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U.S. DEPARTMENT OF THE INTERIOR

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Acronyms and Abbreviations

Acronym or Abbreviation	Description
BC-ESP	Bias-Corrected Ensemble Streamflow Prediction
BCSD	Bias Corrected Spatial Disaggregation
cfs	cubic feet per second
CHPS	Community Hydrologic Forecast System
CMIP5	Coupled Model Intercomparison Project Phase 5
Corps	U.S. Army Corps of Engineers
CRBIA	Columbia River Basin Impact Assessment
CRCWA	Crooked River Collaborative Water Security and Jobs Act of 2014
dSRD	dynamic Storage Reservation Diagram
EbF	Ecosystem-based Function
ESP	Ensemble Prediction System
GCM	Global climate models
HDe	Hybrid Delta Ensemble Method
HRU	hydrologic response units
LWD	Less-warming/dry
LWW	Less-warming/wet
M&I	municipal and industrial
MLR	multiple linear regression
MRM	Multiple Run Manager
MWD	More-warming/dry
MWW	More-warming/wet
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NOAA Fisheries	National Oceanic and Atmospheric Administration Fisheries
NUID	North Unit Irrigation District
NWRFC	Northwest River Forecast Center
OID	Ochoco Irrigation District
PN	Pacific Northwest
PRMS	Precipitation Runoff Modeling System
Reclamation	Bureau of Reclamation
SRD	storage reservation diagram
SWE	snow-water equivalent
TDG	total dissolved gas
TSC	Reclamation Technical Service Center
USFWS	United States Fish and Wildlife Service
WaterSMART	Sustain and Manage America's Resources for Tomorrow
WUA	weighted usable area
WY	water year (October-through-September)

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Executive Summary

The Crooked River Reservoir Operations Pilot Study (Study) was selected to contribute to the Bureau of Reclamation (Reclamation) Reservoir Operations Pilot Initiative, which focuses on identifying innovative approaches to improve water management strategies in the western United States. The initiative began in 2014 to help meet priorities identified in the Department of the Interior's WaterSMART (Sustain and Manage America's Resources for Tomorrow) program and is a key component of Reclamation's implementation of the SECURE Water Act of 2009 (Act). The overarching goal of the Act, and the WaterSMART program, is to help secure reliable water supplies to meet the nation's current and future water needs. Under the initiative, Reclamation selected five pilot studies for implementation, one in each of Reclamation's five regions. The goal of the pilots is to develop guidance for identifying and implementing changes that increase flexibility in reservoir operations in response to variability in water supplies, floods, and droughts.

This Study, which was led by the Pacific Northwest Regional Office (PNRO), fulfills the needs of the program for the Pacific Northwest (PN) Region. It explores alternatives for managing Crooked River reservoir operations to address variations in flows from one year to the next and identifies impacts to various resource areas from changing operations. Results from this Study may provide guidance for other similar basins in the PN Region or elsewhere with similar watershed or operational considerations. This Study was developed with collaboration from the following stakeholders: the Reclamation Technical Service Center (TSC), the U.S. Army Corps of Engineers (Corps) Portland District, the National Center for Atmospheric Research (NCAR), and the Northwest River Forecast Center (NWRFC).

Background

Reservoirs in the Pacific Northwest (PN) Region are in basins that range from snow-dominated at higher elevations to rain-dominated at lower elevations, with most basins spanning both these zones. Since most of the PN Region watersheds have a rain-snow transitional zone, the amount of runoff experienced from either rain or snow has a high degree of variability from one year to the next. These rain-snow transitional zones can be significantly impacted by changes in climate variability. In hotter, drier years, the earlier timing of runoff may result in an increase in winter flows with larger peak events, but also may result in a decrease in summer base flows. These types of changes in the hydrologic regime pose significant challenges to the management objectives of Reclamation reservoirs, which are managed to provide for multiple purposes, such as flood control, water supply, hydropower generation, ecosystem requirements, and recreation.

The Crooked River basin is a subbasin of the larger Deschutes River basin, located in central Oregon. The Crooked River is a regulated system controlled by the Arthur R. Bowman Dam (formerly Prineville Dam). The dam impounds streamflow from the Crooked River and a small tributary (Bear Creek) to create Prineville Reservoir (active storage of 148,600 acre-feet). The dam serves many purposes, including providing flood control under the Flood Control Act of 1944 (33 CFR 209.220), water supply (irrigation and municipal and industrial (M&I)), fish and wildlife benefits, and recreational opportunities.

The Crooked River watershed, which this project focuses on, is characterized as a high desert landscape prone to large, flashy, early-winter rain-on-snow type runoff events, resulting in streamflows rising rapidly. Prineville Reservoir operates during the reservoir refill season (mid-February through April) using refill guidance provided from a dynamic Storage Reservation Diagram (dSRD). The dSRD provides reservoir space requirements based on the forecasted volume of runoff for any date within the refill season. Current forecasting methods are based on the historical hydrologic regime (i.e., post-1955), which contains years with rain-on-snow events in the low- and mid-elevations of the basin and snowmelt-driven runoff at the higher elevations in the basin. If this hydrologic regime changes in the future, forecast equations currently used may not perform as well as they have in the past. The challenge in the future may be developing a forecast method that performs well at capturing both historical variability while also performing well under changing conditions in which runoff variability may increase.

Purpose

The purpose of this Study was to examine how different operational approaches at Prineville Reservoir could be used to better meet management objectives under future climate variability and a changing hydrologic regime. The designed resiliency of Prineville Reservoir to large, flashy runoff events by way of using surcharge storage already provides greater reliability for water supply. The dam design accomplishes this by allowing the reservoir to refill much quicker than it would be able to if it did not have the added security of surcharge space. A changing hydrologic regime, changing stakeholder expectations, and development around the reservoir may alter or limit this surcharge flexibility in the future.

This Study examines the existing resiliency at Prineville Reservoir by looking at how different forecast methods may improve operations and how a suite of future climate scenarios may impact various project resource considerations. Finally, the Study uses the 2080s future climate scenario to develop two alternative reservoir operations: 1) for dry-year scenarios, and 2) for developing a new dSRD based on a 2080s future climate scenario.

Approach

Reclamation used the RiverWare modeling program to simulate the operational impacts to important management objectives, such as flood control, water delivery, water quality, recreation, and ecological resources. The modeling also allowed a comparison of impacts to management objectives between historic conditions and future climate scenarios. For the purposes of this Study, the Deschutes Basin Study Model was modified to include just the Crooked River portion (Pilot Model) to reduce the computational requirements and model run times for Study tasks.

The general modeling approach was to evaluate the differences between simulations by changing the model inputs (e.g., historical flows versus future climate flows) while keeping the operational logic the same. By doing this, the change in reservoir outflows and resulting impacts to management objectives could be investigated. Historical simulations (hereafter called Current Condition) were the baseline results that all other scenarios were compared to.

The Study team developed metrics for evaluating the effects of scenarios on various management objectives. The flood control metrics include downstream flood control, reservoir surcharge, and reservoir refill. The water delivery metrics include storage allocation and storage carryover. The water quality metrics include total dissolved gas (TDG) and water temperature. The recreational resource metrics include downstream recreation and reservoir recreation. The ecological resource metrics include minimum flow and weighted usable area.

Hindcasting was completed using three different forecast methods to investigate whether improvements to water supply forecasting for the Prineville Reservoir were available. A hindcast can be described as a forecast produced for a historical period. Whereas historical simulations are driven by observed, or perfect, forcings (e.g., measured precipitation), and can be used to assess the performance of a hydrologic model, hindcasts are driven by forecasted, or imperfect, forcings, and can thus be used to assess the performance of a hydrologic forecast system. Hindcasts were generated for the 1984-2010 period to compare the performance of each forecast method. Modeling the hindcasts in the Pilot model allowed the Study team to determine what changes to reservoir outflows resulted from the use of an alternative forecast method.

Future climate scenarios were developed using data from the Bias Corrected and Spatially Downscaled (BCSD) CMIP5 Climate and Hydrology Projections archive hosted by the Lawrence Livermore National Laboratory (https://gdo-dcp.ucllnl.org/). These climate projections were generated through the fifth phase of the Coupled Model Inter-comparison Project (referred to as CMIP5) and were statistically downscaled to the 1/8-degree using the BCSD method (Reclamation 2014). These data were combined into scenarios using the Hybrid Delta Ensemble (HDe) Method approach (Reclamation 2010), which uses monthly change factors, calculated from select groups (or ensembles) of downscaled global climate model (GCM) projections, to adjust historical daily gridded meteorological datasets for input to a hydrologic model.

The Study Team selected three future time periods for analysis of future climate impacts, including 30-year periods surrounding the 2040s (2030-2059), 2060s (2050-2079), and 2080s (2070-2099). Five scenarios were developed for each period, including: less-warming/dry (LWD), less-warming/wet (LWW), more-warming/dry (MWD), more-warming/wet (MWW), and median. As a result, 15 HDe future climate scenarios were evaluated for use in this Study. Based on the results of the future climate modeling, the Study developed alternative operations to provide resiliency to hydrologic variability and reduce the impacts on operational objectives.

Findings

Water supply for the Crooked River watershed has historically been difficult to forecast due to the variability in the rain-snow transitional zone during the snow accumulation period. Three different hindcasting methods were used to investigate whether any improvements to the forecast skill might be possible. NCAR hindcasts were found to provide improvements in early season forecasts during January. MLR hindcasts resulted in the smallest errors in February and March while the NWRFC hindcasts had lowest errors in April and May. Resource metrics were used to determine the impact of hindcast errors on actual operational objectives. MLR hindcasts were found to have the fewest number of additional days above 3,000 cfs when compared to the

Perfect Forecast while NCAR hindcasts resulted in 15 fewer days at discharges greater than 2,000 cfs. Overall, impacts to discharges from hindcast methods tended to be minimal due to minimal flood control space requirements for most forecasted runoff volumes (due to surcharge space available). Hindcasts that resulted in more days of surcharge were found to be a result of under-forecasting runoff volume. NWRFC hindcasts had the fewest number of days when surcharge occurred. MLR and NCAR hindcasts resulted in similar number of days of surcharge with 82 percent and 58 percent of those days being minimal with less than 0.2 feet of surcharge. Hindcasts were not found to have an impact on the allocation of water supply. Overall, hindcasts were found to have minimal impacts on both recreation and ecological resources.

The next part of the Study developed various future climate scenarios and modeled these using the Pilot Model to determine impacts to various resource categories. It is important to recognize that future climate projections have uncertainties inherent in the multi-step process of their development. Acknowledging these uncertainties allows to use the best available science to create a robust range of possible future risks and conditions. These potential future risks were used in this Study to help identify appropriate adaptation strategies and meet the overarching goal of the WaterSMART program.

Future climate summary hydrographs showed earlier runoff timing and subsequent earlier recession of flows in April. Some summary plots showed larger magnitude peak flows during the December-through-February period. Most future climate scenarios resulted in water year streamflow volumes that were greater than historical levels (10 out of 15 scenarios). This aligns with most of the future precipitation and temperature projection ensembles, which were wetter than historical as well.

The Study team decided to complete resource metric analysis for the future climate 2080s time horizon because this time horizon provided the largest variation in runoff volumes and provided an opportunity for alternative operations development.

The 2080s future climate scenarios resulted in larger reservoir outflows during the month of March but lower outflows in April. The LWW scenario resulted in the most number of days in which reservoir discharges exceeded 3,000 cfs, with some days exceeding 4,000 cfs (3,000 cfs is current operational flood control target). All scenarios except for LWW resulted in minimal impacts to reservoir surcharge, however; the LWW scenario resulted in a maximum surcharge of 14.9 feet. All 2080s future climate scenarios resulted in the same number of years in which the reservoir accomplished full refill, although the storage carryover volumes were less for drier scenarios and more for the median and wetter scenarios. All future climate scenarios (except for the MWD scenario) resulted in more days when TDG was above 120 percent. Optimal fishing days increased for the LWD and MWD scenarios due to lower reservoir discharges and decreased for the LWW, MWW, and median scenarios. The number of boating days increased for the LWD and MWD scenarios and decreased for the LWW, MWW, and median scenarios. In general, recreation was negatively impacted for the wetter scenarios due to deeper and longer duration reservoir drafts and larger reservoir discharges required for flood control operations from these larger runoff volumes. The drier future climate scenarios resulted in fewer days when flows below the Prineville Reservoir were greater than the 80 cfs recommended minimum flow.

The LWW scenario increased the time flow exceed 80 cfs at the Highway 126 bridge by 13 percent.

Prineville Reservoir's existing 3,000 cfs operating dSRD performed well for all future climate scenarios except the 2080 LWW scenario, which resulted in discharges more than the maximum flood release target of 3,000 cfs. This provided insight into how effective the existing SRD is and how adaptable it is to a changing hydrologic regime. The ability of the existing dSRD to use the maximum outflow discharge of 3,000 cfs and available surcharge allowed the reservoir to meet the dual, but sometimes conflicting, goals of providing flood control while also ensuring reservoir refill for water supply.

Based on the results of the future climate scenario modeling, this Study found two alternative operations to lessen the impacts from the future climate flow variability. Operation criteria considered when developing alternative operations included: 1) modifying in-season operations in dry years to optimize storage; 2) reducing the number of days in which discharge exceeds 3,000 cfs flood control target; and 3) reduce the number of days in which total dissolved gas (TDG) exceeds 120 percent. These operating criteria were used in the development of dry-year alternative operations or changes to the dSRD.

The dry-year alternative operation was developed in response to years of less-than-average runoff volume when the reservoir failed to refill completely but also experienced flood control releases during the static winter flood-space requirement period (November 15 through February 15). This proposed dry-year alternative operation assumed that the current basin conditions indicated a low risk for large rain-on-snow events (e.g., very little snow present in the basin) and that justification for a deviation from the Corps flood control operating criteria could be granted. Years included in the dry-year alternative operation had runoff that ranged from 26 to 86 percent of average. The dry-year alternative showed that for 11 years out of the 30-year 2080 LWW scenario, additional refill was obtained through a 15- or 30-day deviation of the static winter space requirement. The 15-day deviations resulted in an increase of 2,000 to 14,000 acre-feet of additional reservoir refill for water supply, while 30-day deviations resulted in an increase of 3,000 to 23,000 acre-feet.

Due to the 2080s LWW scenario resulting in discharges exceeding 4,000 cfs, an alternative dSRD (FRM3kcfs) was developed to minimize discharges to 3,000 cfs, which is the current downstream flood control target. A second dSRD (EbF120%) was developed based on the current desire of fish managers to limit TDG levels above 120 percent. Runoff volume-storage envelope curves were developed at 15-day intervals during the refill period (December-through-April) to determine the amount of storage required to not exceed the 3,000 cfs (FRM3kcfs curve) or 2,000 cfs (EbF120% curve) maximum discharge targets. After the volume storage curves were developed, space requirements between the 15-day intervals were estimated using the best available correlation. Completing this process developed a continuous space requirement for any day within the entire December-through-April reservoir refill period based on a forecasted runoff volume.

Both the FRM3kcfs and Ebf120% curves resulted in no discharges greater than 3,000 cfs. The EbF120% curve resulted in 317 fewer days in which discharges were greater than 2,000 cfs. The FRM3kcfs reduced maximum surcharge to 0.2 feet compared to the Existing dSRD that resulted in a maximum of 14.9 feet. The FRM3kcfs and Ebf120% curves resulted in minor impacts to storage allocation and reservoir carryover. The EbF120% curve performed well at reducing TDG with only 14 days above 120 percent compared to the Existing dSRD that resulted in 248 days. The FRM3kcfs curve resulted in 68 fewer days at 120 percent TDG when compared to the Existing dSRD. Boating recreation was impacted by both the EbF120% and FRM3kcfs scenarios due to deeper and longer duration flood control drafts. Both the EbF120% and FRM3kcfs scenarios were found to have minimal impact to ecological flow targets.

Overall, both the FRM3kcfs and Ebf120% curves performed well at meeting their specific objectives although ancillary impacts were found on other resource categories. For instance, the reduction in the number of days below 120 percent TDG came at a cost of more days above 115 percent TDG and fewer boating days.

The following is a list of possible future efforts that may be beneficial at similar-type basins:

- Continue to seek ways to improve runoff volume forecasting
- Perform a thorough review of forecast limitations and error analysis
- Identify ways to incorporate a formal dry-year alternative operation into the water control manual
- Review opportunities for updating dSRD or rule curves if project is having problems providing historical probabilities for flood control or water supply.

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1 Study Introduction

This report begins with a discussion of the Study background, purpose, and description. Next, it provides a description of the Study watershed and a project description, which provides the context for the Study. Lastly, an overview of the metrics development process is provided, as well as a modeling description, hindcast modeling methods and results, future climate flow development and modeling results, and alternative operations modeling.

1.1 Study Background and Purpose

The Crooked River Reservoir Operations Pilot Study (Study) was selected to contribute to the Bureau of Reclamation (Reclamation) Reservoir Operations Pilot Initiative. This initiative is part of the WaterSMART (Sustain and Manage America's Resources for Tomorrow) Basin Study Program's West-Wide Climate Risk Assessment strategy to meet the nation's water needs now and in the future (Reclamation 2015).

In the Pacific Northwest (PN) Region, reservoirs are located in basins that range from snow-dominated at higher elevations to rain-dominated at lower elevations, with the majority of the basins containing both of these zones. Since most of the reservoirs have a rain-snow transitional zone, the amount of annual runoff experienced from either rain or snow can have a high degree of variability from one year to the next. Based on current projections of future climate variability, basins with these transitional zones have a greater risk of experiencing a changing hydrologic regime. In basins where an increase in air temperature and a decrease in snow accumulation are projected, the earlier timing of runoff may result in an increase in winter flows with larger peak events but may also result in a decrease in summer base flows due to runoff occurring earlier in the year. These types of changes in the hydrologic regime of a basin will pose increased challenges for the operators of Reclamation reservoirs, which are carefully managed to provide for multiple purposes, such as flood control, water supply, hydropower, ecosystem requirements, and recreation.

1.2 Pilot Study Description

This Study focuses on the Crooked River basin, which is a sub-basin of the larger Deschutes River basin located in central Oregon. The Study explores potential adaptation strategies to mitigate the risks and impacts of future climate variability and the resulting change to the hydrologic regime of a watershed. Results from this Study may provide guidance for other similar basins in the PN Region, as well as other regions that are projecting similar climatic variability of their watersheds. In addition, this Study hopes to provide a knowledge base of adaptation strategies for inclusion in a Reclamation-wide guidance on assessing and responding to the impacts of future climatic variability on reservoir operations.

Current Reclamation-managed project features on the Crooked River Project (Project) include the Arthur R. Bowman Dam on the Crooked River, the Feed Canal and headworks on the Crooked River, Ochoco Dam on Ochoco Creek, Ochoco main and distribution canals, and Lytle Creek Diversion Dam and Wasteway, as well as multiple pumping plants. The geographic scope for this Study was limited to only the Crooked River arm of the Project, starting from the headwaters and extending downstream to the City of Prineville, Oregon, and did not include project features on Ochoco Creek.

As a major tributary to the Deschutes River, the Crooked River drains a semi-arid region of central Oregon (Figure 1). The Crooked River watershed is largely a transitional basin fed by a combination of rain and snow. Both the Deschutes River and Crooked River systems can experience dramatic changes in annual runoff from one year to the next. The Crooked River watershed is more indicative of a snowmelt dominated basin while the Upper Deschutes is highly groundwater dominated basin with less flashy runoff characteristics and a more dampened hydrograph. Both rivers are also highly susceptible to a change in the climatic variability, not only with a flow regime change (earlier peak flow timing, low summer base flows), but also with the likely shift in precipitation form from snow to rain due to the proportion of these basins being in the transitional zone.

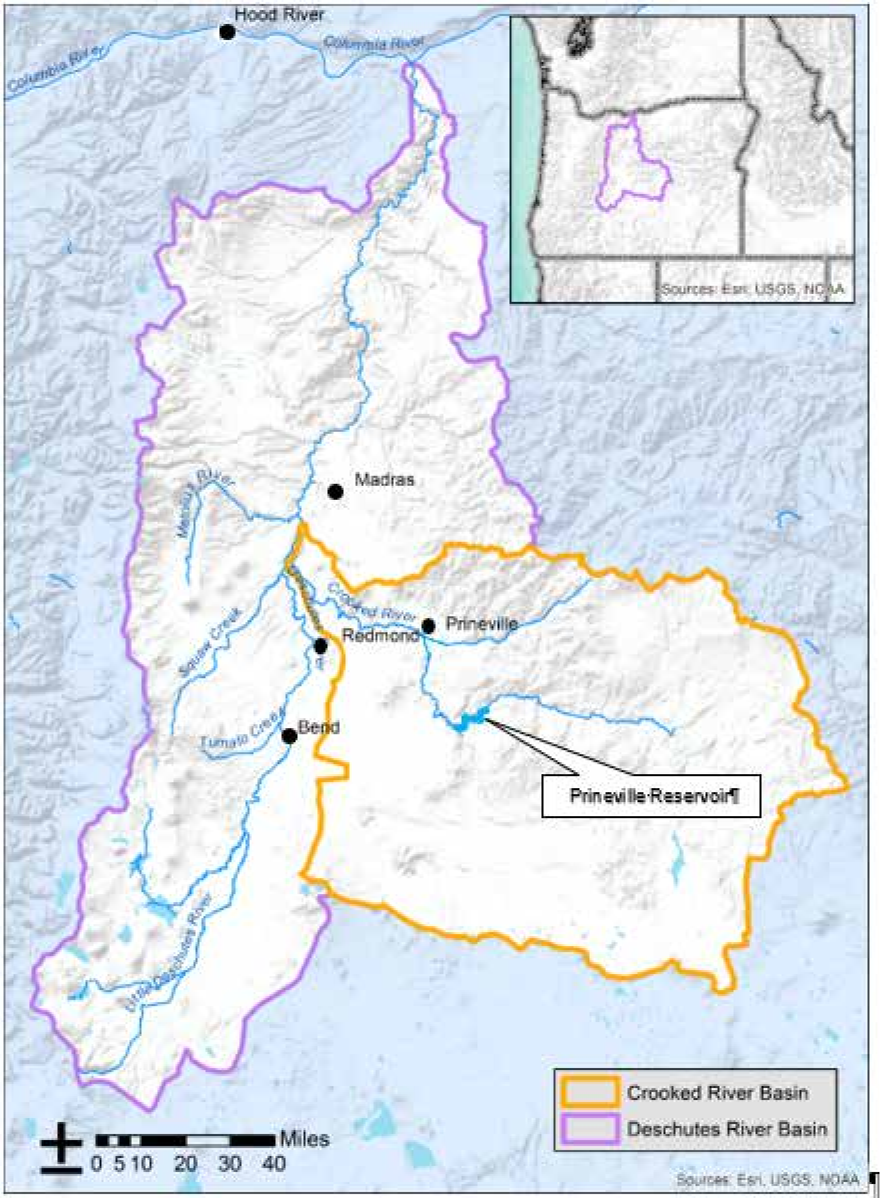

Figure 1. The Deschutes River basin, with the Crooked River sub-basin outlined in orange

1.3 Study Approach Overview

The study approach overview provides a description the various tasks accomplished during this Project, which include the development of resource metrics, runoff volume hindcasting, reservoir operations and surface water modeling, future climatic variability hydrologic modeling and analysis, and modeling of water resource alternative scenarios. This work is a key element of Reclamation's responsibilities for completion of the Pilot Study.

1.3.1 Resource Metric Development

The Study team developed resource metrics to measure the impact of different forecast methods and reservoir inflow scenarios on various project considerations. Prineville Reservoir is authorized for flood control, water supply, and fish and wildlife maintenance flows, as well as other ancillary purposes. Resource metrics were developed to include flood control, water delivery, water quality, recreation, and ecological resources. The description of these resource metrics can be found in Section 3.

1.3.2 Simplify Basin Study Model for use in the Pilot Study

A Riverware model of the Deschutes River basin was updated for the ongoing Deschutes River Basin Study and was adapted to be used for this Study. The Deschutes River Model includes the Deschutes River arm above Lake Billy Chinook, as well as the Crooked River and Ochoco Creek. For this Study, the larger Deschutes River Model was modified to include only the Crooked River and Ochoco Creek portions (Pilot Model) to reduce computational run times and provide more opportunities for project-specific analysis. The Pilot Model uses rules-based logic to complete surface water, groundwater, and water accounting modeling. A rules-based model relies on a user-defined prioritization of several possible operations that allows for the model to determine which action is the most critical. The Pilot Model was also updated to include changes to operations at Prineville Reservoir per the Crooked River Collaborative Water Security and Jobs Act of 2014 (Public Law 133-244). Additional information about the modeling software, assumptions, and calibration results can be found in Section 4.

1.3.3 Runoff Volume Hindcast Development

Runoff volume hindcasts were developed for the Prineville Reservoir using the period of 1984 to 2010 as a calibration and performance testing period. Hindcasts may be defined as a forecast of a historical period (e.g., hindcasting for the 1985 water year). Hindcasts were generated for this Study by the National Center for Atmospheric Research (NCAR), the Northwest River Forecast Center (NWRFC), and by Reclamation’s PN Regional Office. Hindcasts were used as inputs into the Pilot model to direct the reservoir release during the flood control and refill season to determine what, if any, impacts there were to different hindcast methods described above.

1.3.4 Operational Modeling using Hindcast Forecasts

The Pilot Model relies on a water-supply forecast to determine the required space in the reservoir for flood control. Reservoir space is based on a storage reservation diagram (SRD), developed to balance flood risk management with reservoir refill. Whereas historical simulations are driven by observed, or perfect, forcings (i.e., model inputs) and can be used to assess the performance of a hydrologic model, hindcasts are driven by forecasted, or imperfect, forcings, and can thus be used to assess the performance of a hydrologic forecast system. The Pilot Model was used to compare flood control and refill operations of historical hydrology (1984-2010) at Prineville Reservoir using various hindcast methods. Resource metrics (e.g., flood control, reservoir refill, recreation, etc.) were used to determine the impact of three different hindcast methods on operations. Results from the modeling provide insight into any opportunities available for improving forecasting, as well as for measuring how forecast improvements may affect actual operations.

1.3.5 Determine and Prepare Future Climate Flows

This Study leverages the tools and processes developed under the Columbia River Basin Impact Assessment (CRBIA) to generate Hybrid Delta Ensemble future climate scenarios and simulate future streamflows using the Precipitation Runoff Modeling System (PRMS) hydrologic model. The scenarios are based on a subset of the 231 Bias Corrected Spatial Disaggregation (BCSD) Coupled Model Intercomparison Project Phase 5 (CMIP5) projections. After the full set of future streamflows were generated (2040s, 2060s, or 2080s), the Study Team selected the future streamflow time series that best addressed the objectives of this Study. A more detailed description of this process can be found in Section 6.

1.3.6 Operational Modeling of Future Climate Flows

The Pilot Model used future scenarios developed for the 2080s. As stated earlier, the Study Team identified the future climate time series (2080s) used for the modeling, as time limitations did not allow for modeling of all the time series. Impacts to resource metrics identified when these different flow scenarios cause changes to project operations and what impacts these operational changes cause to existing resource considerations. Results from operational modeling using future scenarios led to the development of alternative operations, in which flexibility in operations were identified to reduce impacts to specific resource metrics.

1.3.7 Develop and Test Alternative Operations

Using results from future climate scenario simulations, alternative operations were developed to use any existing operational flexibility to reduce the impacts to specific resource metrics. Alternative operations include actions such as modifying dry-year operations, modifying flood control operations for a different future climate streamflow time series, or modifying operations to reduce impacts to a certain operational flow targets. The objective for alternative operations is to fulfill flood control obligations while still meeting project refill for water supply and ecological constraints.

1.4 Stakeholders

This Study was developed with collaboration from the following stakeholders:

- Reclamation Technical Service Center (TSC)
- Portland District Northwest River Forecast Center (NWRFC)
- National Center for Atmospheric Research (NCAR)
- U.S. Army Corps of Engineers (Corps)

2 Location and Background

2.1 Watershed Description

For the purposes of this Study, the Crooked River watershed is described as the contributing watershed upstream of the City of Prineville, Oregon. The watershed is further delineated into two sub-watersheds that drain into either Ochoco Reservoir or Prineville Reservoir. The watershed consists of desert shrub and juniper at lower elevations, with evergreen forests and meadows at higher elevations. It is characterized as a high desert landscape prone to large, flashy, early-winter events when rain-on-snow events result in rapidly rising streamflows. Temperatures in the lower part of the watershed range from average highs in the winter of 43 degrees, to average highs in the summer of 86 degrees. Periods of below-freezing temperatures in the winter and 100º F+ days in the summer are not uncommon. Table 1 below summarizes various watershed characteristics, separated into sub-watersheds above Prineville Reservoir and Ochoco Reservoir.

Table 1. Watershed characteristics upstream of Prineville Reservoir and Ochoco Reservoir

Watershed	Watershed Area (mi^2)	Mean Basin Elevation (ft)[1]	Min. Basin Elevation (ft)[1]	Max. Basin Elevation (ft)[1]	Mean Annual Runoff (thousand acre-feet)
Prineville Reservoir	2,760	4,530	3,075	7,200	244[2]
Ochoco Reservoir	300	4,435	3,010	6,950	45[3]

[1] Elevations in NAVD88
[2] 1981-2010 average
[3] 1984-2010 average

2.2 Project Description

The Act of August 6, 1956 (70 Stat. 1058; chapter 980; 73 Stat. 554; 78 Stat. 954), authorized the Crooked River Project for irrigation and other beneficial purposes. Flood control is one of the project purposes, as are the preservation and propagation of fish and wildlife, provided for through a minimum release of 10 cubic feet per second (cfs) during months when there is no other discharge from Prineville Reservoir and the installation of a fish ladder and screen at the Feed Canal diversion headworks.

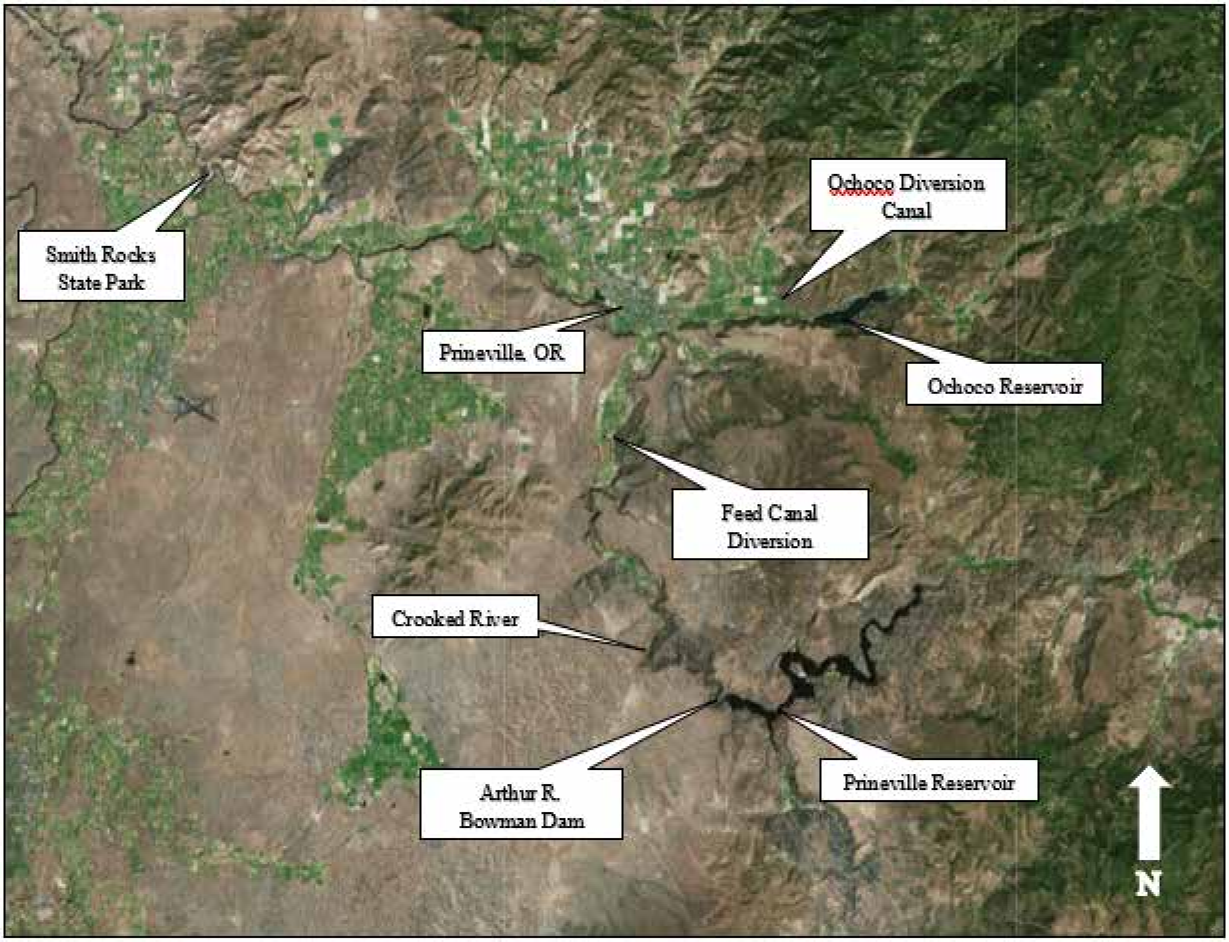

Figure 2. Crooked River Project overview map

The main body of the Crooked River Project (Figure 2) lies north and west of Prineville, Oregon. The water resources of Ochoco Creek and the Crooked River furnish irrigation water for approximately 20,000 irrigated acres. Project features include Arthur R. Bowman Dam (formerly Prineville Dam) on the Crooked River; Ochoco Dam on Ochoco Creek, a diversion canal (Feed Canal) and headworks on the Crooked River; Lytle Creek Diversion Dam and Wasteway; two major pumping plants; nine small pumping plants; and Ochoco Main and distribution canals. Through congressional approval in 1964, the 3,450-acre Crooked River Extension was added to the project. This additional acreage was made possible using the extra capacity included in the canal and pumping plants when the Crooked River Project was constructed, building six additional small pumping plants and using a portion of the uncontracted storage space in Prineville Reservoir.

The Crooked River is a regulated system controlled by the Arthur R. Bowman Dam. The dam impounds streamflow from the Crooked River and a small tributary (Bear Creek) to create Prineville Reservoir. The dam serves many purposes, including providing flood control under the Flood Control Act of 1944 (33 CFR 209.220; further called Section 7 flood control), water supply (irrigation and municipal and industrial (M&I)), fish and wildlife benefits, and recreational opportunities. Section 7 flood control obligations refer to projects that were partially funded by Federal dollars with the requirement that once constructed, the reservoir would be operated to provide flood control benefits for public infrastructure located downstream. During the non-irrigation season, water is released primarily for fish and wildlife purposes (excluding flood control releases); outside of this season, additional releases are made to meet irrigation and M&I demand.

Arthur R. Bowman Dam (Figure 3) is an earthfill structure on the Crooked River about 20 miles upstream from the City of Prineville, Oregon. The dam has a height of 240 feet, crest length of 790 feet, and a volume of 1.42 million cubic yards of material. The spillway consists of an uncontrolled crest inlet structure, chute, and stilling basin. The capacity of the spillway is 8,120 cfs at maximum water surface elevation of 3257.9 feet and results in a flood surcharge storage of 80,330 acre-feet. The outlet works has an intake structure with an 11-foot-diameter circular tunnel upstream from the gate chamber, an 11-foot modified horseshoe tunnel downstream from the gate chamber, and a stilling basin, which is shared with the spillway. The capacity of the outlet works is 3,300 cfs at normal water surface elevation of 3234.8 feet.

Figure 3. Arthur R. Bowman Dam overview

The original total storage capacity of Prineville Reservoir immediately after construction was 154,690 acre-feet (active storage of 152,800 acre-feet). A reservoir sedimentation survey completed in 1998 estimated that the total capacity has reduced to 150,200 acre-feet (active storage of 148,600 acre-feet); approximately 2,600 acre-feet of storage was lost due to sedimentation.

Immediately downstream of Arthur R. Bowman Dam, the Crooked River travels for approximately 8 miles through a deep canyon that is used heavily by recreationists and is regarded as one of the most productive trout fisheries in the State of Oregon. After this initial canyon section, the river travels through a small valley, where the first surface water points of diversion are located. Downstream of this, the river travels through a short canyon section before entering a large valley, where numerous small river pumps are located, as well as two diversion canals, one of which is Feed Canal, the largest diversion constructed per the project authorization. Downstream of the Feed Canal Diversion, the Crooked River continues traveling through this valley, with numerous agricultural fields located on both sides of the river. The Crooked River enters the Prineville Valley approximately 23 miles downstream from the dam and travels along the southern side of the City of Prineville until crossing under Highway 126 (this is the location of the Crooked River at Prineville (CAPO) streamflow gage). Due to additional inflow downstream of the CAPO gage from canal drains and Ochoco Creek, the CAPO stream gage is regarded as a point of lowest flow in the system. Streamflow measurements at the CAPO gage are used to account for water being released from the dam for the benefit of fish and wildlife.

3 Metric Development

Metrics were developed for this Study to measure impacts of a specific future climate flow scenario on an existing project resource[1]. The intent of the metric list was to provide at least one measurement point for all existing project resources that would be of interest to stakeholders when looking at impacts of various hindcast methods, future climate flow scenarios, and alternative operations.

3.1 General Approach

The metrics for this Study were developed by the Study team through an iterative process that started with creating a broad list of any applicable attributes for each resource category. This larger list was later refined into metrics that covered all resource categories and that could be reasonably evaluated with the results from the Pilot Model. The general modeling approach was to run the Pilot Model with historical inflows and then compare these results with the results of modeling with the various future climate flows to determine the differences between them. For this modeling purpose, the results of the modeling with the historical inflows will be referenced herein as the Current Condition. The development of each individual metric followed the same process, which included defining the resource category, attribute of interest, location of interest,

[1] Resources for the Crooked River Project include flood control, water storage and delivery, water quality, recreation, and ecological.

metric type (quantitative or qualitative) and method of quantifying the metric, and identifying the reference value. The following sections provide a short description of what each of these process steps includes.

3.1.1 Resource Category

The first step of developing a metric was to identify which resource category the metric fell under. As stated above, the list of metrics developed provided a measurable attribute that would address all applicable resource category for the Crooked River Project. For this Study, the following resource categories were used:

- Flood Control
- Water Deliveries
- Water Quality
- Recreational Resources
- Ecological Resources

3.1.2 Attribute of Interest

The attribute of interest is the measurable parameter used to identify an impact (positive or negative) for a specific resource category. Attributes can vary significantly depending on the type of resource category they fall under. For example, a recreational resource attribute of interest might be the number of days that boat ramps are usable at Prineville Reservoir, while an attribute of interest for flood control may be the number of days discharge downstream from Prineville Reservoir exceeds 3,000 cfs. While some resource categories may have had numerous attributes of interest during the first iteration of the metrics development process, the Study Team tried to refine the list of metrics to include only the most easily evaluated with the Pilot Model results.

3.1.3 Location of Interest

The location of interest of a metric defines the exact location where the attribute will be measured. Using the example described above between the boat ramp and the flood control targets, the location of interest for the boat ramp would be in Prineville Reservoir, while for flood control, it would be immediately downstream of the dam. Some attributes may have multiple locations of interest, but for purposes of the Study and regarding the level of work effort, only the most significantly important locations were included.

3.1.4 Metric Type (Quantitative or Qualitative)

Defining how the metric would be measured was an important step in the metric development process. While some attributes could be quantitatively measured directly from the basin Study output (flow, elevations, etc.), other attributes of interest, which are equally important but are not easily quantifiable (such as water temperature), were given the qualitative metric type.

Qualitative metric types were applied to attributes that could not be measured directly but could be measured indirectly and would provide an indicator for the impact of that specific metric.

3.1.5 Methods for Quantifying Metrics

The two methods for quantifying an impact of a given future climate flow scenario on a specific quantifiable metric include the reference value method and the relative comparison method. The reference value method uses a known reference value that could aid in determining the impact of a scenario on that value. Reference values were determined based on whether the constraint was a physical constraint, prescribed condition, estimated condition, or historical condition. The second method, the relative comparison method, is useful when there is no known reference value but which, by completing a comparison of a specific attribute of interest between scenarios, would provide an indication of the impact of various scenarios.

3.1.6 Final Metric Table

Table 2 below shows the final metrics used. This table provides a description of the resource category, attribute of interest, location of interest, metric type, method of quantifying, and reference value for all metric used in this Study. For additional explanation of each specific resource metric measure, refer to the following sections.

Table 2. Final resource metrics for the Crooked River Pilot Study

Resource Category	Attribute of Interest	Location of Interest	Metric Type	Method for Quantifying Metric	Reference Value
Flood Control	Downstream Flood Control	Downstream of Dam	Quantitative	Number of days in which discharge is greater than various values	Various flows from 1,000-3,000 cfs
	Reservoir Surcharge	Reservoir	Quantitative	Number of days in which reservoir elevation exceeded various values above full pool.	Various reservoir elevations ranging from 3234.8 to 3238.0 feet.
	Reservoir Refill	Reservoir	Quantitative	Number of years with full reservoir refill	Number of years with storage is greater than or equal to 148,640 acre-feet
Water Deliveries	Storage Allocation	Reservoir	Quantitative	Exceedance values for maximum reservoir refill	Full allocation is 148,640 acre-feet
	Storage Carry-Over	Reservoir	Quantitative	End of WY pool elevations, exceedance curve for Nov 1	Current Condition
Water Quality	Total Dissolved Gas	Downstream of Dam	Quantitative	Number of days discharge is greater than various flows	Various TDG level (110%, 115%, 120%)
	Reservoir Inflow Water Temperature	Reservoir Inflows	Qualitative	Look at inflows during the months of July/August	Current Condition
	Reservoir Water Temperature	Reservoir	Qualitative	Pool elevation exceedance values in October	Current Condition
Recreation Resources	Downstream Fishing Days	Downstream of Dam	Quantitative	Number of days in which discharge below the dam is in the preferred fishing flow range	50-400 cfs
	Reservoir Boating Days	Reservoir	Quantitative	Number of days in which when boat ramps were not available	3210 feet (Powerhouse Cove), 3203 feet (Jasper Point), 3191 feet (State Park)
Ecological Resources	Habitat Suitability	Downstream of Dam, Highway 126	Quantitative	Number of days in which discharge exceeded various flows	Various flows ranging from 20-100 cfs
	Minimum Flow	Downstream of Dam, Highway 126	Quantitative	Number of days in which discharge exceeded various flows	Various flows ranging from 20-100 cfs

3.2 Flood Control Metrics

Flood control is defined as one of the primary purposes of Prineville Reservoir and therefore is an important resource category. Within the Flood Control resource category, three metrics were developed: downstream flood control, reservoir surcharge, and reservoir refill. All three of these metrics were identified as important for understanding the impacts that could be experienced with a changing climate.

3.2.1 Downstream Flood Control

Prineville Reservoir is operated to provide flood control downstream from the dam. For this metric, the location of interest was identified as directly downstream from the dam. Current operations target a flood control discharge no greater than 3,000 cfs to protect life and property downstream from the dam. To provide the comparison between modeled scenarios and quantify impacts to the downstream flood control operation, the number of days the discharge exceeded various flow values, ranging from 1,000 to 3,000 cfs, was calculated. For flood control purposes, damages only start to occur when flows exceed 3,000 cfs; however, for comparison purposes, additional flow levels were included to provide an indication of the number of days flood control operations were required for various inflow scenarios.

3.2.2 Reservoir Surcharge

The spillway and dam were constructed to account for the flashy nature of inflows into Prineville Reservoir. The current dynamic Storage Reservation Diagram (dSRD) uses 12.4 feet (40,340 acre-feet) of available surcharge[2] for the 3,000-cfs flood curve. Historical operations have experienced up to 7.9 feet of surcharge, but typical operations only use surcharge in emergency scenarios, excluding minimal surcharge used annually for removal of debris from the spillway. This metric will use the number of days the reservoir elevation exceeds elevations greater than 3234.8 (full pool) to determine the impacts to reservoir surcharge. The number of days a scenario exceeded a reservoir elevation greater than the uncontrolled spillway invert was compared to what occurred for the Current Condition. This comparison will determine the impact of various scenarios on reservoir surcharge as compared to the Current Condition. The results regarding this metric will also provide some information about impacts to existing infrastructure located around the reservoir that may be impacted by inundation during surcharge conditions.

3.2.3 Reservoir Refill

Reservoir refill occurs during the flood control period and is critical to providing a full reservoir allocation for water supply. The reservoir refill metric describes the number of years that the

[2] Surcharge at Prineville Reservoir is defined as the depth of water over the uncontrolled spillway crest at 3234.8 feet, also considered full pool.

reservoir fills completely, as well as various exceedance values of maximum reservoir content for all water years.

3.3 Water Deliveries Metrics

Prineville Reservoir holds a total of 148,640 acre-feet of storage water that is used for irrigation, municipal and industrial (M&I), and fish and wildlife purposes. Water users downstream of the reservoir and along the Crooked River typically meet water demands through a combination of both natural-flow water rights and stored-flow water rights. Most of the irrigation water users hold a combination of both natural flow and stored flow, and the accounting of this is completed continuously during each water year. Due to the importance of Prineville Reservoir in meeting the demands of stored water flow by all users, possible impacts from hydrologic variability were determined to be of great importance. The Pilot Model used in this Study completes water accounting by using both natural-flow and stored-flow water rights. Water delivery metrics were developed to identify impacts of a modeled scenario on storage allocation and storage carryover.

3.3.1 Storage Allocation

The Prineville Reservoir has a total of 86,013 acre-feet of contracted storage and 62,520 acre-feet of uncontracted storage. The contracted storage is held by 18 contracts, with volumes ranging from 57,899 acre-feet for the largest storage holders to 16 acre-feet held by smallest storage account. The remaining 62,520 acre-feet of uncontracted storage is used for fish and wildlife purposes. Per the Crooked River Collaborative Water Security and Jobs Act of 2014 (Public Law 113-244), the methods in which the contracted and uncontracted storage are allocated are now different. At the end of each water year, all inflow into the reservoir more than 10 cfs is provided to the first-fill accounts, which is linked with contracted storage. Once the first-fill accounts have filled, any additional inflow into the reservoir is allocated to the uncontracted storage account. Use of the prior-water-year storage water by the uncontracted account can occur until the day of allocation (the day that maximum fill of the reservoir occurs). For the storage allocation metric, the volume of water allocated will be calculated to determine the impacts that a modeled scenario would have on the total allocation. Due to the first-fill procedures at Prineville Reservoir, allocation for contracted space would be up to 86,013 acre-feet, while the remaining allocation would go to the uncontracted account.

3.3.2 Storage Carryover

During most water years, carryover of stored water in the contracted and uncontracted storage is typical, as both these accounts are managed for possible subsequent dry water years. The storage carryover metric measures the difference in carryover for both the contracted and uncontracted accounts when compared to the Current Condition. This metric examines whether there is a risk of less carryover stored water with a modeled scenario when compared to the Current Condition. As stated earlier, storage accounting at Prineville Reservoir follows a first-fill methodology in which carryover from the uncontracted account is transferred into the contracted account, first if needed, to provide a full account. For this metric, various exceedance values (10, 20, 50, 80, and

90 percent) will be calculated for the end-of-October carryover volumes to determine any change from the base condition.

3.4 Water Quality Metrics

Water quality below Prineville Reservoir can be negatively affected by periods of increased total dissolved gas (TDG) and higher water temperatures. The water quality metrics described below were developed to provide a quantitative look at the possible impacts of various modeled scenarios on water quality metrics of the Current Condition.

3.4.1 Total Dissolved Gas

Prineville Reservoir has three methods of releasing water through the dam: through an 11-inch-diameter bypass pipe, through an 11-foot-diameter outlet tube, and through a 20-foot-wide uncontrolled spillway. Use of the outlet tube can cause an increase in TDG below the reservoir at high discharges. Determination of TDG levels are complicated due to impacts from the temperature of water at that time, during which water at a warmer temperature could have higher TDG levels than water at a cooler temperature, assuming discharge conditions were the same. The primary effect of TDG supersaturation on fish is typically referred to as gas bubble trauma. This occurs when the total dissolved gas pressures exceed the counter pressures of hydrostatic head, blood, tissue, and water surface tension. Because of this pressure differential, gas bubbles may develop in the blood and tissue of the fish, causing trauma or death. For purposes of this Study, a discharge value of 2,500 cfs or more is assumed to increase TDG levels below the reservoir to 120 percent or more (Figure 4). This metric will be analyzed using a location in the Pilot Model directly downstream of the dam and will evaluate the number of days discharge through the outlets tubes exceeds 670 cfs (110 percent TDG), 1,500 cfs (115 percent TDG), and 2,500 cfs (120 percent TDG) when compared to the Current Condition.

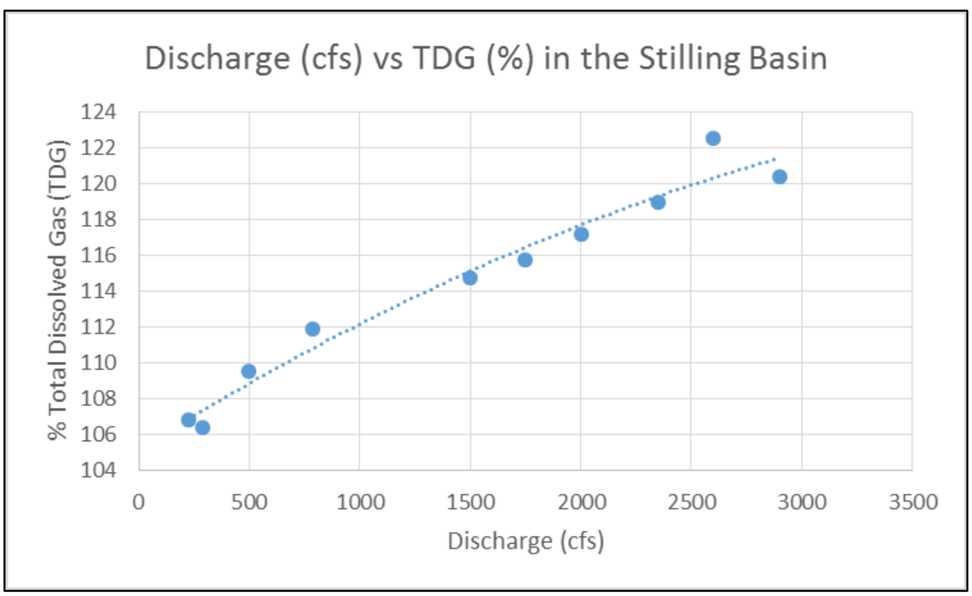

Figure 4. Plot of discharge vs. TDG in the stilling basin below Arthur R. Bowman Dam

3.4.2 Water Temperature

The water temperature metric uses a qualitative method to determine if water temperature would be higher or lower compared to the Current Condition. This Study budget did not allow for a more advanced modeling of water temperate using a more sophisticated model, but results of the Pilot Model can help estimate the relative effects of a modeled scenario. The following are some assumptions about an increase or decrease in water temperature. Regarding inflow into the reservoir, if a certain scenario has less natural flow than in the Current Condition, then for the modeled scenario, the water temperature would be assumed to be different. For purposes of this Study, the team is focusing on inflow into the reservoir during August. If a scenario has less natural flow than in the Current Condition in August, then this Study assumes that the water temperature of the inflow would be higher. Regarding reservoir conditions, if a scenario results in a lower pool elevation than in the Current Condition at the end of the irrigation season, the team would assume that water temperature in the reservoir would be warmer than in the Current Condition. Water temperature below the reservoir was not considered, as this is highly influenced by the mixing of the water and natural stratification of the reservoir that exceeds the level of analysis completed for this Study.

3.5 Recreational Resources Metrics

Recreational usage at both Prineville Reservoir and the Crooked River downstream of the dam is high. In fact, the Crooked River below the dam is regarded by some as the best trout fishery in the State of Oregon. Due to the importance of recreation along the Crooked River, two metrics were developed to measure the impacts of the modeled scenario on both downstream recreation below the dam and recreation on Prineville Reservoir. Other recreational opportunities exist both in the river and in the reservoir, but for the purposes of this Study, fishing the downstream tailwater and boating in the reservoir were examined.

3.5.1 Downstream Recreation

As stated earlier, the trout fishery on the Crooked River below Prineville Reservoir is regarded as one of the most productive in the State of Oregon. In addition to the trout fishery, experimental reintroductions of both steelhead and Chinook salmon are currently being undertaken. Stakeholder engagement has informed operations that ideal fishing conditions on the reach below the reservoir occurs when flows are greater than approximately 50 cfs but less than approximately 400 cfs. The downstream recreation metric was calculated as the number of days that flow is within this optimal range for fishing on the Crooked River, and this was compared to the number of days from the Current Condition model.

3.5.2 Reservoir Recreation

The Prineville Reservoir experiences about 515,000 visitors each year due to boating, fishing, swimming, and camping opportunities on the reservoir. The reservoir recreation metric determines the number of days the boat ramps at Prineville Reservoir would be available for launching boats. The reservoir has four boat ramps accessible at various locations and at different pool elevations, as summarized in Table 3 below.

Table 3. Boat ramps located at Prineville Reservoir

Boat Ramp	Min. Pool Elevation (feet)*	Draft from Full (feet)**
Powerhouse Cove	3210	24.8
Jasper Point	3203	31.8
State Park	3191	43.8

*Minimum pool elevation before boat ramp can no longer be used
**Full elevation is 3234.8 feet

Attempts were made at incorporating an additional fishing metric within the reservoir, but specific information regarding what would constitute optimal fishing opportunities were not available. Due to this and the available output from the Pilot Model, the boat ramp metric was chosen.

3.6 Ecological Resources Metrics

A portion of the stored flow in Prineville Reservoir is used for the benefit of fish and wildlife. This water is managed to provide productive populations of fish and wildlife and recreation opportunities. Ecological metrics were developed that examine the impacts to the minimum flow requirements, measure of habitat suitability throughout the year, and the ability to provide for pulse flows.

3.6.1 Minimum Flow

Uncontracted water at Prineville Reservoir is managed in collaboration with the U.S. Fish and Wildlife Service (USFWS) and the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA Fisheries) to maximize the benefit to fish and wildlife. The current minimum flow value referenced in the legislation is 80 cfs (Public Law 113-244). The minimum flow metric examines the number of days that the 80 cfs minimum flow is met. This metric includes two locations, depending on the timing within the season. During the irrigation season (March through October), the location of interest is at the Highway 126 bridge near the City of Prineville. During the irrigation season, the Highway 126 gage is referred to as the low-flow point in the system. Upstream of the gage the flow is greater due to irrigation water being present while flow increases downstream of the gage due to reach gains and local inflow from ditch drains and Ochoco Creek. The minimum flow metric determines the number of days that the current minimum flow of 80 cfs is met when compared to the Current Condition for all modeled scenarios.

3.6.2 Weighted Useable Area Curve

A weighted useable area (WUA) curve for the Crooked River was obtained from the USFWS Bend Field Office and identifies the flow rates and WUA values for various flows on the Crooked River downstream from the Feed Canal. The WUA curves were developed for juvenile steelhead and Chinook salmon. For the purposes of this Study, the juvenile Chinook WUA curve was used to determine the impacts among various modeled scenarios. To explain any impacts, the number of days at various WUA levels were calculated to identify any differences when comparing the Current Condition and modeled scenarios. Figure 5 below shows the juvenile Chinook WUA curve used in this Study.

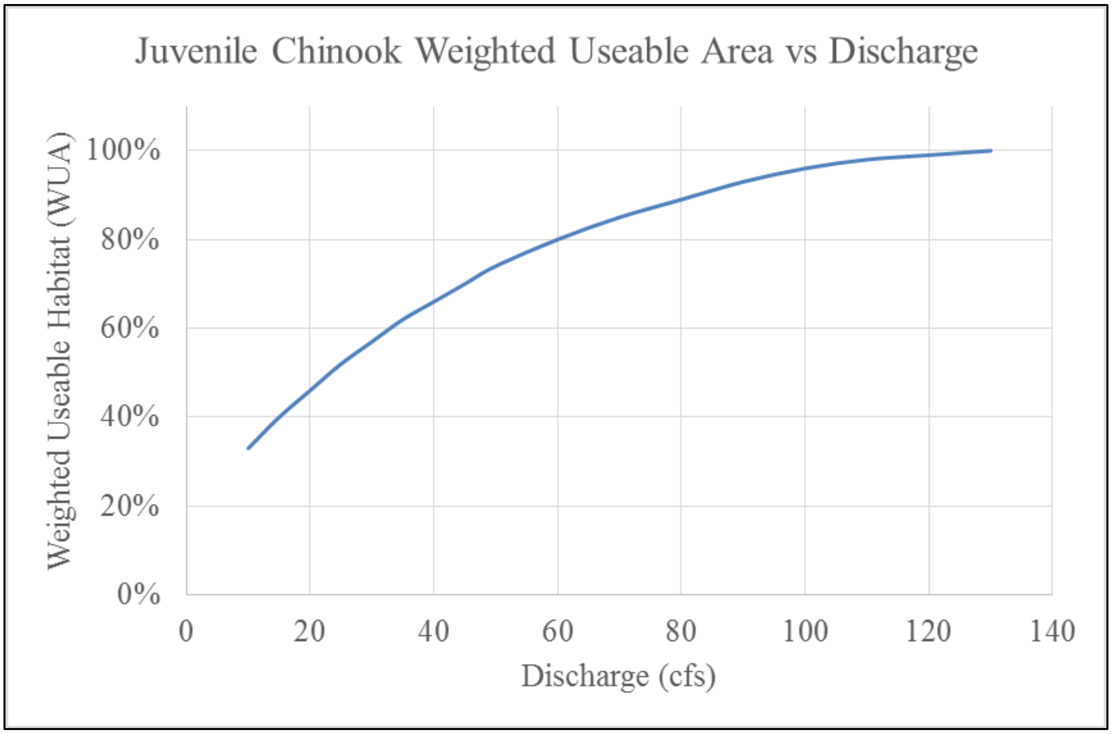

Figure 5. Juvenile Chinook Weighted Useable Area curve used in the Study

4 Overview of Operations Model

4.1 Riverware Model Overview

RiverWare models are object oriented and operate based on user-specified logic that determines how water is distributed in the system. Generally, the model operates in five basic steps for each daily timestep:

1) Objects that receive water, such as reservoirs and water users, are populated with their water request for the current timestep;
2) Water is then distributed based on priority dates;

3) If requests are not met during Step 2 and the “object” has access to available stored water, stored water is released from the reservoirs and delivered to the requesting object;
4) Reservoirs adjust based on balancing logic, if necessary;
5) The solution is passed to the physical objects and the physical objects solve a mass balance.

In addition to the five basic steps, there are individualized operations that are specific to system operations in the Crooked Basin. These include logic to provide water from two tributaries to a single water user for the Ochoco Irrigation District, optimization of fish and wildlife flows based on remaining storage, and flood control operations.

4.2 Deschutes Basin Study Model

Two separate RiverWare models were developed for this effort: a calibration model and a current-conditions model. The calibration model simulates the period of 1984 through 2010 and was used to develop the operational rules that control the model. The current-conditions model is a variation on the calibration model and is used as a baseline for scenario-driven studies.

The calibration and current-conditions models use a similar model structure. The model network was constructed using RiverWare objects to represent physical features such as reservoirs, river reaches, diversions, control points (which monitor minimum instream flow locations), and river gages. Figure 6 shows the layout of the RiverWare model for the Crooked River portion of the model. The red circles indicate water users (representing diversions) and are labeled with the irrigation district acronym that they serve. The yellow boxes indicate stream gages and are named with their four-letter acronym from the Hydromet program (Reclamation 2016), except for the Highway 126 gage on the Crooked River. The green triangles represent locations where gains and losses are input into the model. The blue diamonds represent control points.

The model representation of the system is a simplification of the physical system, and as such, not everything in the physical system is represented in the model. For example, the springs that flow into Crooked River Creek above the CROO stream gage are not represented with a model object; however, their contribution is represented in the reach gains on the Crooked River. In addition, the diagram is a schematic of the system and is not representative of geographic distances between each object. Additional information about the development of the Deschutes Basin Study Model study report (Reclamation 2018a).

4.3 Pilot Study Model

For the purposes of this Study, the larger Deschutes Pilot Model was modified to encompass only the Crooked River portion (Figure 6). The modification was completed to reduce the computational requirements and model run times for Study tasks, thus allowing for the analysis of more model scenarios. All existing rules and accounting criteria developed during the creation of the Deschutes Basin Study Model remained the same as the Crooked River model, herein referred to as the Pilot Model.

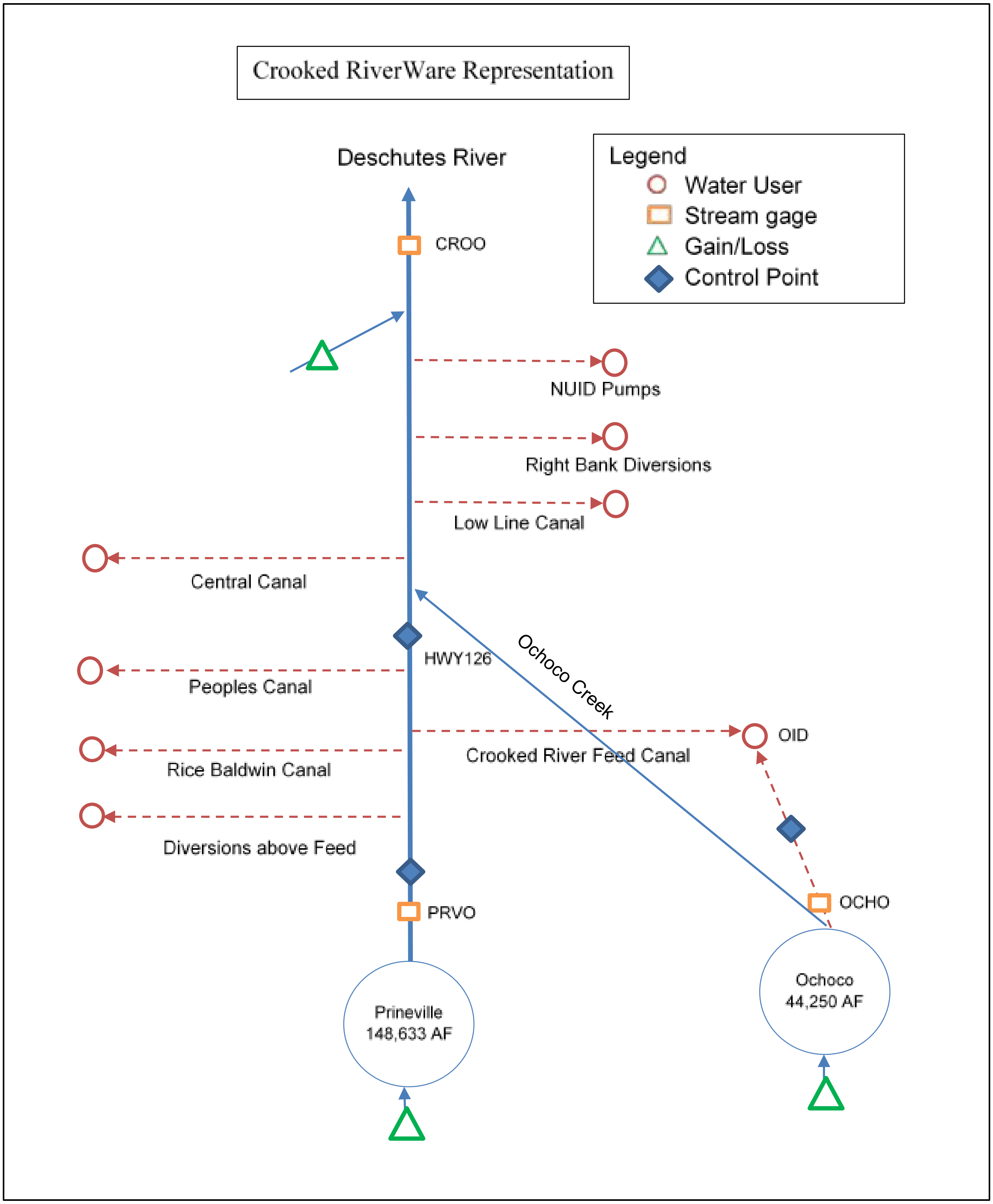

Figure 6. Schematic of RiverWare representation of Crooked River

4.3.1 Flood Operation Rules

4.3.1.1 Prineville Reservoir Flood Regulation Flows

The flood season (time of year the watershed accumulates/depletes snow) for Prineville Reservoir is from November 15 through the month of April. During this period, the reservoir is regulated based on a dSRD. The winter flood control period for Prineville Reservoir begins on November 15 and ends on February 15, at which point refill into the winter flood space requirement can begin. During the winter flood control period, a minimum of 60,000 acre-feet of reservoir storage space must be made available to protect against winter rain-on-snow type flood events. After February 15, the last day of the winter flood control period, the reservoir is operated based on the dSRD, which provides refill curves based on the forecasted runoff and projected fill date around the end of April. Figure 7 below shows the dSRD for Prineville Reservoir using a maximum allowable discharge target of 3,000 cfs. The curve is used to determine the space required using the current date and volume of the runoff projected from that date through the end of August. This curve was also developed using the unique surcharge storage (40,330 acre-feet) available at Prineville Reservoir to regulate outflows to 3,000 cfs and to refill the project effectively. The curve was developed so that flow released from the dam is no greater than 3,000 cfs, which would be released entirely through the outlet tubes during times when the reservoir is below the spillway elevation. When the reservoir goes into surcharge and water discharges over the uncontrolled spillway, the discharge through the outlet tubes is reduced so that the combined discharge remains at 3,000 cfs or less. Using this outlet/spillway operation provides 12.4 feet of surcharge (40,330 acre-feet) to attenuate reservoir inflows before flow over the uncontrolled spillway begins to exceed 3,000 cfs. The use of surcharge provides additional reservoir space to store inflows more than what is being released from the reservoir and greatly increases the flexibility the reservoir operator has for keeping flows below a target discharge and releasing the stored surcharge water later.

The Pilot Study model was developed to calculate space requirements dictated by the dSRD and provides the ability to clearly identify when releases from the reservoir are due to flood control requirements. Reservoir releases are attributed to different space holders' accounts within the reservoir. However, releases associated with flood control are not charged to any storage account holder.

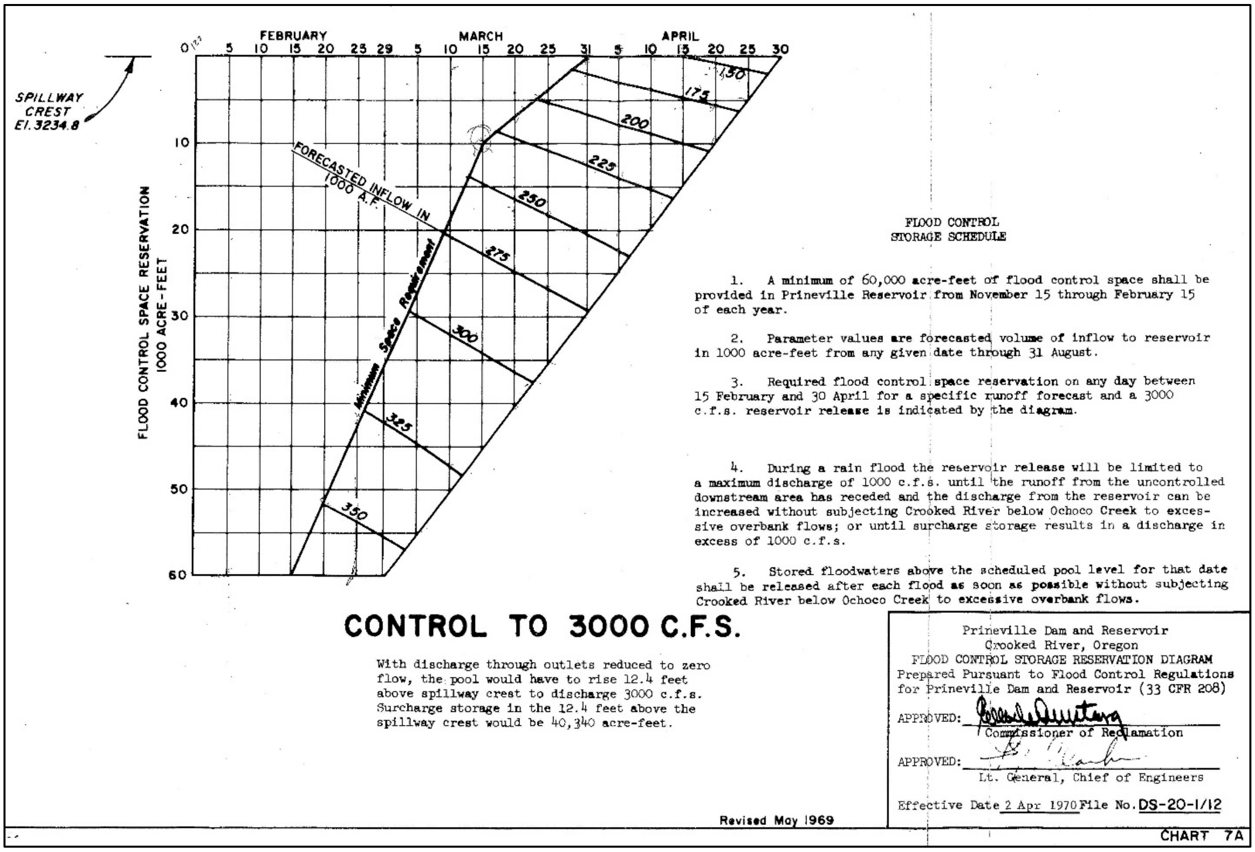

Figure 7. Prineville Reservoir dynamic Storage Reservation Diagram (dSRD) for a maximum regulated discharge of 3,000 cfs.

4.3.2 Irrigation Diversions

The model simulates nine diversion locations on the Crooked River and Ochoco Creek (Table 4). The diversions generally represent canals to which water is diverted from the river for irrigated agriculture. Each diversion location can divert live flow, stored water, or both, depending on the defined water rights; water rights are discussed in Section 4.3.3. The diversions are simplified representations of the physical system and are not fully representative of the distribution system within a district. Canal and on-farm leakage within a district are not represented geographically in the model, but are spatially aggregated and represented in the relative terms to other important features.

Table 4. Annual Diversion for each Water User in Model

Model Water User Name	Entity	Stream	Average Annual Historical[1] Diversion (acre-feet)	Current Conditions Annual Diversion Request[2] (acre-feet)
CrookedAboveFeed	Small private diversions above the Crooked River Feed Canal	Crooked River	1,270	1,270
CrookedRiverFeed	Ochoco Irrigation District	Crooked River	49,400	53,400
RiceB	Rice Baldwin Canal	Crooked River	3,970	3,970
Peoples	Peoples Canal	Crooked River	11,100	11,100
OID	Ochoco Irrigation District	Ochoco Creek	22,400	23,300
Central	Crooked River Central Canal	Crooked River	3,300	3,300
LowLine	Low Line Canal	Crooked River	2,800	2,800
RBCrooked	Small private diversions on the right bank of the Crooked River	Crooked River	4,000	4,100
NUIDCrooked	North Unit Pumps	Crooked River	18,400	19,300

[1]The average annual historical diversion is the average diversion from 1984-2000.
[2]The current annual diversion is the total annual diversion from 2009.

4.3.3 Water Right Accounting

In the Crooked River basin, water is distributed in accordance with the prior appropriation doctrine, which states that the most senior water right holder, reflected by a priority date, may divert up to the water right's maximum allowable diversion rate before the next water right holder can divert. To ensure that water was distributed in the Crooked River basin according to the limitations imposed by water rights, the RiverWare model uses a water rights solver function. This function distributes available live flow to water user objects within the model, following the prior appropriation doctrine. The water-right-informed distribution is applied to the physical system at each timestep of the modeled simulation period. Hence, the water right accounting function reconciles and governs the physical system operations at each timestep.

A set of water rights reflective of the system prior to the year 2000 was used for the calibration model. The operational rules were calibrated to reservoir storage and outflow and the flow at gages. The current-conditions model used a single-year pattern of measured diversions from 2009, which was considered to be a representative average year for the current state of the basin.

Four types of water rights were used in this model:

1. Live flow diversion: The live flow diversion rights are associated with water user diversion objects and have a priority date and maximum flow diversion rate.

2. Live flow storage: The live flow storage rights are associated with reservoir storage objects and have a priority date and maximum storage volume.
3. Stored water: The stored water rights are associated with the water user diversion objects and can call on water stored in the reservoir storage accounts.
4. Instream: The instream flow rights are associated with control points and have a priority date and flow rate. The instream flow rates are not diverted from the river, but they track the amount of water flowing in the stream at that point.

4.3.4 Crooked River Legislation Rules

The Crooked River Collaborative Water Security and Jobs Act of 2014 (CRCWA) (Public Law 113-244) resulted in, among other things, a modification to the use of water storage rights in Prineville Reservoir, how accounts would be filled, and how unused water would be carried over from one water year (WY) to the next WY.

The Prineville Reservoir has a total of 21 contracted storage accounts, which have a combined storage right of 86,113 acre-feet. The remaining 62,520 acre-feet of uncontracted active storage space in Prineville Reservoir is to be used for the benefit of fish and wildlife, as described in the CRCWA. The CRCWA directs Reclamation, in consultation with the USFWS and NOAA Fisheries, to develop an annual release schedule for this uncontracted storage, should it be available, that maximizes benefits to downstream fish and wildlife. Prior to the passage of the CRCWA, there were a total of 18 contracted space holders. The three additional contract space holders included in the passage of the CRCWA were 2,740 acre-feet for McKay Creek Land, 5,100 acre-feet for the City of Prineville for mitigation (described below), and 10,000 acre-feet pursuant to temporary water services contracts. The CRCWA states the 10,000 acre-feet is "… to be made available first to the North Unit Irrigation District [NUID], and subsequently to any other holders of Reclamation contracts as of January 1, 2011 (in that order) …" If none of the eligible Reclamation contract holders have initiated contracting by June 1 of any calendar year, and "with the voluntary agreement of North Unit Irrigation District and other Bureau of Reclamation contract holders referred to in that paragraph, the Secretary may release that quantity of water for the benefit of downstream fish and wildlife as described in section 7 of that Act." The City of Prineville's contracted space of 5,100 acre-feet shall be released every year and is a mitigation action by the city. Similar to uncontracted storage, and per CRCWA requirements, the City of Prineville's contracted water shall be released first to maximize infiltration and secondly to benefit downstream fish and wildlife.

The model used in this Study includes the change in operations and allocation of storage at Prineville Reservoir resulting from the CRCWA.

4.4 Calibration

The calibration model was used to test the operational logic written into the model rules. The calibration comparison period was October 1, 1984, through September 30, 2000, to ensure that the model and logic were reasonably simulating historical conditions. Model output was compared to measured historical data to determine the quality of performance of the operational logic.

4.4.1 Calibration Dataset

The calibration dataset used during the calibration phase of the modeling included the historical inflows, outflows, and reservoir elevations during the 1983-1999 period. The comparison of modeled outflows and reservoir elevations during the 1983-1999 period allowed the determination of how well the modeling logic performed at matching historical operations.

4.4.2 Calibration Results

Figure 8 shows the historical and simulated reservoir contents for Prineville Reservoir, and Figure 9 shows the maximum and minimum annual reservoir contents. The model reasonably simulates reservoir contents for the calibration period. The model only simulates the amount of storage in the reservoir accounts (148,640 acre-feet) and does not include flood storage. So, the maximum storage is not simulated above 148,640, even though measured storage may have been larger than 148,640 acre-feet when water is stored temporarily in flood space. (Note: ability to use surcharge space was added later to allow for the resource metric modeling.)

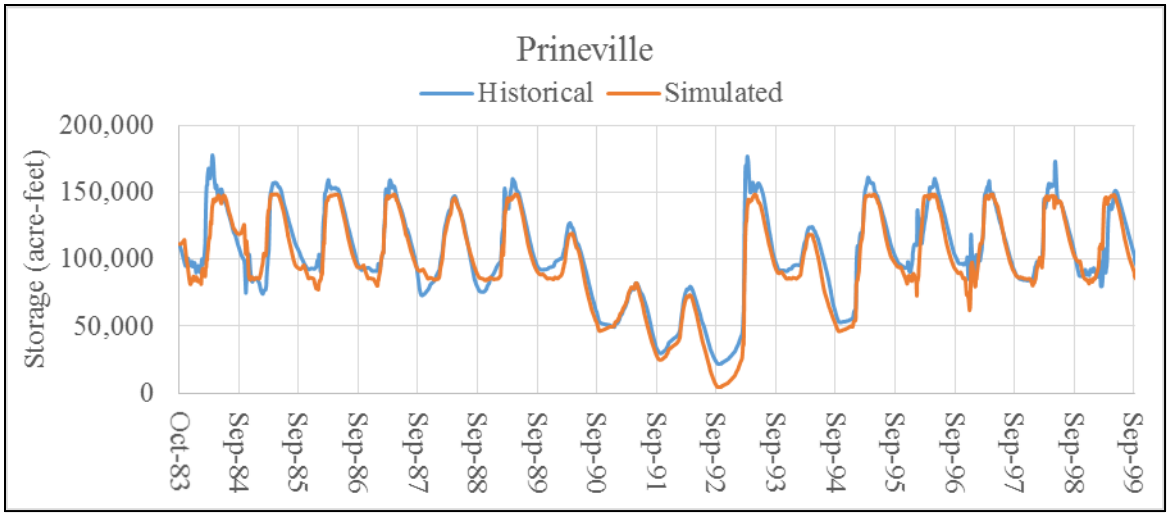

Figure 8. Historical (blue) and model simulated (orange) reservoir contents for Prineville Reservoir

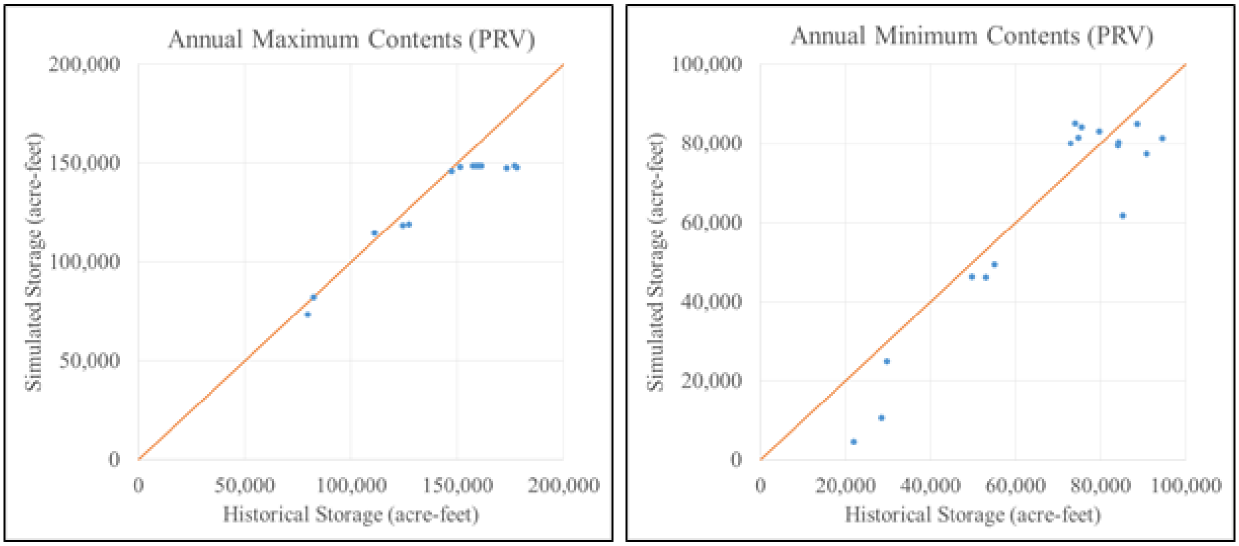

Figure 9. Simulated versus historical annual maximum (left) and minimum (right) reservoir contents for Prineville.

Figure 10 shows the historical and model simulated outflows from Prineville, and Figure 11 shows outflow volumes for the irrigation and no-irrigation seasons.

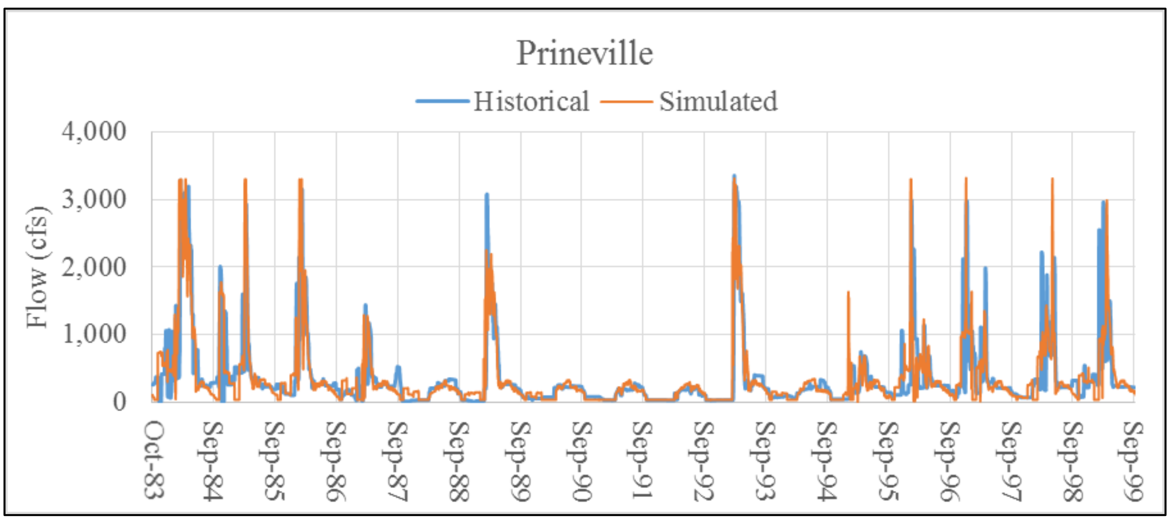

Figure 10. Historical (blue) and model simulated (orange) outflows from Prineville Reservoir.

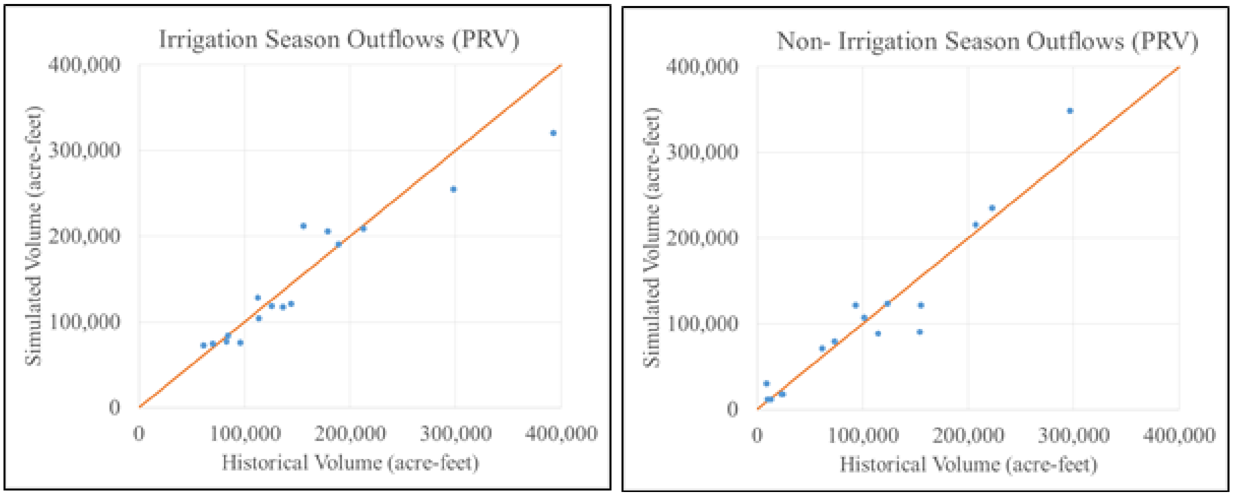

Figure 11. Simulated versus historical irrigation season (left) and non-irrigation season (right) annual outflow volume from Prineville

5 Runoff Volume Hindcast Modeling

5.1 Hindcast Methods

Prineville Reservoir operates during the refill season (mid-February through April) using guidance from the dSRD that is determined by a forecasted volume of runoff for the date of the forecast. Due to the inherent complexities of forecasting runoff volumes by estimating future watershed conditions, errors in forecasts can make reservoir refill challenging. A portion of this Study examines how using different forecast methods might improve or change operations. Currently, operational runoff forecasts are completed by the PN Region using a Multiple Linear Regression (MLR) and Principal Components forecast option. For the purposes of the hindcasting task, three different forecast methods were used, in hindcast mode, to investigate whether any impacts to operational discharges would result in an alternative forecast method. Whereas historical modeling simulations are driven by actual historical inputs and can be used to assess the performance of a hydrologic model, hindcasts are driven by forecasted, or imperfect, forcings (e.g., forecast input variables), and can thus be used to assess the performance of a hydrologic forecast system. Hindcasts were generated for the 1984-2010 period to compare the performance of each forecast method.

5.1.1 Reclamation Multiple Linear Regression Hindcasts

The PN Regional Office completes water supply forecasts for Prineville Reservoir starting in January and typically ending in April. The water supply forecasts are generated using numerous input variables such as antecedent runoff, precipitation, and a March 1 snow-water equivalent (SWE) index. The equations produce an October-through-August volume that is reduced throughout the forecast season by the amount of runoff volume that has occurred during the previous forecast period. The equations were developed by completing a step-wise MLR analysis using the October-through-August historical runoff volume, October-through-December historical runoff volume (antecedent condition), October-through-June historical precipitation, and historical March 1 SWE index. The precipitation index was developed using three gages located in the watershed while the SWE index was developed using three snow courses located in the watershed. As forecasts are generated for each month, typical subsequent conditions (e.g., 80 percent, 100 percent, or 120 percent of average future conditions) are assumed to allow for the calculation for the entire October-through-August period. Each year, the coefficients of the regression equations are updated with the previous year's runoff volume, antecedent runoff, precipitation, and SWE indexes. Table 5 below summarizes the variables included in the MLR forecast equations. For the Prineville MLR equation, unique coefficients are calculated for each of the four variables.

Table 5. Variables used in the MLR equations

Variable	Location	Time Period
Antecedent Runoff	Prineville Res. Unregulated Inflow	Oct-Jan
Precipitation	Grizzly, OR	Oct-Jan, Feb-Jun
	Ochoco Ranger Station, OR	
	Prineville, OR	
Snow Water Equivalent (SWE)	Derr Snow Course, OR	March 1st
	Marks Creek Snow Course, OR	
	Ochoco Meadows Snow Course, OR	

5.1.2 Northwest River Forecast Center Hindcasts

Recently, the NWRFC developed and implemented a hydrologic model to support real-time to long-range Prineville Reservoir inflow forecasts, and the NWRFC agreed to use one aspect of this model to generate hindcasts for this Study. The hydrologic model was calibrated using the 1974-2016 water-year period, which is different from the hindcast modeling period. The precipitation and temperature forcing data used in the calibration process were developed by NWRFC using historical precipitation and temperature station observations.

The NWRFC uses an Ensemble Streamflow Prediction (ESP) modeling procedure to generate long-range water supply forecasts. The ESP procedure uses traces of historical precipitation and temperature data (developed during the calibration process) as inputs (i.e., forcings) for future conditions and produces one streamflow trace (possibility) per set of forcing data. Every streamflow trace is initialized from the same hydrologic model state (i.e., current with respect to the forecast date). The NWRFC offers several varieties of ESP forecasts with varying degrees of short-range weather forecasts that precede the traces of historical observations as model forcings. Due to its reproducibility, the 0-day ESP method was selected for this Study (i.e., uses only the ensemble of historical observations as forcings).

Figure 12 below is a spaghetti plot that illustrates the various of streamflow possibilities produced from one ESP forecast run. Every trace is given an equally likely chance of occurring, thus providing 67 equally likely runoff forecast possibilities.

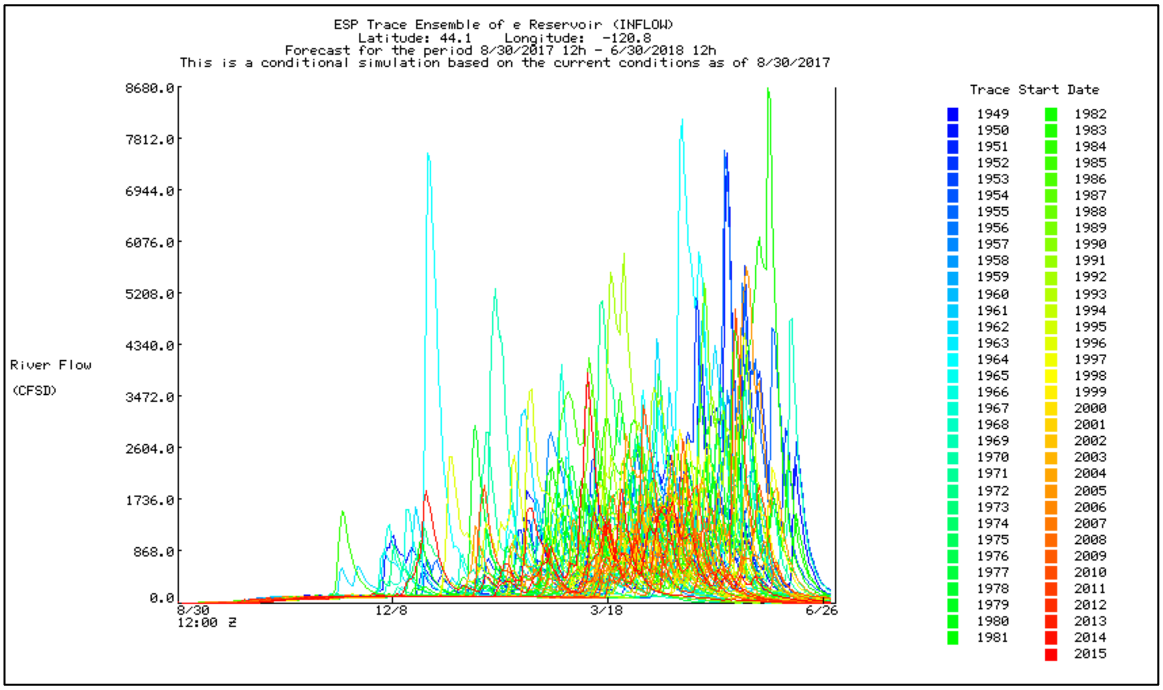

Figure 12. NWRFC ESP traces for inflow into Prineville Reservoir (August 30, 2017-June 30, 2018)

Probabilistic runoff volume forecasts can be calculated from the streamflow ensemble by integrating each flow trace to a volume over the period of interest. The median streamflow ensemble (Figure 13) is assumed to be the most likely runoff volume.

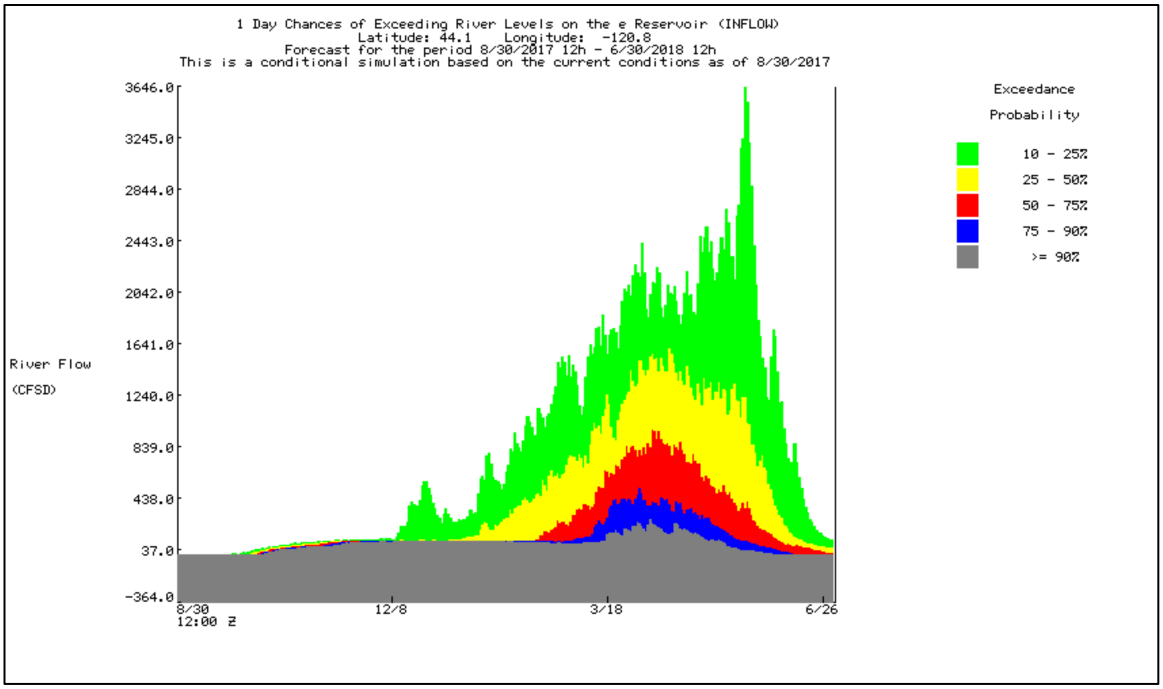

Figure 13. NWRFC ESP exceedance probability plot for daily inflow into Prineville Reservoir (August 30, 2017-June 30, 2018)

The median volume from the ESP procedure was used for the hindcast task. Additional analysis was not completed to look at the performance of other exceedance probabilities, due to the limited time that was available during this Study; however, it is recommended that a more robust analysis be completed in the future.

5.1.3 National Center for Atmospheric Research Hindcasts

Water supply forecast hindcasts were also developed for Prineville Reservoir by the National Center for Atmospheric Research (NCAR). NCAR is a Federally funded research and development center devoted to service, research, and education in the atmospheric and related sciences. NCAR's mission is to understand the behavior of the atmosphere and related Earth and geospace systems; to support, enhance, and extend the capabilities of the university community and the broader scientific community, nationally and internationally; and to foster the transfer of knowledge and technology for the betterment of life on Earth.

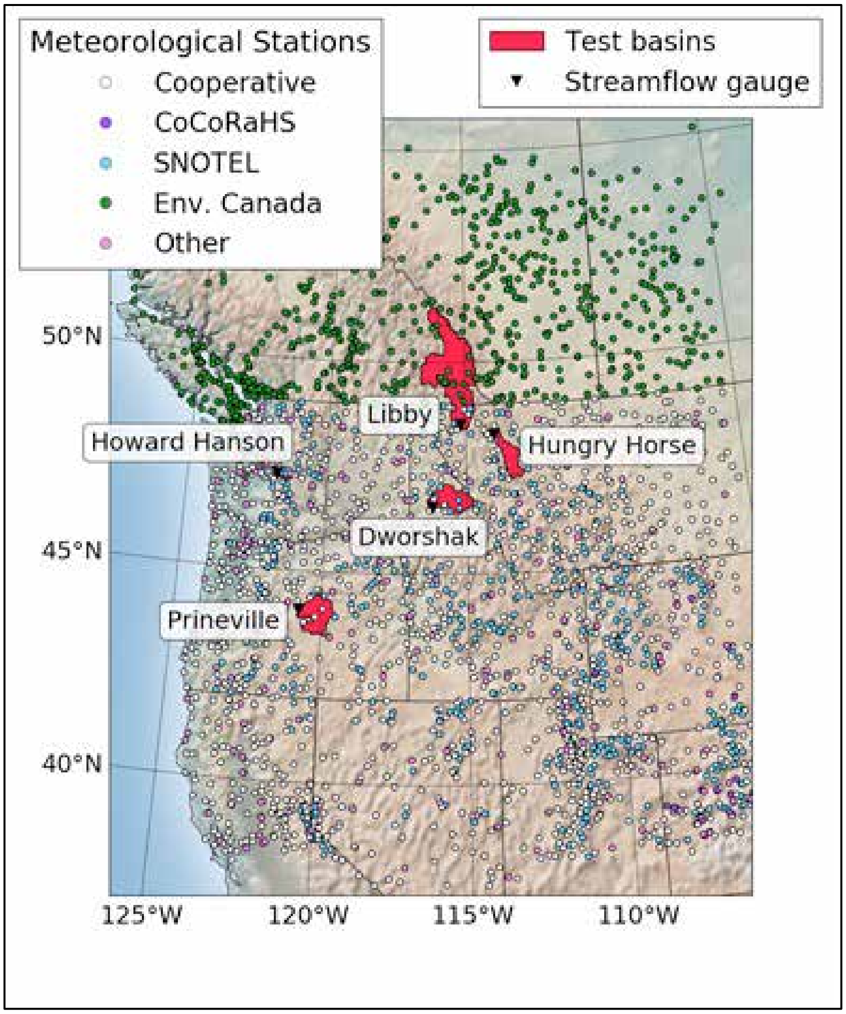

Figure 14. Location map for pilot basins included in the Mendoza et. al 2017 Study

The hindcasts were developed in coordination with a larger runoff forecasting study NCAR was completing for various basins in the Pacific Northwest (Figure 14). During the NCAR study, numerous forecasting methods were completed for Prineville Reservoir; a more detailed description of this process can be found in the Mendoza study (Mendoza et. al 2017). For the purposes of this Study, the Bias-Corrected Ensemble Streamflow Prediction (BC-ESP) was chosen to produce the hindcasts that were used in this Study, because this method performed the best at forecasting for the January-through-August period.

The NCAR hindcasts were completed using a lumped SAC-SMA hydrology model that employed the National Weather Service (NWS) Snow-17 snow model and a unit-hydrograph routing model to forecast water supply volume. The model was calibrated using forcing data during the 1980-to-2016 period and an automated multi-objective parameter estimation procedure to produce observed daily streamflow. The temperature and precipitation forcings were obtained from a 1/16th degree real-time implementation of the ensemble forcing generation method described in Newman et al. (2015). The model was separated into three elevation zones to define the snowline during the snow accumulation period. The final forecast volume went through a simple bias correction process that most likely was a result of limited forcing data. Bias correction is a process used to remove systematic biases in model results. The bias correction was applied for each month and was determined by computing the ratio between the mean of the observed runoff volume and the mean of the forecast median volume. When running the forecasts, only the observed meteorological inputs up to the time of initialization were included.

Using the calibrated hydrology model, the NCAR hindcast procedure initialized the model at the beginning of each month during the November-through-July period. The hydrological conditions up to the date of initialization were forced into the model, and any subsequent conditions were forced by the trace water year's meteorological data, which is referred to as the Ensemble Streamflow Prediction (ESP) method. For example, for the February 1, 2008, hindcast, the hydrological model was forced to match the historical conditions at that time, including current precipitation, SWE, and runoff conditions that had been experienced before the February 1 initialization date. For future subsequent conditions, the model ingested meteorological data from 1980 to 2016 to estimate the resulting runoff volume. The results of this process provided 32 possible runoff volume scenarios that follow the trace-year meteorological sequence. The results of these volumes were then ranked and the median (50 percent exceedance) trace volume was chosen for the hindcast value.

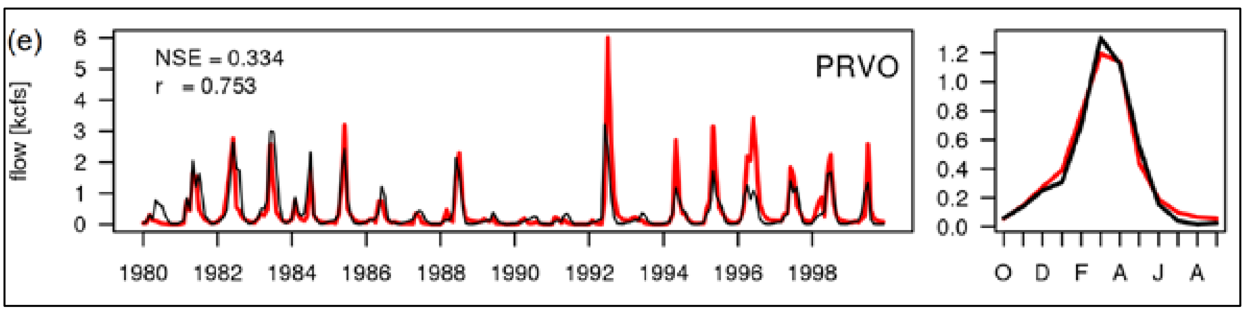

Figure 15. Monthly streamflow simulations (red) and observations (black) for the period from October 1980 to September 2000. The left panel displays monthly time series, with NSE and r denoting Nash-Sutcliffe efficiency and correlation, respectively. The right panel shows simulated and observed seasonal streamflow cycle (Mendoza et. al. 2017).

5.1.4 Perfect Hindcast

To determine the impacts that a specific hindcast method had on the operation of Prineville Reservoir using the Pilot Model, a Perfect Forecast was generated when future runoff volumes were known. The Perfect Forecast is a forecast value that exactly matches the actual observed runoff volume; operations of the Pilot Model following the Perfect Forecast would be considered the optimal operation. Any difference between operations when comparing the Perfect Forecast operation to a hindcast operation can be attributed to the hindcast. The residual volume for every day starting from October 1 through August was calculated within the RiverWare model. This residual volume was calculated for the actual observed inflow for that year of interest and is one of the two ordinates (the other one is the current date) used in the dSRD to determine the flood control space required.

5.2 Hindcast Modeling Results

The following sections summarize the results of the hindcast model simulations and identify impacts to the metrics described in Section 3. The metrics help to determine what, if any, impacts occurred to specific resource categories, and are a good measure of the actual impact of a forecast on actual releases/operations of Prineville Reservoir. Figure 16 below displays the runoff volume residual for the MLR, NWRFC, and NCAR hindcasts and the Perfect Forecast method.

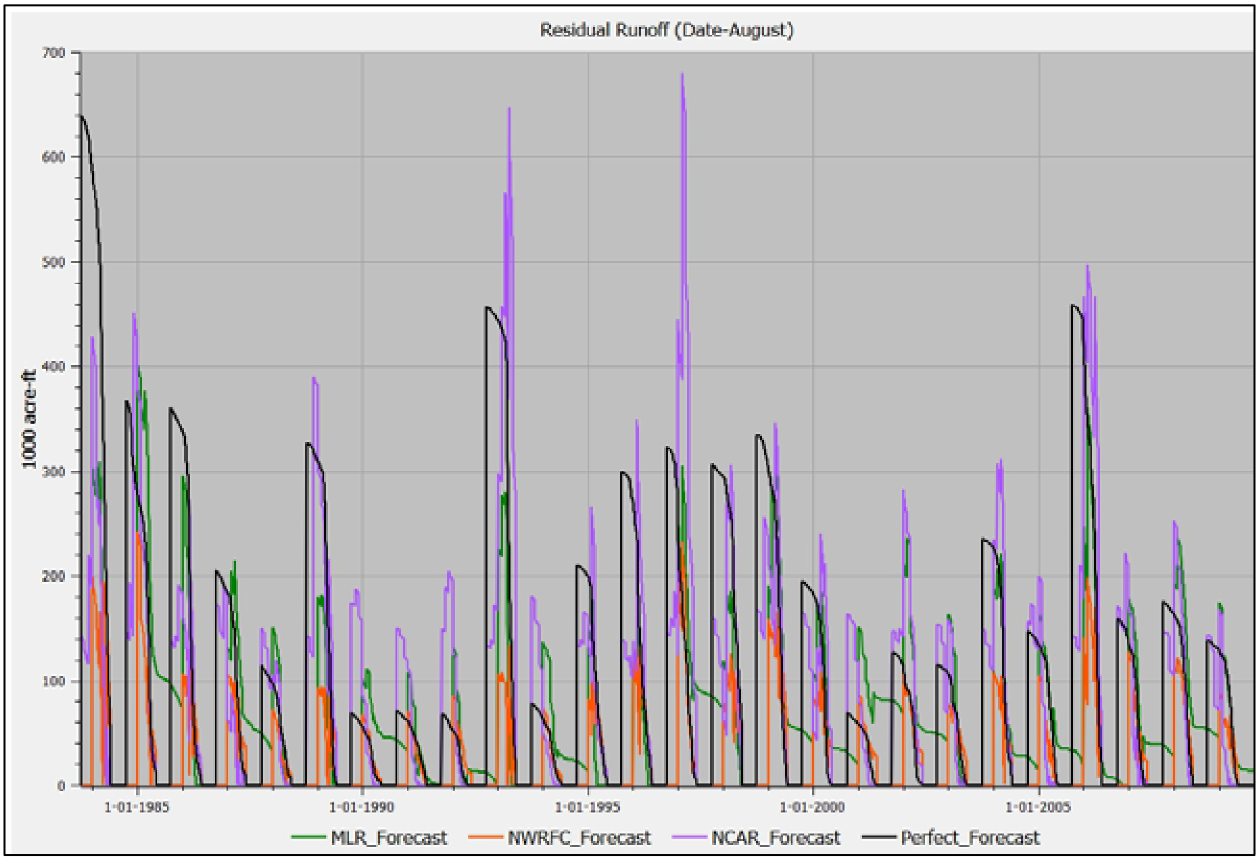

Figure 16. Plot showing residual runoff volume (1,000 acre-feet) for Perfect Forecast (black), MLR (green), NWRFC (orange), and NCAR (purple) hindcasts

The results provided in the metrics discussion are from a 1984-to-2009 modeled period and do not examine any individual change in operation for a specific year; rather, it examines the results over the entire modeled period. Also, when drawing conclusions from the results and comparing the number of days between model runs, the total number of days in the modeled period (9,496 days) are considered.

5.2.1 Hindcast Error Analysis

As stated above, three different hindcasting methods were used to investigate whether any improvements to the forecast skill might be possible. Conditions in the Crooked River watershed historically have been difficult to forecast due to the flashy nature of the runoff regime. This section provides a summary of how the various hindcast methods performed by comparing the forecast error, or difference in forecasted runoff volume when compared to the actual runoff volume, of each. The runoff volume analysis window includes the January-through-April period, which encompasses the snow-accumulation-and-depletion season on the Crooked River.

In general, the actual errors, in thousand acre-feet, tend to decrease through the January-May period due to the runoff volume being lower. For instance, the January average error was the error in the runoff volume for the January-through-August period. The April error would represent the error in the April-through-August period, which is a smaller volume of runoff. The opposite is true when looking at percent errors, as these are calculated relative to the period the error was calculated. For instance, the percent errors in the February hindcasts is the difference between the hindcast runoff volume and actual runoff volume divided by the actual runoff volume.

Key Takeaways

- The Crooked River basin is inherently difficult to forecast due to the flashy nature of runoff conditions
- NCAR hindcasts provided improvements in early-season forecasts during January
- MLR hindcasts resulted in the smallest errors in February and March
- NWRFC hindcasts had the lowest errors in April and May

Figure 17 below shows the average error for all hindcast methods during the January-through-May period. The average error was calculated irrelevant of whether the error was an under- or over-forecast value (i.e., mean absolute error). Additional discussions on over- and under-forecast errors are discussed later in this section. Average forecast errors during the month of January are all within approximately 17,000 acre-feet of each other. For the months of February and March, the MLR method was found to have the smallest average errors of 65,800 and 55,400 acre-feet, respectively. The forecast errors for the month of April calculated for the NWRFC hindcasts were found to be lower than the two other methods. Based on experiences with forecasting runoff volume on the Crooked River watershed, the March-through-April period is the most critical, as this is the time in which the peak snow accumulation occurs and snowmelt begins in the higher elevations of the basin. Figure 18 shows the percent errors for the January-through-April period. The RFC hindcast resulted in the smallest percent error of 40 percent for the month of February. Looking at the January-through-April period, the RFC hindcasts methods resulted in the smallest average error of approximately 53 percent. The percent errors in the month of April are the largest in the forecast period but only represent volumes in the 20,000 to 40,000 acre-feet range (Figure 17).

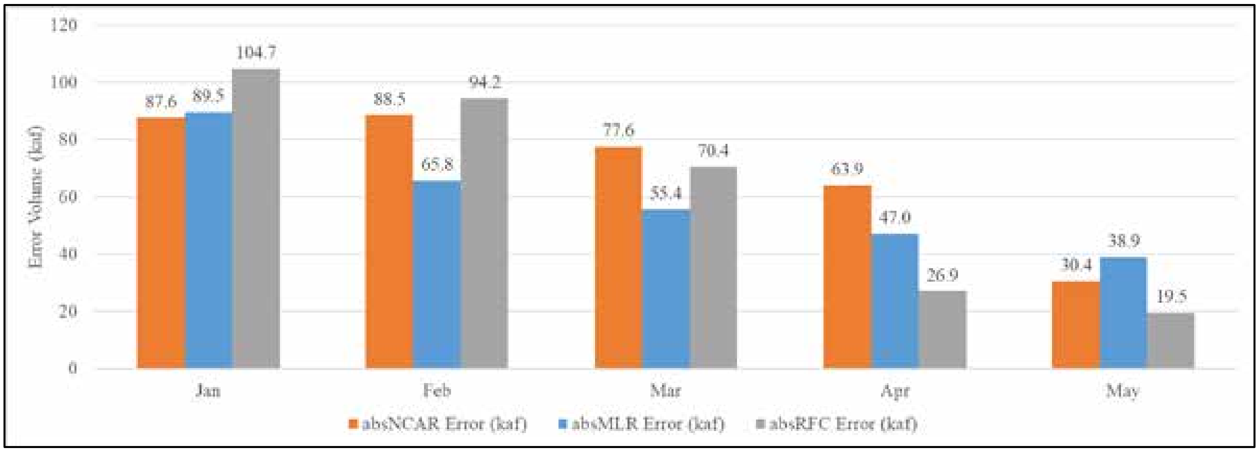

Figure 17. Average monthly forecast errors for the NCAR, MLR, and NWRFC hindcast methods

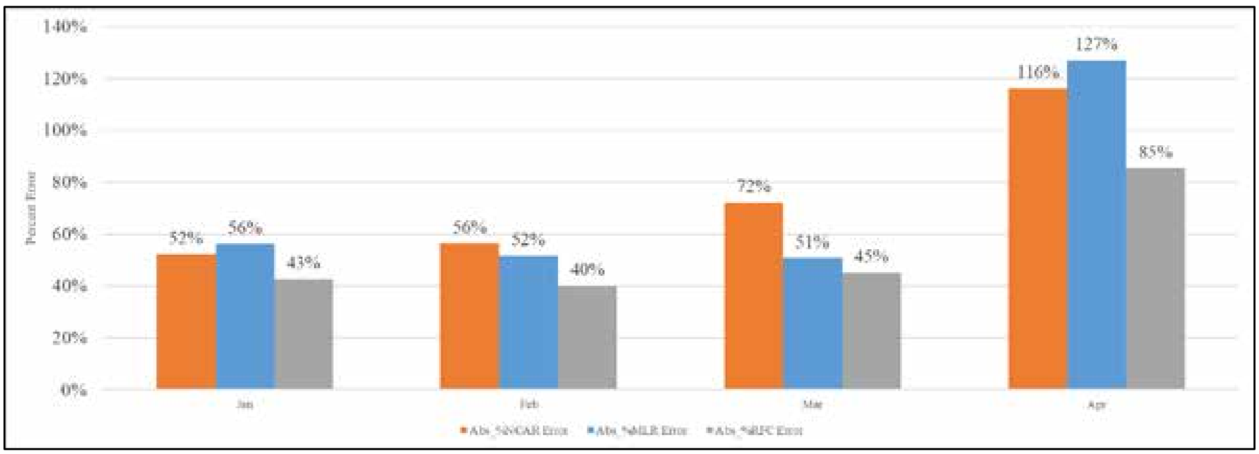

Figure 18. Average monthly percent errors for the NCAR, MLR, and NWRFC hindcasts.

Figure 19 shows the average monthly errors in which the hindcast method resulted in over-forecasting the runoff volume. An over-forecast is when the forecast estimates a runoff volume that is greater than what occurs. When focusing on over-forecasted errors, the NWRFC hindcast method was found to have the smallest errors, which were all within approximately 12,000 to 25,000 acre-feet of the actual runoff volume. Over-forecast errors from the MLR method ranged from approximately 43,500 acre-feet to 59,800 acre-feet, while the NCAR method resulted in the larger over-forecast errors during the February-through-April period but were similar to the other two hindcasts during the months of January and May.

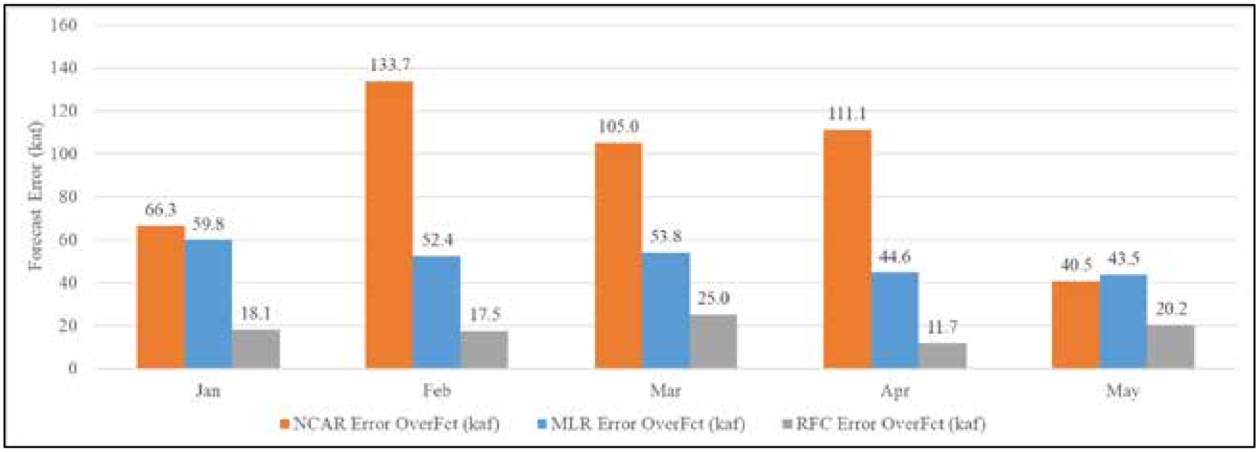

Figure 19. Average monthly over-forecasted errors for the NCAR, MLR, and NWRFC hindcast methods

Figure 20 shows average errors for hindcasts that under-forecasted the runoff volume. An under-forecast is when the forecast estimates a runoff volume that is less than what occurs. The average under-forecast errors for the month of January were found to be similar for all three hindcast methods. The NCAR method resulted in the smallest under-forecast errors for the February, April, and May periods.

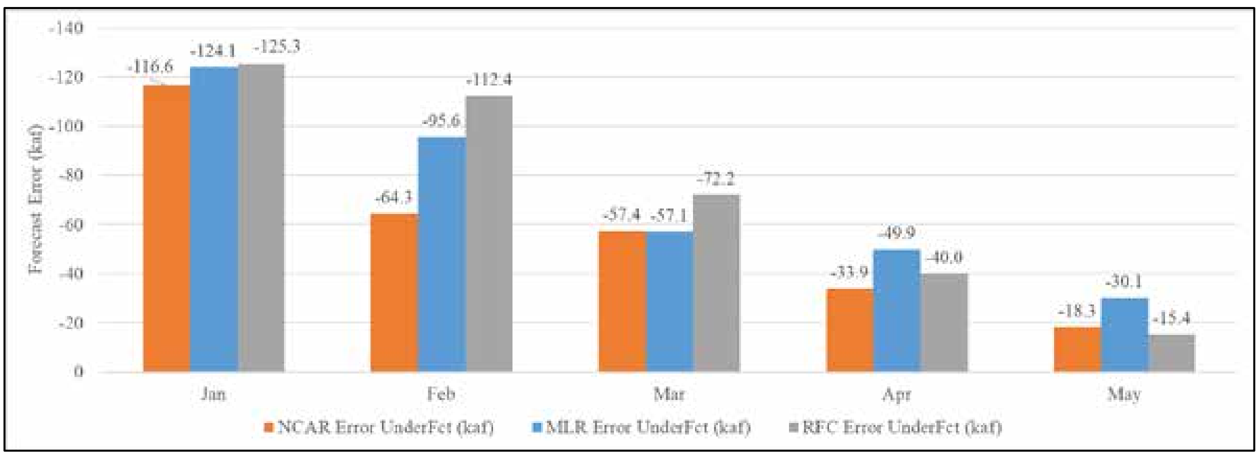

Figure 20. Average monthly under-forecasted errors for the NCAR, MLR, and NWRFC hindcast methods

5.2.2 Flood Control Metrics

> **Key Takeaways**
>
> - MLR hindcasts resulted in the fewest number of additional days above 3,000 cfs compared to the perfect forecast.
> - NCAR hindcasts resulted in 15 fewer days at discharges greater than 2,000 cfs.
> - Overall, impacts to discharges from hindcast methods tended to be minimal due to limited space requirements for most forecasted runoff volumes.

The primary location of focus for the flood control metric was directly downstream from the dam. The number of days in which discharges were greater than various values were calculated, and then that number was compared to the number of days calculated using the Perfect Forecast method. The total number of days in the model period was 9,496 days. Actual flood control operations at Prineville Reservoir use a maximum allowable discharge of 3,000 cfs before damages are assumed to start occurring. For this Study, additional discharges were considered that ranged from 1,000 cfs to 3,000 cfs (note that only discharges larger than 3,000 cfs cause flood damages). Table 6 below summarizes the number of days in which discharges were above a specified amount for each hindcast method, as compared to the Perfect Forecast method.

Both the MLR and NWRFC hindcasts resulted in fewer days with a discharge of 1,000 cfs or more, compared with the Perfect Forecast method. The NCAR method resulted in 15 days less than the Perfect Forecast at a discharge of 2,000 cfs or greater. The MLR hindcast method was found to be the most similar to the Perfect Forecast at the 3,000 cfs discharge level, with only one additional day in which discharges were greater than 3,000 cfs. Although the number of days in which discharge was greater than 3,000 cfs may have been different for the hindcasts methods when compared to the Perfect Forecast, this does not mean that discharges were significantly larger, due to the ability of Prineville Reservoir to use surcharge storage to regulate flows and remain at 3,000 cfs or below. Overall, impacts to discharges above 3,000 cfs when comparing the three different hindcast methods tend to be minimal.

Table 6. Number of days above various discharges when compared to the Perfect Forecast model results

Model Run	# of Days Discharge (cfs) is greater than				
	1,000	1,500	2,000	2,500	3,000
Perfect Forecast	567	294	195	110	4
Hindcast Method	**# Days Different from Perfect**				
MLR Hindcast	-8	1	-3	2	1
NCAR Hindcast	4	-2	-15	9	6
NWRFC Hindcast	-9	-2	6	18	5

The second flood control metric that was examined was the impact of a hindcast on the occurrence of reservoir surcharge. As stated earlier, Reclamation can use surcharge space in Prineville Reservoir to regulate flows to 3,000 cfs, even when the uncontrolled spillway is in use. The typical surcharge operation during flood control situations allows for water to build up onto the uncontrolled spillway, at the same time reducing discharge through the outlet tubes, such that the total discharge downstream of the dam remains the same. The logic of this flood operation was developed for the Pilot Model to mimic real-time operations. Table 7 below summarizes the number of days during the simulation period that the forebay elevation was greater than the full-pool elevation of 3234.8 feet. For both the MLR and NCAR hindcasts, the number of days above 3234.8 feet, as compared to the Perfect Forecast, was 147 and 115 days, respectively. The majority of those days, 82 percent and 58 percent respectively, were within the 0.2 feet of surcharge, so it is difficult to determine if this is an actual impact or a result of modeling limitations. The Perfect Forecast method resulted in 0 days above elevation 3236.0 feet, or 1.2 feet of surcharge, while all three of the hindcast methods resulted in surcharge greater than that. Both the MLR and NCAR hindcasts provided a similar number of days of surcharge, while the NWRFC hindcast resulted in 0 days in which surcharge was greater than 3237.0 feet. The number of days with surcharge at various elevations is a result of the forecast error for that particular year. For example, if a hindcast under-forecasted the runoff volume for a particular period, it would allow for the reservoir to fill into the space that would have been required if the forecast were perfect. The ending result is that as the reservoir fills and outflows are maxed out at the 3,000 cfs target flow, the flood space is not available, and therefore, the reservoir goes into surcharge earlier and for a long period of time. The dSRD that was developed for Prineville Reservoir assumed the ability to use the reservoir surcharge to regulate flood flows to 3,000 cfs; the fact that the reservoir goes into surcharge is not an indicator that the curve is not working as intended.

Key Takeaways

- Hindcasts that resulted in more days of surcharge were a result of under-forecasting runoff volume.
- NWRFC hindcasts had the fewest number of days when surcharge occurred.
- MLR and NCAR hindcasts resulted in similar number of days of surcharge, with 82 percent and 58 percent of those days being minimal with less than 0.2 feet.
- When compared to the Perfect Forecast, both the MLR and NCAR forecasts resulted in approximately 2.5 feet of additional surcharge, while the NWRFC forecast resulted in 1 foot of surcharge.

Table 7. Number of days above various surcharge elevations compared to the Perfect Forecast

Model Run	# of Days Forebay Elevation (feet) is greater than								Max[1]
	3234.8	3235.0	3235.5	3236.0	3236.5	3237.0	3237.5	3238.0	
Perfect Forecast	13	10	3	0	0	0	0	0	3235.7
Hindcast Method	**# Days Different from Perfect Forecast**								
MLR Hindcast	147	27	12	12	11	8	7	1	3238.2
NCAR Hindcast	115	48	16	13	10	9	7	3	3238.3
NWRFC Hindcast	10	10	8	7	1	0	0	0	3236.7

[1] Maximum surcharge elevation for the model run.

The third flood control metric the team examined is whether flood control operations prevented the reservoir from refilling during the year. Table 8 below summarizes the number of years that reservoir refill was obtained for the Perfect Forecast method, and then compared to the three different hindcast methods. Over the modeled period of 1984 to 2010, Prineville Reservoir had complete refill for 18 of the 26 years. Both the MLR and NCAR had the same number of refill years as the Perfect Forecast method, while the NWRFC method resulted in 1 less year of refill. The 1 year that the NWRFC hindcast missed refill only resulted in an allocation of 600 acre-feet less than the total allocation of 148,640 acre-feet, so this may be a result of the precision of the Pilot Model and appears not to be a major impact from the hindcasting method.

Table 8. Number of years Prineville Reservoir refilled as compared to the Perfect Forecast

Model Run	# of Years with Full Refill
Perfect Forecast	18
Hindcast Method	**# Years Different from Perfect Forecast**
MLR Hindcast	0
NCAR Hindcast	0
NWRFC Hindcast	-1

5.2.3 Water Deliveries Metrics

> **Key Takeaways**
>
> - Hindcasts were not found to have an impact on the allocation of water supply.

Similar to the refill metric, storage allocation for the modeled period was similar for all three hindcast methods when compared to the Perfect Forecast (Table 9). Storage allocation among all three hindcast methods were similar, with all methods having an allocation volume of within approximately 400 acre-feet for all exceedance values. In years during which the reservoir went into surcharge, and surcharge was more than what occurred for the Perfect Forecast, the maximum contents resulted in more stored flow. Due to water storage rights not allowing the allocated stored water in surcharge space during any year in which surcharge occurred, the actual allocation of stored flow would not occur until the reservoir was out of surcharge, and therefore, allocation was the same across all methods (10 percent exceedance values).

Table 9. Comparison of storage allocation exceedance values for hindcast scenarios

Model Run	Storage Allocation Exceedance Values				
	10%	20%	50%	80%	90%
Perfect Forecast	148,640	148,394	148,354	113,746	93,275
Hindcast Method	**Acre-feet Different from Perfect Forecast**				
MLR Hindcast	0	246	286	395	300
NCAR Hindcast	0	246	250	355	72
NWRFC Hindcast	0	-227	-309	-306	-290

Storage carryover (the storage left in the reservoir after irrigation deliveries have ended) was effectively the same across the three hindcast methods. Figure 21 below is an exceedance plot of daily reservoir storage at Prineville Reservoir for the month of October, showing very little, if any, difference in storage across the three different hindcast methods.

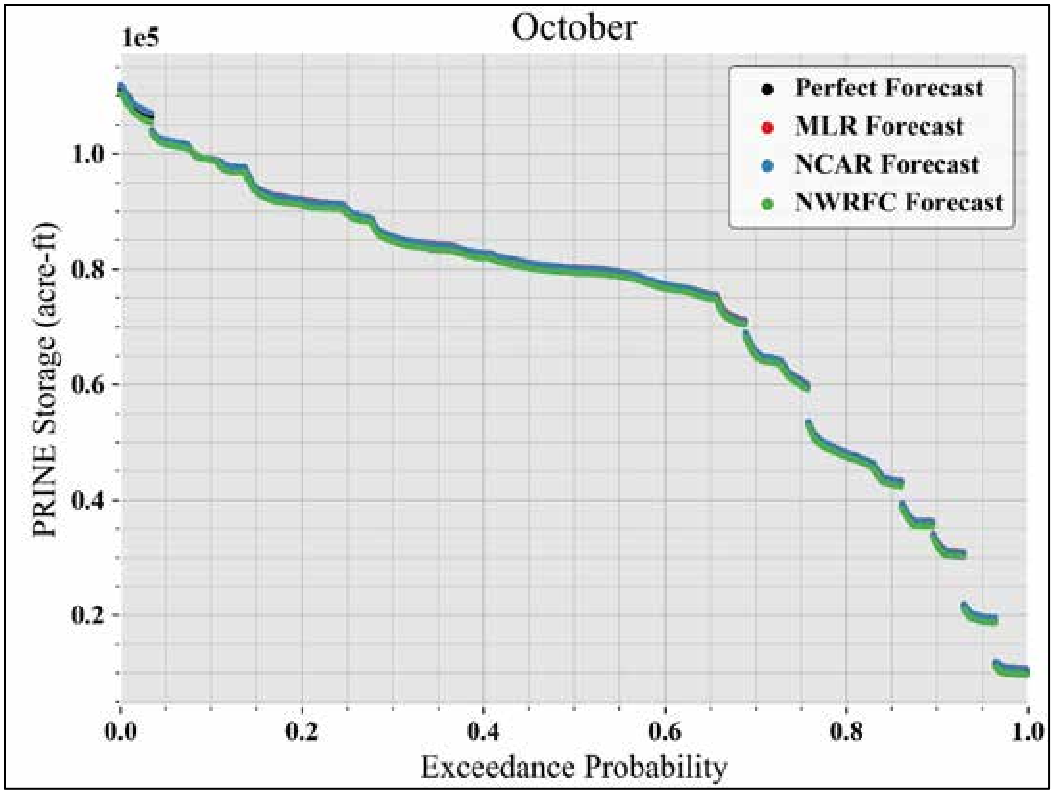

Figure 21. Daily reservoir storage exceedance plot for the month of October comparing hindcast methods and Perfect Forecast

5.2.4 Water Quality Metrics

> **Key Takeaways**
>
> - Results varied, with some hindcasts having fewer days at 110% TDG but more at 120% TDG and vice versa.
> - The MLR hindcast resulted in TDG values similar to the Perfect forecast.
> - NWRFC hindcasts resulted in 18 more days with TDG at 120% or greater.

The first water quality metric examines how the TDG levels may be affected by a different forecast method. A previous Reclamation study that provides estimates on the TDG levels at various discharges was used to determine the impact on TDG by the different hindcast methods. To compare the results, three different discharges were chosen that correlate with 110 percent, 115 percent, and 120 percent estimated TDG levels in the stilling basin at the dam. The percentage of TDG is highly correlated with water temperature, where higher water temperatures can result in higher TDG levels, assuming the discharge is the same. For purposes of this Study, the temperature of the water discharged from the dam is assumed to be similar to the temperature when the correlation in Figure 4 was developed. Table 10 below summarizes the number of days in which the discharge was at various levels for the Perfect Forecast, as well as the difference in the number of days compared to the Perfect Forecast resulting from the three different hindcast methods. The NCAR method produced 34 fewer days than the Perfect Forecast in which discharge was above 670 cfs (110 percent TDG), while the MLR and NWRFC produced 2 and 9 fewer days, respectively, than the Perfect Forecast in which discharge was above 670 cfs. All hindcast methods resulted in more days than the Perfect Forecast with discharge above the 2,500 cfs level (120 percent TDG). At this point, it is difficult to fully understand the impact on fisheries and aquatic habitat, as research is limited regarding whether it is better to have fewer days at 120 percent TDG at the expense of more days at 115 percent TDG. In addition, for the entire modeled period of 26 years (9,490 days), even with the Perfect Forecast method, only 110 days require discharges resulting in TDG levels of 120 percent or greater, which correlates to 1 percent of the modeled period.

Table 10. Number of days TDG is above 110, 115, and 120 percent as compared to the Perfect Forecast

Model Run	# of Days Discharge (cfs) is greater than		
	670 (110%)	1,500 (115%)	2,500 (120%)
Perfect Forecast	890	294	110
Hindcast Method	**# Days Different from Perfect**		
MLR Hindcast	-2	1	2
NCAR Hindcast	-34	-2	9
NWRFC Hindcast	-9	-2	18

Regarding water temperature in the reservoir, all three hindcast methods resulted in similar October reservoir storage exceedance values (Figure 21), and a qualitative assessment would therefore assume that there would be no difference in reservoir water temperatures due to all model runs using the same historical conditions.

5.2.5 Recreational Resources Metrics

The two recreational resource metrics used for this Study were the number of optimal fishing days downstream of the dam and the number of boating days in the reservoir. Table 11 below summarizes the results for the number of optimal fishing days downstream of the dam. Generally, optimal fishing flows are within the 50 to 400 cfs range, a range that provides high enough flows during which fishing doesn’t adversely affect population numbers, but also in which flows are low enough that anglers can safely wade the river. The number of days when flows were greater than 50 cfs was essentially the same for the Perfect Forecast and all three hindcast methods. The MLR and NWRFC model results show 24 more optimal fishing

Key Takeaways

- Overall, the impact to optimal fishing days was minimal, regardless of which hindcast method was used.
- NWRFC hindcasts resulted in fewer boating days while both MLR and NCAR resulted in more boating days.

days (i.e., days when discharges were 50 to 400 cfs) than the Perfect Forecast, while the NCAR method was found to have 4 fewer optimal fishing days compared to the Perfect Forecast. Overall, the impact to optimal fishing days was minimal, based on which hindcast method was used, because typically flows are held in the 50-to-270 cfs range to meet irrigation demand, while flows greater than approximately 270 cfs are a result of flood control operations, and are thus controlled by the hindcast method.

Table 11. Number of days in which flows are within the optimal fishing range of 50 to 400 cfs compared to the Perfect Forecast

Model Run	# of Days Discharge (cfs) is greater than		
	50	400	# Optimal Days
Perfect Forecast	8,813	1,523	7,290
Hindcast Method	**# Days Different from Perfect**		
MLR Hindcast	1	-23	24
NCAR Hindcast	-1	3	-4
NWRFC Hindcast	1	-22	23

Prineville Reservoir has three boat ramps that provide access to the reservoir. The elevation at which the boat ramps become unusable ranges from 3210 feet to 3191 feet. The reservoir boating metric measures how the hindcast method impacts the number of days that each of the three boat ramps would be usable at Prineville Reservoir. The first boat ramp that would become unusable is the Powerhouse Cove ramp, which has a minimum required pool elevation of 3210 feet. The Perfect Forecast method resulted in 5,625 days (59 percent of the time) during the modeled period that the boat ramp would not be usable (Table 12). Results from the hindcast modeling varied from having 43 fewer days than the Perfect Forecast for the MLR hindcast to 93 additional useable days for the NWRFC hindcast. The number of days that the Prineville Reservoir State Park ramp, which has the lowest elevation boat ramp, was usable was similar to the Perfect Forecast method and ranges from 10 fewer days to 10 more days. The Powerhouse Cove ramp is below the elevation required to meet winter flood space requirements during the November 15-to-February-15 period, so it is common for this boat ramp to be usable during this period unless the reservoir was drafted below this level to meet irrigation demand in a low-water year.

Table 12. Number of days various boat ramps are usable, compared to the Perfect Forecast

Model Run	# of Days Pool Elevation is Greater Than		
	3,191 (State Park)	3,203 (Jasper Point)	3,210 (Powerhouse Cove)
Perfect Forecast	8257	7199	5625

Model Run	# of Days Pool Elevation is Greater Than		
	3,191 (State Park)	3,203 (Jasper Point)	3,210 (Powerhouse Cove)
Hindcast Method	**# Days Different from Perfect**		
MLR Hindcast	10	21	43
NCAR Hindcast	9	17	18
NWRFC Hindcast	-10	-13	-93

5.2.6 Ecological Resources Metrics

Key Takeaways

- Hindcasts were found to have minimal impacts to ecological flows, mostly due to the period in which hindcasts impact reservoir releases.
- Ecological flow metrics investigated flows below 100 cfs, while hindcasts generally impacted releases when flows were greater than 100 cfs,

The ecological resource metric focuses on the percent of time that flows below the dam and at the low-flow point in the system (Highway 126 bridge) attain various flow targets. The current minimum flow target for the Crooked River below the reservoir is 80 cfs. However, during low-water years, that cannot always be achieved, so flow targets are adjusted accordingly. The first metric examines the flows directly below the dam upstream of any irrigation withdrawals. Various discharges from 20 cfs to 80 cfs were analyzed, and the number of days that flow exceeded these discharges were calculated (Table 13). In general, for flows of 80 cfs or less, the Perfect Forecast and all three hindcast methods resulted in essentially the same number of days below 80 cfs. Some differences were found between the Perfect Forecast and hindcast for discharges greater than 100 cfs. Both the MLR and NCAR hindcasts resulted in 45 and 41 more days, respectively, above 100 cfs than the Perfect Forecast. The NWRFC hindcast resulted in 16 fewer days that exceeded 100 cfs. Exceedance values for the various discharge rates were common across the methods, with a 20 cfs discharge being exceeded for 95 percent of the modeled period, and the 80 cfs target being exceeded approximately 68 percent of the time. Based on the WUA curve described earlier in Section 3.6.2, the WUA ranged from 46 percent to 96 percent within the flow range investigated.

Table 13. Number of days, exceedance, and WUA for various flows compared to the Perfect Forecast below the dam

Model Run	# of Days Discharge (cfs) is greater than				
	20	40	60	80	100
Perfect Forecast	9,031	8,966	8,652	8,470	6,412

Model Run	# of Days Discharge (cfs) is greater than				
	20	40	60	80	100
Hindcast Method	**# Days Different from Perfect**				
MLR Hindcast	1	1	-2	-4	45
NCAR Hindcast	-1	0	2	4	41
NWRFC Hindcast	2	1	2	-2	-16
Hindcast Method	**% Exceedance**				
Perfect Forecast	95%	94%	91%	89%	68%
MLR Hindcast	95%	94%	91%	89%	68%
NCAR Hindcast	95%	94%	91%	89%	68%
NWRFC Hindcast	95%	94%	91%	89%	67%
Habitat Parameter	**% WUA**				
WUA	46%	66%	80%	85%	96%

Similar to flows below the dam, flows at the system low-flow point near the Highway 126 bridge were similar between the Perfect Forecast and all three hindcast methods, up to a discharge value of 80 cfs. For discharges of 100 cfs or larger, the MLR hindcast resulted in 51 days more than the Perfect Forecast, while the NCAR method resulted in 13 days fewer than the Perfect Forecast. Due to irrigation withdrawal between the dam and the Highway 126 bridge, the exceedance value for the 80 cfs target flow was reduced from 89 percent to 74 percent. For flows greater than 100 cfs, the exceeded flow was reduced from 68 percent below the dam to approximately 24 percent at the Highway 126 bridge. The reduction in exceedance flows between flows downstream from the dam and the Highway 126 bridge is not a result of the different hindcast methods, but rather is because during drier water years, storage flows released from the dam for irrigation also provide a benefit for ecological purposes upstream from the Highway 126 bridge.

Table 14. Number of days, exceedance times, and WUA for various flows, compared to the Perfect Forecast at the Highway 126 bridge

Model Run	# of Days Discharge (cfs) is greater than				
	20	40	60	80	100
Perfect Forecast	8,648	8,293	7,595	6,987	2,235

Model Run	# of Days Discharge (cfs) is greater than				
	20	40	60	80	100
Hindcast Method	**# Days Different from Perfect**				
MLR Hindcast	-1	1	-2	-3	51
NCAR Hindcast	-1	0	2	5	40
NWRFC Hindcast	2	2	2	-2	-13
Hindcast Method	**% Exceedance**				
Perfect Forecast	91%	87%	80%	74%	24%
MLR Hindcast	91%	87%	80%	74%	24%
NCAR Hindcast	91%	87%	80%	74%	24%
NWRFC Hindcast	91%	87%	80%	74%	23%
Habitat Parameter	**% WUA**				
WUA	46%	66%	80%	85%	96%

Per the Crooked River Legislation (Public Law 113-244), the minimum flow target below the dam and the reach downstream is 80 cfs. Current operations attempt to meet this 80 cfs requirement throughout the years when water supplies are available. In general, when allocation of uncontracted space is less than 57,917 acre-feet, the 80 cfs minimum flow target cannot be met for the entire year. For the purposes of simplifying the modeling of the operational constraint, when the uncontracted allocation is less than 57,917 acre-feet, the model considers the estimated number of days before the next day of allocation and then calculates the average release based on that information. Table 15 below summarizes the number of days that the 80 cfs minimum target was met in the Perfect Forecast and all hindcast methods over the modeled period. The results of the hindcasting procedure resulted in the same number of days in which the minimum flow was met.

Table 15. Number of days flow was 80 cfs or more below the dam, compared to the Perfect Forecast modeled results

Model Run	# of Days Discharge is greater than 80 cfs	% Exceedance
Perfect Forecast	8,470	89%
Hindcast Method	**# Days Different from Perfect**	**% Exceedance**
MLR Hindcast	-4	89%

Model Run	# of Days Discharge is greater than 80 cfs	% Exceedance
NCAR Hindcast	4	89%
NWRFC Hindcast	-2	89%

Table 16 shows the same results but for the low-flow point in the system at the Highway 126 bridge. For this location, the results of the hindcast methods were similar to the Perfect Forecast, although the exceedance was less than what was calculated for the location below the dam due to the irrigation withdrawals that occurred between the two locations.

Table 16. Number of days flow was 80 cfs or more at the Highway 126 Bridge compared to the Perfect Forecast

Model Run	# of Days Discharge is greater than 80 cfs	% Exceedance
Perfect Forecast	6,987	74%
Hindcast Method	**# Days Different from Perfect**	**% Exceedance**
MLR Hindcast	-3	74%
NCAR Hindcast	5	74%
NWRFC Hindcast	-2	74%

5.2.7 Hindcast Modeling Conclusions

Various metrics from each hindcast method were considered to investigate what, if any, impacts a corresponding forecast method might have on Prineville Reservoir operations. Forecast skill was examined first and can be described as a metric that portrays the dependability of a particular forecasting method. Differences in forecast skill for the January-through-May runoff volume period were noted at different lead times and across the various hindcast methods. The resource metrics were then examined to translate forecast skill into potential impacts to project resources.

The differences in forecast skill among the hindcast methods translated into impacts on flood control, water quality, recreation, and ecological resources operations, to varying degrees. Although there were impacts, the impacts resulting from the different hindcast methods were found to be relatively small compared to the impacts that occurred regardless of hindcast method (i.e., Perfect Forecast modeling). The impacts were noted primarily during the refill period, when the hindcast volume errors resulted in the reservoir filling into space needed for flood regulation, which required outflows to be increased and remain elevated for a greater duration than the operations driven by the Perfect Forecast.

Regarding the flood control metrics, the number of days in which discharge was more than 3,000 cfs increased for all the hindcasts methods, with the MLR hindcast resulting in the fewest additional days. In addition to discharge, the number of days the reservoir went into surcharge was also affected by the various hindcast methods. When reservoir surcharge was increased, this was typically due to the hindcast method underestimating the runoff volume. The Perfect Forecast did not result in surcharge being greater than 1.2 feet, while the hindcast methods resulted in surcharge values of up to 3.2 feet. Hindcast methods did not show an impact to refill probability, as all hindcast methods resulted in about the same number of years in which the reservoir was filled. All three hindcast methods showed an increase in TDG levels.

Although the current forecasting skill can be quantified for the hindcast methods used in this Study, forecast error in the future cannot be quantified or assumed at this time. Forecast skill in the future may be improved due to advancements in forecasting procedures and methods, or alternatively, forecast skill may decrease due to a changing climate. The current forecasting methods use the historical runoff regime, which is a balance of rain-on-snow events at the mid-elevations of the basin and snowmelt-driven runoff at the higher elevations in the basin. If, for example, in the future, this balance changes, then the current forecast equations may not perform as well as they currently do. The current forecast procedures are developed using a historical dataset that is assumed to capture the variability of the watershed. If a shift in this variability occurs, whether transitioning to a more- or less-snow-dominated watershed, the forecast methods would need to be adapted to account for this shift. The challenge may be developing a forecast method that performs well at capturing historical variability while also preforming well for a different climatic variability that may become more dominant in the future.

6 Future Climate Flow Development and Modeling

This section provides a description of how the future climate flows were developed for this Study. In general, developing future climate flows is a multi-step process using numerous models to predict future climate trends, and then employing these climatic trends as inputs into a hydrologic model to generate inflows into Prineville Reservoir. The following sections describe some of the models used, the methods used to develop the future climate data, and the modeling of the data in a hydrologic model.

6.1 Future Climate Flow Uncertainty

The information presented in this report was developed in collaboration with basin stakeholders and was peer-reviewed in accordance with the Bureau of Reclamation and Department of the Interior polices. This report is intended to inform and support planning for the future by identifying potential future scenarios. The analyses provided in this report reflect the use of best available datasets and methodologies at the time of the study.

Water resources studies are developed in collaboration with basin stakeholders to evaluate potential future scenarios to assess risks and potential actions that can be taken to minimize impacts, including supply and demand imbalances. These types of studies support a proactive approach to water resources management, using the best available science and information to develop scenarios of future conditions within the watershed. This positions communities to take steps now to mitigate the impacts of future water supply management issues, including water shortages, impacts of droughts and floods, variations in water supply, and changing water demands for water for new or different uses.

Because every water resource planning study requires the study partners to make assumptions about future conditions, addressing the uncertainties in those assumptions is an essential component of the planning process. For example, there are uncertainties associated with the characterization of future water supply and demand, demographics, environmental and other policies, economic projections, climate conditions, and land use, to name a few. Moreover, projections are often developed using modeling techniques that are only potential representations of a particular process or variable, and therefore, introduce additional uncertainties into characterizations of the future. The cumulative effect of these interacting uncertainties is not yet well known in the scientific community and is not presented within this study. However, by recognizing this at each process step, uncertainties are adjusted for and reduced when possible, to allow Reclamation and its stakeholders to use the best available science to create a range of possible future risks that can be used to help identify appropriate adaptation strategies, which is fundamental to the planning process. Importantly, scenarios of future conditions should not be interpreted as a prediction of the future, nor is the goal of any water resource planning study to focus on a singular future. Rather, the goal is to plan for a range of possible conditions, thereby providing decision support tools for water managers.

Key Takeaways

- Future climate projections have uncertainties inherent in the multi-step process of developing future projections.
- Acknowledging these uncertainties still allows the use of the best available science to create a robust range of possible future risks and conditions.
- Potential future risks can be used to help identify appropriate adaptation strategies and is essential to the planning process.

Of significant interest are projections of future climate, which ultimately drive many assumptions of water supplies and demands through their influence on the water cycle. Projections of future climate are developed using the scientific communities' best assessment of potential future conditions as characterized by global climate models (GCMs). GCM projections are based upon initial model states, assumptions of future greenhouse gases in the atmosphere, and internal as well as external forcings, such as solar radiation and volcanic activity. Changes in land surface, atmosphere, and ocean dynamics, as well as how such changes are best modeled in GCMs, continue to be areas of active research. Depending on these and other uncertainties, projected future conditions, such as the magnitude of temperature and precipitation changes, may vary.

Observed climatic data and GCM simulations show warming trends over recent decades. However, the degree to which the magnitude of GCM simulated warming agrees with historic observations (Lin 2016) varies based on the data, methods, and time periods used for making such comparisons. Some recent studies have found that models have simulated higher rates of temperature increases relative to observations (Santer et al. 2017); another study has shown that current warming is within a range of model simulations; and yet other studies, have shown the observed and projected warming rates to be similar (Richardson et al. 2016). The evaluation and refinement of GCM performance is an ongoing area of research and includes methods to characterize model outputs and observations, and how measurement errors, internal variability, and model forcings can be improved to enhance future performance.

Further, it is important to recognize that these models perform better at global rather than regional or watershed level scales. Accordingly, techniques must be employed to localize, or downscale, GCM output for applications such as basin-specific water resources planning studies. These downscaled projections of climate are used as inputs to hydrologic models to produce projected streamflows, which are then used to assess impacts to the water resource system in question. Uncertainties at each of the steps necessary to translate GCM output to water resources impacts can be characterized and adjusted for, yet uncertainties remain in the downscaling process that can result in variations depending on the modeling technique used.

Ultimately, future conditions at any particular time or place cannot be known exactly, given the current scientific understanding of potential future conditions. Likewise, it is important to recognize that the risks and impacts are the result of collective changes at a given location. Warming and increased carbon dioxide may increase plant water use efficiency and lengthen the agricultural growing season but may also have adverse effects on snowpack and water availability. These complex interactions underscore the importance of using a planning approach that identifies future risks to water resources systems based on a range of plausible future conditions and working with stakeholders to evaluate options that minimize potential impacts in ways most suitable for all stakeholders involved.

6.2 Future Climate Flow Development

A complete detailed explanation of the future climate flow scenario selection process can be found in the CRBIA technical appendix on climate change and hydrology (Reclamation 2016). A summary of that information is presented in this section.

Future climate scenarios were developed using data from the Bias Corrected and Spatially Downscaled (BCSD) CMIP5 Climate and Hydrology Projections archive hosted by the Lawrence Livermore National Laboratory (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/). These climate projections were generated through the fifth iteration of the Coupled Model Inter-comparison Project (referred to as CMIP5) and were statistically downscaled to the 1/8-degree using the BCSD method (Reclamation 2014). These data were combined into scenarios using the Hybrid Delta Ensemble (HDe) Method approach (Reclamation 2010), which has been used in other basin Study applications.

The HDe approach uses monthly change factors, calculated from select groups (or ensembles) of downscaled global climate model (GCM) projections, to adjust daily gridded meteorological datasets for input to a hydrologic model. In this case, the gridded meteorological datasets that are being adjusted are the Livneh (2013) datasets.

Fifteen HDe future climate scenarios (five scenarios for three future periods) were evaluated for use in this Study. The Study Team determined that the 30-year periods surrounding the 2040s (2030-2059), 2060s (2050-2079), and 2080s (2070-2099) would be most relevant for the alternatives that would be evaluated for the Study.

Figure 22, Figure 23, and Figure 24 show scatter plots of the projections and projection ensembles (scenarios) for the 2040, 2060, and 2080 periods. Each point in these plots represents an individual downscaled CMIP5 projection. Horizontal lines across the plot represent the 20th percentile, 50th percentile, and 80th percentile of change in temperature, and vertical lines represent the 20th percentile, 50th percentile, and 80th percentile of change in precipitation. The 10 nearest neighbors to the intersection of these lines make up the projection ensembles for each of the five scenarios, including: less-warming/dry (LWD), less-warming/wet (LWW), more-warming/dry (MWD), more-warming/wet (MWW), and median. Note that all models agree that temperatures will warm over the next century, hence the use of the terms "less-warming" and "more-warming" as opposed to "cooler" and "warmer". All 15 of these future climate temperature and precipitation projection ensembles were used as inputs into the Precipitation Runoff Modeling System (PRMS) described in the following section.

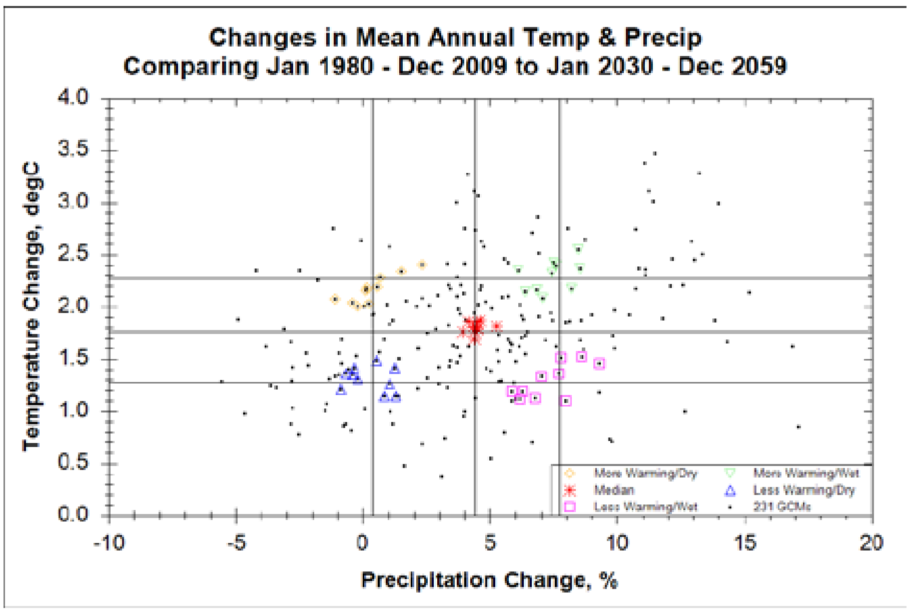

Figure 22. Scatter-graph of projected changes in temperature and precipitation for the entire Columbia River Basin for the 2040s period (January 2030 to December 2059) relative to the historical period (January 1980 to December 2009)

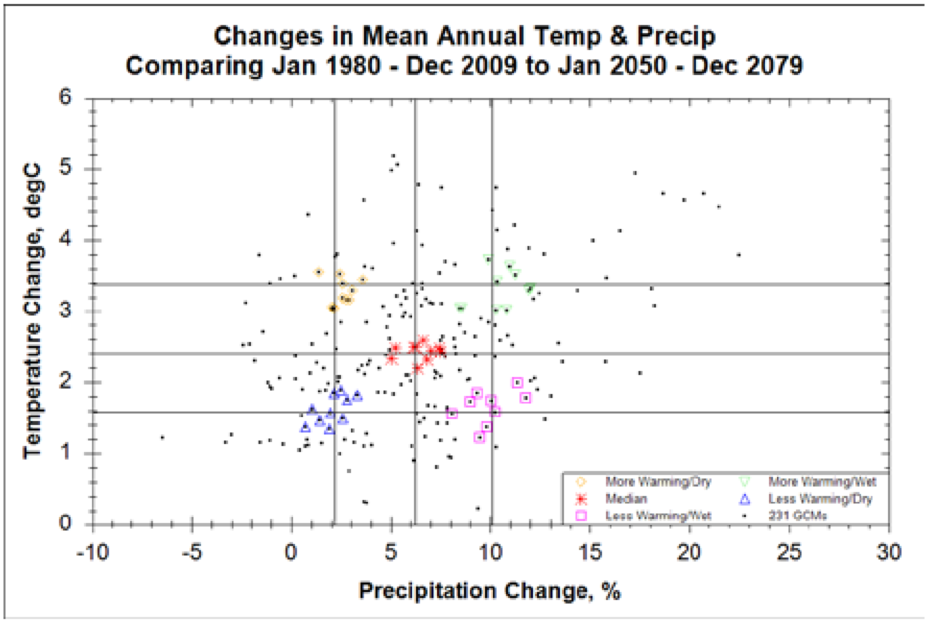

Figure 23. Scatter-graph of projected changes in temperature and precipitation for the entire Columbia River Basin for the 2060s period (January 2050 to December 2079) relative to the historical period (January 1980 to December 2009)

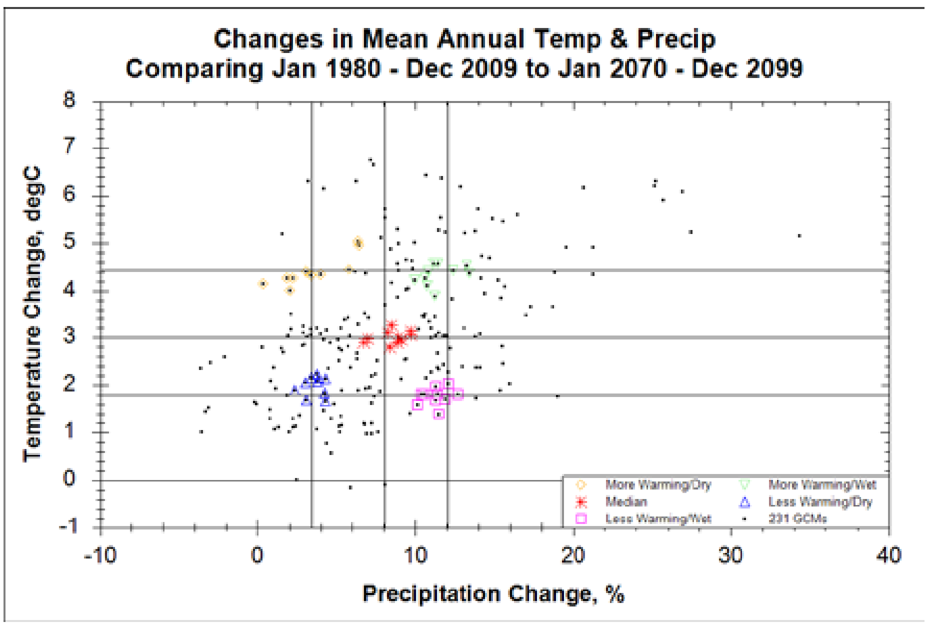

Figure 24. Scatter-graph of projected changes in temperature and precipitation for the entire Columbia River Basin for the 2080s period (January 2070 to December 2099) relative to the historical period (January 1980 to December 2009).

6.2.1 Precipitation Runoff Modeling System

PRMS is a watershed-scale model that uses a distributed parameter approach to model the physical processes of a basin (Markstrom et al. 2015). The basin is separated into Hydrologic Response Units (HRUs) to represent areas of similar hydrologic processes. PRMS can simulate evaporation, transpiration, runoff, infiltration, canopy interception, subsurface flow, and groundwater flow. Each PRMS module performs a water budget to route the precipitation to streamflow. The inputs are simple, requiring, at a minimum, daily precipitation and daily minimum and maximum air temperature.

The Crooked River basin is defined as the drainage area above the Crooker River gage at Opal Springs (CROO, Figure 25). Subbasins were created at the Ochoco Creek below Ochoco Reservoir (OCHO) and Crooked River near Prineville (PRVO) gages, for a total of three subbasins. The model stream network has a total of 166 stream segments to route water from the HRUs downstream toward the basin outlet. Using the stream segments, the HRUs were delineated and further broken up by elevation bands to capture the low-, mid-, and upper-elevation snowmelt. Elevation plays an important role in the Crooked River basin, where low-elevation snow accumulates in the early winter (January or February), then experiences a rain-on-snow event in early winter, leading to a significant streamflow peak. Therefore, by breaking the HRUs into finer elevation bands, the model attempts to capture these low-elevation melt events. A total of 484 HRUs represent the Crooked River basin.

The meteorological inputs to PRMS are daily precipitation and maximum and minimum air temperature. The Crooked River model uses the climate by HRU (*climate_hru*) module in which the inputs are pre-distributed to each HRU. The Livneh daily CONUS near-surface gridded meteorological dataset (Livneh et al. 2013) provides 1/16-degree daily precipitation and maximum and minimum air temperature. The Livneh dataset was too coarse for direct use with the PRMS model, and the dataset was downscaled using the Spatial Modeling for Resources Framework (SMRF; Havens et al. 2017). SMRF downscaled the 1/16-degree dataset to a 100-meter Digital Elevation Model to account for elevational gradients in the precipitation and air temperature at a fine spatial scale. With the dataset downscaled to 100 meters, the average value over the HRU was calculated, taking into account the elevation and size of the HRU. All 15 of the future climate temperature and precipitation projection ensembles were then used as inputs into the PRMS model to generate streamflows to be used in the Pilot Model.

For additional information about the calibration procedure and results, refer to the Deschutes Basin Study documentation (Reclamation 2018b).

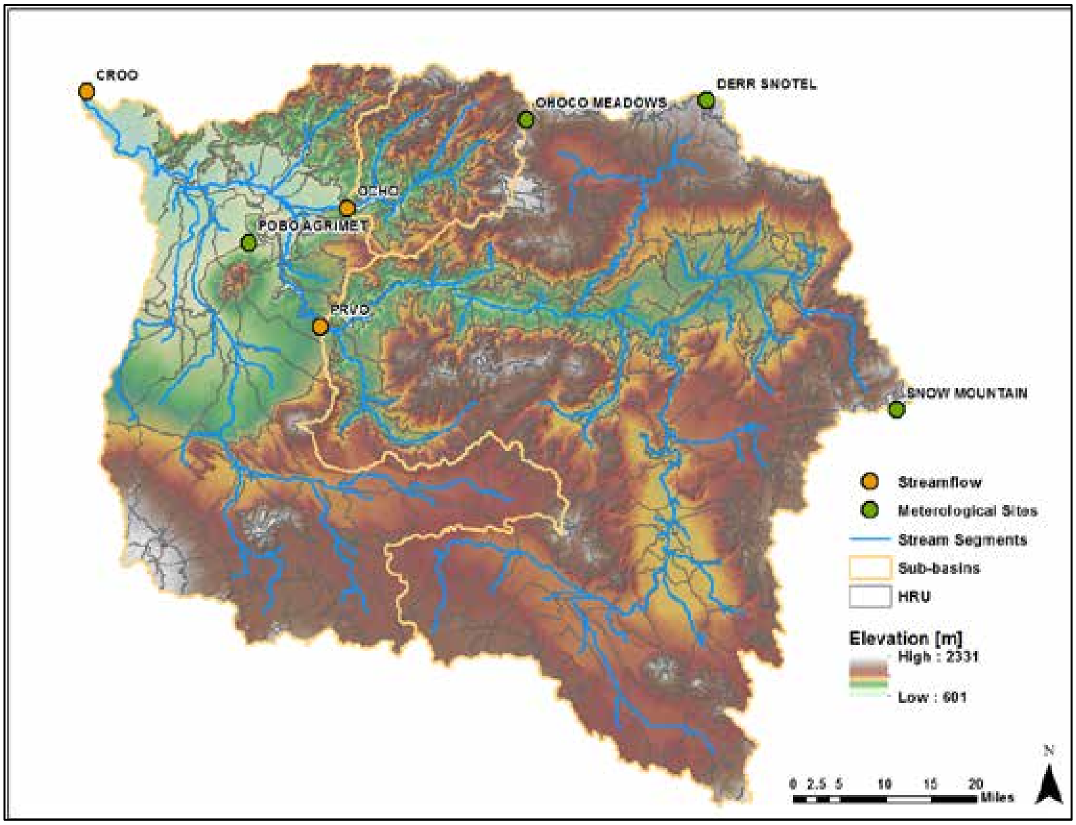

Figure 25. PRMS model setup for the Crooked River with a total of 484 HRUs and 166 stream segments. Three subbasins were delineated based on the three gage locations.

6.2.2 Future Climate Summary Hydrographs

Figure 26 provides a 50 percent exceedance summary hydrograph (i.e., median scenario) for the median precipitation and temperature forcings for the 2040, 2060, and 2080 time horizons. These plots were developed using the 30-year time continuous model run for each time horizon (e.g., 2060 horizon is the 2050-to-2079 time span), wherein the 50 percent exceedance daily value was chosen to develop the annual summary hydrograph. The 50 percent exceedance summary hydrograph shows that there is a general trend of early runoff timing for all time horizons, compared to the historical inflow (yellow line). In addition, an earlier recession of flows occurs during the middle of April through May. Base flows appear to be similar for the future climate flows, and no appreciable difference is seen. For the 2040s time horizon, the peak flow is approximately 150 percent of the historical median peak flow.

Key Takeaways

- 50% exceedance summary hydrographs show earlier runoff timing and subsequent earlier recession of flows in April.
- 10% exceedance summary hydrographs show larger magnitude peak flows during the December-through-February period

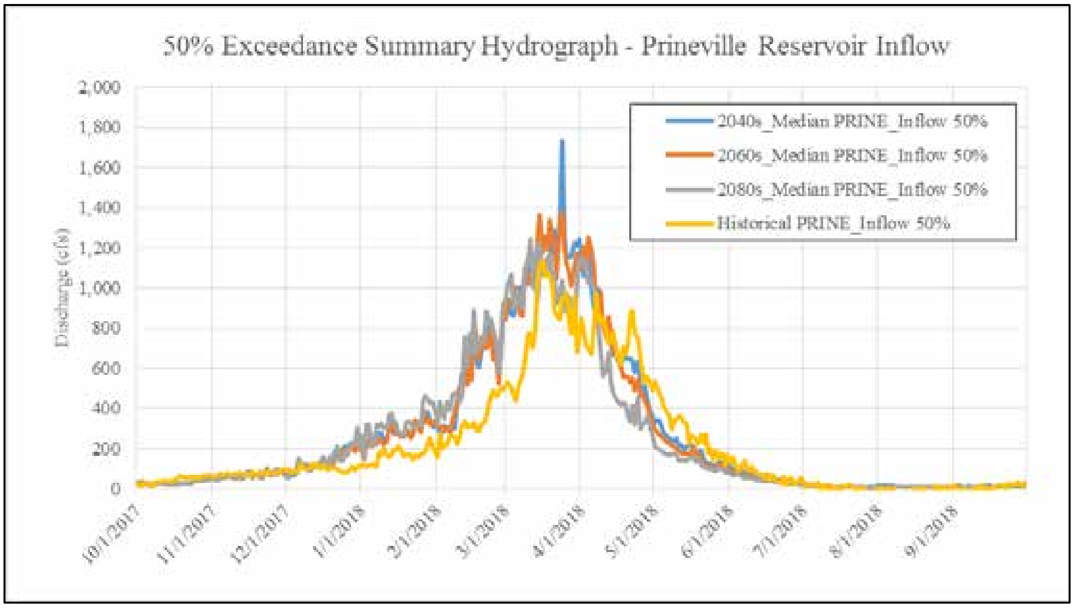

Figure 26. A 50 percent exceedance summary hydrograph of the 2040, 2060, 2080, and historical scenarios

Figure 27 provides a 10 percent exceedance summary hydrograph (i.e., large water year) for the median precipitation and temperature forcings for the 2040, 2060, and 2080 time horizons (note: the y-axis is scaled based on flows). One obvious difference between the future climate inflow and historical inflows is the extent of peak flows seen in the December-through-February period. Peak flows during this time are significantly larger in magnitude than the historical peak flows. The recession limbs of the future climate flows for all time horizon are also earlier in the year, compared to the historical inflows.

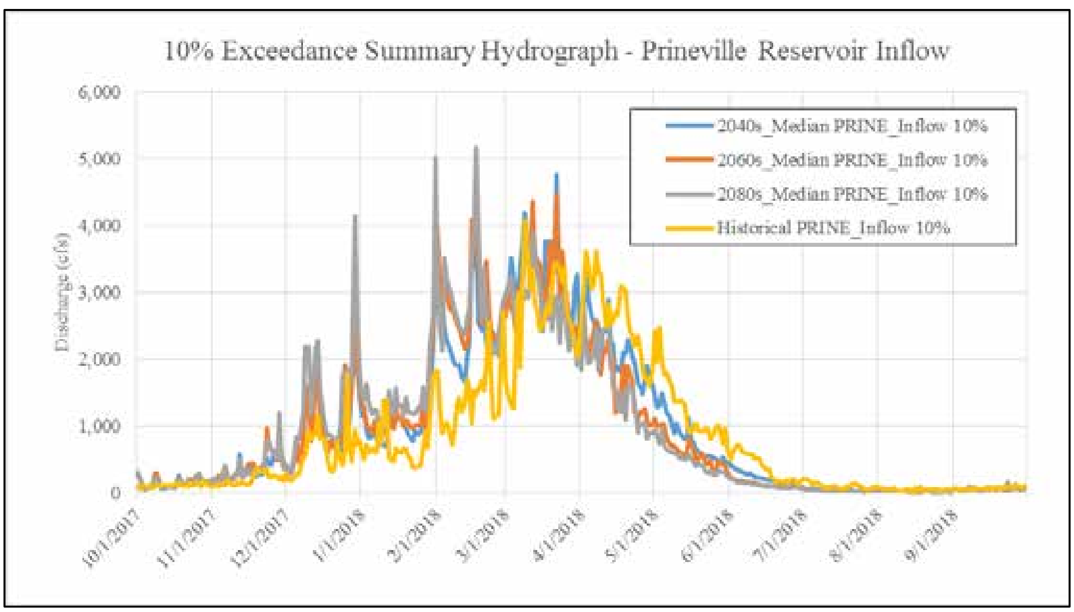

Figure 27. A 10 percent exceedance summary hydrograph of the 2040, 2060, 2080, and historical scenarios

Figure 28 provides a 90 percent exceedance summary hydrograph (i.e., small water year) for the median precipitation and temperature forcings for the 2040, 2060, and 2080 time horizons. The base flows during the November-through-December period show that the predicted future climate flows are lower than historical flows. The future climate scenarios also show an earlier initiation of spring runoff compared with historical inflows during February. The recession limb of the 2080s scenario appears to be approximately 1 month earlier than historical flows and occurs at the beginning of March, rather than the beginning of April. The 2040s scenario recession limb follows the historical well, although the duration of peak flows during March appears to be more constant during this time.

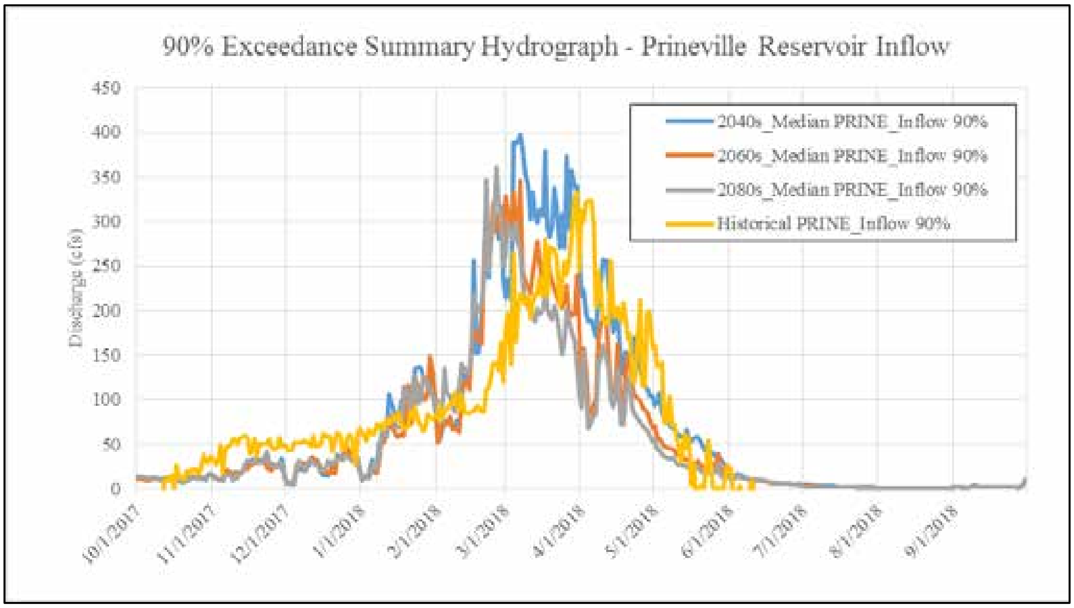

Figure 28. A 90 percent exceedance summary hydrograph of the 2040, 2060, 2080, and historical scenarios

Now that the median flows have been discussed, it is important to look at the individual flows, as well. To review, the flows shown in the median plots are the inflows created using the median precipitation and temperature forcings. Figure 29 shows the monthly exceedance flows for the 2080s time horizon and for each of the quantile precipitation and temperature forcings (i.e., LWD, LWW, Median, MWD, MWW). The monthly flows of February through May are shown, as these are the months with the largest volume of water from snowmelt. In February, all scenarios have larger peak flows compared to historical records. This may identify earlier-than-normal runoff or larger-than-normal peak events. The MWW scenario has the largest exceedance flows in February, but by March, all flows are similar, with only negligible differences between the future climate scenarios and historical records. In April and May, the future climate flows are less than historical flows, indicating a less-than-normal runoff, possibly due to the earlier-than-normal snowmelt that occurred in February.

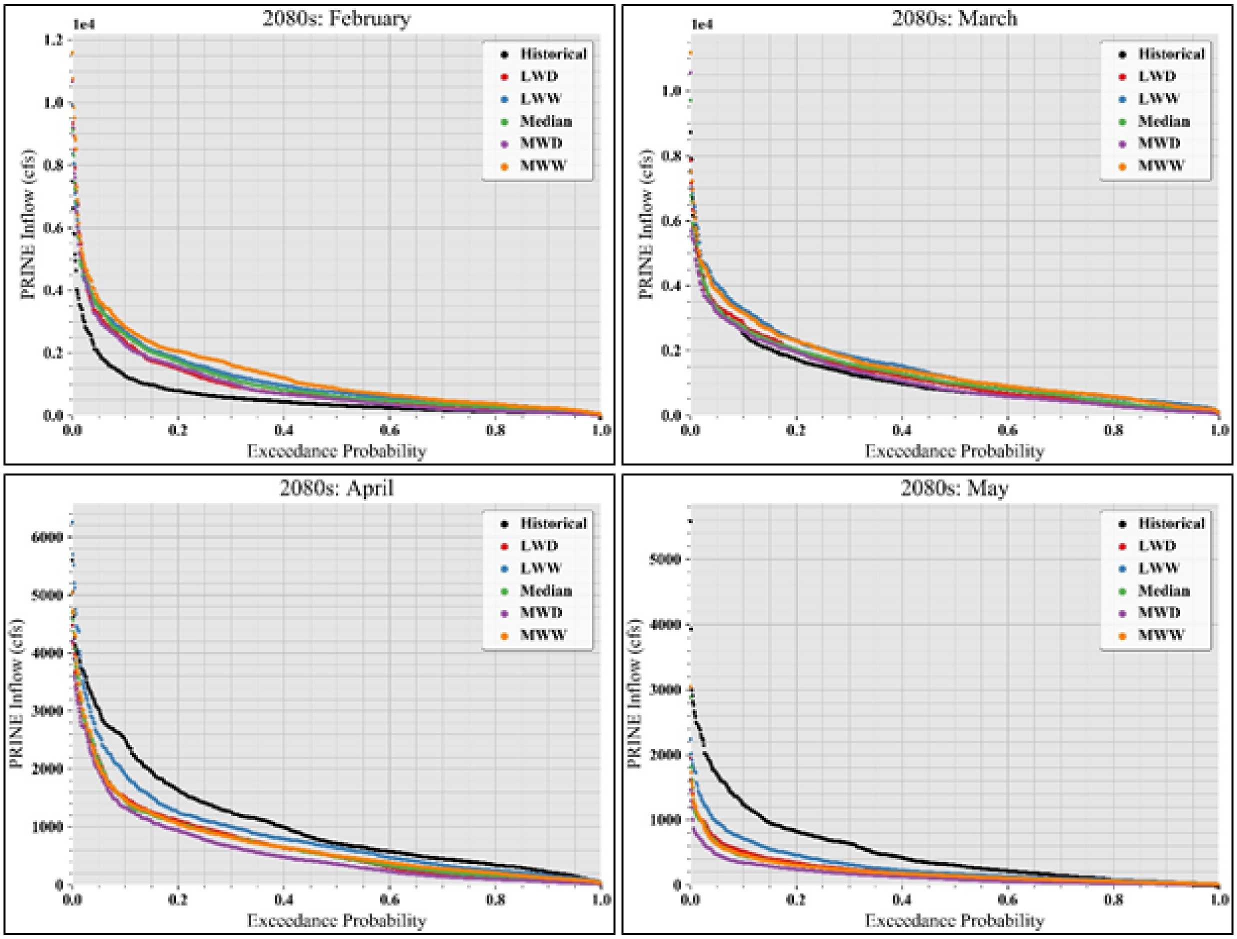

Figure 29. Monthly exceedance flows for the 2080s time horizon and for each of the quantile precipitation and temperature forcings (LWD, LWW, Median, MWD, and MWW)

Table 17 shows how the water year's runoff volume of all the 2040, 2060 and 2080 scenarios compares to historical flows. For each time horizon (2040, 2060, and 2080), a total of six scenarios were modeled, as noted above. This table provides an overview of the minimum, maximum, and average water year streamflow volume for each individual future climate scenario. The last column shows the percent of average of each scenario's maximum water year streamflow volume, indicating the variability of the streamflow volume for each modeled scenario. For example, the scenario with the greatest difference in average water year streamflow volume and maximum water year streamflow volume is the 2080s MWD scenario, with a value of 279 percent of average. To provide a comparison for historical water year streamflow volumes, the percent average of the future climate scenario compared to the historical average was also calculated. The scenarios in Table 17 are ranked by the percent average compared to historical flows. The scenario with the greatest change in water year streamflow volume is at the top of the table, which, in this case, is the 2080s LWW scenario. Table 17 shows that most future climate scenarios result in water year streamflow volumes that are greater than historical levels (10 out of 15 scenarios), which aligns with most of the projection ensembles, which are wetter than historical (Figures 22-24). Not all the 15 future climate scenarios were processed through the performance metrics. For purposes of this Study, the team decided to complete performance metric analysis for the time horizon that provided the largest span of inflow possibilities. Thus, the 2080 time horizon was chosen for metric modeling due to this period containing two of the largest (2080s LWW and MWW), as well as one of the smaller water year streamflow volumes (2080s MWD).

Table 17. Water year (October through September) summary table for all future climate inflow scenarios

Scenario	Max WY Vol.[1]	Min WY Vol.	Avg. WY Vol.	Scenario Max % of Avg.	% Avg. of Historical
2080s_LWW	687	80	329	209%	132%
2080s_MWW	699	71	327	214%	130%
2060s_MWW	658	73	322	204%	128%
2060s_LWW	661	72	314	210%	126%
2040s_LWW	650	71	314	207%	125%
2040s_MWW	633	73	310	204%	124%
2040s_Median	635	71	283	224%	113%
2080s_Median	648	70	278	233%	111%
2060s_Median	621	71	278	224%	111%
2080s_LWD	625	56	254	246%	101%
Historical	645	67	250	257%	100%
2040s_LWD	615	46	233	264%	93%
2080s_MWD	643	46	231	279%	92%
2040s_MWD	551	55	230	240%	92%
2060s_LWD	616	52	225	274%	90%
2060s_MWD	593	48	223	266%	89%

[1] All volumes are measured in thousand acre-feet.

6.3 Future Climate Flow Modeling Results

The Pilot Model was refined to import the various scenarios by using the Multiple Run Manager (MRM) function available within Riverware. The MRM function provides a way for the Pilot Model to run all future climate scenarios through automation of the exchange of inflow data for each scenario.

As stated before, the team decided to complete performance metric analysis for the time horizon that provided the largest span of inflow possibilities due to time limitations; the 2080 time horizon was included in the performance metrics analysis. The Current Condition results presented in this section will be different from the Perfect Forecast values presented in the hindcast section, due to a different timeframe of comparisons. The future climate scenarios use a 30-year time frame, while the hindcast modeling uses a 27-year timeframe. The total number of days in the model period was 10,591 days.

6.3.1 Flood Control Metrics

The primary location of focus for flood control discharges is directly downstream from the dam. In general, the largest flood control discharge occurs during the months of March and April. Figure 30 below shows the exceedance discharge curves below Prineville Reservoir. As can be seen in the March plot, the 20 percent exceedance discharge for the LWW scenario is approximately 1,800 cfs, while historical flow (Current Condition) is approximately 900 cfs. Future climate flows resulted in large discharges in March, which experienced discharges in excess of 4,000 cfs. The number of days in which discharges were larger than a specific value was calculated, and then the difference in days when compared to the Current Condition was also calculated (Table 18). The results of the modeling indicate an increase in discharges above 1,000 cfs compared to Current Condition levels for all future climate scenarios. The largest change in the number of days in which discharge exceeded Current Condition occurred for the LWW and MWW scenarios. The LWW scenario resulted in 22 more days above the flood control target of 3,000 cfs than the Current Condition model run; the MWW scenarios only had 1 additional day. Scenarios that resulted in fewer days above 3,000 cfs compared to Current Condition levels include the LWD, MWD, and median future climate scenarios.

Key Takeaways

- Future climate scenarios resulted in larger reservoir outflows during the month of March but lower outflows in April.
- The LWW scenario resulted in the most days where reservoir discharges exceeding 3,000 cfs, with some days exceeding 4,000 cfs.
- All scenarios except for LWW resulted in minimal impacts to reservoir surcharge compared to the Current Condition.
- The LWW scenario resulted in a maximum surcharge of 14.9 feet.
- All scenarios resulted in the same number of years when the reservoir accomplished full refill.

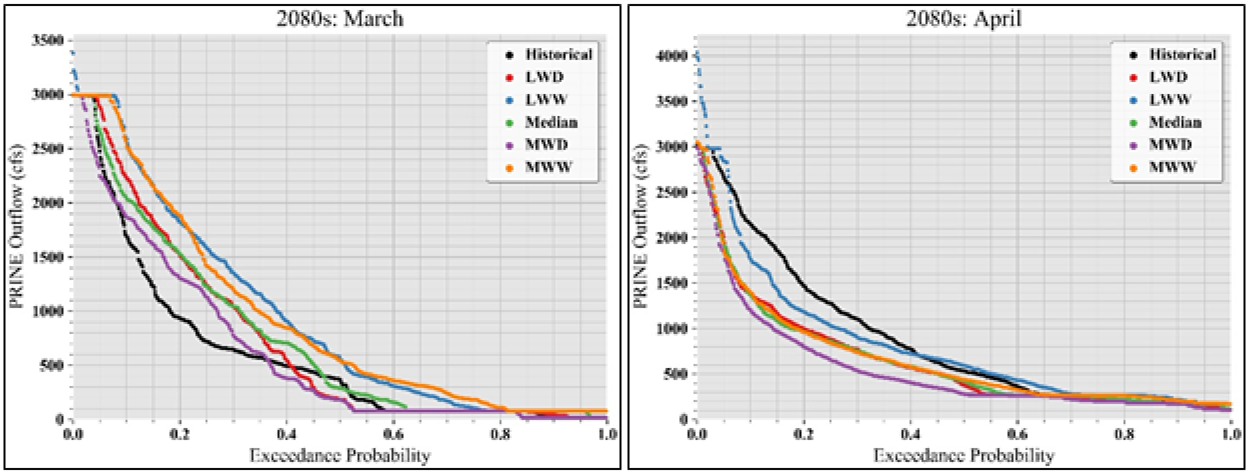

Figure 30. Exceedance discharge curves below Prineville Reservoir for the 2080s scenarios

For all scenarios except the LWW, discharge was greater than 3,000 cfs on days when discharge was also less than 3,300 cfs, so the actual impacts of this may not be significant and might be a limitation of the modeling logic to match actual operations (i.e., reducing discharge through the outlets as flow over the spillway increases while still maintaining no more than a total combined discharge of 3,000 cfs). On the other hand, the LWW scenario resulted in 22 days above 3,000 cfs, with some days exceeding 4,000 cfs.

Table 18. Number of days above various discharges for the 2080s climate flows compared to the Current Condition

Model Run	# of Days Discharge (cfs) is greater than				
	1,000	1,500	2,000	2,500	3,000[1]
Current Condition	726	391	253	139	4
Future climate Scenario	**# Days Different from Current Condition**				
2080s LWD	156	3	-4	16	-4
2080s LWW	499	302	114	109	22
2080s MWD	43	-3	-58	-29	-4
2080s MWW	572	336	142	125	1
2080s Median	289	144	13	27	-4

[1] Existing maximum flood control discharge target.

The reservoir surcharge metric examines the number of days above various reservoir water surface elevations compared to Current Condition levels. Table 19 summarizes the results of this metric for the future climate scenarios and the Current Condition model run. The scenario that was found to have the greatest difference in the number of days the reservoir experienced surcharge is the LWW scenario. The LWW scenario resulted in 177 more days than the Current Condition in which the reservoir went into surcharge, and 44 days in which surcharge was greater than 3.2 feet. The largest surcharge event that occurred for the LWW scenario was at a pool elevation of 3249.7 feet, which corresponds to 14.9 feet of surcharge. This is significantly more surcharge than the historical max of 7.9 feet that occurred in March of 1984 and would be considered an extreme event. The MWW scenario was also found to increase the number of days the reservoir went into surcharge, with all the events being regulated with less than 1.7 feet of surcharge. The LWD, MWD, and Median scenarios resulted in fewer days in which the reservoir went into surcharge, compared to the Current Condition. Current infrastructure around the reservoir, including undeveloped and developed camping and existing state parks bordering the reservoir, may be impacted by the increase in the reservoir surcharge, but this was not examined in detail.

Table 19. Number of days above various surcharge elevations compared to the Current Condition for the 2080s scenarios

Model Run	# of Days Pool Elevation (feet) is Greater than								
	3234.8	3235.0	3235.5	3236.0	3236.5	3237.0	3237.5	3238.0	Max[1]
Current Condition	16	10	3	0	0	0	0	0	3235.7
Future climate Scenario	**# Days Different from Current Condition**								**Max[1]**
2080s LWD	-12	-10	-3	0	0	0	0	0	3234.9
2080s LWW	177	84	76	66	59	53	49	44	3249.7
2080s MWD	-14	-10	-3	0	0	0	0	0	3234.8
2080s MWW	94	1	5	6	3	0	0	0	3236.8
2080s Median	-9	-10	-3	0	0	0	0	0	3234.9

[1] Maximum surcharge elevation for the model run.

Figure 31 is an exceedance plot for the reservoir storage content during the months of April and May. As can be seen in the figure, storage contents are mostly the same, except at the highest and lowest exceedance values. For the month of April, the LWW, MWW, and Median scenarios hit full pool (148,640 acre-feet) at a higher exceedance value compared to the historical data (Current Condition), suggesting an earlier refill timing due to an earlier runoff hydrograph. The LWW scenario shows the large surcharge event in the lowest exceedance values when storage went to approximately 200,000 acre-feet.

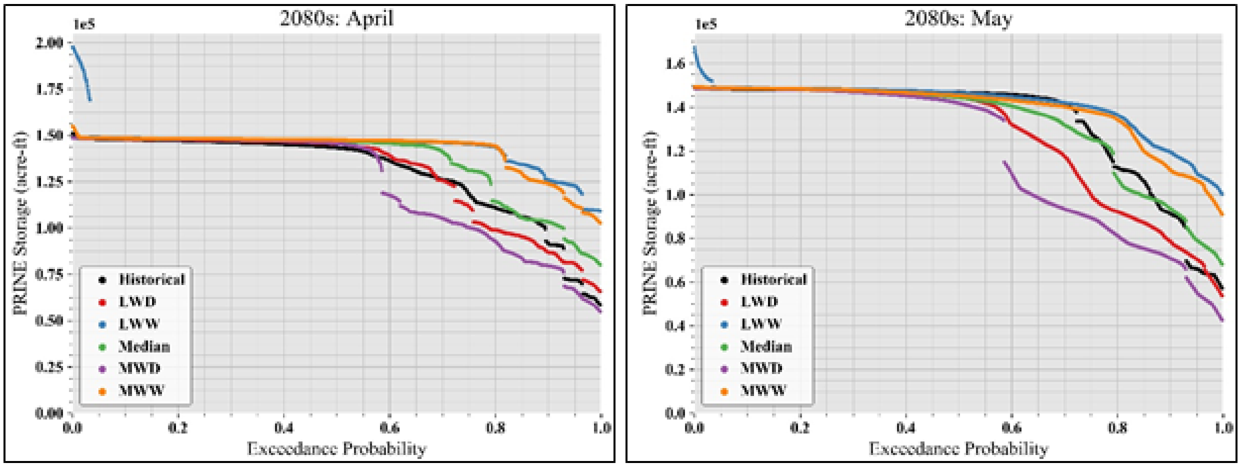

Figure 31. Exceedance plot for the reservoir pool elevations during the months of April and May for the 2080s scenarios

Table 20 below summarizes the impact of the future climate scenarios on reservoir refill compared to the Current Condition model run. As can be seen in Table 20, the reservoir filled in 17 out of 30 years in the future climate scenarios, and therefore, the impact on refill probability didn’t change for any of the scenarios.

Table 20. Number of years Prineville Reservoir filled completely, compared to the Current Condition for the 2080s scenarios

Model Run	# of Years with Full Refill
Current Condition	17
Future climate Scenario	**# Years Different from Current Condition**
2080s LWD	0
2080s LWW	0
2080s MWD	0
2080s MWW	0
2080s Median	0

6.3.2 Water Deliveries Metrics

Table 21 shows various storage allocation exceedance values for all model runs. These exceedance values were developed by ranking all of the maximum reservoir content values for each water year. The 50 percent exceedance value for all model runs was found to be similar, while for the drier water years (80 percent exceedance), there were some notable differences.

Table 21. Comparison of storage allocation exceedance values for the 2080s scenarios

Model Run	Storage Allocation Exceedance Values				
	10%	20%	50%	80%	90%
Current Condition	148,643	148,394	148,354	113,746	93,275
Future climate Scenario	**Acre-feet Different from Current Condition**				
2080s LWD	-6	209	140	-14,508	-5,144
2080s LWW	402	331	300	34,498	33,054
2080s MWD	-10	223	142	-18,247	-13,204
2080s MWW	245	333	226	34,740	32,837
2080s Median	28	238	169	908	11,034

[1] Allocation is restricted to the full allocation amount of 148,640 acre-feet, as this is the maximum legal storage right at Prineville Reservoir.

Table 22 shows various storage carry-over exceedance values for all model runs. These exceedance values were developed by ranking all of the minimum reservoir content values for the month of October. The 50 percent exceedance value for model runs was found to be within approximately 9,000 acre-feet of each other, with all 2080 scenarios resulting in less carryover compared to Current Condition. For the drier water years (80 percent exceedance), there were differences up to approximately 19,000 acre-feet less for the MWD to approximately 17,000 acre-feet more for the LWW scenario.

Table 22. Comparison of carry-over exceedance values for the 2080s scenarios

Model Run	Storage Carry-Over Exceedance Values				
	10%	20%	50%	80%	90%
Current Condition	98,655	90,875	79,284	46,214	30,683
Future climate Scenario	**Acre-feet Different from Current Condition**				
2080s LWD	-10,099	-6,303	-4,707	-10,920	-1,898
2080s LWW	-4,345	-5,998	-4,304	16,604	14,875
2080s MWD	-11,651	-11,411	-8,474	-18,670	-12,647
2080s MWW	-8,437	-6,491	-5,120	13,972	13,807
2080s Median	-9,484	-8,373	-4,650	-3,164	2,533

6.3.3 Water Quality Metrics

> **Key Takeaways**
>
> - All future climate scenarios (except for the MWD scenario) resulted in more days when TDG was above 120%.

The water quality metric examined the change in the number of days at various discharges, which were then correlated to an assumed TDG level, based on the relationship provided in Figure 4. All future climate scenarios, except for the MWD scenario, resulted in more days in which the TDG level exceeded 110 percent. The future climate scenarios with the largest difference are the LWW and MWW scenarios, due to these being larger water volume scenarios. The LWD and Median scenarios resulted in 16 and 27 more days, respectively, than the Current Condition in which TDG exceeded 120 percent. Both the LWW and the MWW scenarios showed a much larger change in the number of days in which TDG exceeded 120 percent. This analysis shows that the LWW and MWW scenarios would result in more days in which TDG would exceed 120 percent, which would have larger ecological impacts downstream compared to Current Condition.

Table 23. Number of Days TDG is above 110, 115, and 120 percent compared to the Current Condition for the 2080s scenarios

Model Run	# of Days Discharge (cfs) is Greater than		
	670 (110%)	1,500 (115%)	2,500 (120%)
Current Condition	1128	391	139
Future climate Scenario	**# Days Different from Current Condition**		
2080s LWD	143	3	16
2080s LWW	724	302	109
2080s MWD	-11	-3	-29
2080s MWW	585	336	125
2080s Median	293	144	27

Regarding reservoir water temperatures, carryover volumes summarized in Table 22 show that for the 50 percent exceedance values, all scenarios resulted in carryover volumes within approximately 8,000 acre-feet, which corresponds to a maximum drop in pool elevation of approximately 4.6 feet. For the 90 percent exceedance values, differences in carryover ranged from approximately 15,000 acre-feet more for the LWW scenario to approximately 14,000 acre-feet for the MWD scenario. The reduction in carryover for the MWD scenario corresponds to a reduction in pool elevation of approximately 16 feet. The qualitative assessment of the impact to this reduction in pool elevation would be that water temperature may be different because the volume of water in the reservoir is lower and the MWD scenario has warmer temperatures than the Current Condition.

6.3.4 Recreational Resources Metrics

The first recreational metric considered was the downstream fishing metric. This metric measures the number of days that were within the optimal fishing flow of 50 to 400 cfs. The Current Condition model run resulted in a total of 7,595 days of optimal fishing flows, which represents 72 percent of the modeled period. An increase in optimal fishing flow days was found for both the LWD and MWD scenarios, in which there were 107 and 104 more days, respectively, than in the Current Condition. A reduction in the number of optimal fishing days was found for the LWW, MWW, and Median scenarios. The reduction of optimal fishing days is a result of more days in which flood control releases occurred. The LWW scenario had the largest change from Current Condition, with 582 fewer days, which equates to 66 percent of the modeled period during which optimal downstream fishing flows were experienced. Overall, the drier scenarios with less runoff volume resulted in an increase in optimal fishing days, while the wetter scenarios and Median resulted in fewer optimal fishing days due to an increase in the amount of flood control release from the reservoir.

Key Takeaways

- Optimal fishing days increased for the LWD and MWD scenarios, and decreased for the LWW, MWW, and median scenarios.
- The number of boating days increased for the LWD and MWD scenarios and decreased for the LWW, MWW, and median scenarios
- Recreation was negatively impacted for the LWW, MWW, and median scenarios due to deeper reservoir drafts and larger reservoir discharges required for flood control operations.

Table 24. Number of days in which flows are within the optimal fishing range of 50 to 400 cfs, compared to the Current Condition for the 2080s scenarios

Model Run	# of Days Discharge (cfs) is Greater than		# Optimal Days
	50	400	
Current Condition	9,496	1,901	7,595
Future climate Scenario	**# Days Different from Current Condition**		
2080s LWD	0	-107	107
2080s LWW	0	582	-582
2080s MWD	-241	-345	104
2080s MWW	0	427	-427
2080s Median	0	91	-91

The reservoir recreation metric examined the number of days various boat ramps at Prineville Reservoir would be usable. There are three boat ramps available at Prineville Reservoir, with different pool elevations at which the ramp would not be usable. The results of the reservoir recreation metric are summarized in Table 25, in which the number of days each boat ramp was available during the modeled period was compared to the Current Condition model run. For the Powerhouse Cove boat ramp, which is the first ramp that becomes unusable, the Current Condition model run resulted in a total of 6,570 days (69 percent of the time) when the boat ramp was usable, while the two drier climate scenarios (LWD and MWD) and the Median resulted in fewer days in which the ramp would be available for use. The greatest difference is with the MWD scenario, which reduced the number of days the boat ramp would be available by approximately 27 percent compared to the Current Condition model run. Both wetter climate scenarios (LWW and MWW) resulted in more days in which the Powerhouse Cove boat ramp would be usable, which is due to inflows to the reservoir being greater than Current Condition levels, as well as more carryover after each irrigation season. The same general impacts of the future climate scenarios resulted for the two other lower-elevation boat ramps, as well.

Table 25. Number of days that various boat ramps are useable as compared to Current Condition for the 2080s scenarios

Model Run	# of Days Pool Elevation (feet) is Greater than		
	3,191 (State Park)	3,203 (Jasper Point)	3,210 (Powerhouse Cove)
Current Condition	9,352	8,294	6,570
Future climate Scenario	**# Days Different from Current Condition**		
2080s LWD	-449	-618	-1,058
2080s LWW	144	859	480
2080s MWD	-1,059	-1,497	-1,753
2080s MWW	144	567	172
2080s Median	144	-101	-568

6.3.5 Ecological Resources Metric

The ecological resource metric focuses on the percent of time that flows below the dam and at the low-flow point in the system (Highway 126 bridge) attain various flow targets. The minimum flow target for the Crooked River below the reservoir is 80 cfs, but during low water years, that cannot always be achieved, so storage is optimized and discharge targets are adjusted accordingly based on the number of days left before the next day of allocation.

Table 26 below summarizes the results for the location directly downstream from the dam. All future climate scenarios were found to be the same as the Current Condition model run for the number of days in which flows were below 40 cfs. The MWD scenario had 458 more days than the Current Condition in which discharges below the dam were less than 60 cfs, which illustrates the reduced inflows of this dry scenario. Both the LWD and the MWD scenarios resulted in 75 and 561 fewer days, respectively, than the Current Condition run, in which flows were greater than 80 cfs. In the Current Condition model run, a flow of 80 cfs was exceeded 100 percent of the time, and in the MWD scenario, it was exceeded 94 percent of the time.

Based on the WUA curve obtained from the USFWS Bend Field Office described in Section 3.6.2, the WUA ranged from 46 percent to 96 percent within the flow range investigated.

Key Takeaways

- The drier future climate scenarios (LWD and MWD) resulted in fewer days when flows below the Prineville Reservoir were greater than 80 cfs compared to the Current Condition.
- The LWW scenario increased the time flow exceed 80 cfs at the Highway 126 bridge by 13% compared to the Current Condition.

Table 26. Number of days, exceedance, and WUA for various flows downstream of the dam compared to the Current Condition below the dam for the 2080s scenarios

Model Run	# of Days Discharge (cfs) is Greater than				
	20	40	60	80	100
Current Condition	9,496	9,496	9,496	9,496	7,373
Future climate Scenario	**# Days Different from Current Condition**				
2080s LWD	0	0	0	-75	-3
2080s LWW	0	0	0	0	833
2080s MWD	0	0	-458	-561	-212
2080s MWW	0	0	0	0	886
2080s Median	0	0	0	0	266
Future climate Scenario	**% Exceedance**				
Current Condition	100%	100%	100%	100%	78%
2080s LWD	100%	100%	100%	99%	78%
2080s LWW	100%	100%	100%	100%	86%

Model Run	# of Days Discharge (cfs) is Greater than				
	20	40	60	80	100
2080s MWD	100%	100%	95%	94%	75%
2080s MWW	100%	100%	100%	100%	87%
2080s Median	100%	100%	100%	100%	80%
Habitat Parameter	**% WUA**				
WUA	46%	66%	80%	85%	96%

Table 27 below summarizes the results for the Highway 125 bridge location. Both the LWD and MWS scenarios resulted in fewer days above all discharges when compared to the Current Condition model run. The MWD scenario resulted in 1,662 fewer days than the Current Condition model in which flows were above 60 cfs. This reduction in days resulted in changing the exceedance value for 60 cfs from 92 percent for the Current Condition to 74 percent for the MWD scenario. The reduction in flow at this location for the dry future climate scenarios is a result of less reservoir refill and therefore less uncontracted storage available to meet the 80 cfs minimum flow. For the wetter future climate scenarios (LWW and MWW), the number of days in which a flow of 80 cfs was met increased by 807 days.

Table 27. Number of days, exceedance, and WUA for various flows compared to Current Condition levels at the Highway 126 bridge for the 2080s scenarios

Model Run	# of Days Discharge (cfs) is greater than				
	20	40	60	80	100
Current Condition	9,496	9,388	8,689	8,060	2,807
Future climate Scenario	**# Days Different from Current Condition**				
2080s LWD	0	-592	-436	-503	-407
2080s LWW	0	108	807	1,291	642
2080s MWD	-419	-1,434	-1,662	-1,251	-670
2080s MWW	0	108	807	1,172	526
2080s Median	0	92	252	354	-150
Future climate Scenario	**% Exceedance**				
Current Condition	100%	99%	91%	85%	30%

Model Run	# of Days Discharge (cfs) is greater than				
	20	40	60	80	100
2080s LWD	100%	93%	87%	80%	25%
2080s LWW	100%	100%	100%	98%	36%
2080s MWD	96%	84%	74%	72%	22%
2080s MWW	100%	100%	100%	97%	35%
2080s Median	100%	100%	94%	89%	28%
Habitat Parameter	**% WUA**				
WUA	46%	66%	80%	85%	96%

The minimum flow target of 80 cfs was exceeded 100 percent of the time for the Current Condition, LWW, MWW, and Median scenarios. The LWD and MWD scenarios resulted in the 80 cfs minimum flow exceedance value dropping to 99 percent and 94 percent. Overall, the drier future climate scenario resulted in meeting the 80 cfs flow target less often than in the Current Condition, while the wetter future climate scenarios resulted in no change.

Table 28. Number of days in which flow was 80 cfs or more below the dam, compared to Current Condition flows for the 2080s scenarios

Model Run	# of Days Discharge (cfs) is greater than 80 cfs	% Exceedance
Current Condition	9,496	100%
Future climate Scenario	**# Days Different from Current Condition**	**% Exceedance**
2080s LWD	-75	99%
2080s LWW	0	100%
2080s MWD	-561	94%
2080s MWW	0	100%
2080s Median	0	100%

At the low-flow location at the Highway 126 bridge, the Current Condition was found to exceed the 80 cfs flow target 85 percent of the time. A reduction in this exceedance was found for both drier future climate scenarios, with the LWD scenario having an 80 percent exceedance and the MWD having a 72 percent exceedance. The 80 cfs target was met 98 percent of the time for the

LWW scenario, 97 percent of the time for the MWW scenario, and 89 percent of the time for the Median future climate scenario.

Table 29. Number of days in which flow was 80 cfs or greater at the Highway 126 bridge, compared to the Current Condition for the 2080s scenarios

Model Run	# of Days Discharge (cfs) is greater than 80 cfs	% Exceedance
Current Condition	8,060	85%
Future climate Scenario	**# Days Different from Current Condition**	**% Exceedance**
2080s LWD	-503	80%
2080s LWW	1,291	98%
2080s MWD	-1,251	72%
2080s MWW	1,172	97%
2080s Median	354	89%

6.3.6 Future Climate Modeling Conclusions

The hydrologic modeling of the median 2040s, 2060s, and 2080s future climate scenarios resulted in summary hydrographs that showed earlier timing of the snowmelt period and quicker recession to base flows in the summer for all scenarios (Figure 26). As shown in the 10 percent exceedance summary hydrographs (Figure 27), larger, earlier winter peaks were identified when compared to the Current Condition, while in the drier 90 percent exceedance summary hydrographs (Figure 28), the early winter baseflows were found to be less than Current Condition levels. Of the 15 future climate scenarios modeled, 10 of these resulted in average water year volumes larger than the Current Condition, indicating an increase in water volume. The 2080s time horizon was chosen to complete the future climate metrics analysis due to this time period containing the largest water year volume, as well as one of the smallest volumes, and provided a large range in the hydrologic variability that this Study tries to address.

Impacts to flood control were found when looking at the number of days in which discharges were greater than 3,000 cfs, as well as the number of days in which the reservoir was in surcharge. The largest increase in discharges was found to be from the LWW scenario, which had 22 more days above 3,000 cfs than the Current Condition. All scenarios except the MWD scenario resulted in more days in which TDG was greater than 120 percent, mostly due to the increased need for more flood control releases due to the large runoff volumes compared to Current Condition levels. The drier future climate scenarios resulted in more days in which flows were in the optimal fishing range, but there were fewer boating days in the reservoir because the boat ramps were unusable due to the low reservoir pool elevation. The main impacts to the ecological metrics resulted from the dry future climate scenarios, which showed less carryover in the reservoir and reduced the flow during the winter for fish and wildlife flows.

7 Alternative Operations Based on Modeling of Future Climate Flows

The modeling of the future climate scenarios identified various impacts to flood control, water quality, water supply, recreation, and ecological resources. The alternatives use the results found in the future climate modeling for the same 2080 time period. The purpose of this section is to identify measures that could be taken to minimize these impacts. Based on the results of the future climate modeling, the following are a list of operation criteria that were considered when developing alternative operations.

- Modify in-season operations in dry years to optimize storage
- Reduce the number of days in which discharge exceeds 3,000 cfs
- Reduce the number of days in which TDG exceeds 120 percent

The operating criteria listed above were met through proposed dry-year alternative operations or changes to the dSRD. The following sections describe these alternative measures to meet the operational goals listed above.

7.1 Dry-year Alternative Operation

Key Takeaways

The dry year alternative operation seeks to maximize reservoir refill when:

- Water supply forecasts indicate inadequate volume for reservoir refill.
- Basin conditions indicate a low risk of large rain-on-snow type events.
- Static winter space requirements would result in a flood control release.
- Deviation request is granted from the Corps.

The dry-year alternative operation plan was developed in response to years of below-average runoff volume, when the reservoir failed to refill completely but also experienced flood control releases during the static winter flood-space requirement period (November 15 through February 15). This proposed dry-year alternative operation assumes that the current basin conditions indicated a low risk for a large rain-on-snow event (e.g., very little snow present in the basin) and that a justification for a deviation from the Corps could be granted. A deviation is required when the operation of the reservoir is outside what is called for by the dSRD. To remain consistent with the future climate modeling completed in previous section, the 2080s future climate flow scenarios were also used to determine the impacts of implementing a dry-year alternative operation to opportunistically maximize reservoir refill when possible. Figure 32 below shows the 2081 MWW water year when the reservoir failed to refill and experienced flood control releases due to static winter space requirements during the November 15-through-February 15 period. The blue line, which indicates reservoir discharges, shows that flood control releases (i.e., discharges greater than 80 cfs) started in early December in order to operate to a maximum reservoir content value (red line) of 88,000 acre-feet. Although perfect foresight is unrealistic to assume when determining a possible change in operations, the dry-year alternative operation may have been able to use current basin conditions that would have allowed refill into the winter space requirement prior to the February 15 date.

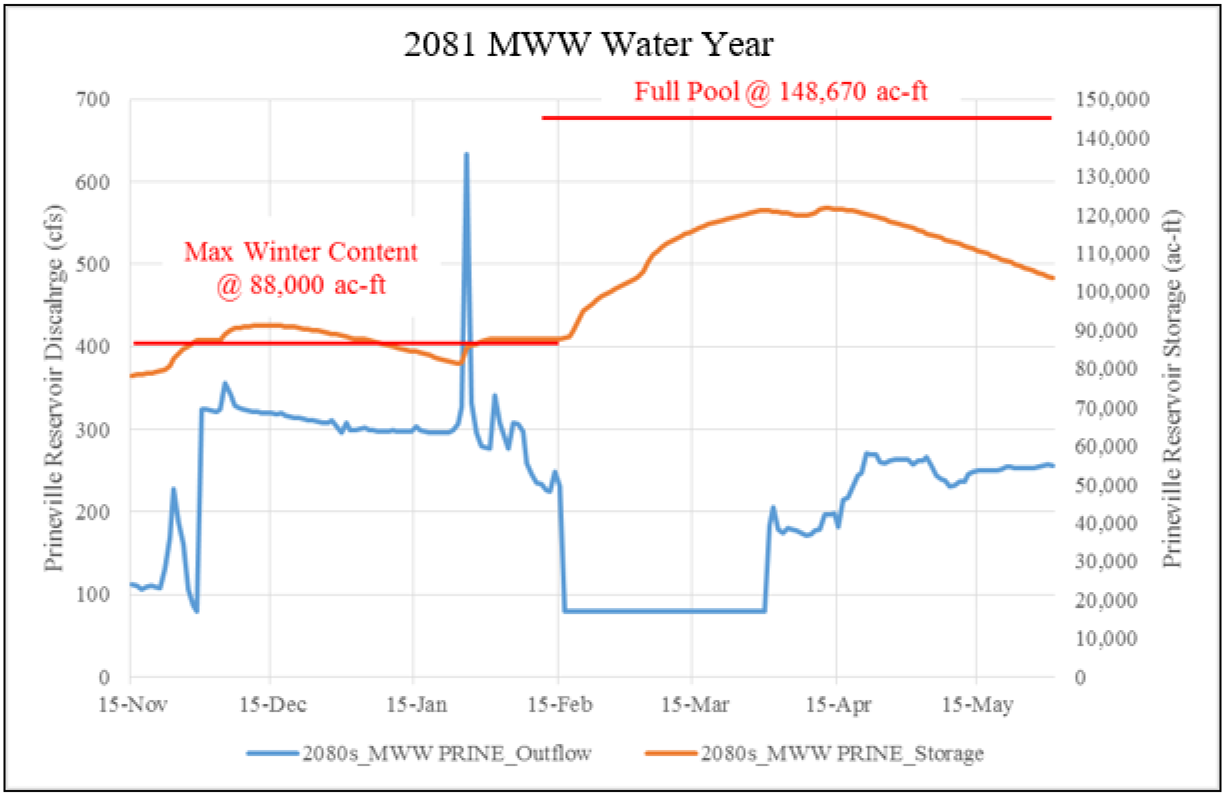

Figure 32. Example of when the reservoir failed to refill after flood control releases occurred during the winter static flood control period (November 15 through February 15)

To provide an example of a dry-year alternative operation, the same 2081 MWW water year shown in Figure 32 will be used for illustration purposes. An alternative operation for this scenario would be to allow refill into the winter space requirement earlier than February 15, based on the current conditions in the basin. This scenario assumes that the basin conditions indicate a low runoff volume for the season. Using the actual 2081 February-through-August runoff level of 58 percent of average, it seems reasonable that the operator would be aware of the low snowpack in the basin on February 1 and would be able to provide justification to obtain a 15-day deviation from the Corps to begin refill into the winter space requirement. Figure 33 shows this dry-year alternative operation in which the reservoir outflows were dropped to the 80 cfs minimums on February 1 and the reservoir was allowed to fill prematurely into the winter space requirement. Performing this operation would result in approximately 5,200 acre-feet more storage on the day of maximum fill. For the case of Prineville Reservoir, where uncontracted storage is used for fish and wildlife releases and uncontracted storage fills after the first 86,113 acre-feet is allocated to contracted storage, this dry-year alternative operation would result in an additional 7 cfs for the preceding year.

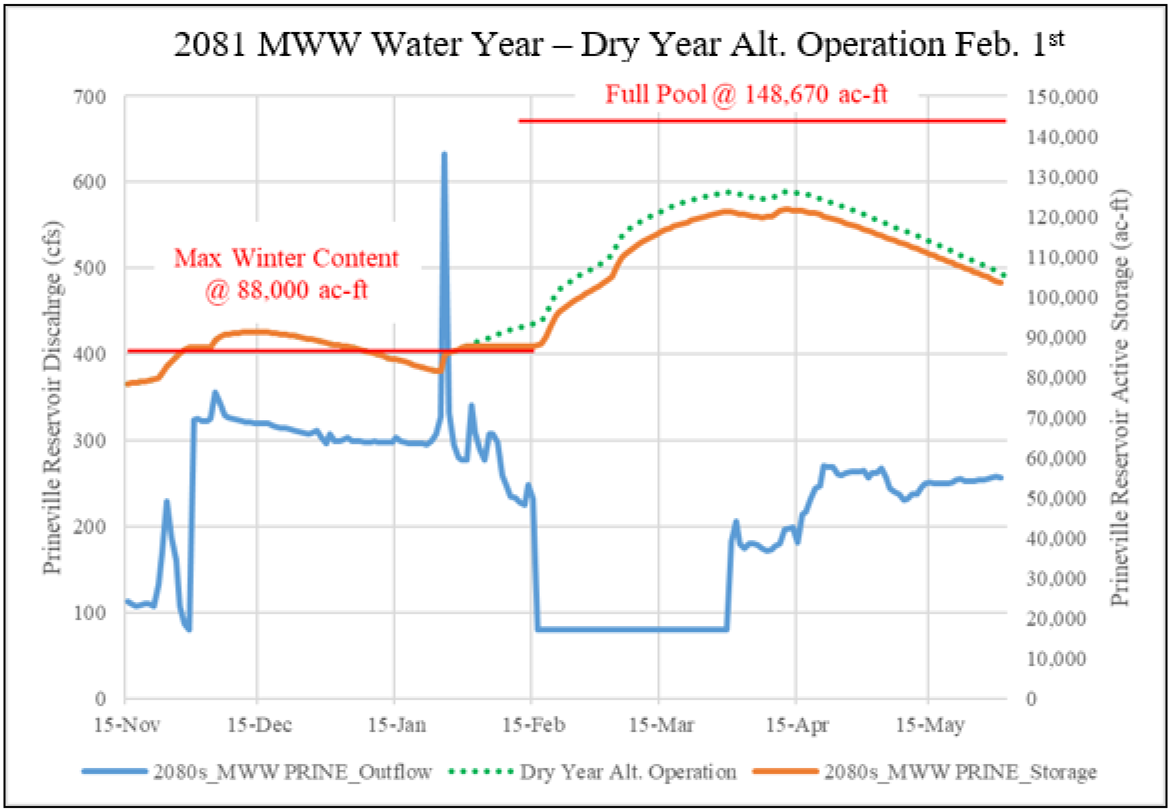

Figure 33. Example of a dry-year alternative operation in which the winter static flood space requirement was relaxed (based on favorable basin conditions) and maximum reservoir fill was increased.

A total of 11 water years were found in the 2080 future climate dataset in which reservoir refill was not obtained and flood control releases were experienced during the winter space requirement period.

Table 30 below shows a summary of scenarios in which this occurred. Two separate operations were assumed for the dry-year alterative operation. The first scenario shows the increase in reservoir refill if a deviation from the winter space requirements were granted on February 1, and the second scenario uses an earlier deviation in the space requirement on January 15. The actual percent of average runoff volume is included to show how this type of operation may be acceptable; this provides some insight into how a deviation from the winter space requirement may be granted in real-time. For example, looking at the 2081 LWW water year in Table 30, if a deviation of the winter space requirements occurred on February 1, approximately 5,400 acre-feet of additional storage could be obtained. In this scenario, the operation staff would need to determine whether the risk of large inflows into the reservoir is low, and in the 2081 LWW years, due to the actual runoff volume being 56 percent of average, this Study assumed that current basin conditions would have indicated this. As Table 30 shows, all actual runoff volumes from both the January 15 and February 1 deviations are below 86 percent of average.

> **Key Takeaways**
>
> - Years included in the dry year alternative operation had runoff that ranged from 26 to 86% of average.
> - 15-day deviations resulted in an increase of 2,000 to 14,000 acre-feet of additional reservoir refill for water supply.
> - 30-day deviations resulted in an increase of 3,000 to 23,000 acre-feet of additional reservoir refill for water supply.

This dry-year alternative operation found 11 years in which complete reservoir refill was not obtained and flood control releases were experienced during the winter space requirement period. Of these 11 years, additional maximum fill ranged from 1,939 acre-feet to 14,554 acre-feet for the 15-day deviation and 3,067 acre-feet to 23,346 acre-feet for the 30-day deviation. As stated before, this operation would only be allowed when conditions indicate a low risk for large rain-on-snow events, but as can be seen in the results, it can increase reservoir refill and water supply.

Table 30. 2080s Future climate dataset years in which the reservoir missed refill and experienced flood control releases during the static winter space requirement period

2080s Dataset WY	2077		2081		2083		2094				
	LWW	MWW	LWW	MWW	LWW	MWW	LWD	LWW	MWD	MWW	Median
Modeled Fill (ac-ft)	134,494	127,243	125,637	126,112	136,318	132,344	96,151	126,329	95,500	116,579	110,984
% AVG Jan15-Aug	86%	73%	65%	68%	73%	67%	32%	81%	26%	71%	58%
30-day Dev. (ac-ft)	19,704	17,980	12,635	12,770	9,867	3,067	6,959	23,346	5,856	23,359	18,241
30-day Dev. Max	154,198[1]	145,224	138,271	138,882	146,184	135,412	103,110	149,675[1]	101,356	139,938	129,225
% AVG Feb01-Aug	71%	61%	56%	58%	70%	66%	28%	68%	23%	58%	49%
15-day Dev. (ac-ft)	13,460	14,554	5,367	5,178	4,198	1,939	3,439	10,391	3,198	11,282	9,352
15-day Dev. Max	147,954	141,798	131,004	131,290	140,516	134,283	99,590	136,719	98,697	127,861	120,337

[1] Maximum allocated fill at Prineville Reservoir is 148,640 acre-feet; therefore, volumes greater than this would be released as flood control in real-time operations.

7.2 Modified dynamic Storage Reservation Diagram

> **Key Takeaways**
>
> - Two dSRDs were developed based on results of LWW 2080s climate scenario.
> - The FRM3kcfs curve was developed to minimize the number of days reservoir discharge exceeds the 3,000 cfs flood control target.
> - The EbF120% curve was developed to minimize the number of days TDG exceeds 120 percent below the reservoir.

The Prineville Reservoir existing 3,000 cfs operating dSRD performed well for all the future climate scenarios except the 2080 LWW scenario, which resulted in discharges in excess of the maximum flood release target of 3,000 cfs. This provides insight into how effective the existing SRD is and how adaptable it is to a changing hydrologic regime (Figure 34). The ability of the existing dSRD to use the high maximum outflow discharge of 3,000 cfs and available surcharge allows the reservoir to meet the dual, but sometimes conflicting, goals of providing flood control while also ensuring reservoir refill for water supply. Results of future climate modeling showed more days in which TDG levels exceeded 120 percent downstream from the dam compared to the Current Condition. The objective of this portion of the Study is to determine whether two new dSRDs could be developed, the first one with the primary purpose of flood risk management that limits the maximum target flood release to 3,000 cfs (FRM3kcfs), and the second task focusing on ecosystem-based function (EbF) benefits with the primary purpose of limiting the number of days in which TDG levels are more than 120 percent (EbF120%). Both curves will balance meeting the determined objective of the curve while also providing reservoir refill assurance for water supply. Unlike the Existing dSRD, which uses approximately 12.4 feet of surcharge, the new curves will try to limit the surcharge due to the infrastructure (e.g., state parks, etc.) around the reservoir that was built since the development of the curve. The following sections provide a summary of the process that was used to develop the FRM3kcfs and EbF120% dSRDs.

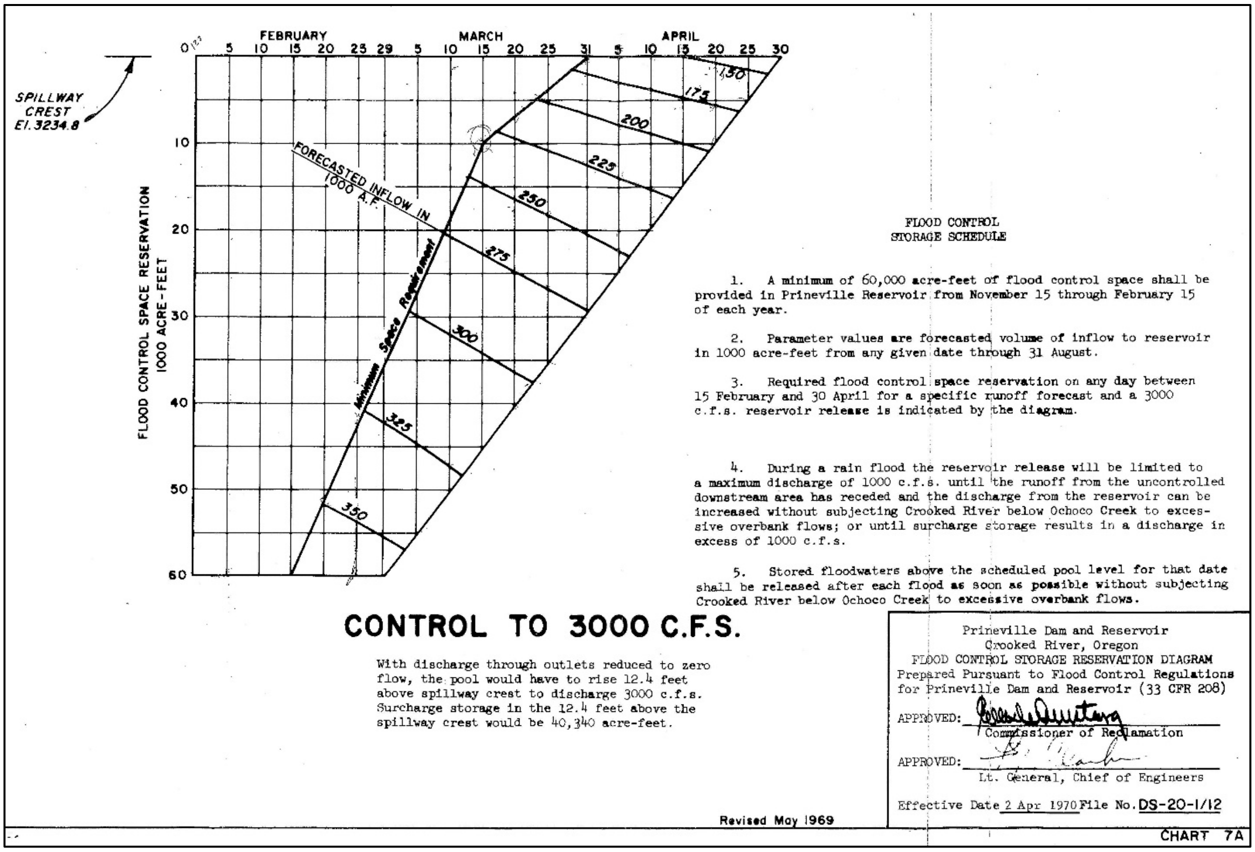

Figure 34. Existing Prineville Reservoir dSRD

As stated earlier, the existing dSRD can be thought of as a two-part curve in which the first part has a static winter space requirement of 60,000 acre-feet from November 15 through February 15, while the second part is dynamic and relies on the forecasted runoff volume into the reservoir for any point during the reservoir refill period (February 15 through April 30). The development of the dynamic part of the curve requires being able to define the amount of flood space required with a maximum flood release target. For the purposes of this Study, the primary focus will be on the dynamic part of the curve, as determining new winter space requirements using the 2080s future climate inflows is not prudent and is outside the precision of current future climate modeling. This process will consider an increase in the amount of static winter space, if required, but does not consider reducing the amount of static winter space. While there may be an opportunity to re-analyze a static winter space requirement, in the case of Prineville Reservoir (which experienced a December 1965 event that required all the static winter space to regulate an extremely large rain-on-snow event with estimated inflows of 20,000 cfs), this will not be reduced. Although this Study may provide some insight into the process of developing a new dSRD, it did not complete all of the critical required tasks, such as a robust analysis of incorporating runoff volume forecast errors into the dynamic part of the curve. In addition to a significant amount of additional analysis that would be required, this analysis would need to be completed using a coordinated work effort with the Corps Division and District offices.

The first part of the dSRD development process is defining the dataset that was used, which, for practical purposes, is typically the entire historical record of inflows at the location of the reservoir. However, for the purposes of this Study, the dataset was selected based on the future climate scenario that resulted in the largest impact to the flood-control and water-quality metrics (2080 LWW scenario).

In general, guidance available on the development process of a dSRD is limited, but the procedures described in the following sections were obtained through guidance found in *Volume 7 Flood Control by Reservoirs of Hydrologic Engineering Methods for Water Resources Development* (Corps 1976), as well as NRCS *Technical Release No. 75 Reservoir Storage Volume Planning* (NRCS 1991).

7.2.1 dSRD Inflow Dataset

To develop the new FRM3kcfs and EbF120% curves, a single future climate scenario (2080 LWW) dataset was chosen. The 2080 LWW scenario was chosen because this scenario has the largest impacts to the resource metrics regarding flood control and water quality. As shown in Table 18 and Table 20, the 2080 LWW scenario resulted in 22 days in which discharge was greater than 3,000 cfs and had the second-largest number of days in which TDG was greater than 120 percent. The 2080 LWW scenario contains a 30-year period that spans the years from 2070 through 2099. Although a larger dataset would be preferable when developing a dSRD in actual practice, for purposes of this Study, the 30-year period is sufficient to provide a proof of concept while remaining within the overall larger scope of the Study. Figure 35 below is the 2080 MWW scenario daily inflow to Prineville Reservoir showing daily peak flows ranging from approximately 14,000 cfs in large water years to approximately 1,200 cfs in drier water years. The 2080s MWW dataset also provides some variability in the runoff volume in both large water years (258 percent of the 8110 average[3]) and dry water years (27 percent of the 8110 average). Some years, such as 2073, show a double peak during the snowmelt period, while other years, such as 2075, show a single defined peak during runoff.

[3] 1981 through 2010 (referred to as 8110) historical average

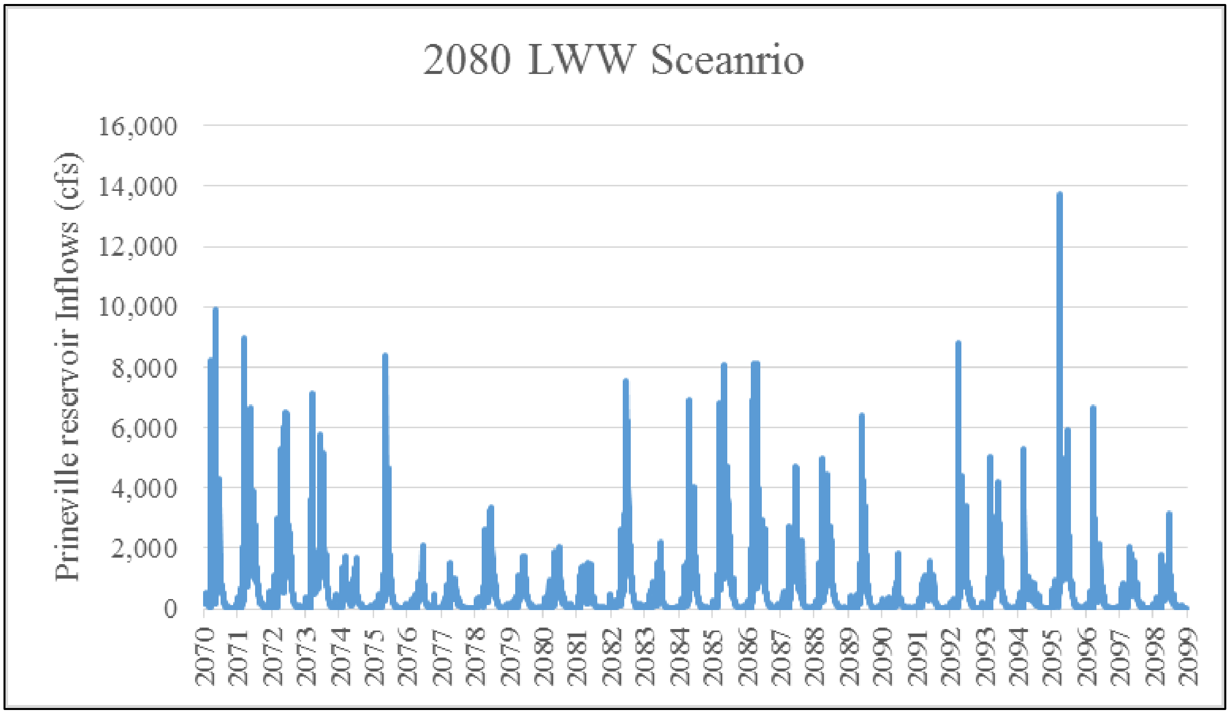

Figure 35. 2080 LWW scenario inflows into Prineville Reservoir used in the development of a new dSRD

In addition to variability in the peak flow, the 2080 LWW scenario also provides variability in the total runoff volume. Figure 36 illustrates the variability in runoff volume into Prineville Reservoir for the January-through-July period. For this Study, the runoff volumes were calculated through the end of July, unlike the current curve that calculated volumes through the end of August. This period volume was modified due to the inflows into the reservoir dropping significantly in August and do not account for much volume. Runoff volumes into Prineville Reservoir range from approximately 610,000 acre-feet for the 2083 water year to approximately 60,000 acre-feet in the 2091 water year. The average runoff volume for the 2080 LWW scenario is 272,000 acre-feet, while the median is skewed slightly to the left at 250,000 acre-feet. The average of 272,000 acre-feet for the January-through-July period is 123 percent of the historical 1981-2010 (8110) average for Prineville Reservoir, so the 2080 LWW scenario represents a 23 percent increase in average runoff volume. The 2080s LWW scenario typically has more monthly inflow in the November-through-March period. The largest increase in flow occurs during the month of December, when the 2080 LWW scenario is 272 percent of the 8110 historical average. The largest reduction in flow occurs during the month of June, when flows are 52 percent of the 8110 historical average.

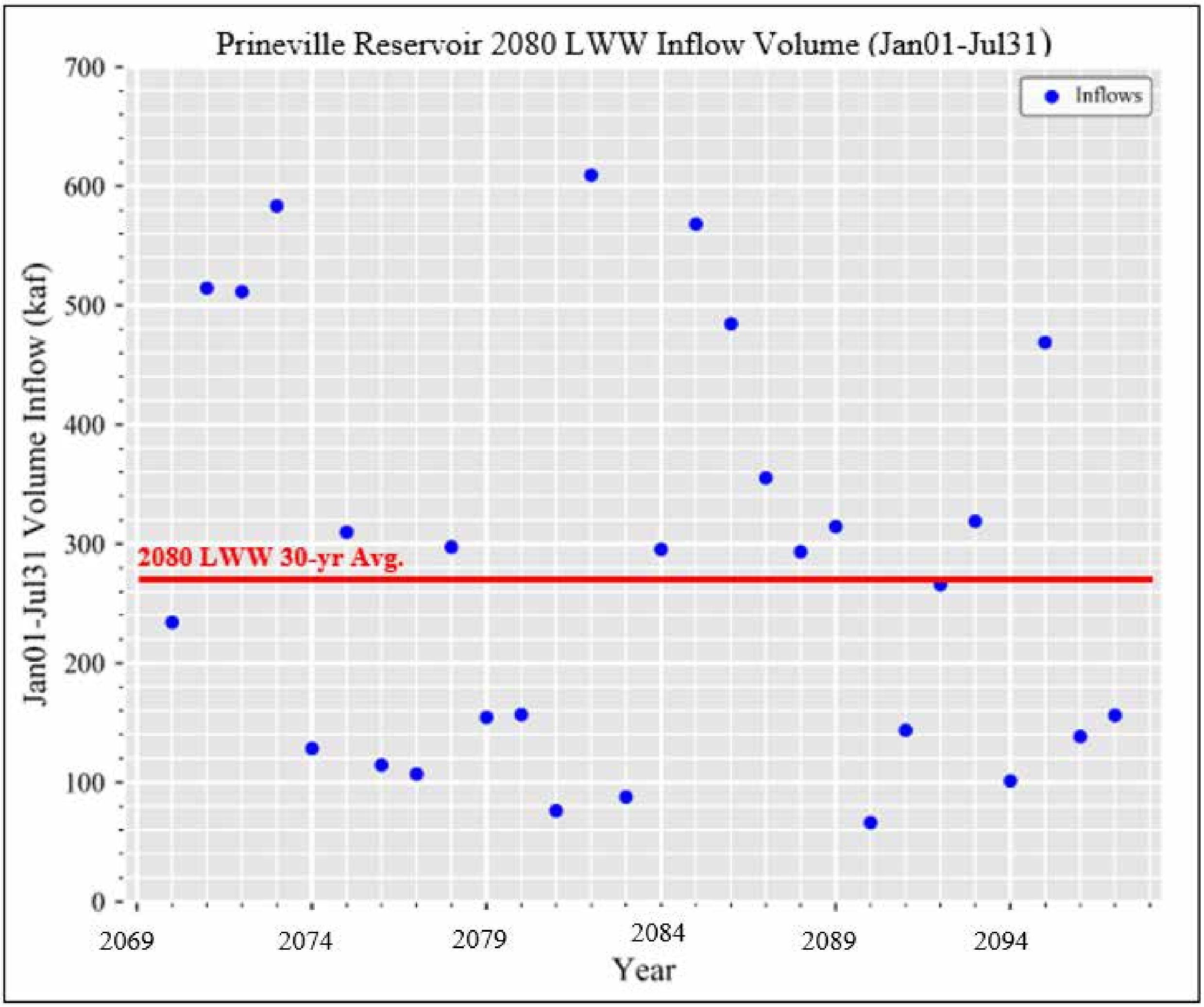

Figure 36. Runoff volumes into Prineville Reservoir for the January-through-July period of the 2080 LWW scenario[4]

7.2.2 Development of Runoff Volume-Storage Curves

To determine the required space for anytime within the reservoir refill period, a set of runoff volume-storage curves were calculated at 15-day intervals starting with the November 1-through-July period and ending at the May15-through-July period. The current dynamic part of the flood curve starts on February 15, but this Study adjusted this start date, if necessary, to meet the objective of the curve. The runoff volume-storage curves determine the amount of storage required to not exceed the 3,000 cfs (FRM3kcfs) or 2,000 cfs (EbF120%) maximum flood discharge target. After the volume storage curves are developed, space requirements between the 15-day intervals can be estimated using the best available correlation. Completing this process

[4] Kaf stands for thousand acre-feet

allows to develop a continuous space requirement for any day within the entire reservoir refill period.

The following is a description of the process used for the FRM3kcfs alternative to develop the runoff volume-storage curve for the February 15-through-July period. This same procedure was used for all other 15-day intervals (e.g., November 1 through July, November 15 through July, December 1 through July, etc.) up to the May 15-through-July period. The first step in this process is to determine the storage required based on a maximum flood discharge target starting and ending date. The LWW 2073 water year is used as an example to illustrate the method used to determine the runoff volume-storage curve for the February 15-through-July period. The 2073 water year had a February 15-through-July 31 runoff volume of 498,287 acre-feet. The volume of runoff when inflows into the reservoir were larger than the FRM3kcfs maximum flood discharge target of 3,000 cfs was determined to be 64,695 acre-feet. This procedure assumes that the outflows of the reservoir are set to match inflows up until inflow exceeds 3,000 cfs, at which point flows more than 3,000 cfs would be stored. With this assumption, an operation using perfect foresight of the 2073 water year runoff timing would draft the reservoir to provide 64,695 acre-feet of storage space by February 15, after which outflows would be set to match inflows until inflows exceed the 3,000 cfs maximum flood discharge target. Using this operation, outflows would never exceed 3,000 cfs and the reservoir would reach complete refill on March 21. Figure 37 below illustrates how the required storage is determined, assuming reservoir outflows (orange line) are set to match inflows (blue line) up until 3,000 cfs, after which storage space is required (dashed green line). This process determined that for the 2073 water year with a runoff of approximately 500,000 acre-feet for the February 15-through-July period, approximately 65,000 acre-feet of storage space would be required if discharges were limited to 3,000 cfs. This is just one data point, and the same process is completed for all 30 years in the 2070-through-2099 dataset. Automation was used to complete this task for all the time periods, starting with the November 1-through-July period and ending at the May 15-through-July period at 15-day intervals (for a total of 390 simulation runs).

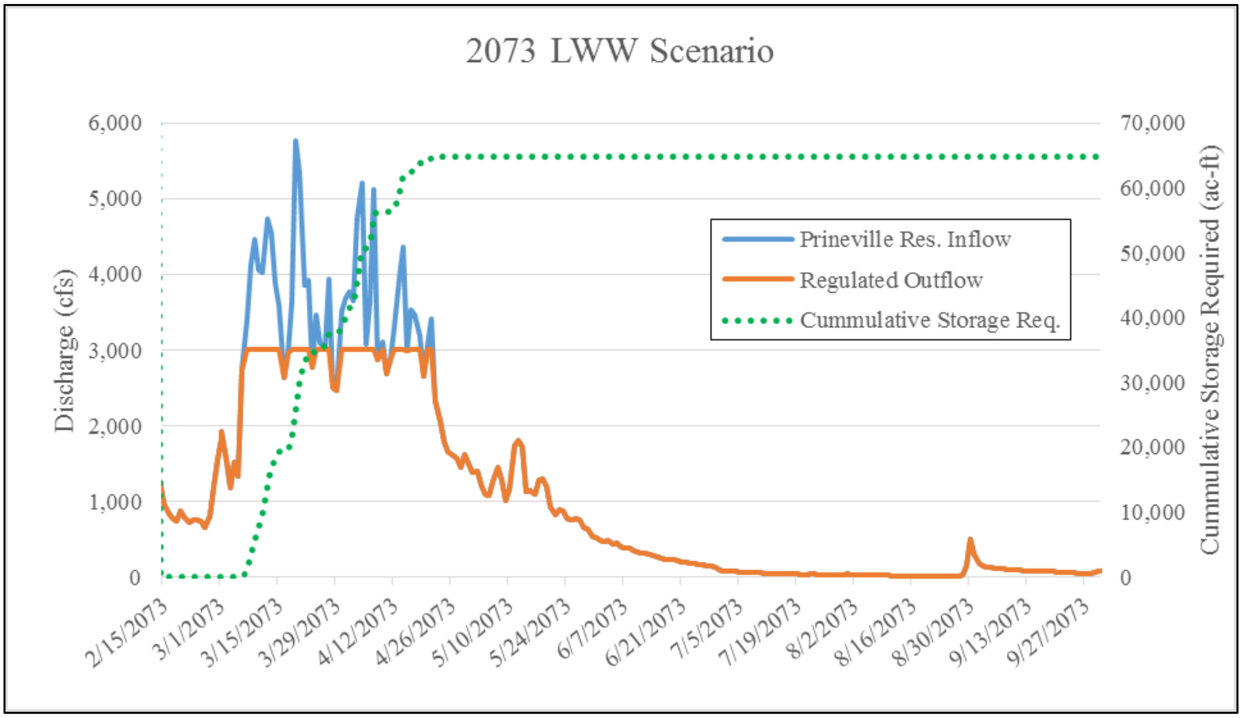

Figure 37. 2073 LWW water year showing cumulative storage (acre-feet) required during the February15-through-July period

Table 31 summarizes the results (ranked by storage required) from the procedure described above for the February 15-through-July period. Only the years in which the inflow dataset exceeded the 3,000 cfs maximum flood discharge target are shown in the table, as these are the only years that would require storage space. Of the 30 years in the 2080 LWW dataset, half of them (15 years) required storage space to meet the 3,000 cfs discharge value. In some cases, due to the different runoff timing of a specific water year, a smaller runoff volume may have resulted in more required storage than a larger runoff volume, as is the case when comparing the 2070 and 2085 water years. The timing of the runoff for the 2070 water year was much more rapid and resulted in more of the runoff volume running off when inflows exceeded 3,000 cfs. Stated differently, if the 2070 water year's timing was such that the discharge rarely exceeded 3,000 cfs, then less storage space would be required; if discharge exceeded 3,000 cfs more often, the storage space requirement would be much larger, even though the February 15-through-July volume was the same.

Table 31. 2080 LWW February 15-through-July runoff volume versus storage required, assuming a maximum flood discharge target of 3,000 cfs

2080 MWW Year	Feb. 15-July Volume[1]	Storage Required
2082	545	121
2073	499	63
2072	409	46
2070	208	37
2085	372	30
2071	384	30

2080 MWW Year	Feb. 15-July Volume[1]	Storage Required
2075	280	27
2087	274	17
2089	298	11
2095	284	8
2088	226	4
2084	165	4
2093	224	3
2086	278	3
2078	256	2

[1] All volumes and storage required are measured in thousand acre-feet.

In developing a dSRD for FRM purposes, the more conservative storage requirement was chosen to develop the runoff volume-storage curves; in the case of the 2070 example described above, the larger space requirement of the 2070 water year would be used. Determining which water years to include when developing the runoff volume-storage curves is required for all date-through-July periods. An easier way of determining which water years to include is to develop a scatter plot of runoff volume versus storage requirement for each water year, which aids in identifying which water years to use to envelop all possible storage requirements. For example, in Figure 38, in order to define a runoff volume versus storage envelope curve that would also provide enough storage for any other water year in the dataset (i.e., RAW data), the number of data points could be reduced to include only the 2082 and 2070 water years, and a data point could be manually added at 0 (considered as edited data). By doing this, the dataset is now reduced to only include three data points. In general, it is optimal to include more than three edited data points, but due to the 2070 anomaly in the February 15-through-July period, this required using only three.

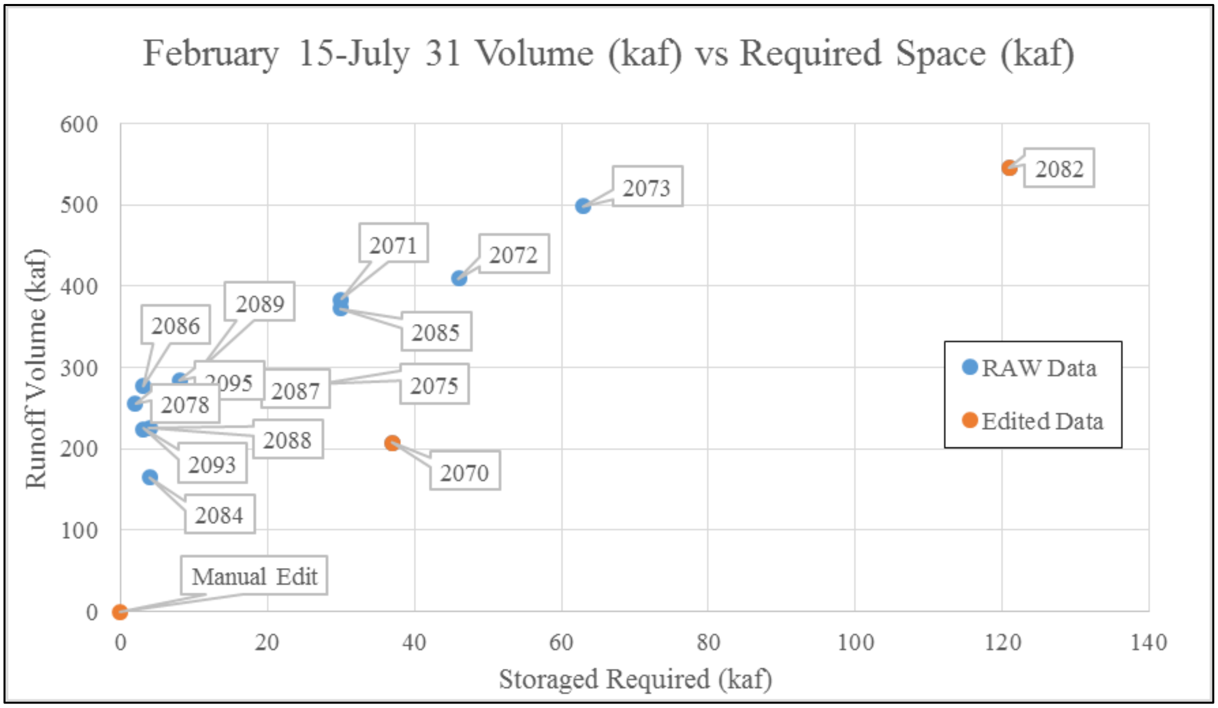

Figure 38. Scatter plot of RAW and edited data used to determine a runoff volume-storage envelope curve

Figure 39 shows the next step of defining the runoff volume-storage envelope curve by fitting the edited data using a 2^{nd} degree polynomial. The envelope curve was fit to match the more conservative storage requirements while also allowing it to estimate storage required for all other water years that are greater than what was required. The correlation of the curve fits well (mainly due to having only three data points) but getting a closer look at the actual errors between the estimated and actual runoff volumes requires a more thorough error analysis. Alternative techniques were employed to develop the envelope curves, and depending on the time interval when the correlation was made, this may have included relaxing the more conservative storage requirement (e.g., a December 15 space requirement that was not actually required until February), adding a data point to bend the envelope curve to contain and fit the data better, and/or adding a data point for zero storage required for a runoff volume of 0. Figure 40 is an example of when the December 15 space requirement of water year 2070 was relaxed to get the envelope curve to fit the remaining data better.

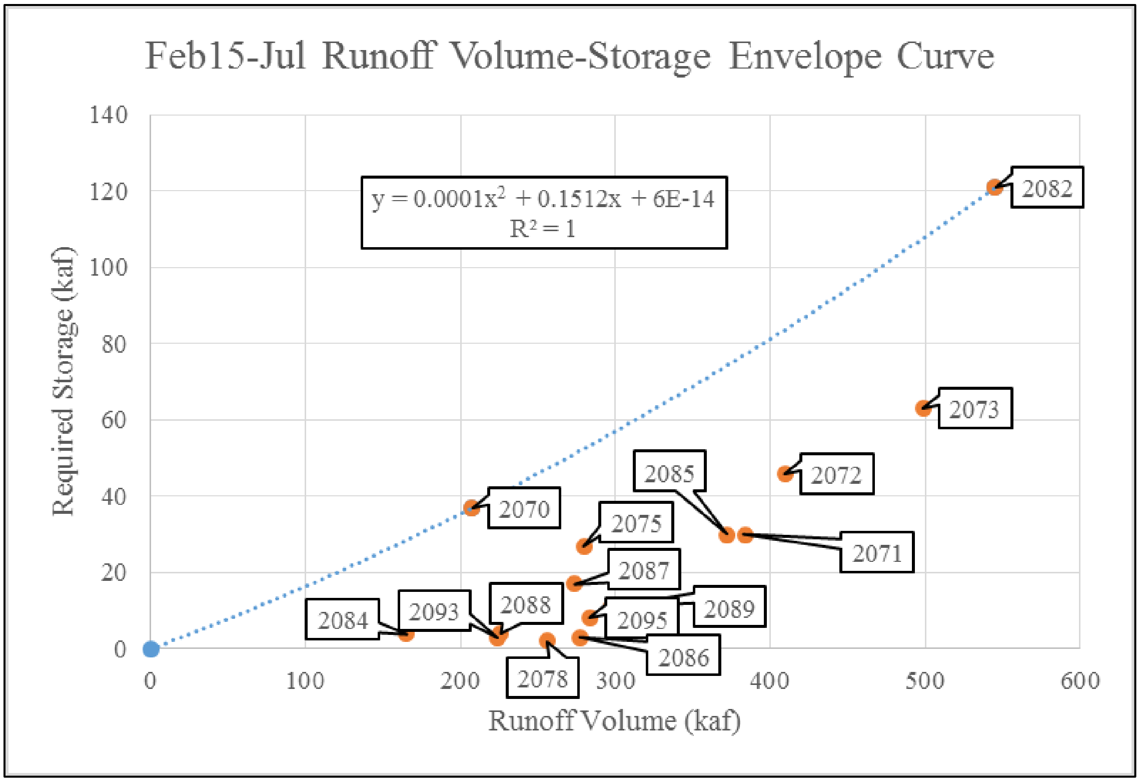

Figure 39. 2080 LWW February 15-through-July runoff volume-storage envelope curve

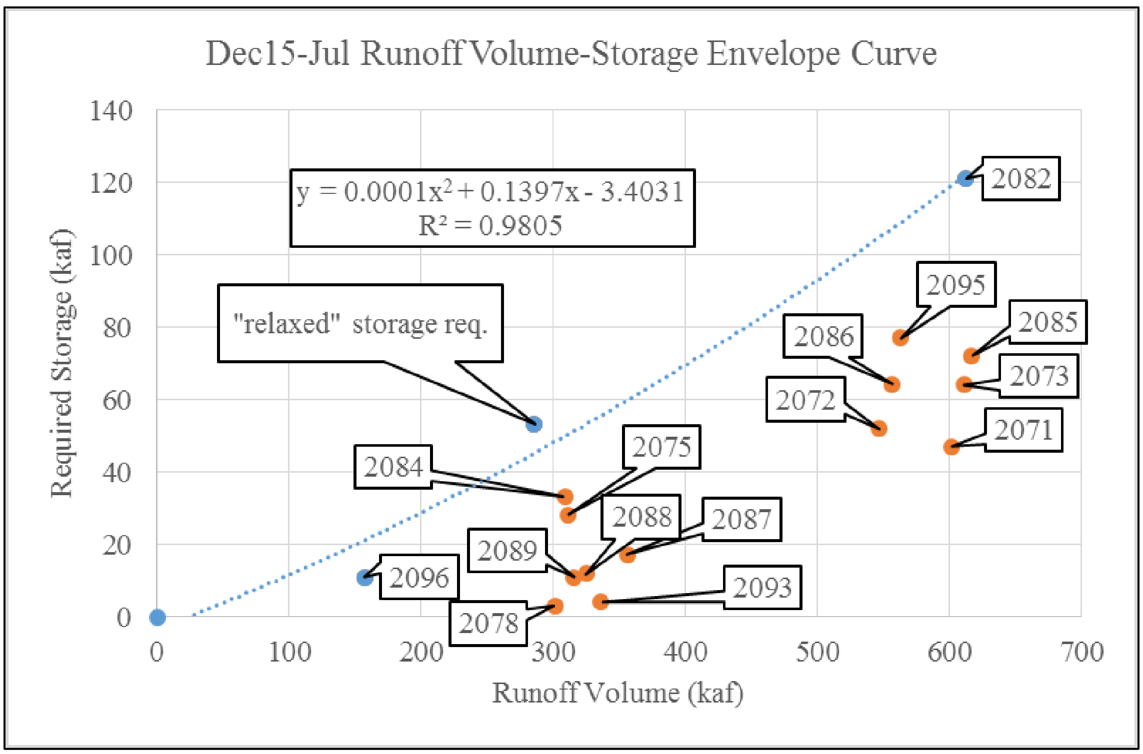

Figure 40. Example of when a storage requirement was relaxed to provide a better fit for the December 15-through-July runoff volume-storage envelope curve.

Table 32 shows the estimated storage required using the February 15-through-July runoff volume-storage envelope curve, compared to the actual storage required. As the table shows, all estimated storage requirements are greater than or equal to what was required. The average error in what the envelope curve estimated for storage required was 35,000 acre-feet more than what was required, while the median was 38,000 acre-feet and the 10 percent exceedance error was 48,000 acre-feet. Additional analysis of these errors would typically be completed if developing an actual operating curve, but for this Study, only the average, median, and 10 percent exceedance were calculated. At this point in the runoff volume-storage envelope curve development process, these errors were noted.

Table 32. Error analysis of the FRM3kcfs February 15-through-July runoff volume-storage envelope curve

Water Year	Runoff Volume[1]	Actual Storage Required	Estimated. Storage	Error (Estimate - Actual)
2082	545	121	121	0
2073	499	63	108	45
2072	409	46	84	38
2070	208	37	37	0
2085	372	30	74	44
2071	384	30	77	47
2075	280	27	52	25
2087	274	17	51	34
2089	298	11	57	46
2095	284	8	53	45
2088	226	4	41	37
2084	165	4	29	25
2093	224	3	40	37
2086	278	3	52	49
2078	256	2	47	45
			Average Error	35
			Median Error	38
			10% Exceedance Error	48

[1] Runoff volume, actual storage, estimated storage, and errors are all measured in thousand acre-feet

The process described above illustrates how a runoff volume-storage envelope curve was developed for the February 15-through-July period. The next step would be to do this same process for all of the other 15-day intervals; in the case of this Study, this included a runoff volume-storage envelope curve every 15 days during the November-to May-15 period. Curves were not developed for dates later than May 15 because there were no water years in which runoff required storage past May 1.

After this process was completed for all other 15-day intervals, a two-way look-up table was created that prescribes the amount of storage required on a specific date based on a runoff volume. Using this table, a set of lines was drawn (one for each runoff volume) that span the November-through-May 1 period. Figure 41 below is the FRM3kcfs curve, and Figure 42 is the

EbF120% curve. It is an iterative process of drawing the runoff volume-storage required lines to capture all actual storage requirements, and then running the new curve through the Pilot Model to determine how the curve performed. During this process, it was determined that this interactive process does not work with automation, as the developer of the dSRD needs to be aware of all details of the dataset used to develop the curve. The FRM3kcfs and EbF120% curves were modified as necessary to meet the objective of the curve (i.e., flood risk management or EbF) while also not impacting reservoir refill for water supply. The static winter space requirement of 60,000 acre-feet was found to perform well with the model results and provided the necessary flood space for the 2080 LWW dataset. As stated before, and due to the inherent risks to life and property, creating a new dSRD that would be implemented for real-time operations would require a much more robust analysis, including, but not limited to, an in-depth analysis of runoff volume forecast error on the storage requirements defined in the dSRD. This Study used the Perfect Forecast mode in the Pilot Model in which the model knew exactly what the runoff volume was; however, in actual operations, this error is not known, so any possible errors in the runoff volume forecast would need to be considered. Based on experience, developing a new operational dSRD is a multi-year process involving numerous levels of multi-agency involvement and review.

The following section examines how the FRM3kcfs and EbF120% curves performed when modeling the 2080 LWW inflow scenario compared to the Existing dSRD.

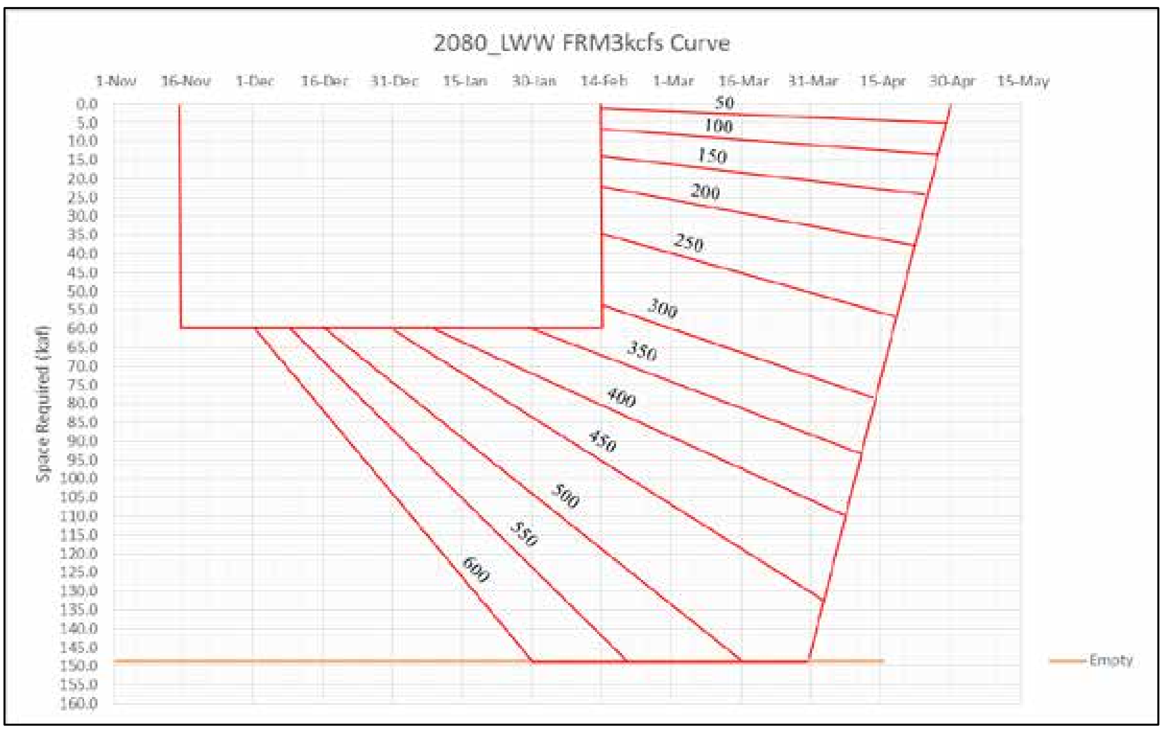

Figure 41. FRM3kcfs curve developed using the 2080 LWW scenario dataset and 3,000 cfs maximum flood discharge target

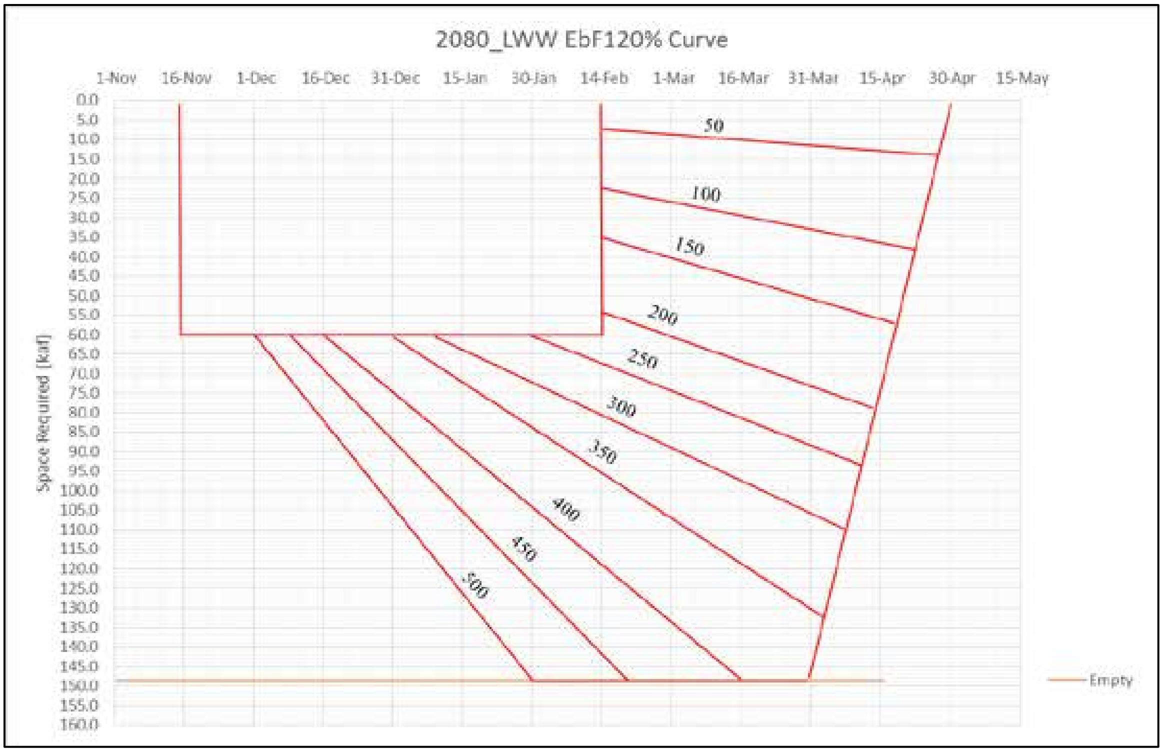

Figure 42. EbF120% curve developed using the 2080 LWW scenario dataset and 2,000 cfs maximum flood discharge target

7.3 Modeling of Future Climate Flows using the Modified dSRDs

Similar to the resource metric modeling completed for the hindcast and future climate flow modeling, this same modeling was completed for the FRM3kcfs and EbF120% curves. For this analysis, three model runs were completed. All three model runs used the 2080 LWW inflow dataset but operated using the Existing dSRD, FRM3kcfs, or EbF120% curves. The Existing dSRD was developed using the historical record at that time and uses a maximum flood discharge target of 3,000 cfs. The FRM3kcfs and EbF120% curves were developed using the 2080 LWW dataset and had maximum flood discharge targets of 3,000 cfs and 2,000 cfs, respectively. The following sections summarize the results from the modeling of the alternative dSRDs and how this impacted the resource metrics. The total number of days in the model period was 10,591 days.

7.3.1 Flood Control Metrics

> **Key Takeaways**
>
> - Both the FRM3kcfs and Ebf120% curves resulted in no discharges greater than 3,000.
> - The EbF120% curve resulted in 317 fewer days in which discharges were greater than 2,000 cfs.
> - The FRM3kcfs reduced maximum surcharge to 0.2 feet compared to the Existing dSRD that resulted in a maximum of 14.9 feet.

The Existing dSRD resulted in 26 days in which discharges were greater than 3,000 cfs (Table 33). All 26 days occurred during the 2082 water year when the reservoir was surcharged to 14.9 feet and resulted in a maximum release of approximately 4,000 cfs. Both the FRM3kcfs and Ebf120% curves resulted in no discharges greater than 3,000 cfs. The FRM3kcfs curve regulated the 2082 event without exceeding releases of 3,000 cfs, but the curve did result in more days in which discharge was greater than 2,000 cfs compared to the Existing dSRD. The EbF120% curve resulted in 317 fewer days in which discharges were greater than 2,000 cfs but resulted in 263 more days when discharges were greater than 1,500 cfs, compared to the Existing dSRD. The EbF120% curve resulted in 50 days in which discharges were greater than the maximum flood release target of 2,000 cfs used to develop the curve. This result was because the space required to regulate to 2,000 cfs was more that the total space available at Prineville Reservoir (148,560 acre-feet). Of the 50 days, 29 of these days occurred during the 2082 event, and the remaining 21 days had discharges less than 2,100 cfs.

Table 33. Number of days above various discharges for the FRM3kcfs and Ebf120% curves compared to the Existing dSRD

Model Run	# of Days Discharge (cfs) is Greater than				
	1,000	**1,500**	**2,000**	**2,500**	**3,000**
2080 LWW Existing dSRD	1,225	693	367	248	26
# Days Different from Existing dSRD					
2080 LWW FRM3kcfs	92	8	13	-68	-26
2080 LWW EbF120%	84	263	-317	-234	-26

All three model runs resulted in some occurrence of surcharge (Table 34). The FRM3kcs curve resulted in 95 fewer days above 3234.8 feet and 44 fewer days above 3238.0 feet compared to the Existing dSRD. The EbF120% curve resulted in 131 more days above the surcharge elevation of 3238.0 feet and 10 more days above 3238.0 feet compared to the Existing dSRD. The maximum surcharge for the Existing dSRD, FRM3kcfs, and EbF120% curves were 14.9, 0.2, and 12.3 feet, respectively. For the EbF120% curve, the 2082 event caused 86 days above 3234.8 feet, while the remaining days above 3234.8 feet all resulted in less than 3.7 feet of surcharge.

Table 34. Number of days above various surcharge elevations for the FRM3kcfs and Ebf120% curves compared to the Existing dSRD

Model Run	# of Days Pool Elevation (feet) is Greater than								Max[1]
	3234.8	3235.0	3235.5	3236.0	3236.5	3237.0	3237.5	3238.0	
2080 LWW Existing dSRD	203	94	79	67	59	53	49	44	3249.7
# Days Different from Existing dSRD									Max[1]
2080 LWW FRM3kcfs	-95	-83	-79	-67	-59	-53	-49	-44	3235.1
2080 LWW EbF120%	131	112	37	30	16	13	10	10	3247.1

[1] Maximum surcharge elevation for the model run.

All three curves resulted in complete reservoir refill in 17 of the 30 modeled years in the 2080 LWW scenario (Table 35). No impact on reservoir refill can be seen, or stated differently, the FRM3kcfs and Ebf120% curves did not result in fewer years in which the reservoir refilled compared to the Existing dSRD.

Table 35. Number of years Prineville Reservoir filled using the FRM3kcfs and Ebf120% curves compared to the Existing dSRD

Model Run	Number of Years with Full Refill[1]
2080 LWW Existing dSRD	17
# Days Different from Existing dSRD	
2080 LWW FRM3kcfs	0
2080 LWW EbF120%	0

[1] Full Refill refers to when the maximum reservoir contents reached 148,640 acre-feet

7.3.2 Water Deliveries Metrics

> **Key Takeaways**
>
> - The FRM3kcfs and Ebf120% curves resulted in minor impacts to storage allocation and reservoir carryover.

Table 36 shows various storage allocation exceedance values for all model runs. These exceedance values were developed by ranking all the maximum reservoir content values for each water year, restricted to the maximum legal storage right at Prineville Reservoir. The 10 percent and 20 percent exceedance storage allocation values for all three model runs were found to be the same. Regarding drier water years, the 80 percent exceedance allocation was found to be 1,013 acre-feet less for the FRM3kcfs curve and 2,401 acre-feet less for the EbF120% curve when compared to the Existing dSRD. The reduction in the 80 percent exceedance allocation for the EbF120% curve would impact the volume of uncontracted storage used for fish and wildlife purposes and is equivalent to a 3 cfs reduction over the entire water year. For the 90 percent exceedance allocation, all model runs resulted in similar values.

Table 36. Comparison of storage allocation exceedance values for the Existing dSRD, FRM3kcfs, and Ebf120% curves

Model Run	Storage Allocation Exceedance Values				
	10%	20%	50%	80%	90%
2080 LWW Existing dSRD	148,640[1]	148,640[1]	148,640[1]	148,244	126,329
	Acre-feet Different from Existing dSRD				
2080 LWW FRM3kcfs	0	0	-193	-1,013	18
2080 LWW EbF120%	0	0	-227	-2,401	320

[1] Maximum storage allocation is restricted to the full allocation amount of 148,640 acre-feet, as this is the maximum legal storage right at Prineville Reservoir.

Table 37 shows various storage carry-over exceedance values for all model runs. These exceedance values were developed by ranking all the minimum reservoir content values for the month of October. The month of October was chosen because this is the month that irrigation releases typically end, and there is no impact from flood control releases. The 10 percent exceedance value for all three model runs was found to be within 54 acre-feet of each other. For the 20 percent exceedance storage carryover, the FRM3kcfs model run was 13 acre-feet less, while the EBF120% model run was 138 acre-feet more compared to the Existing dSRD. In general, for all practical purposes, the impacts from the new curves should be considered minimal because the 10 percent and 20 percent exceedance values are so close to the Existing dSRD results. With regards to drier water years, the 80 percent exceedance allocation was found to be 704 acre-feet less for the FRM3kcfs curve and 1,313 acre-feet less for the EbF120% curve compared to the Existing dSRD. The 90 percent carryover exceedance was found to be 3,296 and 3,793 more for the FRM3kcfs and EbF120% curves compared to the Existing dSRD curve.

Table 37. Comparison of carry-over exceedance values for the Existing dSRD, FRM3kcfs, and Ebf120% curves

Model Run	Storage Carryover Exceedance Values				
	10%	20%	50%	80%	90%
2080 LWW Existing dSRD	94,310	84,877	74,980	62,818	45,558
	Acre-feet Different from Existing dSRD				
2080 LWW FRM3kcfs	14	-13	-213	-704	3,296
2080 LWW EbF120%	54	138	-112	-1,313	3,793

7.3.3 Water Quality Metrics

> **Key Takeaways**
>
> - The EbF120% curve performed well at reducing TDG with only 14 days above 120 percent compared to the Existing dSRD that resulted in 248 days.
> - The FRM3kcfs curve resulted in 68 fewer days at 120 percent TDG when compared to the Existing dSRD.

Table 38 shows the number of days in which TDG levels were above various levels compared to the Existing dSRD model run. The Existing dSRD resulted in 248 days in which TDG levels were greater than 120 percent. The FRM3kcfs model run resulted in 68 fewer days at 120 percent TDG and 8 fewer days at 115 percent TDG compared to the Existing dSRD. The EbF120% model run resulted in 234 fewer days with TDG exceeding 120 percent compared to the Existing dSRD. This result is good, considering that the main objective of the EbF120% curve was to limit this occurrence. Although there were fewer days above 120 percent TDG with the EbF120% model run, the number of days that TDG was greater than 115 percent increased by 263 days compared to the Existing dSRD. The determination of whether fewer days at a higher TDG level is less impactful than more days at a slightly lower level is outside the scope of the Study and would require consultation with fishery experts.

Table 38. Number of days TDG is above 110, 115, and 120 percent with the FRM3kcfs and Ebf120% curves compared to the Existing dSRD

Model Run	# of Days Discharge (cfs) is greater than		
	670 (110%)	1,500 (115%)	2,500 (120%)
2080 LWW Existing dSRD	1,852	693	248
# Days Different from Existing dSRD			
2080 LWW FRM3kcfs	25	8	-68
2080 LWW EbF120%	-95	263	-234

Regarding water temperatures, carryover volumes summarized in Table 37 show very little change in carryover for the month of October. Because of this, it seems reasonable to assume that water temperatures in the reservoir during the July-August periods would be about the same across all model runs.

7.3.4 Recreation Resource Metrics

> **Key Takeaways**
>
> - Boating recreation was impacted by both the EbF120% and FRM3kcfs scenarios due to deeper and longer-duration flood control drafts.

The Existing dSRD curve resulted in 7,013 days of flow within the optimal fishing range of 50 to 400 cfs (Table 39). With the FRM3kcfs model run, there was a reduction of 54 days in which streamflows were in the optimal fishing range. The EbF120% model run resulted in 5 more days in the optimal range compared to the Existing dSRD. In general, there were very few impacts to the number of days in which flows below the reservoir were in the optimal range across all modeled runs.

Table 39. Number of days in which flows are within the optimal fishing range of 50 to 400 cfs for the FRM3kcfs and Ebf120% curves compared to the Existing dSRD

Model Run	# of Days Discharge (cfs) is greater than		
	50	400	# Optimal Days
2080 LWW Existing dSRD	9,496	2,483	7,013
# Days Different from Existing dSRD			
2080 LWW FRM3kcfs	0	54	-54
2080 LWW EbF120%	0	-5	5

Table 40 summarizes the results for the reservoir recreation metric that estimates the number of days various boat ramps would be useable across each modeled run. The FRM3kcfs curve resulted in 322 fewer days in which the Powerhouse Cove ramp would be available and 391 fewer days in which the Jasper Point ramp would be available, compared to the Existing dSRD model run. The results for the EbF120% are similar to the FRM3kcfs model run, although there are 471 fewer days in which the Powerhouse Cove ramp would be useable and 526 fewer days in which the Jasper Point ramp would be useable, compared to the Existing dSRD model run. The reduction of the number of days in which these boat ramps would be useable is a result of deeper reservoir drafts required of the FRM3kcfs and Ebf120% to meet their operational objectives.

Table 40. Number of days various boat ramps are useable for the FRM3kcfs and Ebf120% curves compared to the Existing dSRD

Model Run	# of Days Pool Elevation (ft) is greater than		
	3,191 (State Park)	3,203 (Jasper Point)	3,210 (Powerhouse Cove)
2080 LWW Existing dSRD	9,496	9,155	7,052
# Days Different from Perfect			
2080 LWW FRM3kcfs	0	-391	-322
2080 LWW EbF120%	0	-526	-471

7.3.5 Ecological Resources Metrics

Key Takeaways

- Both the EbF120% and FRM3kcfs scenarios were found to have minimal impact to ecological flow targets.

Table 41 and Table 42 provide a summary of the impacts to fishery-related issues. In general, the FRM3kcfs and EbF120% model runs resulted in 51 and 134 more days, respectively, in which flow was greater than 100 cfs below the dam compared to the Existing dSRD model run (Table 41). The impact from this increase in flow resulted in an increase in WUA of 1 to 2 percent over the WUA of the Existing dSRD model run. The FRM3kcfs and EbF120% model runs resulted in 18 and 37 more days, respectively, in which flow were greater than 80 cfs at the Highway 126 bridge, representing a 1 percent increase in WUA over the Existing dSRD model run (Table 42).

Table 41. Number of days, exceedance, and WUA for various flows downstream of the dam for the FRM3kcfs and Ebf120% curves compared to the Existing dSRD

Model Run	# of Days Discharge (cfs) is greater than				
	20	40	60	80	100
2080 LWW Existing dSRD	9,496	9,496	9,496	9,496	8,206
# Days Different from Perfect					
2080 LWW FRM3kcfs	0	0	0	0	51
2080 LWW EbF120%	0	0	0	0	134
% Exceedance					
2080 LWW FRM3kcfs	100%	100%	100%	100%	87%
2080 LWW EbF120%	100%	100%	100%	100%	88%
2080 LWW Existing dSRD	100%	100%	100%	100%	86%
Habitat Parameter	% WUA				
Weighted Usable Area (WUA)	46%	66%	80%	85%	96%

Table 42. Number of days, exceedance, and WUA for various flows at the Highway 126 bridge for the FRM3kcfs and Ebf120% curves compared to the Existing dSRD

Model Run	# of Days Discharge (cfs) is greater than				
	20	40	60	80	100
2080 LWW Existing dSRD	9,496	9,496	9,496	9,352	3,449
# Days Different from Perfect					
2080 LWW FRM3kcfs	0	0	0	144	18
2080 LWW EbF120%	0	0	0	114	37
% Exceedance					
2080 LWW FRM3kcfs	100%	100%	100%	100%	37%
2080 LWW EbF120%	100%	100%	100%	100%	37%
2080 LWW Existing dSRD	100%	100%	100%	98%	36%
Habitat Parameter	% WUA				
Weighted Usable Area (WUA)	46%	66%	80%	85%	96%

Table 43 and Table 44 provide a summary of the impacts to the minimum flow requirement of 80 cfs. Downstream of the dam, there was no difference found across all modeled runs. The FRM3kcfs and EbF120% model runs resulted in 144 and 114 more days, respectively, in which flows were greater than 80 cfs at the Highway 126 bridge (Table 43). This indicates that the increased reservoir draft required by the FRM3kcfs and EbF120% model runs increased the number of days flows were more than 80 cfs. Additional investigation into whether flows above 80 cfs were beneficial to fish and wildlife (as any flow above 670 cfs results in TDG levels exceeding 110 percent) was not completed for this Study.

Table 43. Number of days flow was 80 cfs or more below the dam for the FRM3kcfs and Ebf120% curves compared to the Existing dSRD

Model Run	# of Days Discharge is greater than 80 cfs	% Exceedance
2080 LWW Existing dSRD	9,496	100%
# Days Different from Perfect		% Exceedance
2080 LWW FRM3kcfs	0	100%

Model Run	# of Days Discharge is greater than 80 cfs	% Exceedance
2080 LWW EbF120%	0	100%

Table 44. Number of days flow was 80 cfs or more at the Highway 126 bridge for the FRM3kcfs and Ebf120% curves compared to the Existing dSRD

Model Run	# of Days Discharge is greater than 80 cfs	% Exceedance
2080 LWW Existing dSRD	9,352	98%
# Days Different from Perfect		**% Exceedance**
2080 LWW FRM3kcfs	144	100%
2080 LWW EbF120%	114	100%

7.3.6 Modified dSRD Alternative Modeling Conclusions

Similar to the resource metric modeling completed for both the hindcast and future climate flow modeling, this same process was completed for the FRM3kcfs and EbF120% curves. For this analysis, three model runs were completed. All three model runs used the 2080 LWW inflow dataset but operated using the Existing dSRD, FRM3kcfs, or EbF120% curves.

Key Takeaways

- Overall, both the FRM3kcfs and Ebf120% curves performed well at meeting their specific objectives, although ancillary impacts were found on other resource categories. For instance, the reduction in the number of days below 120 percent TDG were at a cost of more days above 115% TDG and fewer boating days.

The Existing dSRD resulted in 26 days in which discharges were greater than 3,000 cfs, with all 26 days occurring during the 2078 water year, when the reservoir was surcharged to 14.9 feet, and resulted in a maximum release of approximately 4,000 cfs. Both the FRM3kcfs and Ebf120% curves resulted in no discharges greater than 3,000 cfs. The EbF120% curve resulted in 317 fewer days in which discharges were less than 2,000 cfs but resulted in 263 more days when discharges were greater than 1,500 cfs compared to the Existing dSRD. The EbF120% curve resulted in 50 days in which discharges were greater than the maximum flood release target of 2,000 cfs used to develop the curve. This result occurred because the space required to regulate to 2,000 cfs was more than the total space available at Prineville Reservoir (148,000 acre-feet). Of the 50 days, 29 of these days occurred during the 2078 event, and the remaining 21 days experienced discharges less than 2,100 cfs.

All three curves resulted in complete reservoir refill in 17 of the 30 modeled years. The FRM3kcfs and Ebf120% curves did not result in fewer years in which the reservoir refilled compared to the Existing dSRD.

The Existing dSRD had 248 days in which TDG levels were greater than 120 percent. The FRM3kcfs model run resulted in 68 fewer days at 120 percent TDG and 8 fewer days at 115 percent TDG compared to the Existing dSRD. The EbF120% model run resulted in 234 fewer days with TDG exceeding 120 percent compared to the Existing dSRD. The FRM3kcfs curve resulted in 322 fewer days in which the Powerhouse Cove ramp would be available compared to the Existing dSRD model run, and the EbF120% had 471 fewer days. The reduction in the number of days in which these boat ramps would be useable is a result of a deeper reservoir draft required of the FRM3kcfs and Ebf120% to meet their operational objectives. The FRM3kcfs and EbF120% model runs resulted in 51 and 134 more days, respectively, in which flow was greater than 100 cfs below the dam compared to the Existing dSRD model run. The impact from this increase in flow resulted in an increase of 1 to 2 percent in WUA over the WUA from the Existing dSRD model run.

Overall, both the FRM3kcfs and Ebf120% curves performed well at meeting their specific objectives, although ancillary impacts were found on other resource categories. For instance, the reduction in the number of days below 120 percent TDG were at a cost of more days above 115 percent TDG and fewer boating days. This Study illustrated how a curve could be developed for a single objective using a 2080s future climate scenario.

8 Conclusion

Key Takeaways

- The Study found two alternative operations that may lessen impacts from climate variability by implementing a dry-year alternative operation and a modification to the dSRD.
- Changing a dSRD for one purpose may result in unintended impacts to another resource category.
- Surcharge space available at Prineville Reservoir provides a built-in resiliency to climate variability and forecast errors.

The purpose of this Study was to examine the resiliency and adaptability of Prineville Reservoir to a changing hydrologic regime. This Study accomplished this by looking at how different forecast methods may improve operations using historical inflows, determining impacts to project resource considerations with regard to possible future climate flows, and optimizing operations through dry-year alternative operations and modifications to the dSRD.

Some operational impacts were found based on the three different hindcast methods (MLR, NWRFC ESP, and NCAR ESP). These impacts were dampened due to the current dSRD using available surcharge to allow the reservoir to fill much sooner for various forecasted runoff volumes compared to a reservoir without surcharge available. Regardless, a changing hydrologic regime, changing stakeholder expectations, and development of state parks around the reservoir may take this surcharge flexibility away. With respect to a changing hydrologic regime, the future climate modeling completed in Section 7 provides insight into which project resource impacts may result if this were to happen. Due to these impacts, this Study found two alternative operations that may lessen these impacts by implementing a dry-year alternative operation and a modification to the dSRD. Implementation of the dry-year alternative showed that for 11 years out of the 30-year 2080 LWW scenario, additional refill was obtained through a 15- or 30-day deviation of the static winter space requirement when basin conditions indicated a low risk to large rain-on-snow events that the winter static space was designed for. With regard to discharges exceeding the 3,000 cfs flood control discharge target, as well as the current desire of fish managers to limit the times TDG exceeds 120 percent, two modified curves were developed (FRM3KCFS and EbF120%). The FRM curve limited flows to 3,000 cfs or less, and the EbF120% curve reduced the number of days above 120 percent TDG from 248 days for the Existing dSRD to 14 days for the EbF120% curve. Although the FRM3kcfs and EbF120% resulted in the same number of years in which reservoir refill was obtained in real-time operations when errors in the runoff volume are assumed to occur, this same result may not occur. The designed resiliency of Prineville Reservoir to large, flashy runoff events by way of ability to surcharge the reservoir already provides resiliency to obtain a water supply by allowing the reservoir to fill much quicker than it would if it did not have the surcharge ability. One way to think about this built-in resiliency is that the available surcharge at Prineville Reservoir allows for flood control while being almost completely full. Results of this Study found that the existing dSRD currently performs well at balancing all reservoir resources. If in the future, operations at Prineville Reservoir result in an increase in reservoir outflows above the flood control target or if reservoir refill becomes problematic, the process outlined in this Study may provide a starting point on how operations may be modified.

Going forward, the following is a list of possible future efforts that may be beneficial at similar-type basins:

- Continue to seek ways to improve runoff volume forecasting
- Perform a thorough review of forecast limitations and error analysis
- Identify ways to incorporate a formal dry-year alternative operation into the water control manual
- Review opportunities for updating the dSRD or rule curves if the project is having problems providing historical flood control or water supply probabilities.

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