McKay Reservoir Operations Pilot Study

Evaluating Forecasting Techniques for Adapting Reservoir Operations to Increased Water Supply Variability at McKay Reservoir

Umatilla Basin Project, Oregon
Columbia-Pacific Northwest Region

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14. ABSTRACT

A study to explore potential modifications to the water supply forecast (WSF) and space reservation diagram (SRD) that help inform operations of McKay Reservoir. The intent of the study is to explore whether these modifications can provide water managers additional useful tools to help manage future high flow events while also maintaining a balance of the authorized purposes of the reservoir.

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Mission Statements

Disclaimer

Cover photograph: McKay Dam, northeastern Oregon, during April 2019 high flow conditions (Reclamation photo)

Acronyms and Abbreviations

Acronym or Abbreviation	Definition
ARBO SE	Arbuckle SNOTEL SWE
ARBO SU	Arbuckle snow course SWE
cfs	cubic feet per second
CPN	Columbia-Pacific Northwest Region
dSRD	Dynamic space reservation diagram
Dsto	Change in storage
ESP	Ensemble Streamflow Prediction
FRM	Flood risk management
GEFS	Global Ensemble Forecasting System
HEFS	Hydrologic Ensemble Forecasting System
kaf	Thousand acre-feet
LGD PM	La Grande, Oregon Monthly Precipitation
MCHO SU	Meacham snow course SWE
MCK	McKay Reservoir
MCK FB	McKay Reservoir forebay elevation (feet)
MCK AF	McKay Reservoir storage content (acre-feet)
MCKO QD	McKay Creek near Pendleton, Oregon observed streamflow (cfs)
MCKO QU	Calculated unregulated McKay Reservoir inflow
MEFP	Meteorological Ensemble Forecast Processor
MLR	multiple linear regression
NASA	National Aeronautics and Space Administration
NRCS	USDA Natural Resources Conservation Service
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	NOAA National Operational Hydrologic Remote Sensing Center
NSE	Nash-Sutcliffe Efficiency
NWRFC	Northwest River Forecast Center
OWRD	Oregon Water Resources Department
PCR	Principal Component Regression

Acronym or Abbreviation	Definition
PDT PM	Pendleton E OR RGNL AP, OR monthly precipitation
PMF	Probable maximum flood
PILO PC	Pilot Rock 11E 15-minute cumulative precipitation
PLTO PM	Pilot Rock 11E monthly precipitation
PRMS	Precipitation Runoff Modeling System
r^2	Coefficient of determination
Reclamation	Bureau of Reclamation
RMJOC-II	River Management Joint Operations Committee, Part II
RMSE	Root-mean-square error
SD	Standard deviation
SE	Standard error
SNOTEL	SNOwpack TELemetry Network
SRD	Space reservation diagram
sSRD	Static space reservation diagram
Study	McKay Reservoir Operations Pilot Study
SWE	Snow water equivalent
TOLO SU	Tollgate snow course SWE
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WaterSMART	Sustain and Manage America's Resources for Tomorrow
WSF	Water supply forecast
WY	Water year (October through September)

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Executive Summary

A high flow event during 2019 in the McKay Reservoir basin in northeast Oregon (Reclamation 2019a) prompted the Bureau of Reclamation (Reclamation) to develop this Reservoir Operations Pilot Study (Study) to explore potential modifications to the water supply forecast (WSF) and space reservation diagram (SRD) that help inform operations of McKay Reservoir. The intent of the Study is to explore through modeling exercises whether these modifications can provide water managers additional useful tools to help manage future high flow events while also maintaining a balance of the authorized purposes of the reservoir. The dam was originally constructed for the purpose of irrigation water supply, and a full reservoir (hydrology permitting) is critical to the water users in the basin. However, flood control (now termed flood risk management (FRM)) became an authorized purpose in 1976 through legislation and has also become an important purpose in the basin with continued development along McKay Creek downstream of the dam.

The McKay Creek watershed is largely a transitional basin fed by a combination of rain and snow and is highly influenced by difficult-to-forecast rain events during the spring runoff season. Snowpack alone does not drive high runoff. Rain and rain-on-snow events are major contributors to runoff and are difficult to predict with any significant lead time. McKay Creek hydrology may be susceptible to a change in climatic variability in the future with more frequent extreme weather events and a shift in precipitation from less snow to more rain, causing earlier peak flow timing, lower summer base flows, and flashier, higher peak events.

This Study consisted of the development of updated WSF equations, water supply hindcasting and performance analysis, development of updated SRDs, future climatic variability hydrologic modeling and analysis, and computer simulation of alternative reservoir operation scenarios.

Water Supply Forecast (WSF) Analysis

The McKay Creek basin does not exhibit the characteristics of a typical snowmelt dominant basin. The runoff is much "flashier" with high peak inflow events primarily caused by rain or rain-on-snow often occurring throughout the November through June period. During the early summer, even after the snowpack has melted, high flow events may still occur with rain events in the basin. With this type of relationship, a highly skilled WSF of future runoff cannot be made based on current basin conditions (i.e., existing snowpack) and is highly reliant on future weather conditions.

Even so, significant improvement in WSF performance for all forecast periods was achieved through the development of new McKay Creek near Pendleton PCR (Principal Component Regression) and Z-Score WSF equations in PyForecast, a WSF development software package.

Figure ES-1 summarizes the improvements across six different statistical measures used for evaluating forecast skill (a full explanation of each statistic can be found in Appendix C). For each metric and period grouping, the three bars (blue, dark blue and maroon) on the left side of the groups represent the performance of the historical WSF equations (Reclamation Multiple Linear Regression (MLR), Northwest River Forecast Center Ensemble Streamflow Prediction Climatology (NWRFC ESP 0) and Hydrologic

Ensemble Forecasting System (NWRFC HEFS)). The four bars (gray, yellow, light blue, and green) on the right side of the groups represent the performance of the updated PyForecast PCR and Z-Score WSF equations. The individual statistical measure's performance was considered improved if:

- Root-mean squared error (RMSE) is lower
- Error standard deviation (SD) is lower
- Standard error (SE) is lower
- Maximum absolute error is lower
- Coefficient of determination (r^2) is higher
- Nash-Sutcliffe Efficiency (NSE) is higher

Though WSF performance was improved significantly compared to existing procedures, the rain-snow transitional nature of the McKay Creek basin makes forecasting more difficult and less accurate than in other more snow dominated basins. Significant under- and over-forecast events remain a possibility. To further complicate forecasting, future climate change projections indicate the basin could become more rain dominated, making runoff even less dependent on snowpack and more dependent on future precipitation events.

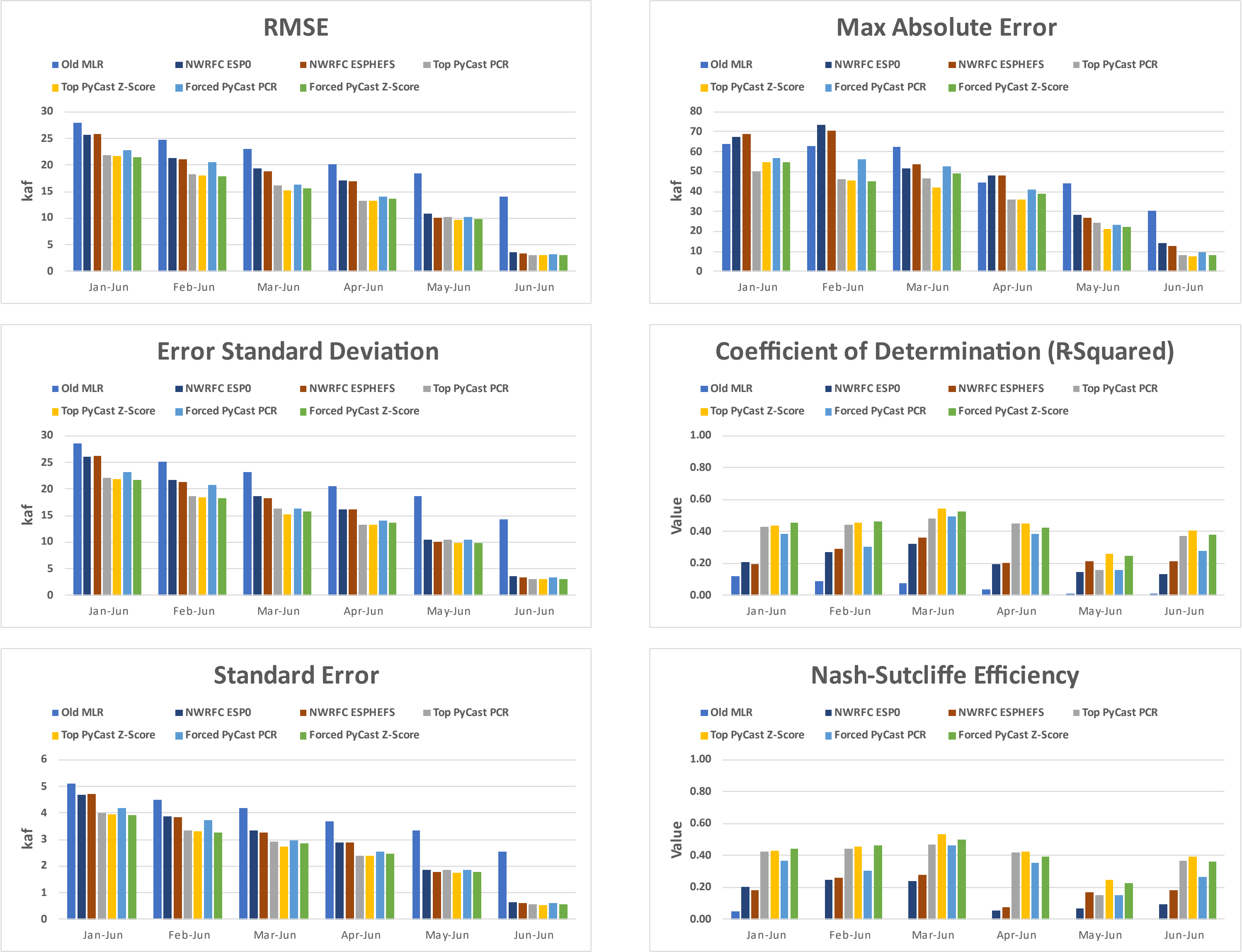


Figure ES-1. Summary statistic graphs for the McKay Creek near Pendleton forecasts comparing the WY1989-WY2019 period common to WSF products examined in this Study

Future studies may provide additional tools for water managers, such as: a) improvements in weather forecasting, both in terms of rainfall amount prediction and longer lead time, b) locating additional SNOwpack TELemetry Network (SNOTEL) sites in the basin to capture lower elevation snowpack conditions, and c) continuing to develop, improve, and utilize remote sensing datasets in WSFs. It is anticipated the PyForecast WSFs developed for this Study may continue to be improved in the future as technology evolves.

Space Reservation Diagram (SRD) Analysis

A static SRD (sSRD) identifies a fixed minimum amount of space for FRM for each day of the season and does not consider basin conditions. An sSRD is generally most effective for basins in which the runoff volume cannot be forecast with a reasonable level of certainty, typically rain dominated basins. A dynamic SRD (dSRD) identifies a variable minimum amount of FRM space for each day of the season dependent on a WSF of runoff volume that is expected to occur. A dSRD does consider basin conditions and is generally most effective for basins in which the runoff can be forecast with a reasonable level of certainty, typically in snow dominated basins. Reclamation has historically utilized an sSRD at McKay Dam to guide water managers in regulating the rate with which the reservoir fills to balance reduction of flood risk downstream with filling the reservoir for water supply.

Each version of SRD has its own set of strengths and weaknesses. In a perfect forecast paradigm, dSRDs typically do a better job of balancing fill of the reservoir with capturing high flow events. However, with the challenges related to forecasting in the McKay basin, significantly under- or over-forecast events are likely to occur, which could result in too little space reservation (resulting in higher than desired flows downstream) or too much space reservation (resulting in less reservoir fill than desired) in actual real-time application. The strength of an sSRD is typically controlling flows downstream within desired levels since they are designed to manage historically observed events. However, if the hydrologic paradigm shifts (e.g., as a result of climate change), and events outside of the historical range occur, the sSRD may no longer provide the protection originally intended. In addition, in drought years when high flow events are unlikely to occur, the static space identified by the sSRD may be too much for the conditions and can result in the reservoir missing refill if strictly followed.

The McKay Existing sSRD (see Figure ES-2) includes a qualifying note in the diagram that states:

> *"More space will be provided if snow pack so indicates"*

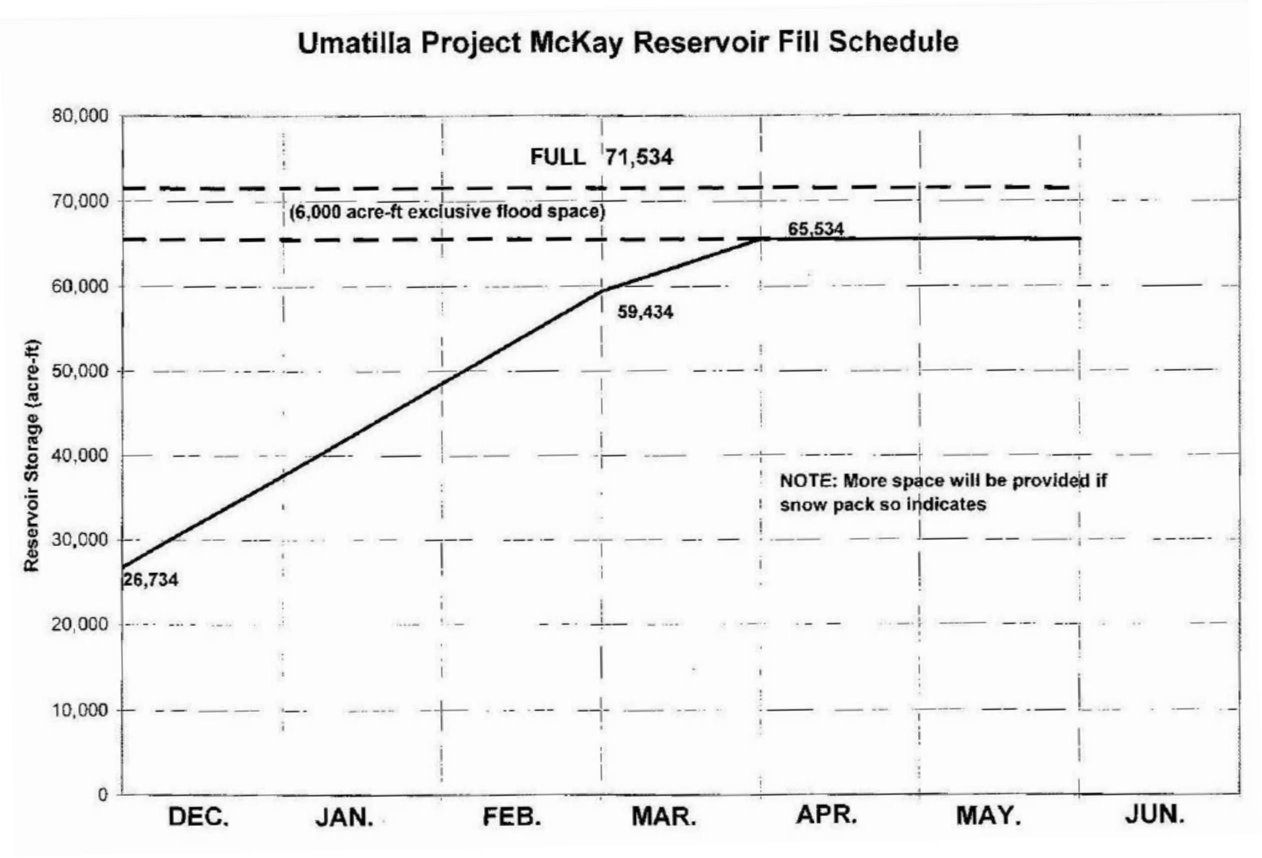


Figure ES-2. MCKO Existing sSRD

However, no guidance is provided to quantify the conditions or the additional space reservation if such conditions materialize. During the water year (WY) 2019 high flow event, which was found to have between a 20- and 50-year return interval, more space was held in the reservoir than indicated by the Existing sSRD leading up to the event. However, to ensure safety of the dam, flows downstream still needed to be increased above the safe channel capacity of 1,200 cubic feet per second (cfs).

By incorporating additional years of record, new SRDs were created that account for recent high runoff events and, together with the updated WSF products, provide water managers with additional tools to help inform how much space to reserve if conditions warrant. Development consisted of two sSRDs (800sSRD and 1200sSRD) and two dSRDs (800dSRD and 1200dSRD); see Figures ES-3 and ES-4. Each type of SRD was designed for both a 1,200 cfs control flow (current safe channel capacity) and an 800 cfs control flow (to provide additional buffer to account for periods of reduced channel capacity such as was the case after the 2019 high flow event).

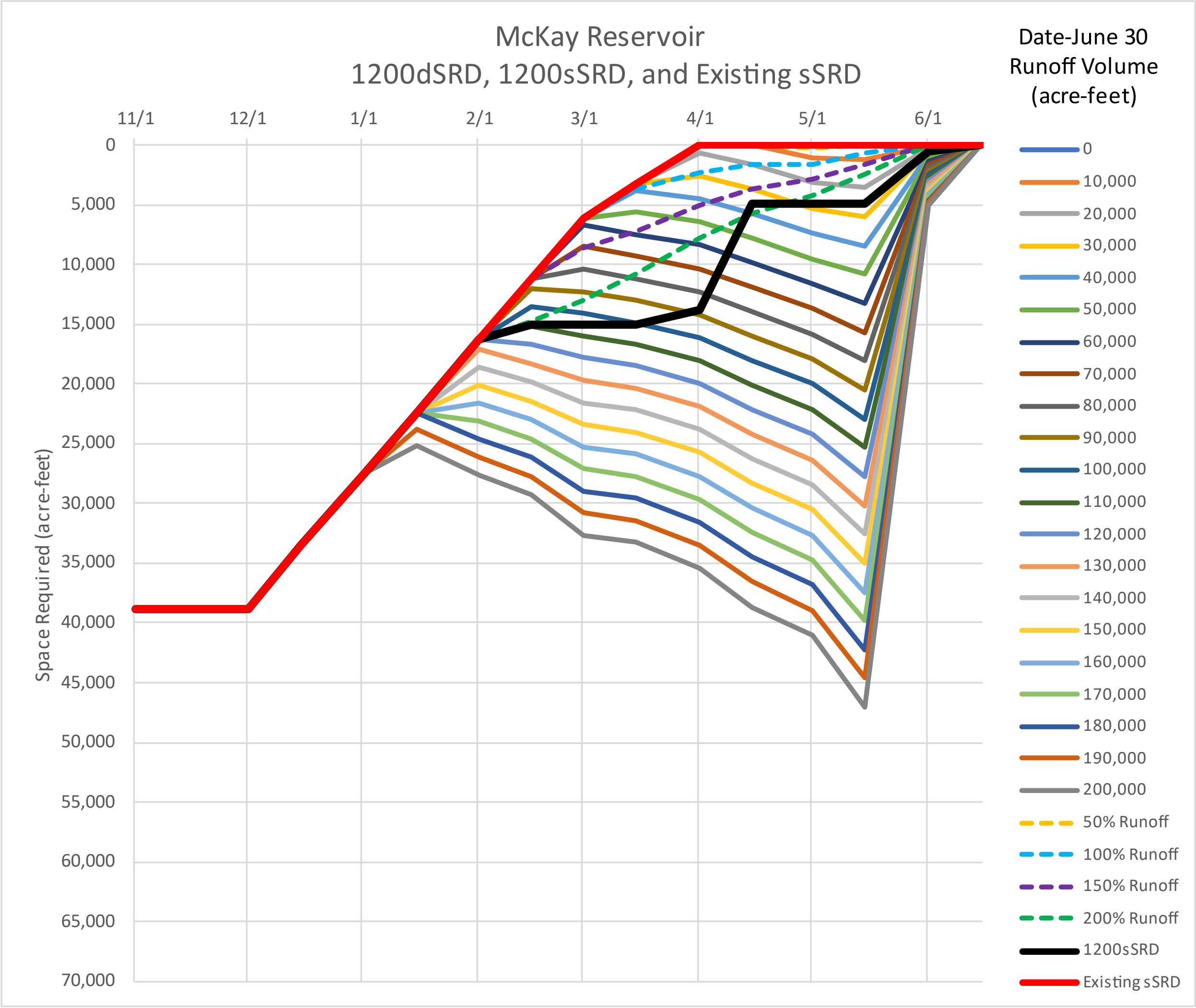


Figure ES-3. Existing sSRD, 1200dSRD, and 1200sSRD shown together for comparison. Dashed lines represent historical (WY1991-WY2020) below normal to above normal period volumes to illustrate the amount of space that would be required by the 1200dSRD.

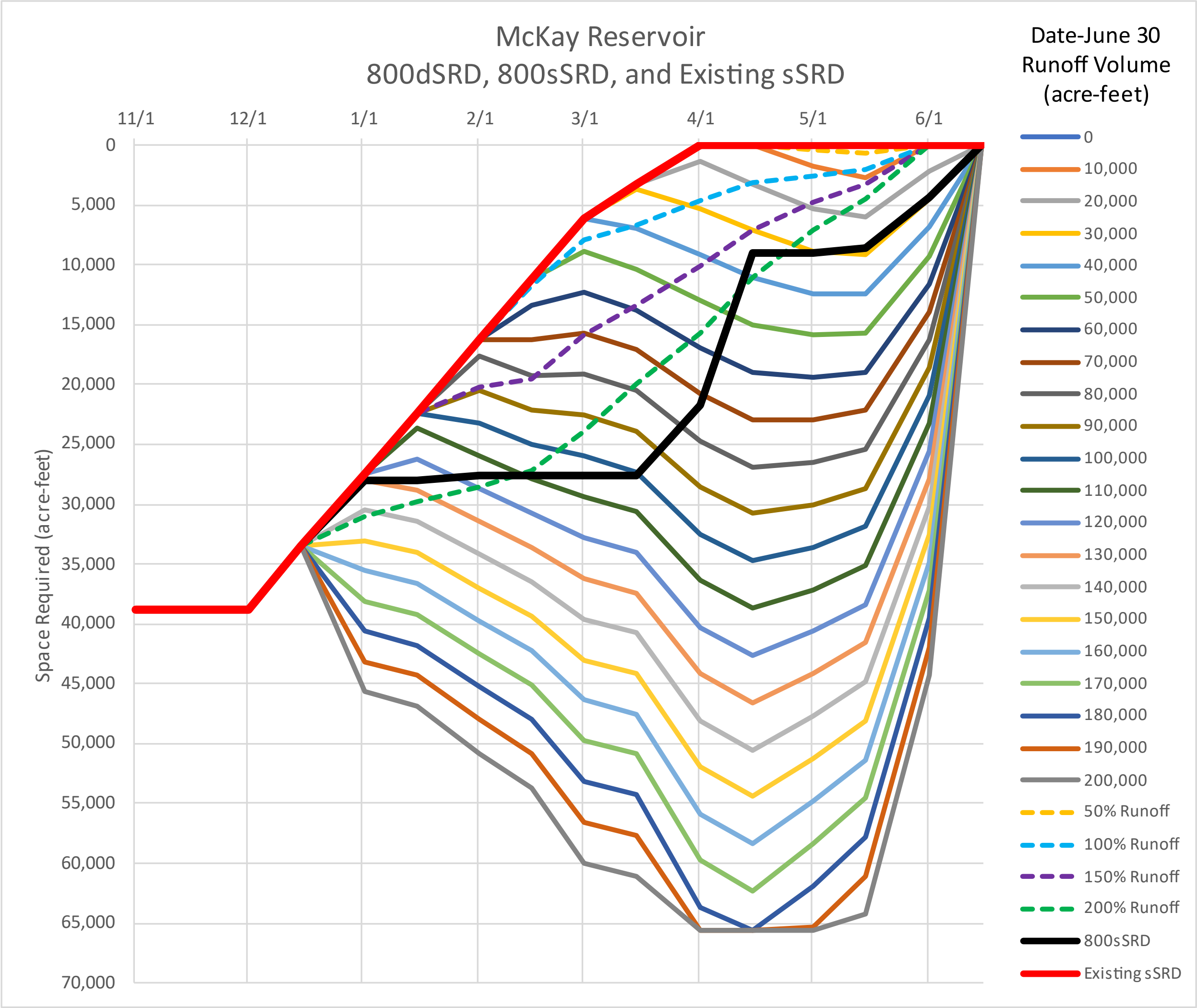


Figure ES-4. Existing sSRD, 800dSRD, and 800sSRD shown together for comparison. Dashed lines represent historical (WY1991-WY2020) below normal to above normal period volumes to illustrate the amount of space that would be required by the 800dSRD.

Modeling Analysis – Historical Hydrology

An existing RiverWare model was modified to utilize the updated WSF and SRD products developed as part of this Study. The RiverWare model was used to simulate McKay Reservoir operations using those WSFs and SRDs under historical hydrologic conditions to determine the effects to reservoir fill and flow rate downstream of the dam, in comparison to the existing operations base case (Existing sSRD). Ultimately, the objective was to determine if improvement to operations (i.e., a reduction to peak flow downstream without impact to maximum reservoir fill) can be achieved.

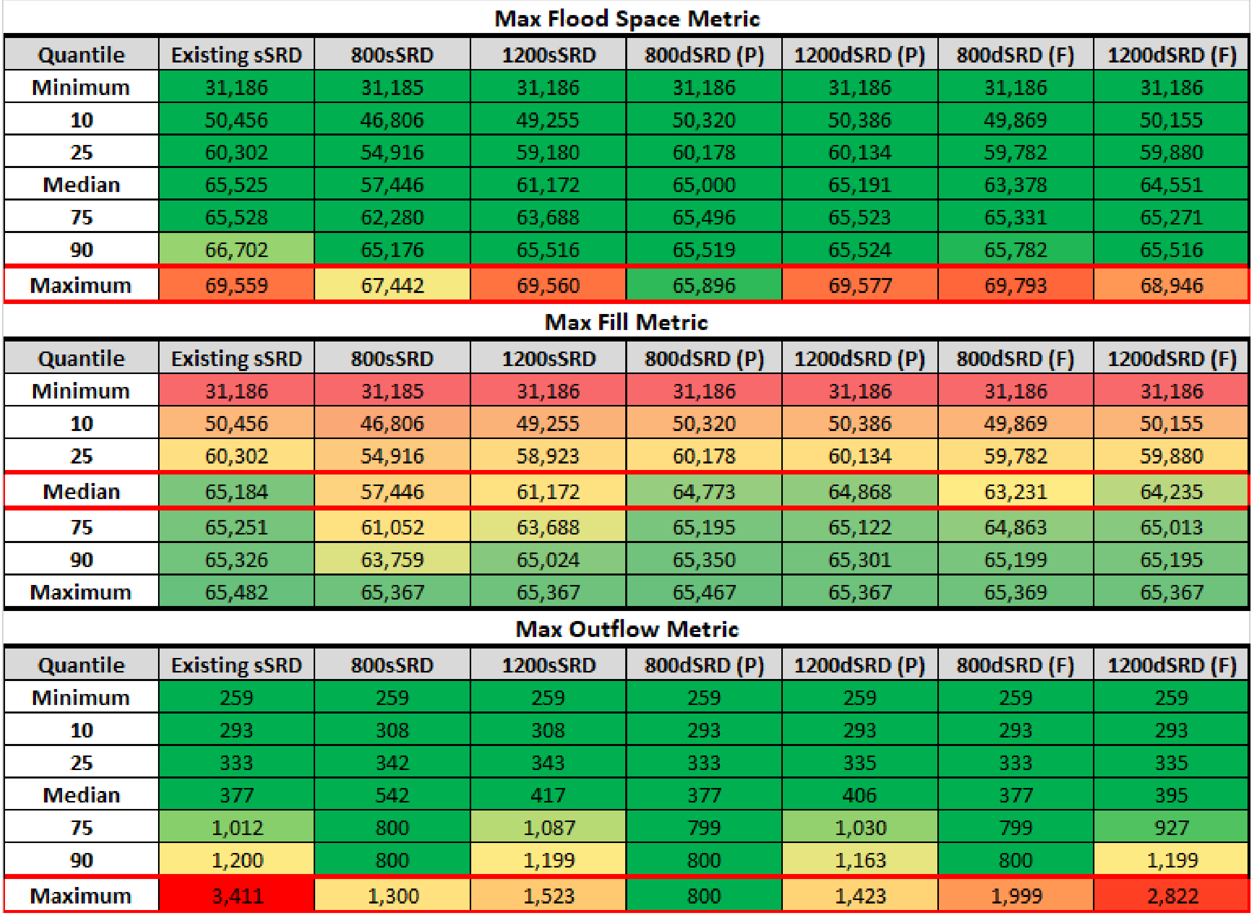
A summary of the three metrics explored in the historical hydrology modeling analysis (Max Flood Space – examines use of the 6,000 acre-feet exclusive flood space; Max Fill – examines peak storage supply; and Max

Outflow – examines peak outflow) is shown in Table ES-1. Using the historical hydrologic record, the analysis found the following:

- The maximum peak outflow (Max Outflow metric) for the 800sSRD (period peak of 1,300 cfs) and 1200sSRD (period peak of 1,523 cfs) perform better than the Existing sSRD (period peak of 3,411 cfs). However, the median reservoir fill (Max Fill metric) for the 800sSRD (57,446 acre-feet) and 1200sSRD (61,172 acre-feet) perform worse than the Existing sSRD (65,184 acre-feet).
- When run in perfect (P) forecast mode, the maximum peak outflow for the 800dSRD (P) (period peak of 800 cfs) and 1200dSRD (P) (period peak of 1,423 cfs) perform better than the Existing sSRD (period peak of 3,411 cfs) and for median reservoir fill perform similarly to the Existing sSRD (64,773 acre-feet, 64,868 acre-feet, and 65,184 acre-feet, respectively). However, this result is tempered when forecast error in the system is considered. The purpose of including the perfect forecast scenarios is to illustrate that additional benefit to operations may be possible if forecast performance can be improved in the future as technology improves. This does not imply that a perfect forecast, and therefore optimal operation, can be achieved now or in the future.
- When run in imperfect (F) forecast mode, the maximum peak outflow for the 800dSRD (F) (period peak of 1,999 cfs) and 1200dSRD (F) (period peak of 2,822 cfs) perform better than the Existing sSRD (period peak of 3,411 cfs) but worse than the 800sSRD (period peak of 1,300 cfs) and 1200sSRD (period peak of 1,523 cfs). The median reservoir fill for the 800dSRD (F) (63,231 acre-feet) and 1200dSRD (F) (64,235 acre-feet) perform worse than the Existing sSRD (65,184 acre-feet), but better than the 800sSRD (57,446 acre-feet) and 1200sSRD (61,172 acre-feet).

In other words, when forecast uncertainty is considered, the additional FRM protection downstream of McKay Reservoir provided by the newly created sSRDs and dSRDs in a rare year may come at the risk of less reservoir fill in a more normal year. However, models use assumptions and simplifications to develop repeatable logic for a suitable test environment and are not intended to exactly replicate real-time operations on a day-to-day basis. The possibility for improvement compared to the Existing sSRD remains, especially when considering additional flexibility of real-time operations compared to model simulation.

Table ES-1. Statistical tabular summary results for the seven different operational scenarios of the Lower Umatilla River Model as they relate to the three metrics



Max Flood Space Metric

Quantile	Existing sSRD	800sSRD	1200sSRD	800dSRD (P)	1200dSRD (P)	800dSRD (F)	1200dSRD (F)
Minimum	31,186	31,185	31,186	31,186	31,186	31,186	31,186
10	50,456	46,806	49,255	50,320	50,386	49,869	50,155
25	60,302	54,916	59,180	60,178	60,134	59,782	59,880
Median	65,525	57,446	61,172	65,000	65,191	63,378	64,551
75	65,528	62,280	63,688	65,496	65,523	65,331	65,271
90	66,702	65,176	65,516	65,519	65,524	65,782	65,516
Maximum	69,559	67,442	69,560	65,896	69,577	69,793	68,946

Max Fill Metric

Quantile	Existing sSRD	800sSRD	1200sSRD	800dSRD (P)	1200dSRD (P)	800dSRD (F)	1200dSRD (F)
Minimum	31,186	31,185	31,186	31,186	31,186	31,186	31,186
10	50,456	46,806	49,255	50,320	50,386	49,869	50,155
25	60,302	54,916	58,923	60,178	60,134	59,782	59,880
Median	65,184	57,446	61,172	64,773	64,868	63,231	64,235
75	65,251	61,052	63,688	65,195	65,122	64,863	65,013
90	65,326	63,759	65,024	65,350	65,301	65,199	65,195
Maximum	65,482	65,367	65,367	65,467	65,367	65,369	65,367

Max Outflow Metric

Quantile	Existing sSRD	800sSRD	1200sSRD	800dSRD (P)	1200dSRD (P)	800dSRD (F)	1200dSRD (F)
Minimum	259	259	259	259	259	259	259
10	293	308	308	293	293	293	293
25	333	342	343	333	335	333	335
Median	377	542	417	377	406	377	395
75	1,012	800	1,087	799	1,030	799	927
90	1,200	800	1,199	800	1,163	800	1,199
Maximum	3,411	1,300	1,523	800	1,423	1,999	2,822

Modeling Analysis – Climate Change Hydrology

Potential future climate change flows for the WY2030-WY2059 (i.e., 2040s) and the WY2060-WY2089 (i.e., 2070s) periods were selected from River Management Joint Operating Committee (RMJOC-II) projections following the standardized techniques used in a prior study (Reclamation 2020b) to attempt to bracket the likely range of hydrologic variability. For both the 2040s and 2070s, a general pattern shift to earlier timing and overall increased water supply is seen in the median condition. The larger 90th percentile and maximum flow events showed the potential for not only earlier timing but also higher magnitude inflows during the winter and early spring months. Potential future climate change flows in some cases fall outside the range of historically observed inflow, both in earlier timing and higher magnitude.

The purpose of this effort was to stress test the existing and newly developed SRD products under perfect forecast simulations to determine how well they may or may not perform into the future independent of potential future forecast error. This was accomplished by comparing simulations of each scenario to the historical hydrology simulation results. Future forecast uncertainty was not analyzed as part of this Study and would result in additional variability in the performance of the dSRDs under climate change hydrology.

Under perfect forecast mode, all scenarios, including the Existing sSRD, may be able to maintain flows downstream to less than the historical 1,200 cfs safe channel capacity more than 90 percent of the time. However, in extreme cases due to climate change hydrology falling outside of the historically observed range, climate change hydrology may result in higher outflows from McKay Reservoir than under historical hydrology when comparing historical and climate change hydrology runs for the same SRD. In the maximum case, the newly developed sSRDs and dSRDs generally result in a lower range of potential outflows than the Existing sSRD; however, for the dSRDs, this result would likely be tempered when forecast uncertainty is considered and would need further study. Like the historical hydrology analysis, the climate change analysis showed the benefit of lower outflows during extreme events may come at the cost of less fill of the reservoir in the median case.

SRDs created for this exercise were developed based on historical hydrology and therefore do not incorporate potential future extreme events that may need additional space reservation. Future study to develop SRDs based on potential climate change flows may provide protection against future extreme events, but this would likely exacerbate the effects to reservoir fill seen in the historical hydrology modeling.

Summary

This Study found that there appears to be opportunity to provide additional FRM protection downstream of McKay Dam through use of updated WSF and SRD products. However, the analysis showed this improvement may come at the risk of less reservoir refill. The possibility for improvement compared to the Existing sSRD remains, especially when considering additional flexibility of real-time operations compared to model simulation. No formal adoption of a single updated WSF or SRD product is being recommended as part of this study. Rather, the WSF and SRD products developed as part of this study will all provide additional tools to help water managers work within the latitude provided in the Existing sSRD qualifier that states “more space will be provided if snow pack so indicates,” while the Study itself provides for a better understanding of the trade-offs between peak flows downstream of McKay Dam and fill of McKay Reservoir.

Future studies may provide additional tools for water managers in the basin. This research may include:

- Investigating additional improvements to WSF products, such as:
    - Improvements in weather forecasting, both in terms of rainfall amount prediction and longer lead time
    - Determining locations for additional SNOwpack TELemetry Network (SNOTEL) sites in the basin to capture lower elevation snowpack conditions, and use of those sites in future iterations of WSF updates
    - Utilizing remote sensing datasets (such as snow water equivalent, soil moisture, etc.) in future iterations of WSF updates
- Additional climate change hydrology analysis, such as:
    - Developing SRDs based on potential climate change flows
    - Examining WSF uncertainty under future climate change hydrology conditions

    - Modeling analysis using this information to analyze potential effects to flows downstream of McKay Dam and fill of McKay Reservoir under imperfect forecast mode
- Investigating infrastructure flexibilities in the managed system, such as:
    - Examining downstream channel capacity flexibilities to provide for additional operational flexibility

If WSFs can continue to improve in the future with new technology, the full benefit of the updated dSRDs may eventually be realized. However, if water supply forecasting becomes more difficult in the future, or if the hydrologic regime changes such that the past is no longer a good indicator of the future, the updated sSRDs and dSRDs as currently assessed may need to be reviewed.

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1. Introduction

This report details a study of potential modifications to existing operational tools to help address the impact that increased water supply variability in the McKay Creek basin has on McKay Reservoir operations during the spring reservoir fill season. This report begins with a discussion of the background, purpose, and description of the study. Next, it provides a description of the watershed and project facilities. The report then provides descriptions of potential modifications to existing operational tools, computer simulations of the modifications, and simulation results, finishing with a discussion of conclusions from the Study.

1.1. Study Background and Purpose

In water year (WY) 2019, the Umatilla River basin experienced a major spring runoff event (Reclamation 2019a). The river flows upstream of McKay Reservoir during the event were determined to be between a 20- and 50-year flood event (i.e., having between a 1-in-20 (5 percent) and a 1-in-50 (2 percent) chance of being equaled or exceeded in any given year).[1] The operation of the Bureau of Reclamation's (Reclamation) McKay Reservoir helped to moderate the event and reduce the severity of the flood damages downstream. However, even with more space provided than identified by the existing space reservation diagram (Existing sSRD), the high inflow resulted in flows downstream of the reservoir exceeding the 1,200 cubic feet per second (cfs) safe channel capacity. The WY2019 event prompted Reclamation to conduct this McKay Reservoir Operations Pilot Study (Study) to explore potential modifications to the water supply forecast (WSF) and space reservation diagram (SRD) that help inform operations of McKay Reservoir in order to improve the reservoir operator's ability to manage future flood events while maintaining balance of meeting the other competing authorized purposes (e.g., water supply) provided by the reservoir.

This Study was selected to contribute to Reclamation's 2021 Reservoir Operations Pilot initiative. This initiative is part of the WaterSMART (Sustain and Manage America's Resources for Tomorrow) Basin Study Program and uses modeling and forecasting tools to identify ways to increase flexibility in reservoir operations to support optimal water management.

1.2. Pilot Study Description

This Study focuses on the McKay Creek basin, which is a sub-basin of the larger Umatilla River basin located in northeastern Oregon (Figure 1). The McKay Creek watershed is largely a transitional basin fed by a combination of rain and snow. McKay Creek can experience dramatic changes in annual runoff from one year to the next and is subject to difficult-to-forecast precipitation events in the winter and spring. If there are dramatic changes with climatic variability in the future, McKay Creek hydrology may be susceptible to a

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[1] Based on calculations by Reclamation using the HEC Bulletin-17 process with McKay Creek near Pilot Rock, Oregon peak-flow data from the Oregon Water Resources Department.

shift in precipitation from less snow to more rain, causing earlier peak flow timing, lower summer base flows, and flashier, higher peak events.

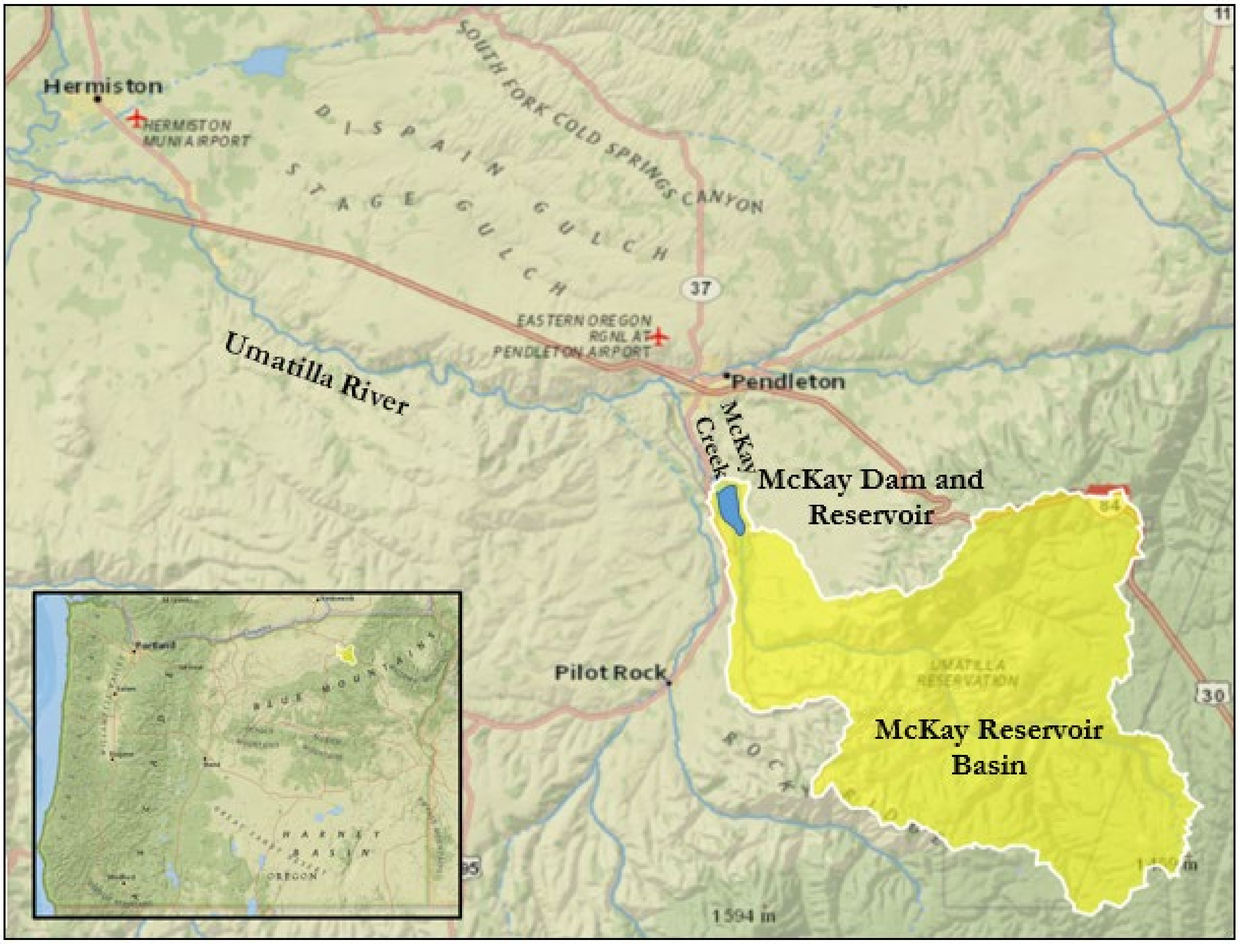

Figure 1. The Umatilla River basin, with the McKay Creek sub-basin shown in yellow (Reclamation 2019a)

The Study consisted of:

- Development of new WSF equations
- WSF hindcasting and performance analysis
- Development of updated SRDs
- Computer simulation of alternative reservoir operation scenarios
- Future climatic variability hydrologic modeling and analysis

1.2.1. WSF and Hindcasts

Accurate and timely prediction of water supply volume provides water managers with critical information necessary for planning effective reservoir operation strategies to maximize benefits for a wide variety of purposes. The transitional nature of the McKay Reservoir basin makes water supply forecasting difficult because: 1) conditions on the ground are less predictive, and 2) unknown future rain events are more controlling of future runoff compared to purely snow dominated basins. This effort sought to develop new WSF products that supplement the WSF products currently used to inform operations.

1.2.2. SRDs

Many of Reclamation's facilities utilize SRDs to help guide water managers in regulating the rate at which a reservoir is filled to balance maximizing water supply with providing flood risk management (FRM) benefits downstream. McKay Reservoir is no exception and water managers have historically utilized a static SRD (Existing sSRD) which identifies a fixed minimum space reservation for each day of the fill season. The WY2019 high flow event highlighted the opportunity to re-examine the Existing sSRD through this Reservoir Operations Pilot Study. This effort sought to determine if updates to the SRD can provide additional FRM benefit downstream of the dam without impacting reservoir fill, while accounting for additional years of observed historical hydrology.

1.2.3. Reservoir Operations Modeling

Computer modeling can be used to understand the potential effects of incorporating new WSF and SRD operating criteria in the basin. For this effort, simulations were developed to replicate current operating criteria. The model was then adjusted to test potential changes in operations by inclusion of the new WSF and SRD products. Review of model output allows trends and effects to be analyzed based on key metrics such as reservoir storage and outflow. This provides an opportunity to understand potential operational changes (i.e., flexibilities) before implementing the change.

1.2.4. Future Climate Flows

When considering operational changes, it is important to not only consider historical observations of basin conditions, but also to attempt to understand how the hydrology may behave in the future. Projections of future hydrology comes with limitations and uncertainty; however, ranges of potential effects can be developed to help provide insight into future operations. This effort focused on the selection of potential future climate change hydrology projections in the McKay Reservoir basin, and the use of that hydrology in complimentary computer simulations to "stress test" the newly developed SRD products to determine how well they may or may not perform into the future.

1.3. Collaboration

The National Weather Service Northwest River Forecast Center (NWRFC) provided hindcasts from their WSF products to allow comparison of forecast performance. These are discussed further in Section 3.

2. Location and Background

2.1. Watershed Description

McKay Reservoir is located on McKay Creek approximately 6 miles south of Pendleton, Oregon, and has a drainage area of 186 square miles with elevations ranging from 1,200 feet at the dam to 4,700 feet along the southeastern divide.

Below 2,000 feet elevation, the basin has gently rolling slopes and land use is predominately agricultural. Between 2,000 feet and 4,000 feet elevation, the basin tends to be "V" shaped with steep side slopes and numerous rock outcrops. Vegetative cover in the bottom of the draws is comprised of scrub brush and some deciduous trees. The steep side slopes are open with native grass cover. Conifer trees begin to appear above the confluence of the North and South Forks of McKay Creek. A transition from the steep slopes to a bench occurs at an elevation between 3,500 and 4,000 feet, depending on location. The area above 4,000 feet has gentle slopes and is heavily forested with very little underbrush.

McKay Creek joins the Umatilla River approximately 6.2 river miles downstream of McKay Dam. There are many small farms and homes in the valley downstream of the dam. Much of the area is pasture or meadow land. Below McKay Dam, the safe channel capacity of McKay Creek has historically been 1,200 cfs. However, there has been considerable development of homesites, particularly at the lower end of the creek near Pendleton, resulting in the channel and floodplain capacity being constrained.

Watershed characteristics of the basin are listed below.

- Watershed – McKay Reservoir
- Watershed area – 186 square miles
- Median basin elevation – 3,200 feet
- Minimum basin elevation – 1,200 feet
- Maximum basin elevation – 4,700 feet
- Mean annual water year runoff, 1991-2020 – 80,000 acre-feet

Figure 2 shows the McKay Creek basin "hypsometric curve."[2] A hypsometric curve relates basin area to basin elevation to provide better understanding of the topography of the basin. For example, 50 percent of the basin lies below approximate elevation 3,200 feet.

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[2] The hypsometric curve was generated based on a 1/3rd arc-second Digital Elevation Model (approximately 10-meter) resolution. The elevation model used for this effort was originally published by the USGS and stored within Reclamation's geodatabase. Geoprocessing using the ESRI suite of GIS tools were then used to develop the curve by taking the area within the drainage basin and binning grid cells by their respective elevation bands.

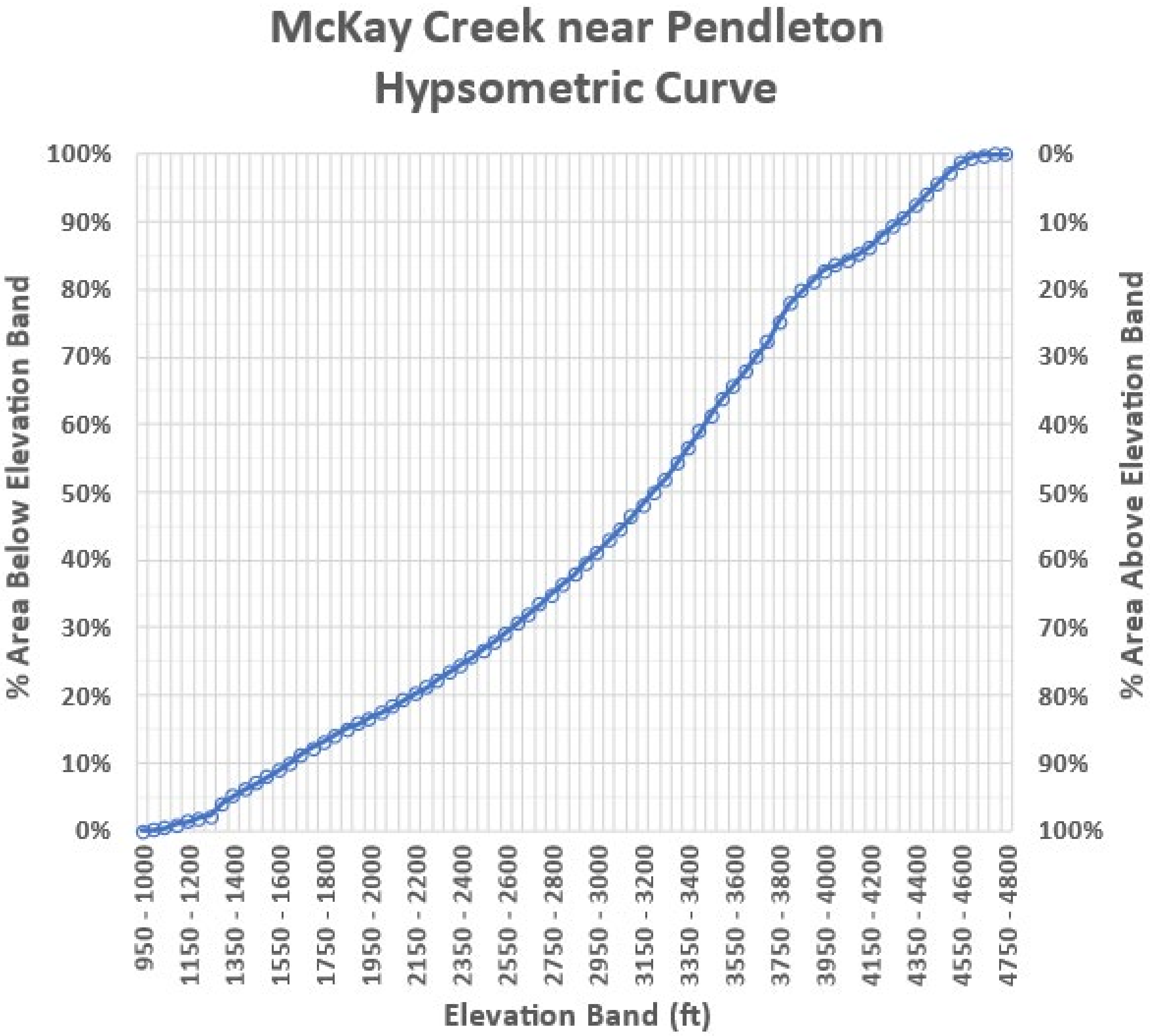


Figure 2. McKay Creek near Pendleton, Oregon basin hypsometric curve showing the relationship between area and elevation in the watershed

Due to its low elevation, the McKay Creek basin is highly susceptible to rain events that can be exacerbated by background snowmelt, resulting in flashy runoff. This type of event has historically occurred from November through June. Peak snowpack in the basin typically occurs in early March. Peak daily unregulated McKay Reservoir inflow (MCKO QU) data is available starting in WY1974 through WY2022 (at the time of this Study) and has ranged from 340 cfs in WY1988 to slightly more than 3,400 cfs in WY1975 and WY2019. Figure 3 shows the precipitation, snowpack, temperature, and runoff characteristics of the basin at representative sites for the 30-year period of WY1991-WY2020.

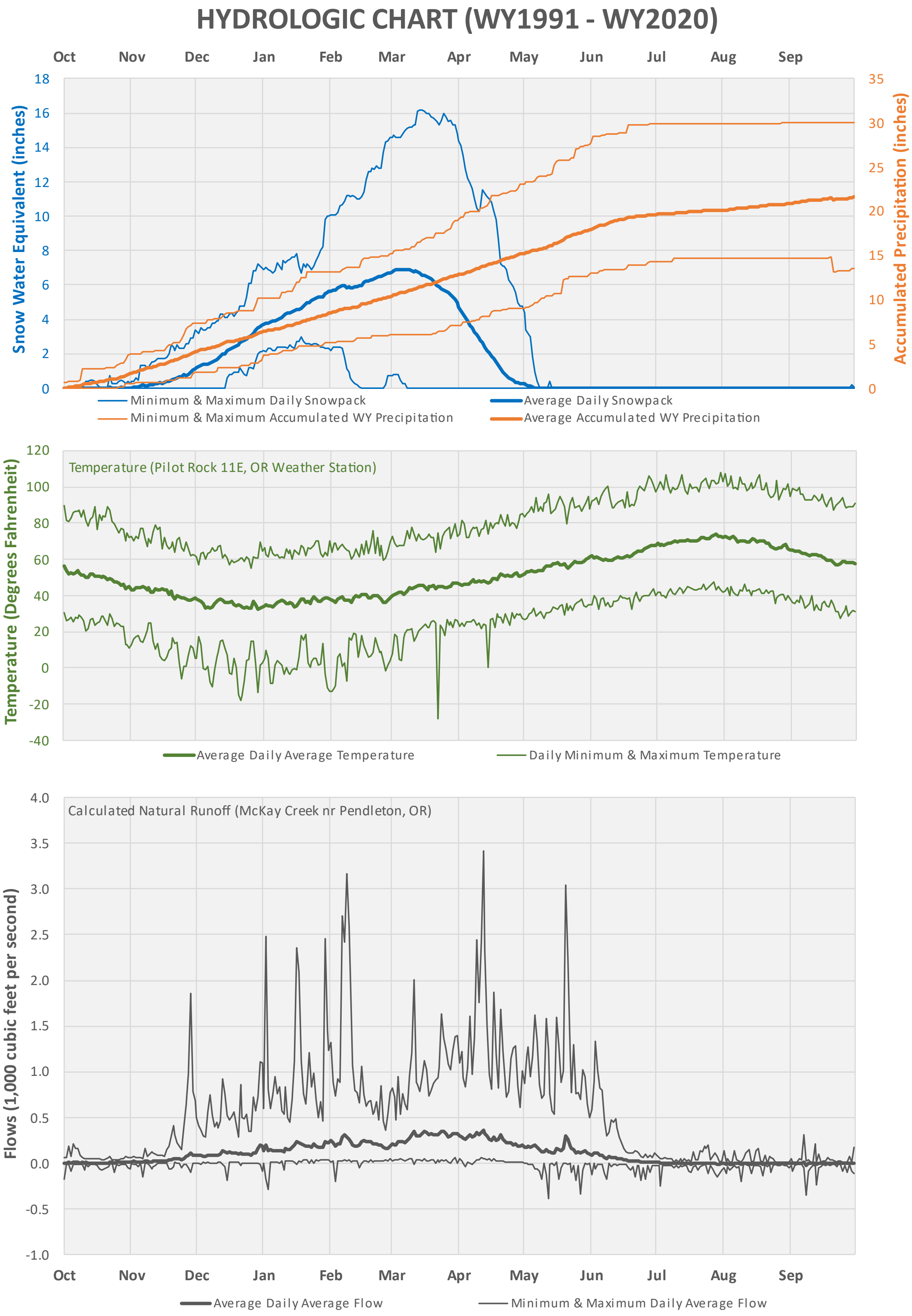


Figure 3. McKay Reservoir basin hydrologic chart

Annual WY MCKO QU data is available from WY1928 through WY2022 and has ranged from 20 thousand acre-feet (kaf) in WY1977 to 175 kaf in WY2011, with a WY1991-WY2020 median of approximately 77 kaf. Figure 4 shows an exceedance plot of historical annual WY MCKO QU runoff volume for the period of record (WY1928-WY2022) and for the 30-year periods of WY1981-WY2010 and WY1991-WY2020, respectively.

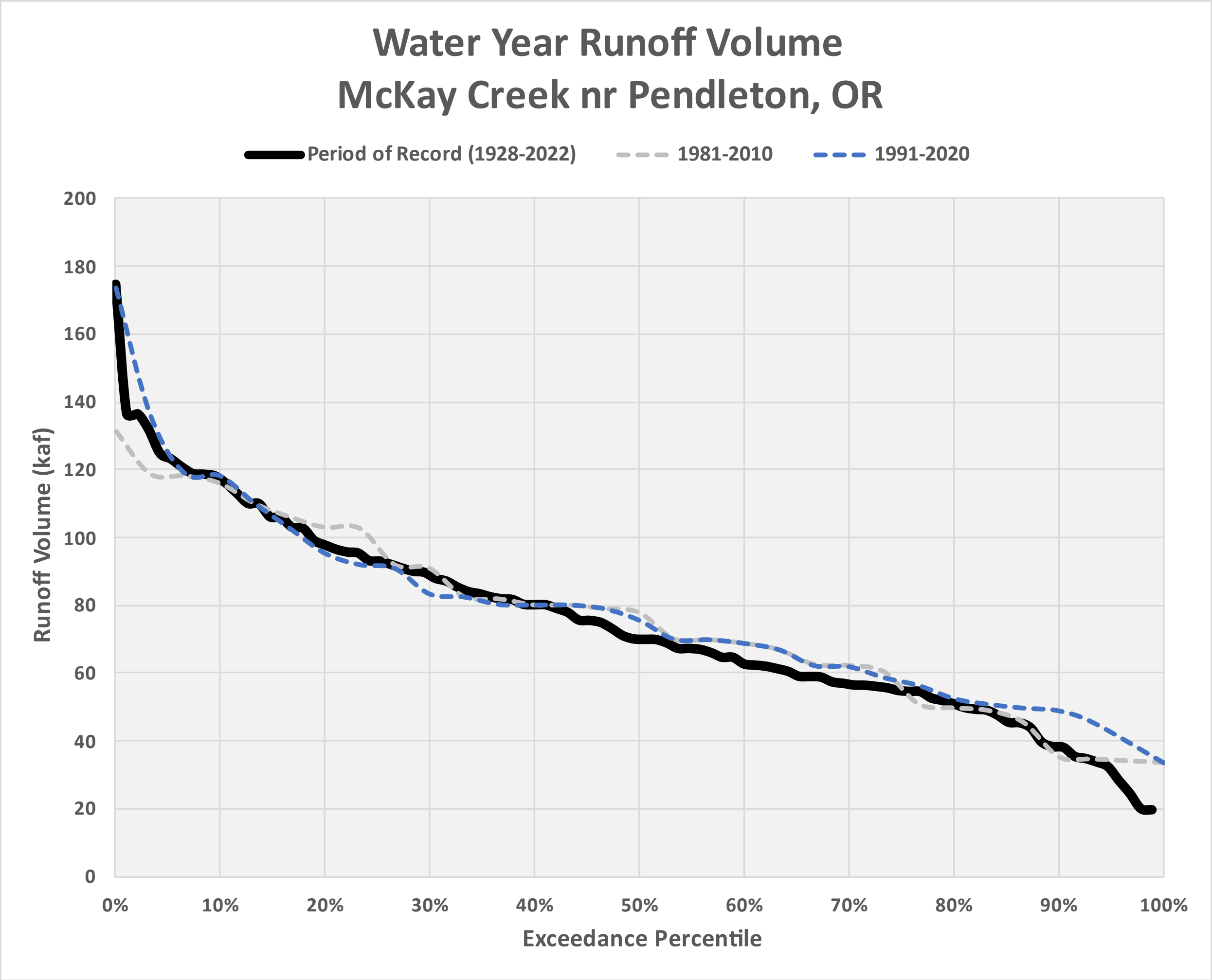


Figure 4. Annual WY MCKO QU runoff volume exceedance plot

2.2. McKay Dam and Reservoir Description

McKay Dam is an earthfill structure. The dam is 165 feet high with a reinforced concrete upstream face. The reservoir has a total capacity of 71,534 acre-feet at elevation 1,322.0 feet. The total capacity is divided between active storage of 65,534 acre-feet at normal full pool elevation 1,317.16 feet, and an exclusive flood control space of 6,000 acre-feet between elevations 1,317.16 to 1,322.0 feet. The exclusive flood control space is generally only used during extreme events to avoid exceeding the safe channel capacity downstream to the extent possible. The outlet works capacity is approximately 1,200 cfs while the spillway capacity is approximately 27,000 cfs. The greatest instantaneous release from the dam was 3,620 cfs and occurred during a flood event on May 20, 1991.

McKay Dam was constructed by Reclamation during the period 1923-1927 for the single purpose of irrigation. Though constructed for irrigation, incidental benefits for flood control, recreation, and fish and wildlife were realized from the reservoir. Activities were initiated in the mid-1980s under the Umatilla Basin Project to restore instream flows for anadromous fish and to allow established irrigation to continue. These activities resulted in: Umatilla River channel modifications; construction of fish ladders, fish traps and fish screens; and the construction of water exchange facilities (Phase I and Phase II) to deliver partial irrigation replacement water from the Columbia River. The reservoir is part of the McKay National Wildlife Refuge area which is currently jointly managed by Reclamation and the U.S. Fish and Wildlife Service for habitat for a variety of wildlife, including osprey, bald eagles and an abundance of waterfowl.

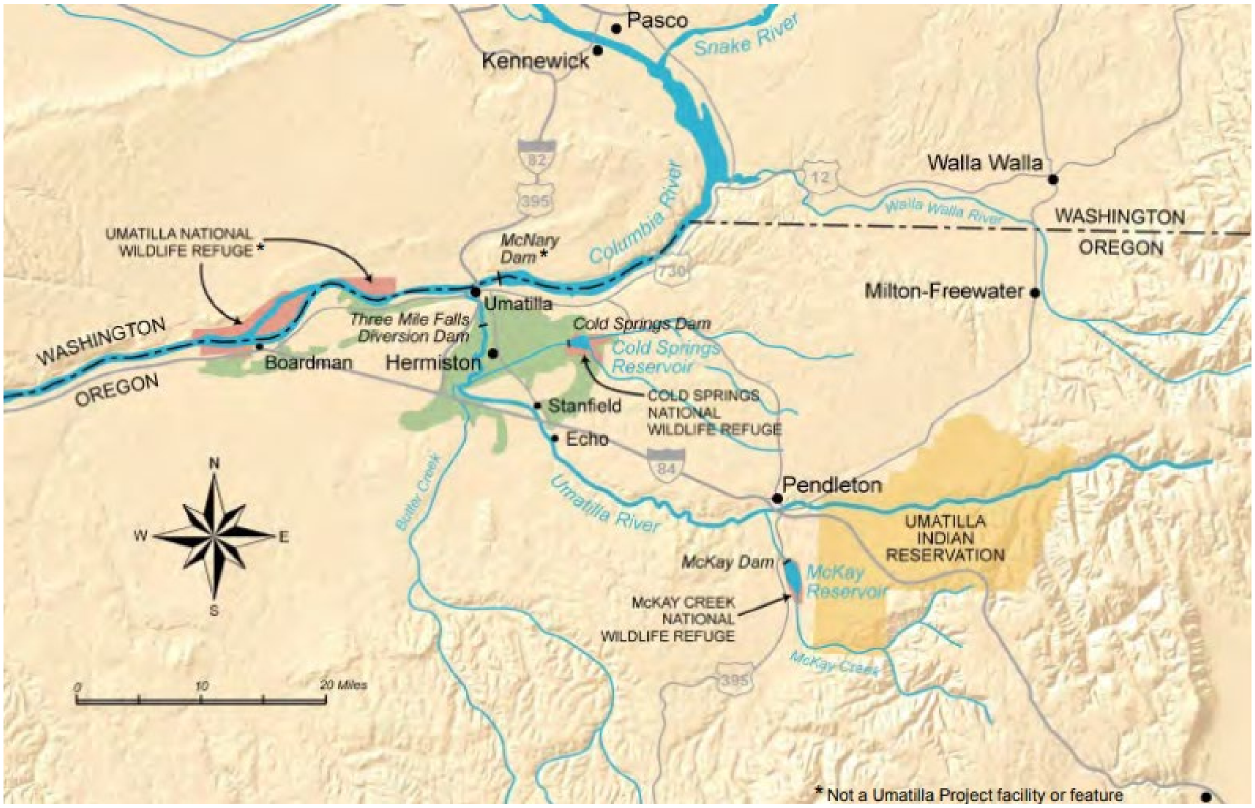


Figure 5. Umatilla Basin Project overview map (Reclamation 2023a)

A flooding event in 1958, with a daily average release of 2,520 cfs, caused extensive damage downstream of the dam, prompting Reclamation to increase the level of flood protection by informally reserving 1,500 acre-feet of storage space for flood control. Later, the space reservation was increased to 3,000 acre-feet, and then increased again in 1972 to its current level of 6,000 acre-feet.

Congress re-authorized the project on March 11, 1976 (PL 94-228), including flood control, recreation, and fish and wildlife as authorized project functions, and funded modification of the spillway to safely pass the probable maximum flood (PMF) without overtopping the dam embankment. In the Act, storage capacity for flood control was authorized as follows:

> *Sec. 303. Not to exceed six thousand acre-feet of storage capacity in McKay Reservoir shall be allocated for the primary purpose of retaining and regulating flood flows.*

3. Water Supply Forecasts

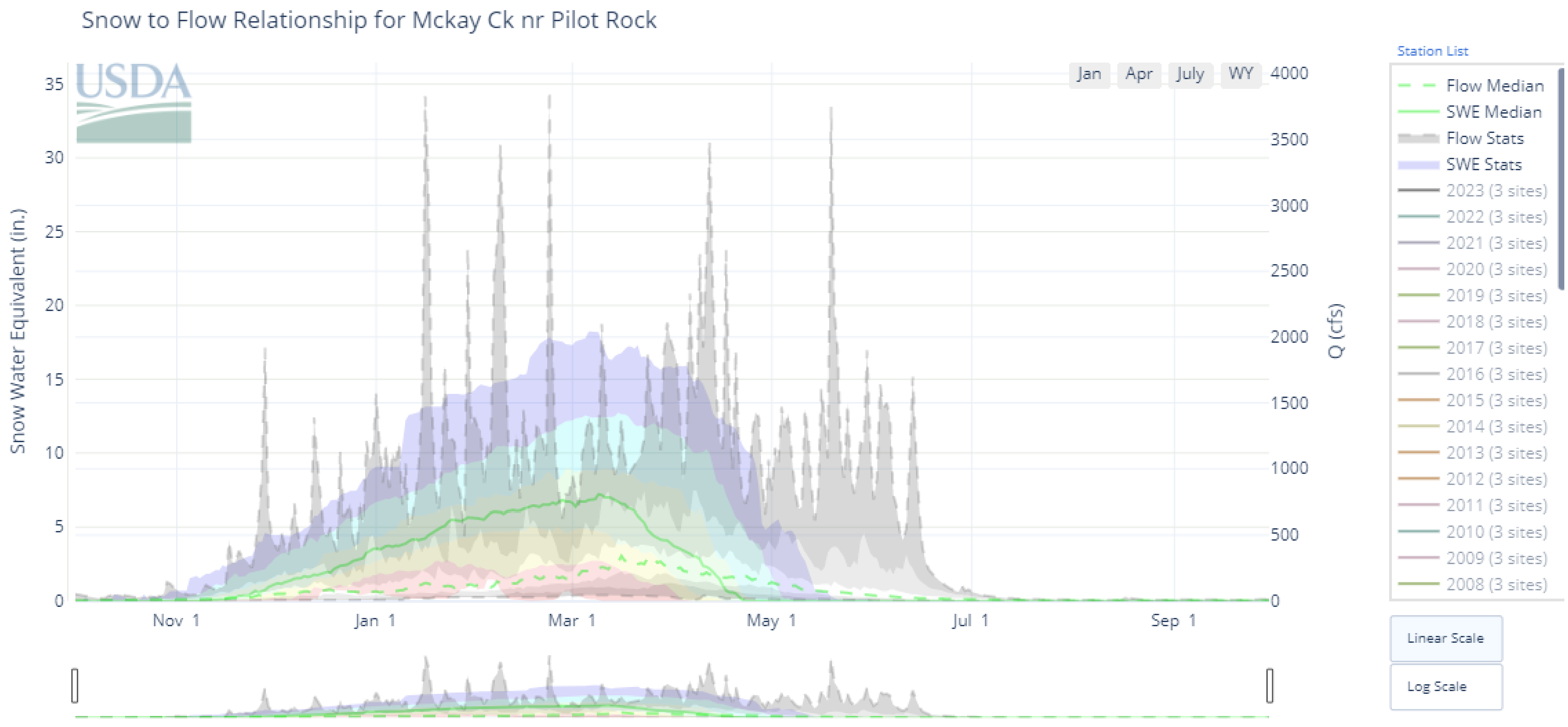
WSFs are a prediction of the volume that will flow past a point on a stream during a specified season, generally during the spring runoff (NRCS 2023a). Accurate and timely prediction of the water supply provides water managers with critical information necessary for planning effective reservoir operation strategies to maximize benefits for a wide variety of purposes. WSF models can use current snowpack and other basin conditions, along with potential future weather conditions, as inputs to predict a range of potential future water supply volumes. WSFs are made with the best available data at the time, but uncertainty in future weather conditions plays a large role in determining the water supply that is ultimately realized.

As described by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS), WSFs rely on the fact that the spring runoff in the Western United States is generally driven by the melting of mountain snowpack. For rain dominated basins or rain/snow transitional basins such as McKay, forecasting becomes more difficult as conditions on the ground (i.e., snowpack) become less predictive of future runoff. In this case, future rain events (or lack thereof) become a major driver of future runoff; future rain events are currently difficult to predict with sufficient accuracy and lead time.

WSFs are produced both internally by Reclamation and externally by numerous federal and private entities. This Study focuses on WSFs of McKay Reservoir inflow for the date of forecast through June 30 period. WSFs for McKay Reservoir inflow are produced by Reclamation, NWRFC, and the NRCS. This Study primarily uses the Reclamation and NWRFC forecasts as hindcasts were not available from NRCS at the time of this Study.

3.1. General

For snow dominated basins, good relationships between on the ground snowpack conditions and future runoff can be developed. However, the McKay Basin does not exhibit the characteristics of a typical snowmelt dominant basin (NRCS 2022). Figure 6 depicts the “snow to flow” relationship for the McKay Creek near Pilot Rock gage (NRCS 2023b), showing a flashy pattern with high peak inflow events often occurring throughout the November through June period caused by rain or rain-on-snow events. During the early summer, even after the snowpack has melted, high flow events may still occur with rain events in the basin. With this type of relationship, snowpack alone does not drive all high runoff events and rain is a major contributing factor.



Snow to Flow Relationship for Mckay Ck nr Pilot Rock

* # of sites does not meet basin threshold, data from this year will not be used in calculation of statistics.
Updated: Monday, Nov 07, 2022 @ 12 PM CST

Snow Statistics Percentile Classes					Snow	Flow Statistics Percentile Classes					Flow
🟥	🟨	🟩	🟦	🟪	—	▨	▨	⬜	▨	▨	- - -
Min - 10%	10% - 30%	30% - 70 %	70% - 90%	90% - Max	in.	Min - 10%	10% - 30%	30% - 70 %	70% - 90%	90% - Max	cfs
Much Below Median	Below Median	Near Median	Above Median	Much Above Median		Much Below Median	Below Median	Near Median	Above Median	Much Above Median	

Figure 6. NRCS “snow to flow” relationship for McKay Creek near Pilot Rock (NRCS 2023b). Snow water equivalent (SWE) statistics are shown in colored shading, while flow statistics are shown in gray shading.

Figure 7 shows the relationship between the March 1 Bowman Springs SNOwpack TELemetry Network (SNOTEL) snow water equivalent (SWE) value vs. March-June runoff volume at the McKay Creek near Pilot Rock gage. A weak correlation is present with an r^2 value of less than 0.18. With this type of relationship, a highly skilled WSF of future runoff cannot be made based on current basin conditions and is highly reliant on future weather conditions.

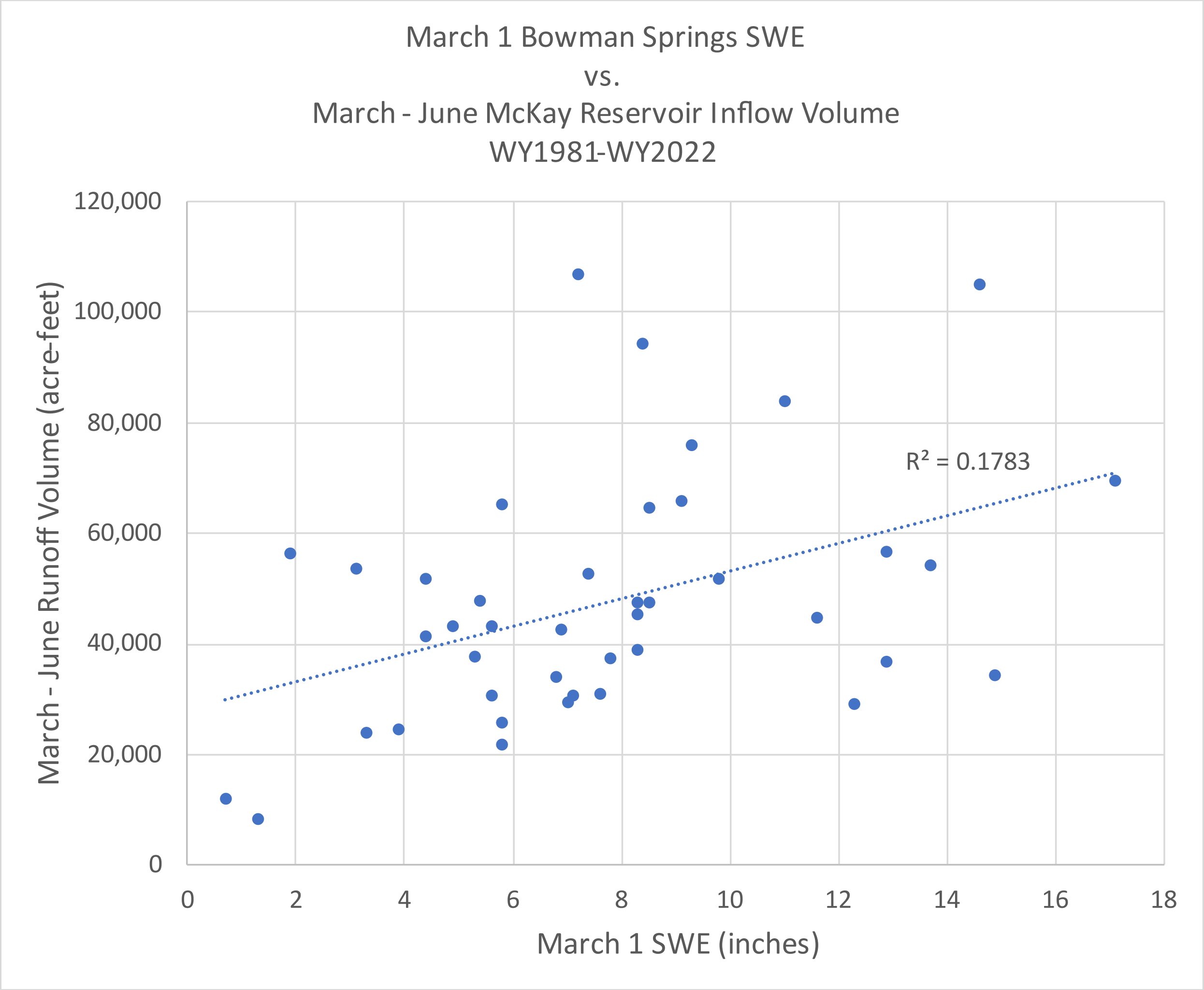


Figure 7. March 1 Bowman Springs SNOTEL SWE value vs. March-June McKay Reservoir inflow volume

Further complicating water supply forecasting in the basin, only around 20 percent of the basin is represented by existing SNOTEL sites; see Figure 8. It is common for snow to be present down to McKay Reservoir at elevation 1,300 feet. Water managers currently must rely on National Aeronautics and Space Administration (NASA) MODIS satellite imagery (NASA 2023) and other tools such as the National Oceanic and Atmospheric Administration's (NOAA) National Operational Hydrologic Remote Sensing Center (NOHRSC) modeled SWE data (NOAA 2023) to attempt to understand the contribution low elevation snow may have on runoff. Incorporation of additional low elevation SNOTEL sites may provide additional forecasting benefit in the future.

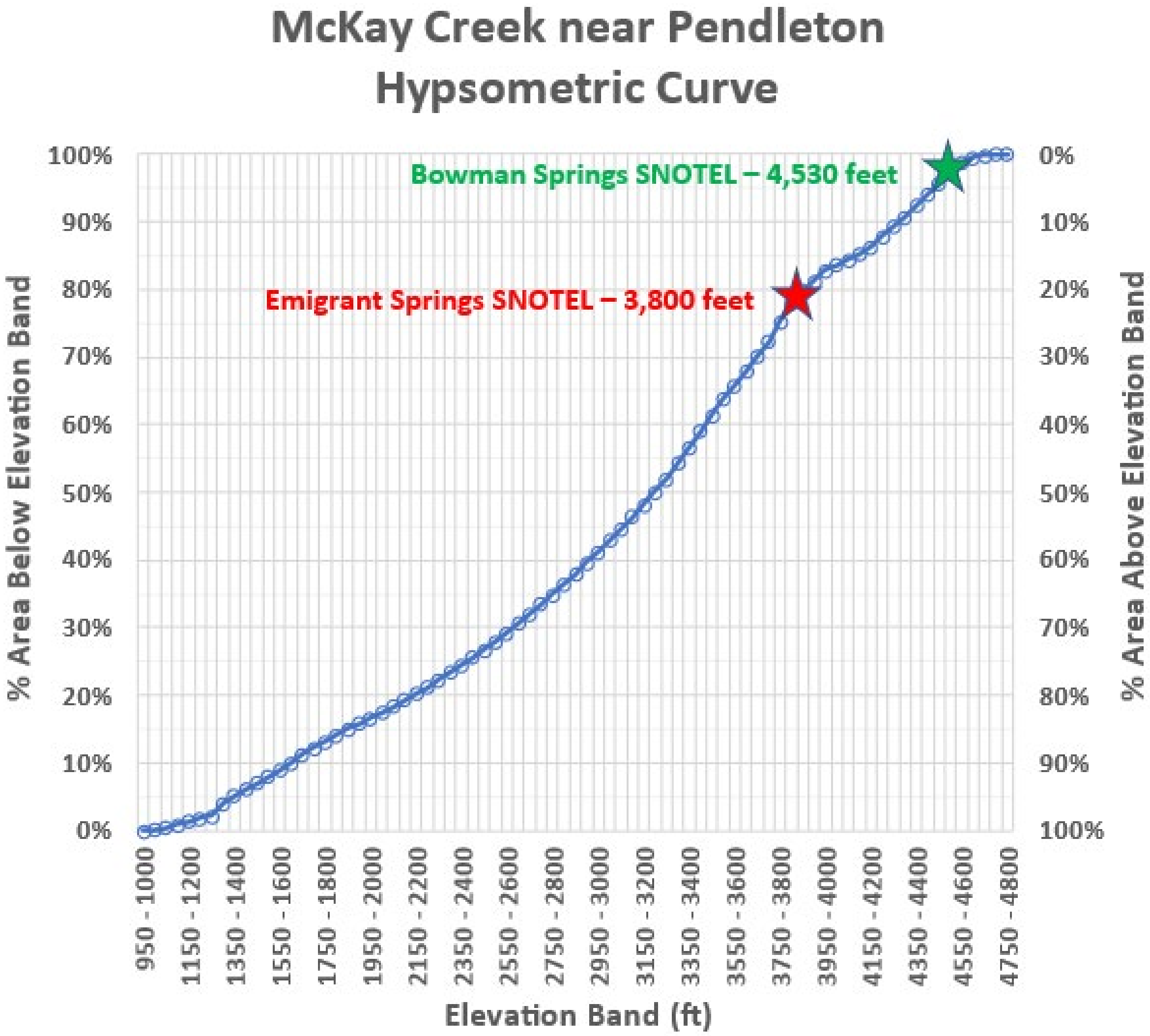


Figure 8. McKay Creek near Pendleton, Oregon basin hypsometric curve showing the elevation of the Bowman Springs and Emigrant Springs SNOTEL sites in relation to the basin elevation distribution

These examples illustrate the difficulty in forecasting runoff in the McKay Basin. Despite these challenges, an objective of this Study was to attempt to develop WSF products that perform better than existing WSF products in the basin. The following sections describe the existing WSF products that are available in the basin, provide a description of the updated WSF products, and analyze the performance of the WSFs.

3.2. Existing WSFs

3.2.1. Reclamation

3.2.1.1. Multiple Linear Regression (MLR)

Reclamation's Columbia-Pacific Northwest (CPN) Region has historically used a Multiple Linear Regression (MLR) statistical method to forecast seasonal water supply in the McKay basin. The MLR WSF uses a single equation that is applicable to the entire forecast season. The equation is used to forecast a runoff season volume for the period October through June. The remaining residual (i.e., date through June) runoff is then calculated by subtracting the runoff that has already occurred from the forecasted runoff season volume.

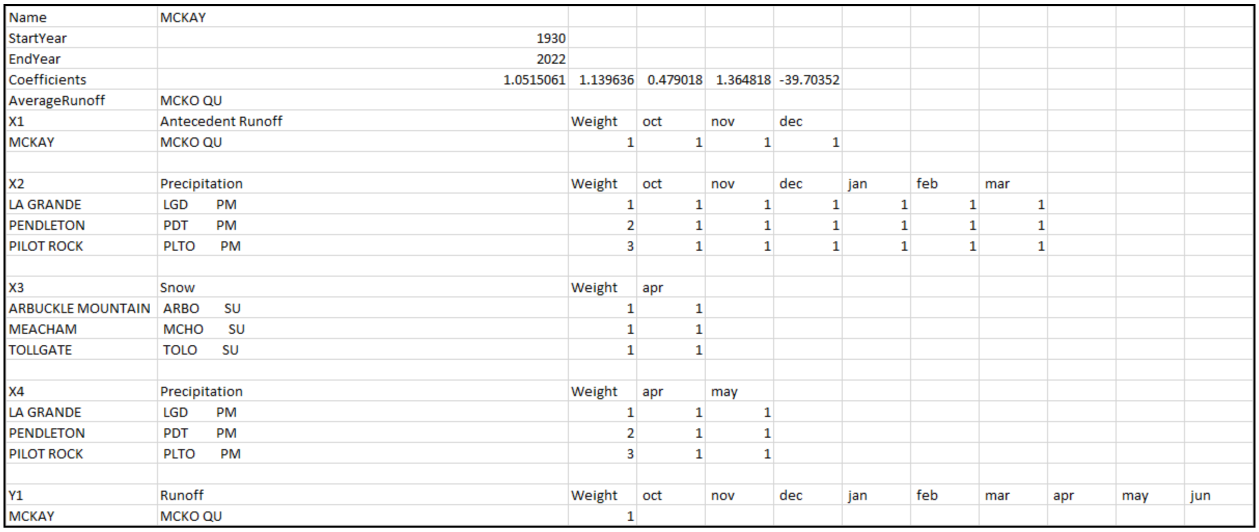
The procedure uses a series of four indexed and weighted variables regressed using MLR to develop the water supply forecast equation, which takes the following form:

$$Y = C_1*X_1 + C_2*X_2 + C_3*X_3 + C_4*X_4 + C_0$$

Where:

- Y = Forecasted October through June Runoff Season Volume in kaf
- C_1-C_4 = Regression Coefficients – annually, CPN Region staff append the period of record with data from the latest completed water year and the regression coefficients for each variable are updated
- X_1 = Antecedent Runoff Index (kaf) – this index utilizes MCKO QU data for the fall period and serves as an indicator of soil moisture conditions leading into the following runoff season
- X_2 = Fall through Early Spring Precipitation Index (inches) – this index consists of the LA GRANDE, OR (LGD PM) and Pendleton E OR RGNL AP, OR (PDT PM) National Weather Service co-op precipitation stations, and the PILOT ROCK 11E (PLTO PM) Agrimet precipitation station which are in the valleys and lower elevations and represents the low-elevation conditions prior to the spring runoff
- X_3 = April 1 Snow Water Equivalent (SWE) Index (inches) – this index consists of the Arbuckle Mountain (ARBO SU), Meacham (MCHO SU), and Tollgate (TOLO SU) sites which are calculated by Reclamation through a correlation with real-time SWE data from the NRCS Arbuckle SNOTEL site. There is no documentation to describe the process used to develop this relationship. This index represents the peak mid- to high-elevation snowpack.
- X_4 = Spring Precipitation Index (inches) – this index consists of the LGD PM, PDT PM, and PLTO PM precipitation stations and represents the springtime weather conditions in the basin and their overall contribution to runoff efficiency and volume
- C_0 = Intercept

The McKay Reservoir MLR WSF equation as of WY2023 is shown in Figure 9.

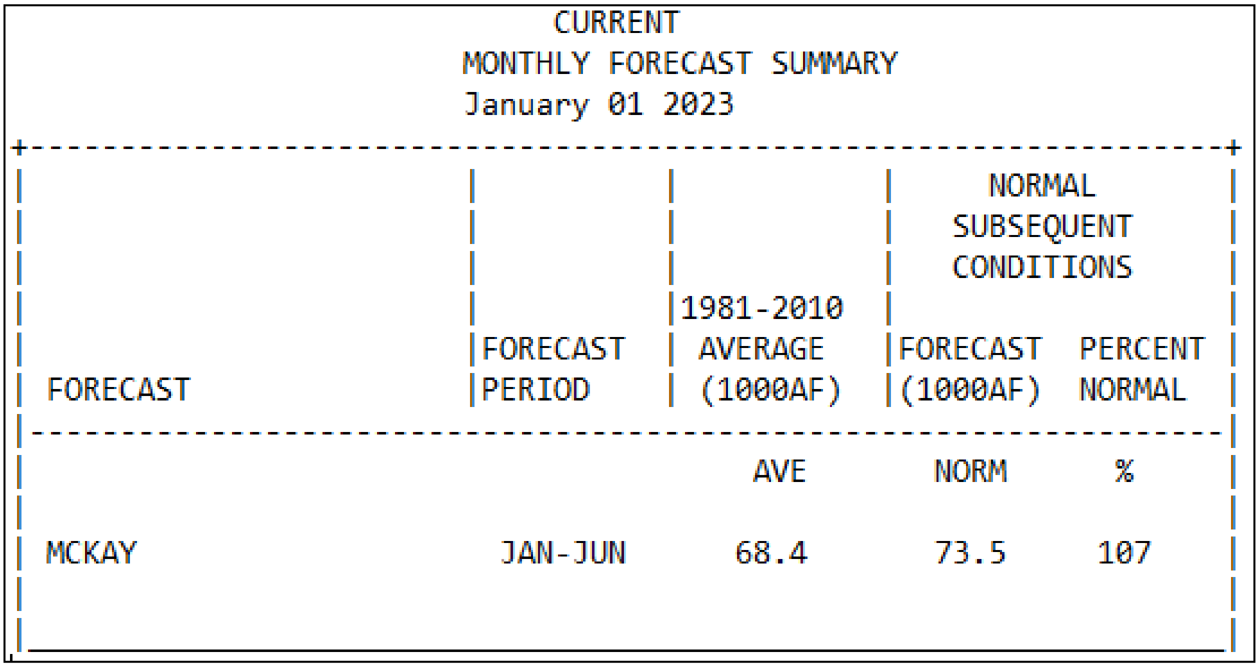


Name	MCKAY										
StartYear	1930										
EndYear	2022										
Coefficients	1.0515061	1.139636	0.479018	1.364818	-39.70352						
AverageRunoff	MCKO QU										
X1	Antecedent Runoff	Weight	oct	nov	dec						
MCKAY	MCKO QU	1	1	1	1						
X2	Precipitation	Weight	oct	nov	dec	jan	feb	mar			
LA GRANDE	LGD PM	1	1	1	1	1	1	1			
PENDLETON	PDT PM	2	1	1	1	1	1	1			
PILOT ROCK	PLTO PM	3	1	1	1	1	1	1			
X3	Snow	Weight	apr								
ARBUCKLE MOUNTAIN	ARBO SU	1	1								
MEACHAM	MCHO SU	1	1								
TOLLGATE	TOLO SU	1	1								
X4	Precipitation	Weight	apr	may							
LA GRANDE	LGD PM	1	1	1							
PENDLETON	PDT PM	2	1	1							
PILOT ROCK	PLTO PM	3	1	1							
Y1	Runoff	Weight	oct	nov	dec	jan	feb	mar	apr	may	jun
MCKAY	MCKO QU	1									

Figure 9. McKay Reservoir MLR WSF equation as of WY2023

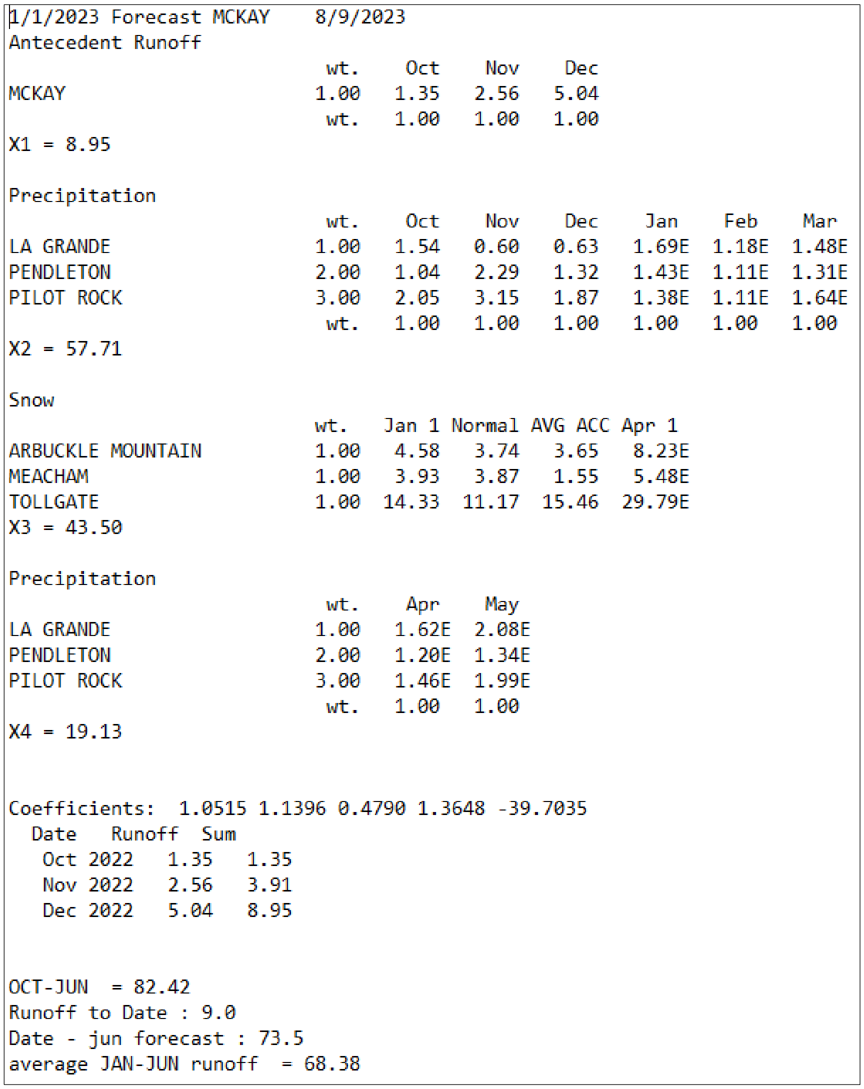
In real-time operations, observed data for the appropriate sites is entered into Hydromet (Reclamation 2023b) beginning in October. On the first of each month starting in January and continuing into June, once all applicable data is entered for the prior month, a graphical user interface is used to run the MLR WSF. A report is returned displaying the forecast and the data that was used to produce the forecast.

The MLR equation provides a transparent and generally understandable process through review of the output files. Examples of the Summary and Detail output files are presented in Figure 10 and Figure 11, respectively.



```
                           CURRENT
                     MONTHLY FORECAST SUMMARY
                      January 01 2023
+-----------------------------------------------------------+
|                    |         |          |     NORMAL      |
|                    |         |          |   SUBSEQUENT    |
|                    |         |          |   CONDITIONS    |
|                    |         |1981-2010 |                 |
|                    |FORECAST | AVERAGE  |FORECAST PERCENT |
| FORECAST           |PERIOD   | (1000AF) |(1000AF) NORMAL  |
|-----------------------------------------------------------|
|                                  AVE      NORM      %     |
|                                                           |
| MCKAY               JAN-JUN     68.4      73.5     107    |
|                                                           |
|___________________________________________________________|
```

Figure 10. MLR Summary output file example for McKay Reservoir



```
1/1/2023 Forecast MCKAY    8/9/2023
Antecedent Runoff
                            wt.    Oct    Nov    Dec
MCKAY                      1.00   1.35   2.56   5.04
                            wt.   1.00   1.00   1.00
X1 = 8.95

Precipitation
                            wt.    Oct    Nov    Dec    Jan    Feb    Mar
LA GRANDE                  1.00   1.54   0.60   0.63   1.69E  1.18E  1.48E
PENDLETON                  2.00   1.04   2.29   1.32   1.43E  1.11E  1.31E
PILOT ROCK                 3.00   2.05   3.15   1.87   1.38E  1.11E  1.64E
                            wt.   1.00   1.00   1.00   1.00   1.00   1.00
X2 = 57.71

Snow
                           wt.    Jan 1 Normal AVG ACC Apr 1
ARBUCKLE MOUNTAIN          1.00   4.58   3.74   3.65   8.23E
MEACHAM                    1.00   3.93   3.87   1.55   5.48E
TOLLGATE                   1.00  14.33  11.17  15.46  29.79E
X3 = 43.50

Precipitation
                            wt.    Apr    May
LA GRANDE                  1.00   1.62E  2.08E
PENDLETON                  2.00   1.20E  1.34E
PILOT ROCK                 3.00   1.46E  1.99E
                            wt.   1.00   1.00
X4 = 19.13


Coefficients:  1.0515 1.1396 0.4790 1.3648 -39.7035
  Date    Runoff   Sum
   Oct 2022    1.35    1.35
   Nov 2022    2.56    3.91
   Dec 2022    5.04    8.95


OCT-JUN   = 82.42
Runoff to Date : 9.0
Date - jun forecast : 73.5
average JAN-JUN runoff  = 68.38
```

Figure 11. MLR Detail output file example for McKay Reservoir

In general, the MLR WSF has provided a reliable, understandable process for predicting runoff in the CPN Region. The equation is easy to decipher and the graphical user interface used in the forecast allows for easy interpretation. However, one of the purposes of this Study was to examine whether improvements can be made to the historical forecasting procedures.

3.2.1.2. MLR Hindcasts

The MLR program also allows for hindcasting (a forecast produced for a historical period) using the most recent WSF equation for each historical month with the data that would have been available at the time (imperfect forecast). This is a useful tool for understanding the historical performance of the forecast and was used in this Study to determine how well the MLR WSF performs compared to other forecast products. A table of MLR hindcasts produced for this Study can be found in Appendix A.

3.2.2. Northwest River Forecast Center

The NWRFC uses an Ensemble Streamflow Prediction (ESP) modeling procedure to generate long-range probabilistic WSFs. ESP utilizes a physically-based conceptual modeling system to simulate soil moisture, snowpack, regulation, and streamflow. ESP then accesses the current hydrologic model states and uses historical meteorological data to create equally likely sequences of future hydrologic conditions, each starting with the current hydrologic conditions. Statistical analysis is performed on those sequences to generate probabilistic WSFs (NWRFC 2023a). NWRFC uses ESP to produce "natural" forecasts by simulating the unregulated, naturally occurring streamflow at a point. All known reservoir operations and river diversions are accounted for and returned to the streamflow simulation.

The ESP procedure uses historical (WY1981-WY2021 for hindcasts used in this Study) precipitation and temperature data as inputs (i.e., forcings) for future conditions and produces one streamflow trace (possibility) per set of forcing data, for a total of 41 equally likely traces. Every streamflow trace is initialized from the same current hydrologic model state on the forecast date (i.e., basin snowpack, soil moisture, etc.). 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:

- ESP 0 – This method uses historical observations (i.e., climatology) as forcings starting on day 0 of the model
- ESP HEFS – This method uses a 15-day weather forecast ensemble derived from the ensemble mean of the GEFS (Global Ensemble Forecasting System) by post-processing using the HEFS (Hydrologic Ensemble Forecasting System) Meteorological Ensemble Forecast Processor (MEFP) for the first 15 days of inputs to the model, followed by climatology after day 15
- ESP 10 – This method utilizes a 10-day weather forecast for the first 10 days of inputs to the model, followed by climatology after day 10

Figure 12 is a "spaghetti plot" that illustrates the various streamflow possibilities produced from one ESP forecast run.

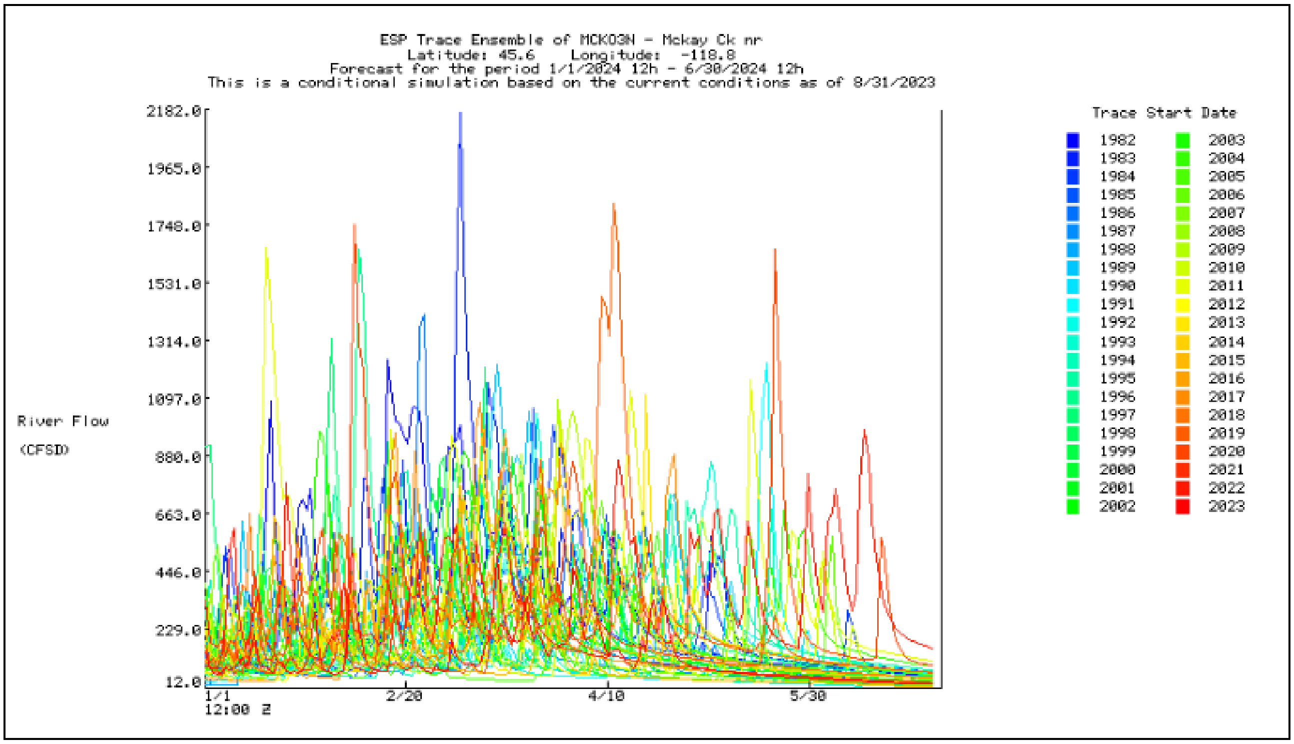


Figure 12. NWRFC ESP traces for inflow into McKay Reservoir (January 1, 2024-June 30, 2024) (NWRFC 2023b)

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 (50 percent exceedance probability) of the volume ensemble (Figure 13) is assumed to be the most likely runoff volume. The median volume from the ESP procedure was used for the hindcast task for this Study.

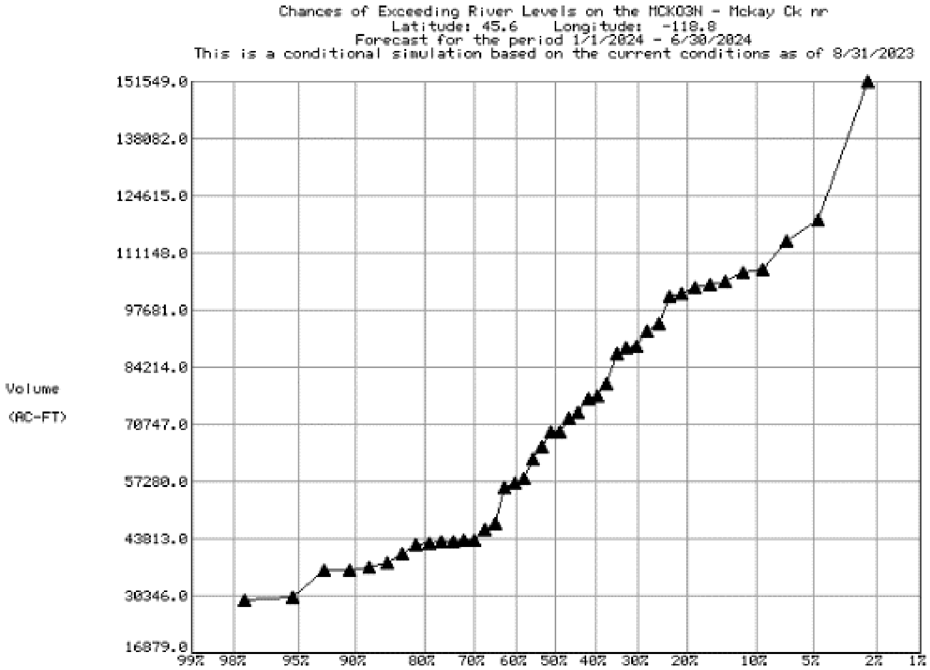


Figure 13. NWRFC ESP exceedance probability plot for inflow volume into McKay Reservoir (January 1, 2024-June 30, 2024) (NWRFC 2023b)

3.2.2.1. NWRFC Hindcasts

NWRFC generated 1st and 15th of month McKay Reservoir natural inflow hindcasts for this Study for the ESP 0 and ESP HEFS methods. The hydrologic model was calibrated using the WY1981-WY2021 period. For ESP 0, hindcasts were available for the WY1981-WY2021 period. For ESP HEFS, hindcasts were available for the WY1989-WY2019 period. The precipitation and temperature forcing data used in the calibration process was developed by NWRFC using historical precipitation and temperature station observations. A table of NWRFC hindcasts produced for this Study can be found in Appendix A.

It is important to note that the NWRFC calculation of natural inflow for McKay Reservoir (MCKO3N) corrects for reservoir surface evaporation and consumptive use effects upstream of the reservoir. This is different from the unregulated inflow (MCKO QU) calculated by Reclamation (see Appendix B for Reclamation's calculation), which does not correct for those parameters. For the WY1981-WY2021 period, the observed annual WY volume based on the MCKO3N methodology was on average 16.5 percent higher than that based on the MCKO QU methodology.

3.2.3. NRCS

Though this Study focuses on Reclamation and NWRFC forecasts, it is important to note that NRCS also produces WSFs for the basin utilizing a statistical approach similar to Reclamation. The NRCS uses statistical models to produce WSF equations that express a fitted mathematical relationship (usually linear) between several predictor variables and the target seasonal streamflow volume. Predictor variables are primarily SWE at selected measurement sites but can also include precipitation, antecedent streamflow, and a few other miscellaneous quantities.

The primary data source for predictor variables is SNOTEL and manual snow course data; other data comes from various federal, state, and Canadian provincial agencies. Data for the target seasonal streamflow volume comes from the U.S. Geological Survey and other federal and state agencies. In addition, the target streamflow volumes are usually adjusted for the effects of human water management, such as changes in reservoir storage and irrigation canal diversions, to correspond, as closely as possible, to natural flow conditions.

Statistical forecasting models are developed using spreadsheets and custom software. Predictor variables are carefully selected to balance the multiple goals of forecast accuracy, month-to-month consistency, spatial representativeness, and physical understandability.

During forecast operations, hydrologists retrieve the necessary data and run the forecast models. They then review the results in consultation with the state NRCS Water Supply Specialists. If needed, adjustments are made, and then the forecasts are published (NRCS 2023a).

3.2.3.1. NRCS Hindcasts

NRCS hindcasts were not available for this Study.

3.3. New WSF Development

PyForecast is a statistical modeling software package developed in collaboration between Reclamation's CPN and Missouri Basin Regions for use in developing statistical WSFs for predicting seasonal runoff volume. The software provides a single interface wherein users may specify and download meteorological and hydrologic datasets, analyze varying predictor subsets, define statistical model training and selection options, and generate well-performing statistical regressions between predictors and seasonal streamflow volumes. PyForecast was successfully used in recent years to improve numerous WSFs in the CPN Region.

Full documentation of the PyForecast software (Reclamation 2019b) and the procedure used to develop WSFs with PyForecast (Reclamation 2021) is available.

These procedures were used to develop a suite of new statistical water supply forecast equation products that can be used to predict unregulated streamflow volume at the McKay Creek near Pendleton, OR gage (MCKO QU). The forecast equations were developed utilizing snow water equivalent, precipitation, antecedent streamflow, and climatic index datasets. Four sets of equations were developed:

- Top Principal Component Regression (PCR)
- Forced PCR
- Top Z-Score
- Forced Z-Score

The "Top" equations are constructed solely by the PyForecast software. The software determines the best combination of predictors to return a forecast equation with the best performance in terms of root mean squared error (RMSE), without regard to factors such as basin or elevation coverage. In contrast, "Forced" equations are constructed by the PyForecast software with the aid of the user. Forced equations utilize specific datasets selected by the user, often to ensure adequate basin coverage or to utilize predictors that have generally been relied upon.

A table of PyForecast hindcasts produced for this Study can be found in Appendix A. A full description of the development of the McKay PyForecast WSFs is provided in Appendix B.

3.4. WSF Performance

3.4.1. Hindcast Modeling Results

To compare performance, the MLR, NWRFC ESP 0, NWRFC ESP HEFS, Top PyForecast PCR, Top PyForecast Z-Score, Forced PyForecast PCR, and Forced PyForecast Z-Score were all calibrated to the WY1981-WY2021 period. Hindcasts were then run for the common NWRFC ESP HEFS WY1989-WY2019 period for all WSF products. Summary statistics were then calculated from the hindcasts.

Figure 14 and Table 1 summarize the improvements across six different statistical measures used for evaluation forecast skill (a full explanation of each statistic can be found in Appendix C). For each metric and period grouping, the three bars (blue, dark blue and maroon) on the left side of the groups represent the performance of the historical WSF equations (MLR, NWRFC ESP 0 and NWRFC HEFS). The four bars (gray, yellow, light blue, and green) on the right side of the groups represent the performance of the updated PyForecast PCR and Z-Score WSF equations. The individual statistical measure's performance was considered improved if:

- Root-mean squared error (RMSE) is lower
- Error standard deviation (SD) is lower
- Standard error (SE) is lower
- Maximum absolute error is lower
- Coefficient of determination (r^2) is higher
- Nash-Sutcliffe Efficiency (NSE) is higher.

RMSE

Max Absolute Error

Error Standard Deviation

Coefficient of Determination (R-Squared)

Standard Error

Nash-Sutcliffe Efficiency

Figure 14. Summary statistic graphs for the McKay Creek near Pendleton forecasts comparing the WY1989-WY2019 period common to all WSF products

Table 1. Summary statistics for the McKay Creek near Pendleton WSF

Forecast Equation	Jan-Jun	Feb-Jun	Mar-Jun	Apr-Jun	May-Jun	Jun-Jun
RMSE (kaf)						
Previous MLR	28	25	23	20	18	14
NWRFC ESP0	26	21	19	17	11	4
NWRFC ESP HEFS	26	21	19	17	10	3
Top PyForecast PCR	22	18	16	13	10	3
Top PyForecast Z-Score	22	18	15	13	10	3
Forced PyForecast PCR	23	20	16	14	10	3
Forced PyForecast Z-Score	21	18	16	14	10	3
Error Standard Deviation (kaf)						
Previous MLR	28	25	23	20	19	14
NWRFC ESP0	26	22	19	16	10	4
NWRFC ESP HEFS	26	21	18	16	10	3
Top PyForecast PCR	22	19	16	13	10	3
Top PyForecast Z-Score	22	18	15	13	10	3
Forced PyForecast PCR	23	21	16	14	10	3
Forced PyForecast Z-Score	22	18	16	14	10	3
Standard Error (kaf)						
Previous MLR	5	4	4	4	3	3
NWRFC ESP0	5	4	3	3	2	1
NWRFC ESP HEFS	5	4	3	3	2	1
Top PyForecast PCR	4	3	3	2	2	1
Top PyForecast Z-Score	4	3	3	2	2	1
Forced PyForecast PCR	4	4	3	3	2	1
Forced PyForecast Z-Score	4	3	3	2	2	1
Max Absolute Error (kaf)						
Previous MLR	64	63	62	45	44	31
NWRFC ESP0	68	73	52	48	28	14
NWRFC ESP HEFS	69	70	54	48	27	13
Top PyForecast PCR	50	46	47	36	24	8
Top PyForecast Z-Score	55	46	42	36	21	8
Forced PyForecast PCR	57	56	53	41	23	10
Forced PyForecast Z-Score	55	45	49	39	22	8

Forecast Equation	Jan-Jun	Feb-Jun	Mar-Jun	Apr-Jun	May-Jun	Jun-Jun
Coefficient of Determination (R-Squared)						
Previous MLR	0.12	0.09	0.08	0.04	0.01	0.01
NWRFC ESP0	0.21	0.27	0.32	0.19	0.14	0.13
NWRFC ESP HEFS	0.20	0.29	0.36	0.20	0.22	0.22
Top PyForecast PCR	0.43	0.44	0.48	0.45	0.16	0.37
Top PyForecast Z-Score	0.43	0.46	0.55	0.45	0.26	0.41
Forced PyForecast PCR	0.38	0.30	0.49	0.39	0.16	0.28
Forced PyForecast Z-Score	0.45	0.46	0.53	0.42	0.24	0.38
Nash-Sutcliffe Efficiency						
Previous MLR	0.05	-0.02	-0.07	-0.32	-1.75	-12.46
NWRFC ESP0	0.20	0.25	0.24	0.06	0.07	0.10
NWRFC ESP HEFS	0.18	0.26	0.28	0.07	0.17	0.18
Top PyForecast PCR	0.42	0.44	0.47	0.42	0.15	0.36
Top PyForecast Z-Score	0.43	0.45	0.54	0.42	0.24	0.39
Forced PyForecast PCR	0.36	0.30	0.46	0.35	0.15	0.27
Forced PyForecast Z-Score	0.44	0.46	0.50	0.39	0.23	0.36

3.5. WSF Conclusion

Significant improvement in WSF performance for all forecast periods, as measured by improvement in all summary statistic metrics, was achieved through the development of new McKay Creek near Pendleton PCR and Z-Score WSF equations in PyForecast. The new PyForecast WSF products were able to improve forecasts both early (when snow accumulation is just starting) and late (when variable snowmelt and future weather conditions make it harder to predict) in the season. The NWRFC ESP0 and ESP HEFS products both perform better than the existing MLR product; however, as described in Section 3.2.2.1, the MCKO3N volume computed by NWRFC is slightly different (and greater) than the MCKO QU volume computed by Reclamation. Overall, the updated McKay PyForecast WSF equations statistically provide the best MCKO QU forecast of the available products. For purposes of this Study, the average of the four PyForecast equations was used as input for the operational modeling described in Section 5.

Though WSF performance was improved significantly compared to existing procedures, the rain/snow transitional nature of the McKay Creek basin makes forecasting more difficult and less accurate than in other more snow dominated basins. Significant under- and over-forecast events remain a possibility. To further complicate forecasting, it is possible in the future the basin could become even more rain dominated, making runoff even less dependent on on-the-ground conditions and more dependent on future precipitation events. Improvements in weather forecasting, both in terms of rainfall amount prediction and longer lead time, may provide water managers a useful tool for managing operations in the basin.

Additionally, adding new SNOTEL sites in the basin to capture lower elevation snowpack conditions and/or continuing to develop, improve, and utilize remote sensing datasets may provide additional improvement to WSF in the basin. It is anticipated the WSF developed for this Study may continue to be updated in the future to continue to strive to provide the most accurate forecast possible in the basin.

4. Space Reservation Diagrams (SRDs)

SRDs are commonly utilized at Reclamation facilities to help guide water managers in regulating the rate with which a reservoir is filled while balancing the reservoir's ability to capture potential high flows that could cause flooding downstream. Professional judgment is generally employed to balance the SRD with constantly changing basin conditions and competing purposes of the facility. SRDs are typically developed utilizing historical observed hydrology and generally fall into the following two categories.

1) Static SRD (sSRD): An sSRD identifies a fixed minimum amount of space for each day of the season based on space needed to manage historical flood events and does not consider basin conditions. The sSRD is most effective for basins in which runoff cannot be forecasted with a reasonable level of certainty, typically rain dominated basins. The strength of an sSRD is typically controlling flows downstream within desired levels since they are designed to capture large historical events. However, if the hydrologic paradigm shifts, and events outside of the historical range occur, the sSRD may no longer provide the protection originally intended. In addition, in drought years when high flow events are unlikely to occur, the static space indicated by the sSRD may be too much for the conditions and can result in the reservoir missing refill if strictly followed.
2) Dynamic SRD (dSRD): A dSRD identifies a variable minimum amount of space for each day of the season dependent on a WSF of runoff volume that is expected to occur. A dSRD does consider basin conditions and are most effective for basins in which the runoff can be forecast with a reasonable level of certainty, typically snow dominated basins. In a perfect forecast paradigm, dSRDs typically do a better job of balancing fill of the reservoir with capturing high flow events. However, WSFs inherently are not perfect. If observed runoff is significantly higher than forecast, less space than necessary will be reserved in the reservoir to capture the runoff, and higher flows than desired may occur downstream. Conversely, if observed runoff is significantly lower than forecast, more space than necessary will be reserved in the reservoir to capture the runoff, and refill of the reservoir may be compromised.

FRM operations at McKay Dam are not managed in coordination with the U.S. Army Corps of Engineers under the Flood Control Act of 1944, P.L. 78-534 (Section 7). Rather, Reclamation retains the authority to provide FRM, sometimes referred to as "informal flood control." For this purpose, Reclamation has historically utilized an sSRD at McKay Dam, which will be described in the sections below. A main component of this Study is to re-examine the Existing sSRD to determine if updates to the SRD can benefit flows downstream of the dam while balancing the many purposes of the reservoir.

The following subsections describe the Existing sSRD along with an analysis of the development of new sSRDs and dSRDs.

4.1. Existing sSRD

The development of the Existing sSRD at McKay is not fully known. The Existing sSRD has generally been used to guide water managers in regulating the rate with which the reservoir fills to balance reduction of flood risk downstream with filling the reservoir for water supply. It considers the historical safe channel capacity to be 1,200 cfs.

The Existing sSRD indicates the reservoir should be drafted so the content of the reservoir is no higher than 26,734 acre-feet content (38,800 acre-feet space) from the end of the irrigation season (October) through November. From December through February, the Existing sSRD allows the reservoir to refill in a linear fashion and allows storage content on March 1 of 59,434 acre-feet (6,100 acre-feet of space). On April 1, the Existing sSRD allows the reservoir to be at normal full pool with a storage content of 65,534 acre-feet for water supply later in the spring into the summer. For McKay reservoir, there is an additional 6,000 acre-feet of exclusive flood space available that is intended for storing and regulating flood flows. These storage levels are shown graphically by the Existing sSRD in Figure 15.

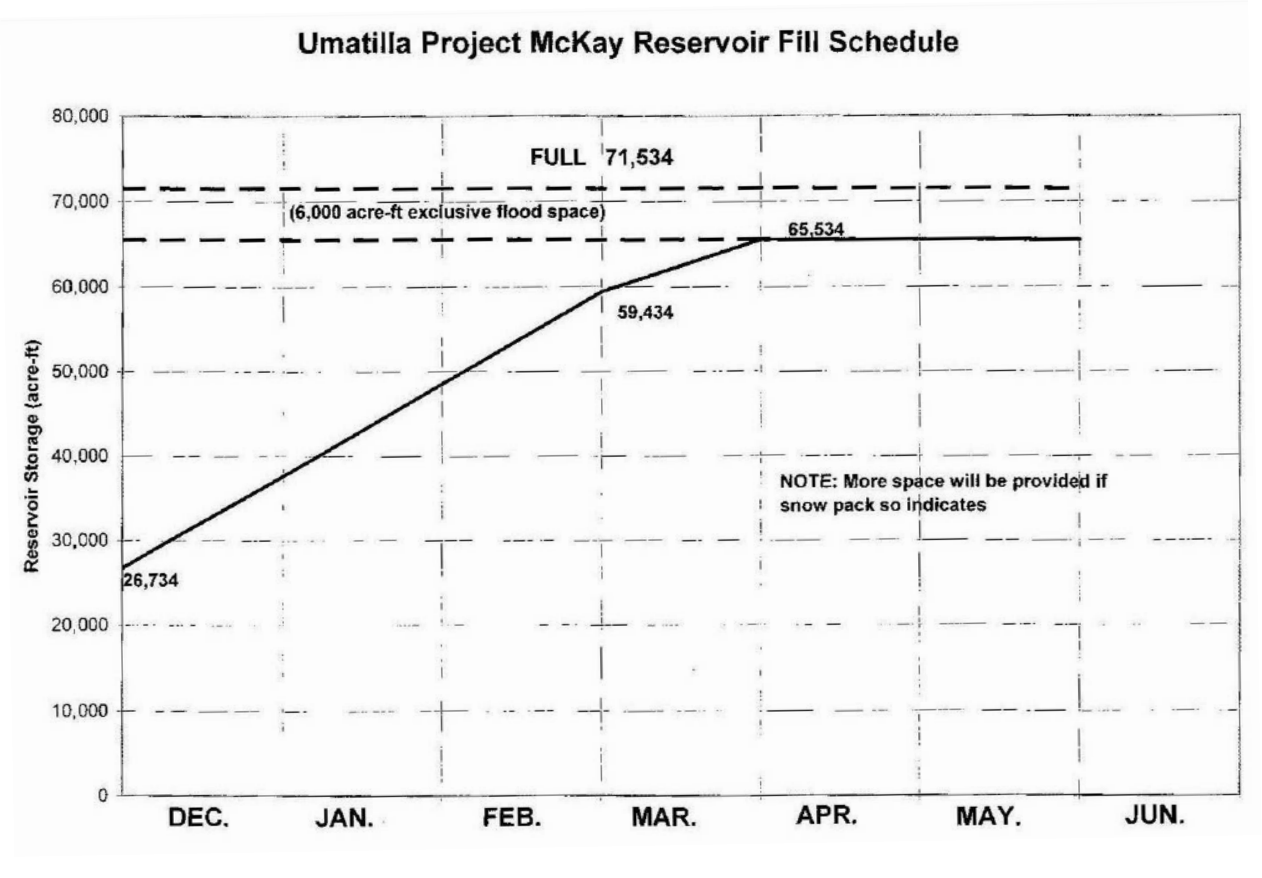


Figure 15. MCKO Existing sSRD

Although the risk of flooding reduces at a progressive rate after February 15, the possibility of such a flood continues until late spring. For this reason, the above filling schedule is subject to change, should conditions in the watershed warrant, and includes a qualifying note that states:

> *"More space will be provided if snow pack so indicates"*

However, no guidance is provided to quantify the conditions or the additional space reservation if such conditions materialize. The current sSRD provides flexibility for the operator to determine additional space reservation based on current basin conditions, and this study provides additional tools (updated WSF and SRD products) to help inform that determination.

During the WY2019 event, more space was held in the reservoir than indicated by the Existing sSRD leading up to the event. However, to ensure safety of the dam, flows downstream still needed to be increased to approximately 2,900 cfs, well over the 1,200 cfs safe channel capacity. This highlights the opportunity to re-examine the Existing sSRD.

4.2. Updated dSRD

The following is a description of the process used to develop the 1,200 cfs control flow dSRD (1200dSRD) and 800 cfs control flow dSRD (800dSRD) and is based on the methodology described in the April 2019 Reclamation Crooked River Pilot Study (Reclamation 2019c). Daily calculated McKay Reservoir inflow data is available for the period WY1974 through WY2022 and was used in this process. The control flow of 1,200 cfs is based on historical safe channel capacity downstream of McKay Dam. The control flow of 800 cfs was used to provide for periods of reduced channel capacity such as was the case after the 2019 high flow event. The exclusive 6,000 acre-feet flood control space is separate from this process and provides additional buffer against high flows in the system. The purpose of this Study was to examine the spring runoff period; therefore, the Existing sSRD was used from the end of the irrigation season (October) through December. Additionally, the Existing sSRD was used as an upper bound in all cases. In context of this report, the terms "required" and "requirement" are operational terms used by water managers and do not indicate a legal or policy requirement.

4.2.1. 1200dSRD

The first step in the development of a dSRD is to create a runoff volume to space required curve for each 15-day interval during the runoff season. For purposes of this Study, the runoff season was considered to be January 1 through June 30 as: a) historically the runoff is nearly complete by June 30, and b) historical WSFs cover this period. The periods of interest therefore were January 1 through June 30, January 15 through June 30, etc. up to the June 1 through June 30 period. Curves were not developed for dates later than June 1 because there were no historical water years in which runoff required space past June 1. The purpose of this process is to determine the amount of space required during each period to control historical events to the desired downstream control flow, in this case 1,200 cfs.

WY2019 is used as an example to illustrate the runoff volume to space required relationship for the February 15 through June 30 period. WY2019 had a February 15 through June 30 runoff volume of 109,368 acre-feet. Assuming outflow of the reservoir would be set to match inflow up until inflow exceeds 1,200 cfs, additional inflows that would ideally be stored totaled 15,059 acre-feet. With this assumption, an operation using perfect foresight of the WY2019 runoff timing would draft the reservoir to provide 15,059 acre-feet of space by February 15, after which outflow would be set to match inflow up to a maximum of 1,200 cfs and the reservoir would reach complete refill on April 21. Figure 16 provides a graphical depiction of this process with reservoir outflow shown as an orange line, inflow shown as a blue line, and cumulative space required shown as a dotted green line.

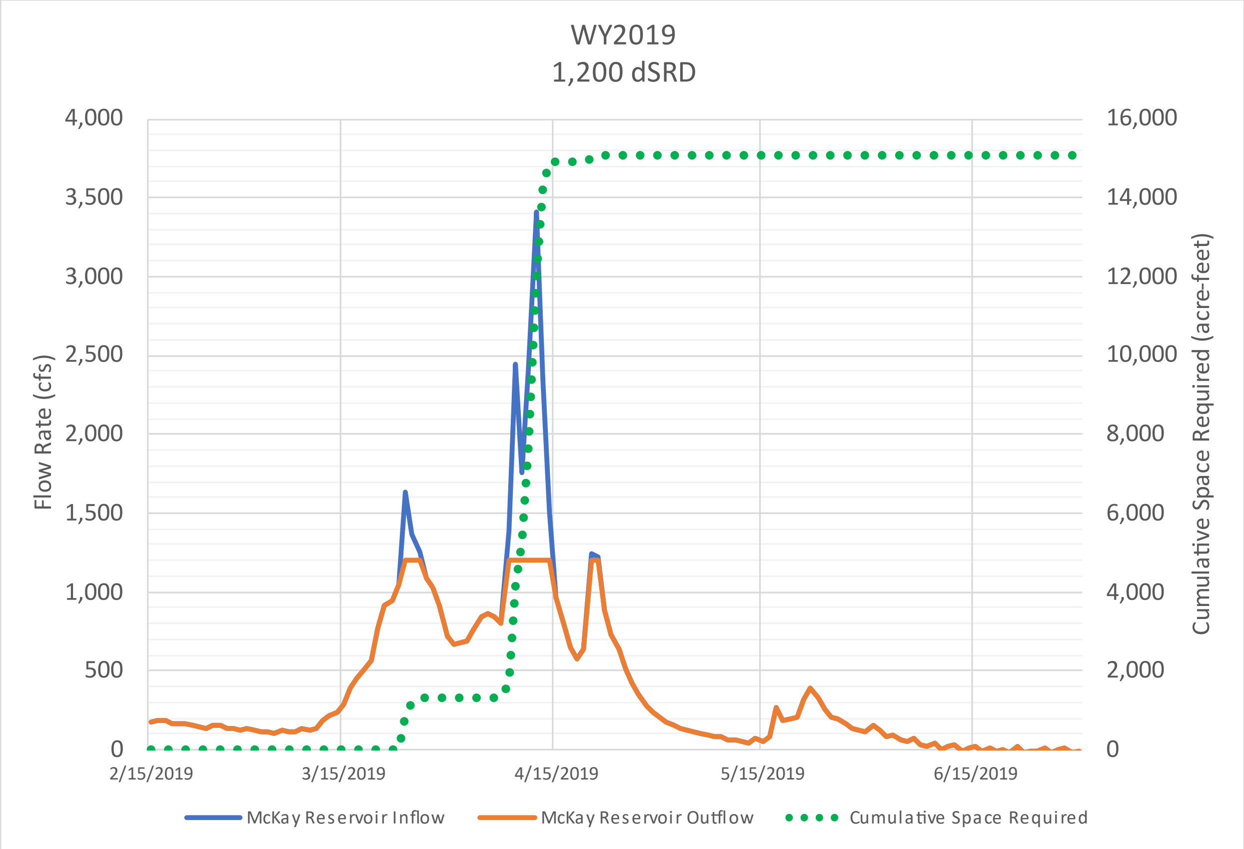


Figure 16. WY2019 runoff volume to space required development for the February 15 through June 30 period for 1,200 cfs control flow

The same process is completed for all the 49 years in the WY1974 through WY2022 historical dataset. Table 2 summarizes the results (ranked by space required). Of the 49 years in the WY1974-WY2022 dataset, 43 percent (21 years) required space on February 15 to meet the 1,200 cfs control flow. In some cases, due to the different runoff timing of a specific water year, a smaller runoff volume may have resulted in more required space than a larger runoff volume, as is the case when comparing WY1986 and WY2011. The timing of the runoff for WY1986 was much more rapid and resulted in more volume materializing as inflow exceeding 1,200 cfs.

Table 2. February 15 through June 30 runoff volume versus space required, assuming a control flow of 1,200 cfs. Volumes are in acre-feet.

Water Year	Feb. 15 – June 30 Runoff Volume	Space Required
2019	109,368	15,059
1986	56,846	6,531
1991	65,214	4,892
2020	52,243	3,574
2011	113,851	3,079
2022	97,082	2,692
1995	74,586	2,077
2014	51,892	1,589
1981	68,560	1,508
2013	36,631	953
2006	47,004	802
1993	78,352	580
1974	64,376	409
1982	75,194	318
2017	77,172	316
2010	55,065	261
2004	67,135	184
1989	77,229	108
1979	74,764	95
2009	67,484	80
1983	64,153	44
1984	92,289	0
1997	59,825	0
2000	58,083	0
2003	57,741	0
1996	53,130	0
1975	53,052	0
2008	52,593	0
1980	51,086	0
2012	47,879	0
2001	45,582	0

Water Year	Feb. 15 – June 30 Runoff Volume	Space Required
1999	44,126	0
1985	43,455	0
1976	42,436	0
1998	42,025	0
2018	41,854	0
1978	41,169	0
2021	40,729	0
2002	36,897	0
1987	35,518	0
1990	33,761	0
2007	32,719	0
2016	32,224	0
1994	30,966	0
1988	28,669	0
2005	24,872	0
1977	19,386	0
2015	15,044	0
1992	13,290	0

Figure 17 provides a visual representation of the data in Table 2 and is a scatter plot of the runoff volume to space required relationship for each WY. This plot will aid in identifying which water years to use to envelop all possible space requirements ("envelope curve").

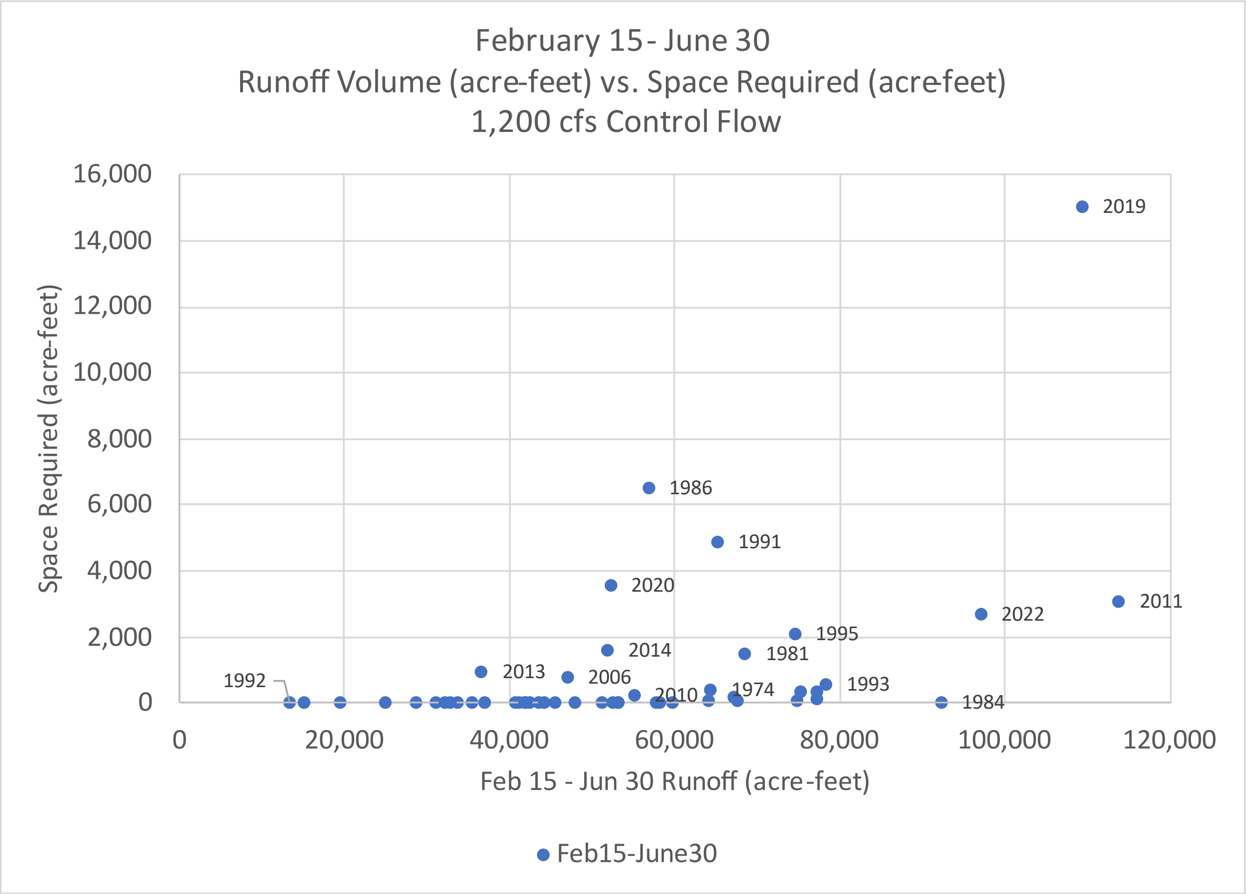


Figure 17. Scatter plot of runoff volume to required space data for a 1,200 cfs control flow

Figure 18 shows the next step of defining the runoff volume to space required envelope curve that provides sufficient space for all water years in the dataset to control outflow to 1,200 cfs. In this case, the number of data points could be reduced to include only the WY1992 and WY2019 water years with the envelope curve being a line fitted to those two points.

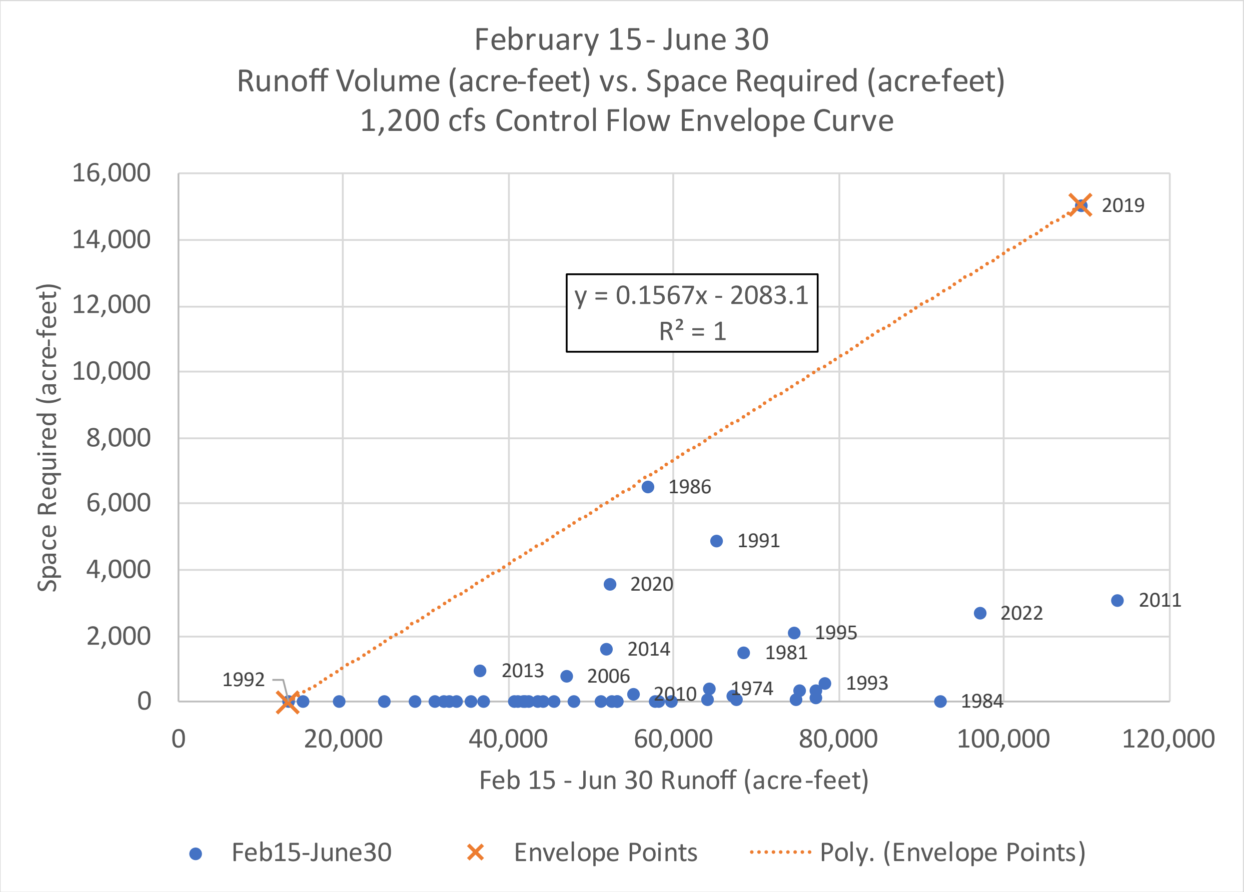


Figure 18. February 15 through June 30 runoff volume to space required envelope curve for a 1,200 cfs control flow

Table 3 shows the estimated space required using the February 15 through June 30 runoff volume to space required envelope curve, compared to the actual space required. As the table shows, all estimated space requirements are greater than or equal to what was required except for minor negative amounts for the two anchor points of WY2019 and WY1992. The average error of the envelope curve estimate compared to the actual requirement was 5,453 acre-feet, while the median was 4,831 acre-feet and the 10 percent exceedance error was 9,630 acre-feet.

Table 3. Error analysis of the February 15 through June 30 runoff volume to space required envelope curve. Volumes are in acre-feet.

Water Year	Runoff Volume	Actual Space Required	Estimated Space Required	Error (Estimated minus Actual)
2019	109,368	15,059	15,055	-4
1986	56,846	6,531	6,825	294
1991	65,214	4,892	8,136	3,244
2020	52,243	3,574	6,103	2,529
2011	113,851	3,079	15,757	12,678
2022	97,082	2,692	13,130	10,438
1995	74,586	2,077	9,605	7,528
2014	51,892	1,589	6,048	4,459
1981	68,560	1,508	8,660	7,152
2013	36,631	953	3,657	2,704
2006	47,004	802	5,282	4,480
1993	78,352	580	10,195	9,615
1974	64,376	409	8,005	7,596
1982	75,194	318	9,700	9,382
2017	77,172	316	10,010	9,694
2010	55,065	261	6,546	6,285
2004	67,135	184	8,437	8,253
1989	77,229	108	10,019	9,911
1979	74,764	95	9,632	9,537
2009	67,484	80	8,492	8,412
1983	64,153	44	7,970	7,926
1984	92,289	0	12,379	12,379
1997	59,825	0	7,291	7,291
2000	58,083	0	7,019	7,019
2003	57,741	0	6,965	6,965
1996	53,130	0	6,242	6,242
1975	53,052	0	6,230	6,230
2008	52,593	0	6,158	6,158
1980	51,086	0	5,922	5,922
2012	47,879	0	5,420	5,420
2001	45,582	0	5,060	5,060
1999	44,126	0	4,831	4,831

Water Year	Runoff Volume	Actual Space Required	Estimated Space Required	Error (Estimated minus Actual)
1985	43,455	0	4,726	4,726
1976	42,436	0	4,567	4,567
1998	42,025	0	4,502	4,502
2018	41,854	0	4,475	4,475
1978	41,169	0	4,368	4,368
2021	40,729	0	4,299	4,299
2002	36,897	0	3,699	3,699
1987	35,518	0	3,483	3,483
1990	33,761	0	3,207	3,207
2007	32,719	0	3,044	3,044
2016	32,224	0	2,966	2,966
1994	30,966	0	2,769	2,769
1988	28,669	0	2,409	2,409
2005	24,872	0	1,814	1,814
1977	19,386	0	955	955
2015	15,044	0	274	274
1992	13,290	0	-1	-1
			Average Error	5,453
			Median Error	4,831
			10% Exceedance Error	9,630

This process is completed for each 15-day interval starting with the January 1 through June 30 period and ending with the June 15 through June 30 period. After the curves are developed, space requirements between the 15-day intervals can be estimated using interpolation. Completing this process allows development of a continuous space requirement for any day within the entire reservoir refill period.

After this process was completed for each period, a two-way look-up table was created that defines the amount of space 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 January 1 to June 15 period. An iterative process of making minor adjustments to the envelope curves was used to “smooth” the space requirements. The Existing sSRD was used as an upper bound for the new 1200dSRD.

Figure 19 is the final 1200dSRD used in this Study; it can also be found in tabular form in Appendix D. In practice, a date through June 30 WSF can be used to determine the space requirement on each day. For example, if on April 1 the WSF for the April 1 through June 30 period is determined to be 100,000 acre-feet, 16,121 acre-feet of space would be required.

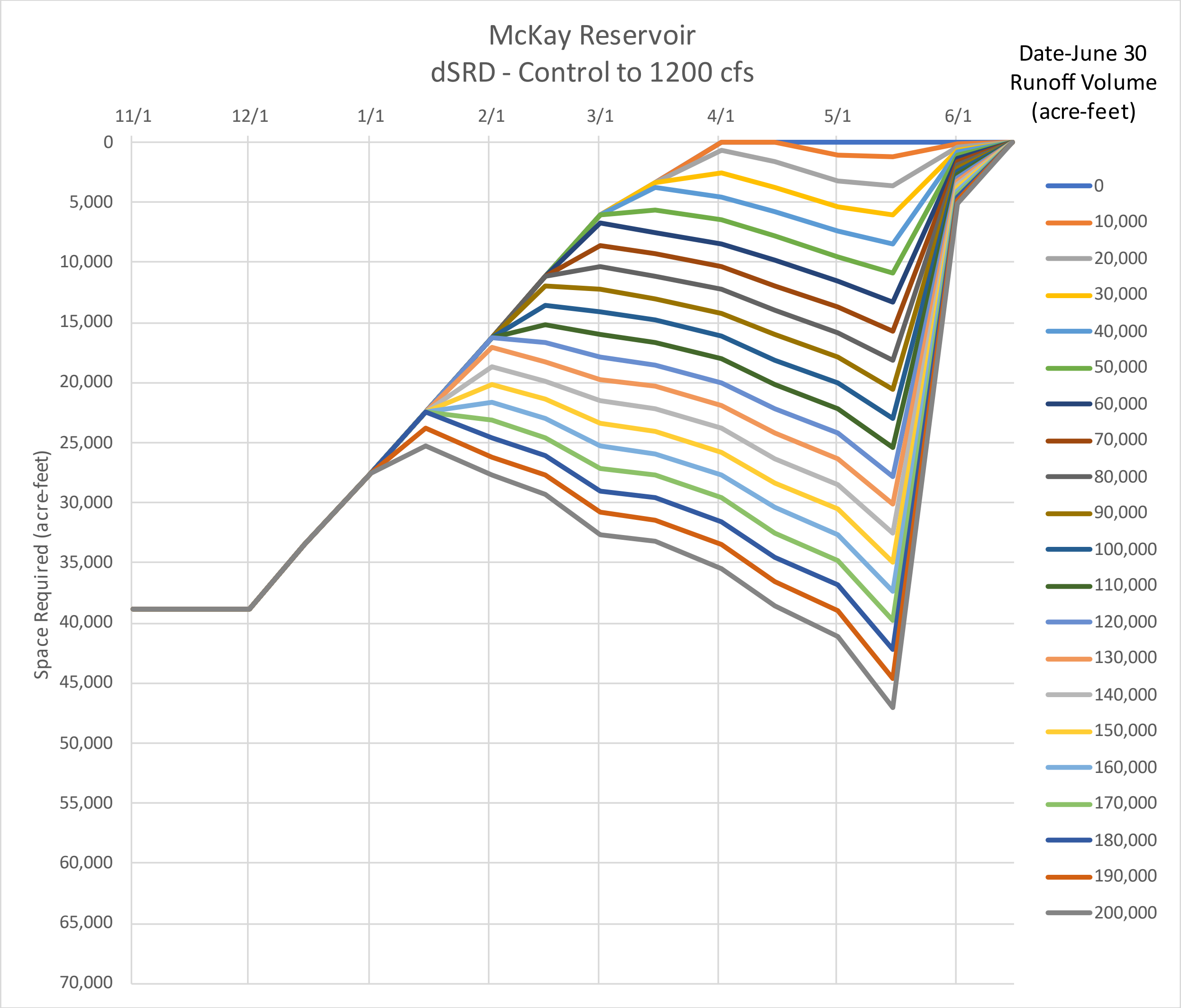


Figure 19. 1200dSRD developed using historical WY1974-WY2022 data and 1,200 cfs control flow

4.2.2. 800dSRD

The same process was repeated to produce the 800dSRD, with the only modification being the control flow being changed from 1,200 cfs to 800 cfs. This change results in more space being required for the same future runoff volume due to reduced outflow capacity. For example, for an April 1 through June 30 runoff of 100,000 acre-feet, the required space based on the 1200dSRD would be 16,121 acre-feet and for the 800dSRD would be 32,518 acre-feet. Figure 20 is the final 800dSRD used in this Study; it can also be found in tabular form in Appendix D.

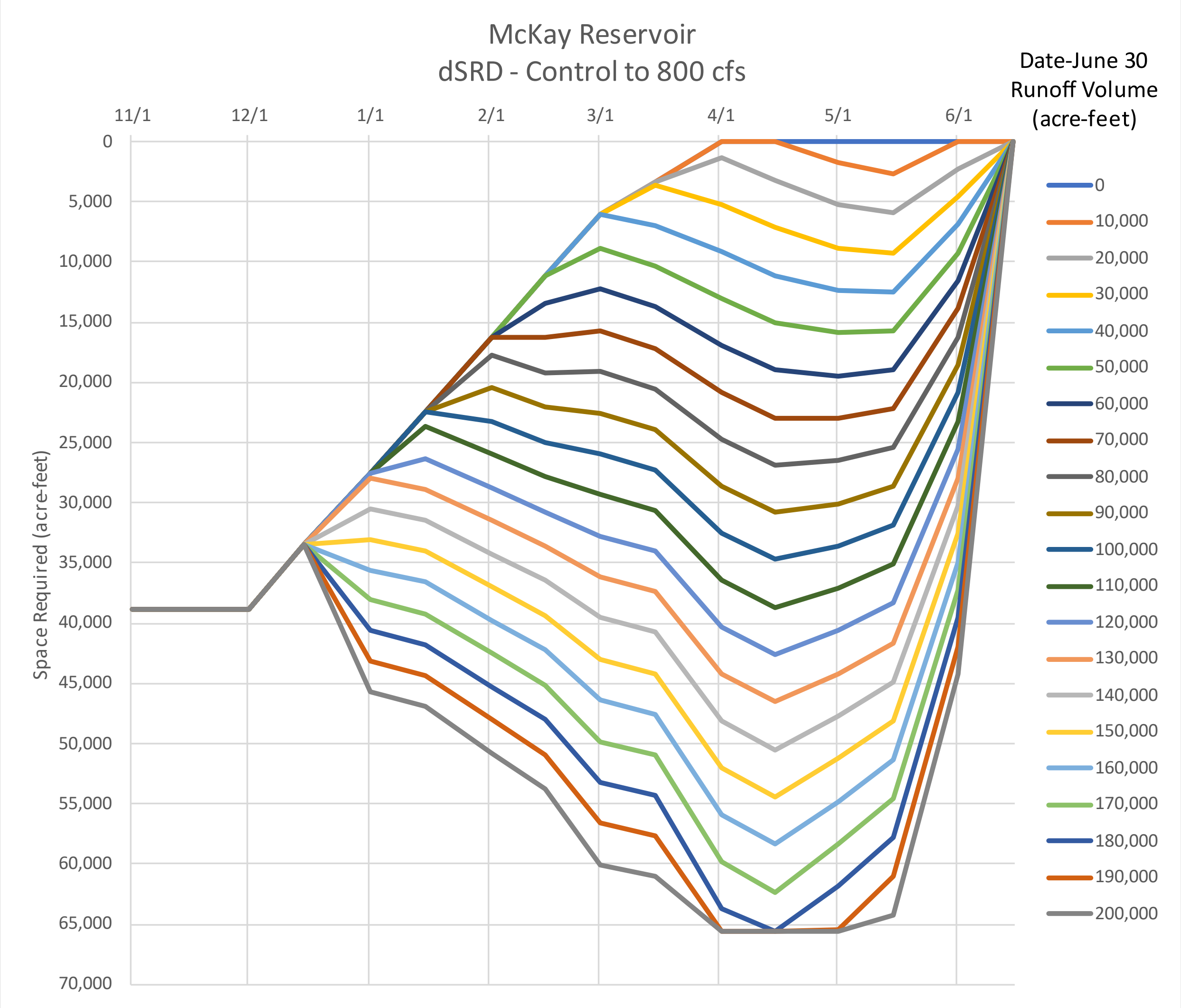


Figure 20. 800dSRD curve developed using historical WY1974-WY2022 data and 800 cfs control flow

4.3. Updated sSRD

The following is a description of the process used to develop the 1,200 cfs control flow sSRD (1200sSRD) and 800 cfs control flow sSRD (800sSRD), which are built with additional inflow data collected since the creation of the Existing sSRD. As described previously, sSRDs are different from dSRDs in that they do not consider basin conditions and do not require a WSF of future runoff. Rather, sSRDs are designed to provide sufficient space on each day of the runoff season to inherently control all historical observed events to the control flow downstream.

This process utilizes data produced in the development of the dSRDs described in Section 4.2 to develop the sSRD. As with the dSRD, daily calculated McKay Reservoir inflow data for the period WY1974 through WY2022 was used. The control flow of 1,200 cfs is based on historical safe channel capacity downstream of

McKay Dam. The control flow of 800 cfs was used to account for potential future reductions in channel capacity due to channel encroachment and development downstream. The exclusive 6,000 acre-feet flood control space is separate from this process and provides additional buffer against high flows in the system. The Existing sSRD was used as an upper bound.

4.3.1. 1200sSRD

All the data necessary to build the 1200sSRD was produced during the 1200dSRD development process. The 1200sSRD simply utilizes the greatest space requirement for each 15-day interval period examined. For example, for the February 15 through June 30 period, it was determined that the greatest space requirement for all historical events was 15,059 acre-feet in WY2019. This is the value that is used as the February 15 space requirement for the 1200sSRD. This same procedure is applied to determine the maximum space requirement for each period. Table 4 summarizes the results.

Table 4. Maximum space requirement in acre-feet for each period, assuming a control flow of 1,200 cfs

Period	Space Required
January 1 - June 30	15,059
January 15 – June 30	15,059
February 1 – June 30	15,059
February 15 – June 30	15,059
March 1 – June 30	15,059
March 15 – June 30	15,059
April 1 – June 30	13,758
April 15 – June 30	4,892
May 1 – June 30	4,892
May 15 – June 30	4,892
June 1 – June 30	584

The Existing sSRD was used as an upper bound and requires additional space in some periods. Table 5 shows a comparison between the maximum space required by the dSRD process and the space required by the Existing sSRD and shows the maximum requirement of the two.

Table 5. Comparison of maximum space required by the dSRD process and the space required by the Existing sSRD in acre-feet

Period	Maximum Space Required by dSRD	Space Required by Existing sSRD	Maximum Requirement
January 1 – June 30	15,059	27,500	27,500
January 15 – June 30	15,059	22,400	22,400
February 1 – June 30	15,059	16,300	16,300
February 15 – June 30	15,059	11,200	15,059
March 1 – June 30	15,059	6,100	15,059
March 15 – June 30	15,059	3,300	15,059
April 1 – June 30	13,758	0	13,758
April 15 – June 30	4,892	0	4,892
May 1 – June 30	4,892	0	4,892
May 15 – June 30	4,892	0	4,892
June 1 – June 30	584	0	584

Figure 21 shows the final 1200sSRD used in this Study; it can also be found in tabular form in Appendix D. The 1200sSRD is shown as the black line, with the Existing sSRD shown in red to allow comparison. Notice the 1200sSRD requires more space from February 1 through June 15 than the Existing sSRD. In practice, a date through June 30 WSF is not needed, and the space requirement for each day can simply be read from the graph. For example, on April 1, whether the WSF for the April 1 through June 30 period is determined to be 100,000 acre-feet or 20,000 acre-feet, the 1200sSRD space requirement is 13,758 acre-feet.

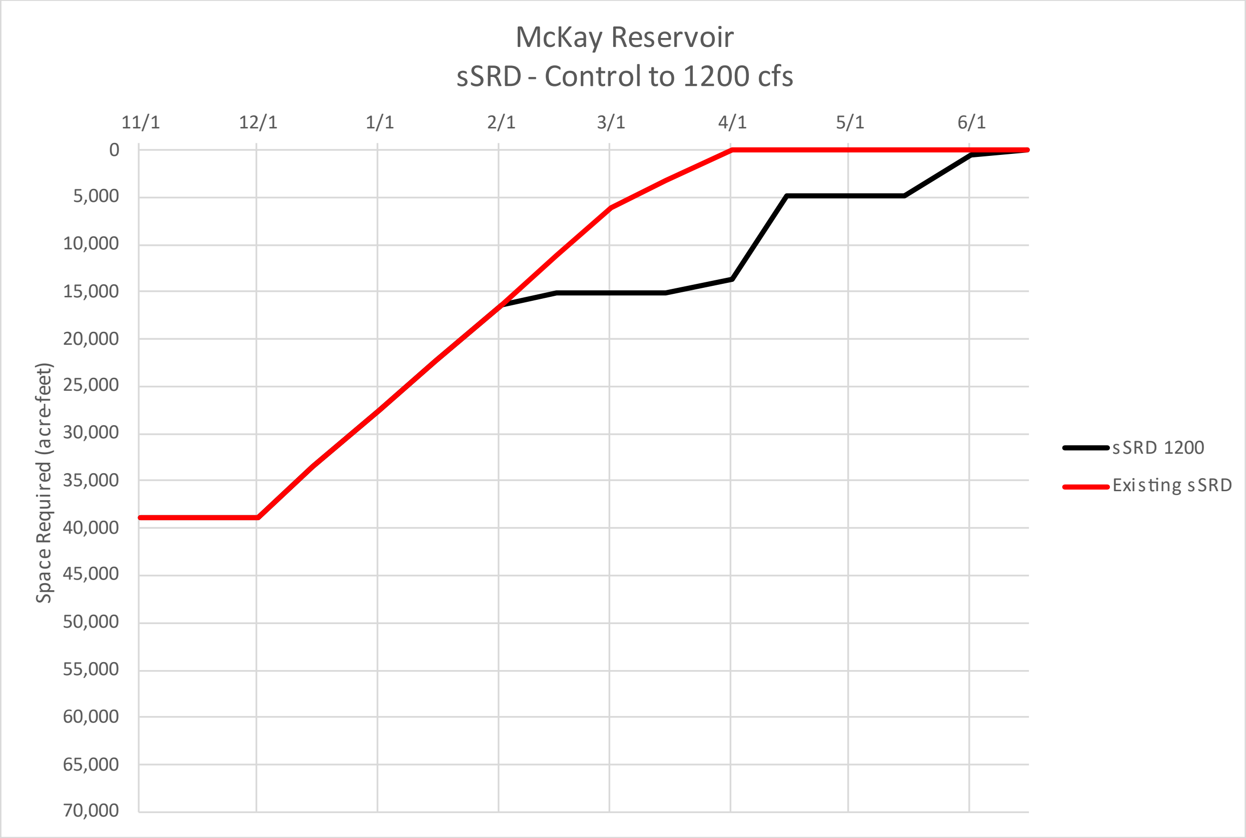


Figure 21. 1200sSRD curve (black line) developed using historical WY1974-WY2022 data and 1,200 cfs control flow. Existing sSRD (red line) is shown for comparison.

4.3.2. 800sSRD

The same process was repeated to produce the 800sSRD, with the only modification being the control flow being changed from 1,200 cfs to 800 cfs. This change results in more space being required due to reduced outflow capacity. For example, on April 1, the required space based on the 1200sSRD would be 13,758 acre-feet and for the 800sSRD would be 21,713 acre-feet. Figure 22 shows the final 800sSRD used in this Study; it can also be found in tabular form in Appendix D. The 800sSRD is shown as the black line, with the Existing sSRD shown in red to allow comparison. Notice the 800sSRD requires more space from January 1 through June 15 than the Existing sSRD.

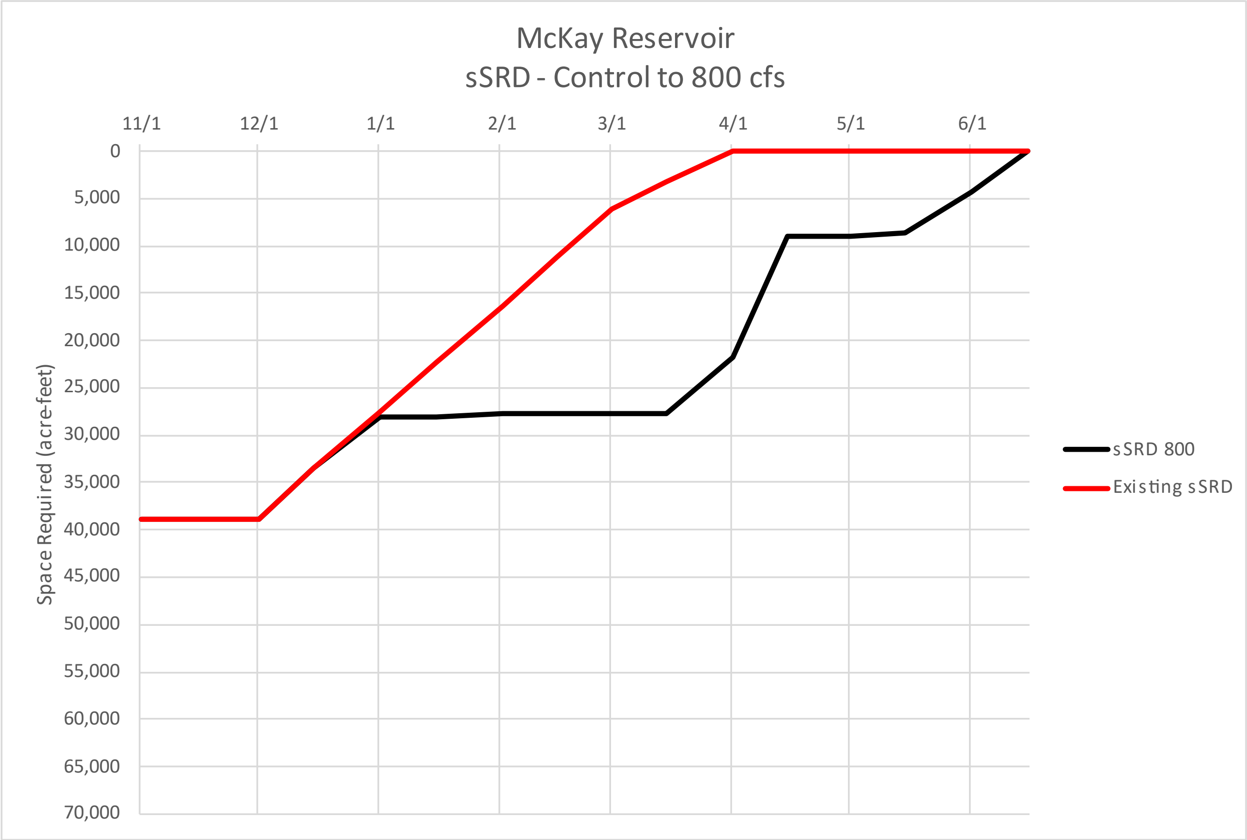


Figure 22. 800sSRD curve (black line) developed using historical WY1974-WY2022 data and 800 cfs control flow. Existing sSRD (red line) is shown for comparison.

4.4. SRD Conclusion

The McKay Existing sSRD has historically provided water managers with a useful tool to help guide the fill of the reservoir. However, during the WY2019 high flow event, more space was held in the reservoir than indicated by the Existing sSRD leading up to the event. However, to ensure safety of the dam, flows downstream still needed to be increased above the safe channel capacity of 1,200 cfs. That event was a primary driver for re-examining the Existing sSRD. By incorporating additional years of record, new SRDs were created that account for recent high runoff events.

Both a dSRD and an sSRD were produced for two different control flows, 1,200 cfs and 800 cfs. The dSRDs consider basin conditions by identifying space reservation for variable potential future runoff volumes. The sSRD identifies space reservation without regard to basin conditions. The resulting SRDs require more space during the runoff season than the Existing sSRD.

Figure 23 shows the Existing sSRD, 1200dSRD, and 1200sSRD together for comparison. Notice more space is required by the 1200dSRD and 1200sSRD than for the Existing sSRD. Dashed lines represent historical (WY1991-WY2020) below normal to above normal period volumes to illustrate the amount of space that would be required by the 1200dSRD for each.

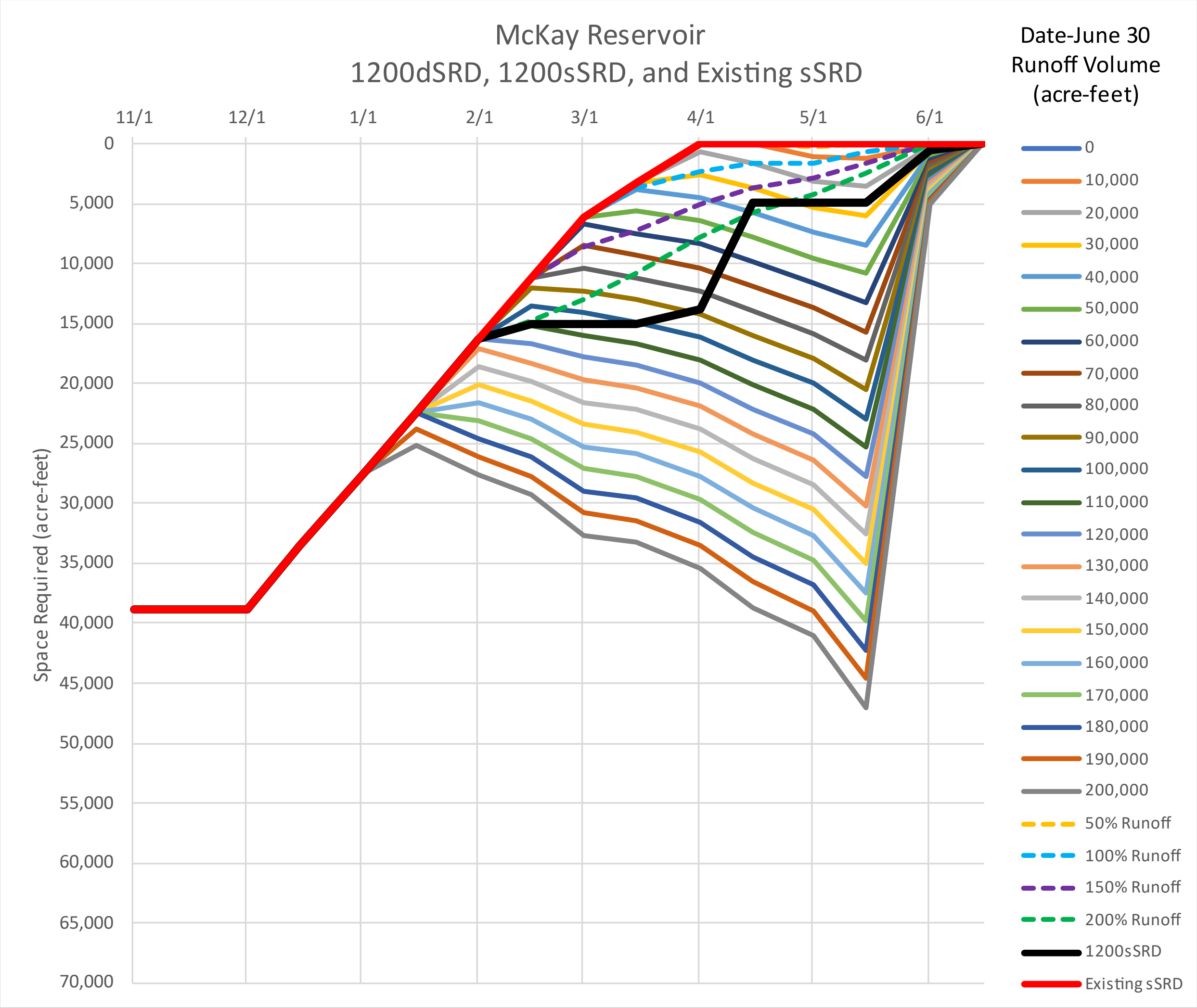


Figure 23. Existing sSRD, 1200dSRD, and 1200sSRD shown together for comparison. Dashed lines represent historical (WY1991-WY2020) below normal to above normal period volumes to illustrate the amount of space that would be required by the 1200dSRD.

Figure 24 shows the Existing sSRD, 800dSRD, and 800sSRD together for comparison. Notice more space is required by the 800dSRD and 800sSRD than for the Existing sSRD. Dashed lines represent historical (WY1991-WY2020) below normal to above normal period volumes to illustrate the amount of space that would be required by the 800dSRD for each.

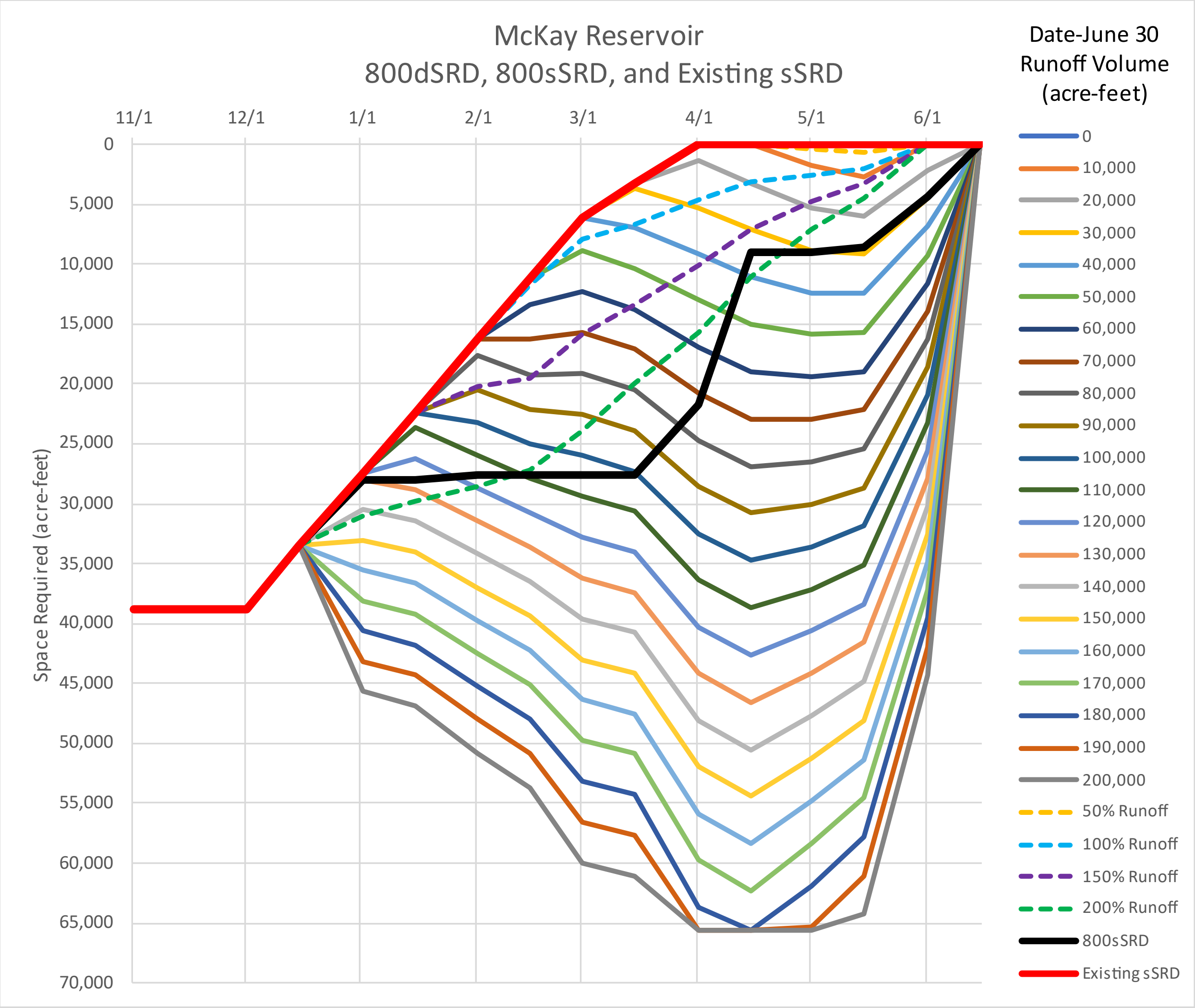


Figure 24. Existing sSRD, 800dSRD, and 800sSRD shown together for comparison. Dashed lines represent historical (WY1991-WY2020) below normal to above normal period volumes to illustrate the amount of space that would be required by the 800dSRD.

Each version of SRD has its own set of strengths and weaknesses. Generally, dSRDs are most effective for basins in which the runoff can be forecast with a reasonable level of certainty. In a perfect forecast paradigm, dSRDs typically do a better job of balancing fill of the reservoir with capturing high flow events. However, as described in Section 3, forecasting in the McKay basin is difficult, and significantly under- or over-forecast events are likely to occur, which could result in too little space reservation (resulting in higher than desired flows downstream) or too much space reservation (resulting in less reservoir fill than desired) in actual real-time application. The sSRD is most effective for basins in which runoff cannot be forecast with a reasonable level of certainty, typically rain dominated basins. The strength of an sSRD is typically controlling flows downstream within desired levels since they are designed to capture all historically observed events. However, if the hydrologic paradigm shifts (e.g., as a result of climate change), and events outside of the historical range begin to occur, the sSRD may no longer provide the protection originally intended and may need to be re-evaluated using the methods described in Section 4.3. In addition, in drought years when high flow events are unlikely to occur, the static space identified by the sSRD may be too much for the conditions and can result in the reservoir missing refill if strictly followed.

To better understand the potential effects of incorporating a new SRD into the operation of McKay Reservoir, use of each SRD was simulated using computer modeling. Section 5 will describe this process and will describe the potential effects to reservoir fill and streamflow.

5. Operational Model Analysis

This effort focused on adapting an existing RiverWare model to utilize the updated WSF and SRD products developed as part of this Study. The RiverWare model was used to simulate McKay Reservoir operations using those WSF and SRDs under historical hydrologic conditions to determine the effects to reservoir fill and flow rate downstream of the dam, in comparison to the existing operations base case (Existing sSRD). Ultimately, the objective was to determine if improvement to operations (reduction to peak flow downstream without impact to maximum reservoir fill) can be achieved. The following sections describe this effort.

5.1. RiverWare Model Overview

The Lower Umatilla River Planning Model is a RiverWare computer modeling tool that uses logic to simulate reservoir operations. RiverWare is a generalized river basin modeling tool that can be used to simulate detailed, site-specific river and reservoir operations. The model adheres to physical constraints of the river and reservoir system at a daily timestep for a 29-year period spanning October 1, 1993, through September 30, 2022, which was the period for which all data necessary to run the model was available. It was previously developed in RiverWare® ver. 8.1.1 (Reclamation 2020a). From the 2020 model, the model was updated in RiverWare® ver. 8.5.1 to incorporate the WSF and SRDs developed for this Study.

It should be noted that real-time operations occur on a sub-daily, often sub-hourly timestep, and provide more flexibility than the daily timestep and rigid rule adherence of the model.

5.2. Model Structure

The 2020 model served as the starting point from which the model used in this Study was developed. See the documentation summarizing development of the 2020 model (Reclamation 2020a) for more information on that model. The model used in this Study is identical to the 2020 model with the exception of the following modifications:

1. The maximum storage in Cold Springs Reservoir was reduced from 38,000 acre-feet to 35,000 acre-feet to reflect the results of a recent bathymetric survey.

2. The period of record was extended from October 1, 1993, through September 30, 2019, to October 1, 1993, through September 30, 2022, to capture recent high flow years.

The model network was constructed using RiverWare objects to represent physical features such as reservoirs, river reaches, diversions, and river gages. A schematic of the Umatilla River Planning Model is shown in Figure 25. The red circles indicate water users (representing diversions) and are labeled with the water user name or acronym. The orange boxes indicate stream gages and are named with their four-letter acronym from the Hydromet program (Reclamation 2023b). The green triangles represent locations where gains and losses are input into the model. The purple pentagons represent exchanges which pump water from the Columbia River in return for leaving water in the Umatilla River.

It is important to understand that 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. In addition, the diagram is a schematic of the system and is not representative of geographic distances between each object.

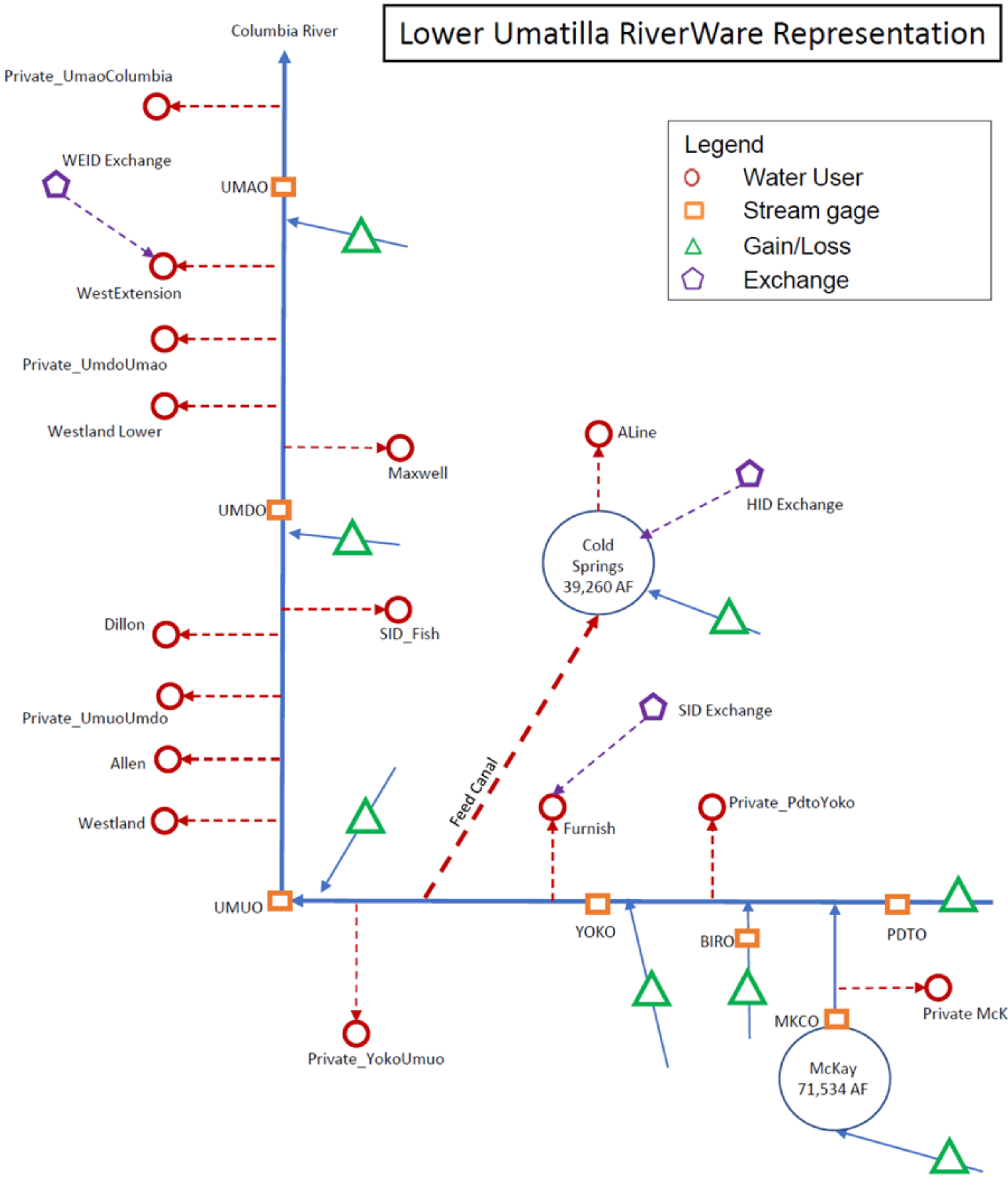


Figure 25. Schematic of RiverWare representation of Lower Umatilla River basin

5.3. Model Calibration

RiverWare models operate based on user-specified logic that determines how water is distributed in the system. Individualized operations that are specific to system operations are written as rules to compute reservoir outflow. This includes the use of the Existing SRD used to guide fill of the reservoir.

The model was previously calibrated by adjusting rules to match historical reservoir contents and outflows, streamflow at the gages, and grouped diversions represented on Water User objects. The calibration period was October 1, 2010, through September 30, 2018, to ensure the model and logic reasonably simulated recent historical operations. Model output was compared to measured historical data to determine the quality of performance of the operational logic.

5.4. Model Operation

The model development described above created a "Baseline" scenario from which changes to current operations could be simulated to compare results and determine effects to the system. The Baseline scenario utilizes the Existing SRD. Six other scenarios were developed to incorporate the SRDs and WSFs developed as part of this Study:

1. 800sSRD – this scenario utilizes the 800sSRD and does not require a forecast to inform space requirements.
2. 1200sSRD - this scenario utilizes the 1200sSRD and does not require a forecast to inform space requirements.
3. 800dSRD perfect forecast (P) – this scenario utilizes the 800dSRD with a "perfect forecast" to inform space requirements. The perfect forecast is a forecast value that exactly matches the actual observed runoff volume, and therefore would be considered the optimal operation. Note that the purpose of including the perfect forecast scenarios (800dSRD (P) and 1200dSRD (P) is to illustrate that additional benefit to operations may be possible if forecast performance can be improved in the future as technology improves. This is not to imply that a perfect forecast, and therefore optimal operation, can be achieved now or in the future.
4. 1200dSRD perfect forecast (P) – this scenario utilizes the 1200dSRD with a "perfect forecast" to inform space requirements.
5. 800dSRD imperfect forecast (F) – this scenario utilizes the 800dSRD with an "imperfect forecast" to inform space requirements. The four PyForecast hindcast average was used as the imperfect forecast for this purpose, and therefore considers forecast error that would have been present during real-time operations.
6. 1200dSRD imperfect forecast (F) - this scenario utilizes the 1200dSRD with the "imperfect" four PyForecast hindcast average to inform space requirements.

5.5. Metrics

For purposes of this study, it was important to understand if operating to a different SRD would result in lower peak flows below McKay Dam. However, a reduction in peak flow downstream should not come at the expense of reservoir fill in the spring, resulting in a corresponding loss to water supply later in the season. Therefore, three metrics were developed for this study to assess potential effects of changing system operations:

1. "Max Flood Space" – this metric measures the annual maximum reservoir content reached. The purpose of this metric is to understand to what extent (if any) the 6,000 acre-feet of exclusive flood control space is used. When compared to the Baseline, if the scenario resulted in exclusive flood control space being used to less of an extent, it was considered an improvement.
2. "Max Fill" – this metric measures the annual maximum reservoir fill just prior to the reservoir drafting for the season for downstream demand. The purpose of this metric is to understand to what extent storage water supply availability is affected, if at all. A separate reservoir fill metric was needed for this purpose because in some cases, it is possible McKay Reservoir could fill into the exclusive flood control space (Max Flood Space), but then be required to draft back below normal full pool per the SRD, and ultimately miss refill (Max Fill). When compared to the Baseline, if the scenario resulted in McKay Reservoir being at the same or higher reservoir content just prior to drafting on an annual basis, it was considered an improvement.
3. "Max Outflow" – this metric measures the annual peak discharge below McKay Dam. The purpose of this metric is to understand to what extent peak discharge below McKay Dam exceeds the historical safe channel capacity of 1,200 cfs. When compared to the Baseline, if the scenario resulted in an annual peak discharge that was less than the Baseline, it was considered an improvement.

5.6. Results

This analysis used the Lower Umatilla River Planning Model with historical inflow hydrology from WY1994 through WY2022 (which was the period for which all data necessary to run the model was available) with seven operational scenarios: 1) Existing SRD (Baseline), 2) 800sSRD, 3) 1200sSRD, 4) 800dSRD (P), 5) 1200dSRD (P), 6) 800dSRD (F), and 7) 1200dSRD (F). Statistics were compiled for each metric: 1) Max Flood Space, 2) Max Fill, and 3) Max Outflow, to determine if improvement (or detriment) over the baseline condition was achieved.

5.6.1. Max Flood Space Metric

Figure 26 summarizes the results from the seven different operational scenarios of the Lower Umatilla River Model as they relate to the Max Flood Space metric. The statistics for each scenario are displayed as a box plot. The red boxes represent the interquartile range (25th percentile to 75th percentile) with the median shown as a black horizontal line. The blue boxes represent between the 10th and 25th percentiles, and between the 75th and 90th percentiles. The clear boxes represent between the minimum and 10th percentiles, and between the 90th percentile and maximum. Two gray dashed lines are shown to represent the normal full pool content of 65,534 acre-feet and the top of exclusive flood control space of 71,534 acre-feet.

For example, for the 1200sSRD scenario, the 90th percentile Max Flood Space metric (top of the upper blue box) was 65,516 acre-feet, just below normal full pool level of 65,534 acre-feet. In other words, 90 percent of years reached a lower elevation than 65,516 acre-feet for this metric.

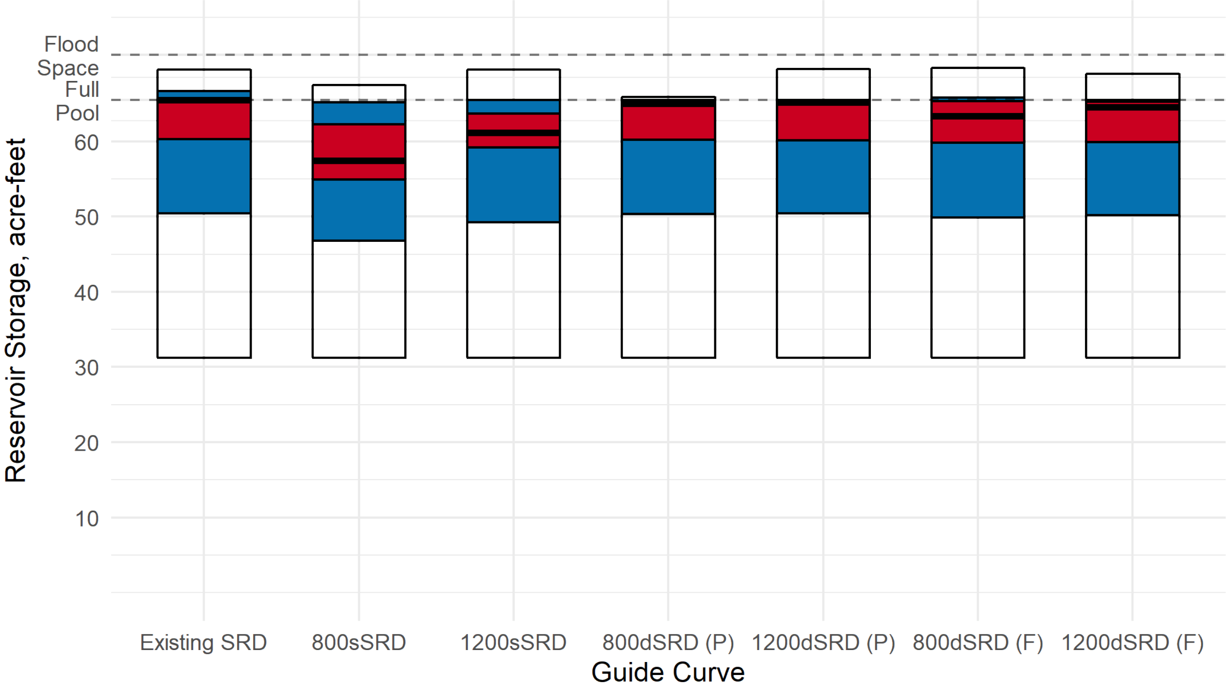
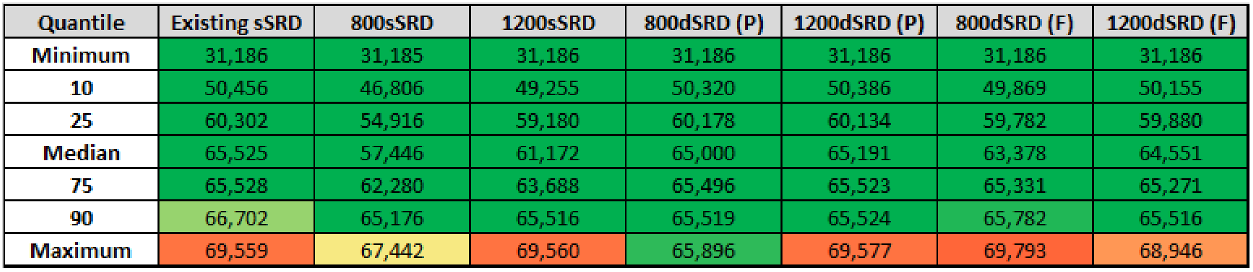


Figure 26. Statistical box plot summary results for the seven different operational scenarios of the Lower Umatilla River Model as they relate to the Max Flood Space metric

The data can also be found in tabular form in Table 6. A heat map has been added to the table to help distinguish effectiveness of the scenario in terms of the Max Flood Space metric. Green colors generally mean the metric is being met and red colors generally mean the metric is not being met. For instance, for the maximum case, the 800dSRD (P) results in a maximum content of 65,896 acre-feet which only utilized 362 acre-feet of the 6,000 acre-feet of exclusive flood control space, and therefore has been colored green to signal that scenario has minimized the use of exclusive flood control space. Conversely, the Existing sSRD results in a maximum content of 69,559 acre-feet in the maximum case, a use of 4,025 acre-feet of the 6,000 acre-feet of exclusive flood control space. This entry has been colored in a red tone to indicate that the scenario is utilizing more of the exclusive flood space.

Table 6. Statistical tabular summary results of maximum reservoir fill (acre-feet) for the seven different operational scenarios of the Lower Umatilla River Model as they relate to the Max Flood Space metric



Quantile	Existing sSRD	800sSRD	1200sSRD	800dSRD (P)	1200dSRD (P)	800dSRD (F)	1200dSRD (F)
Minimum	31,186	31,185	31,186	31,186	31,186	31,186	31,186
10	50,456	46,806	49,255	50,320	50,386	49,869	50,155
25	60,302	54,916	59,180	60,178	60,134	59,782	59,880
Median	65,525	57,446	61,172	65,000	65,191	63,378	64,551
75	65,528	62,280	63,688	65,496	65,523	65,331	65,271
90	66,702	65,176	65,516	65,519	65,524	65,782	65,516
Maximum	69,559	67,442	69,560	65,896	69,577	69,793	68,946

From these results, several observations can be drawn:

1. Up to the 75th percentile, no scenarios need to utilize the exclusive flood space to help manage large inflow events in the basin.
2. At 90th percentile, all six of the new SRDs result in no use of exclusive flood space, while the Existing sSRD makes use of nearly 1,200 acre-feet of the 6,000 acre-feet of exclusive flood space. This indicates that the new SRDs are resulting in an improvement.
3. In the maximum case, the Existing sSRD, 1200sSRD, 1200dSRD (P), and 800dSRD (F) all perform similarly, utilizing around 4,000 acre-feet of the 6,000 acre-feet of exclusive flood space. The 1200dSRD (F) performs slightly better, utilizing around 3,400 acre-feet. The 800sSRD and 800dSRD (P) perform the best, utilizing only 1,900 and 400 acre-feet, respectively, of flood space in this maximum case.

Overall, all the new SRDs show improvement over the Existing sSRD in terms of the Max Flood Space metric.

5.6.2. Max Fill Metric

Figure 27 summarizes the results from the seven different operational scenarios of the Lower Umatilla River Model as they relate to the Max Fill metric. The statistics for each scenario are displayed as a box plot, formatted similarly to the plot described above for Figure 26.

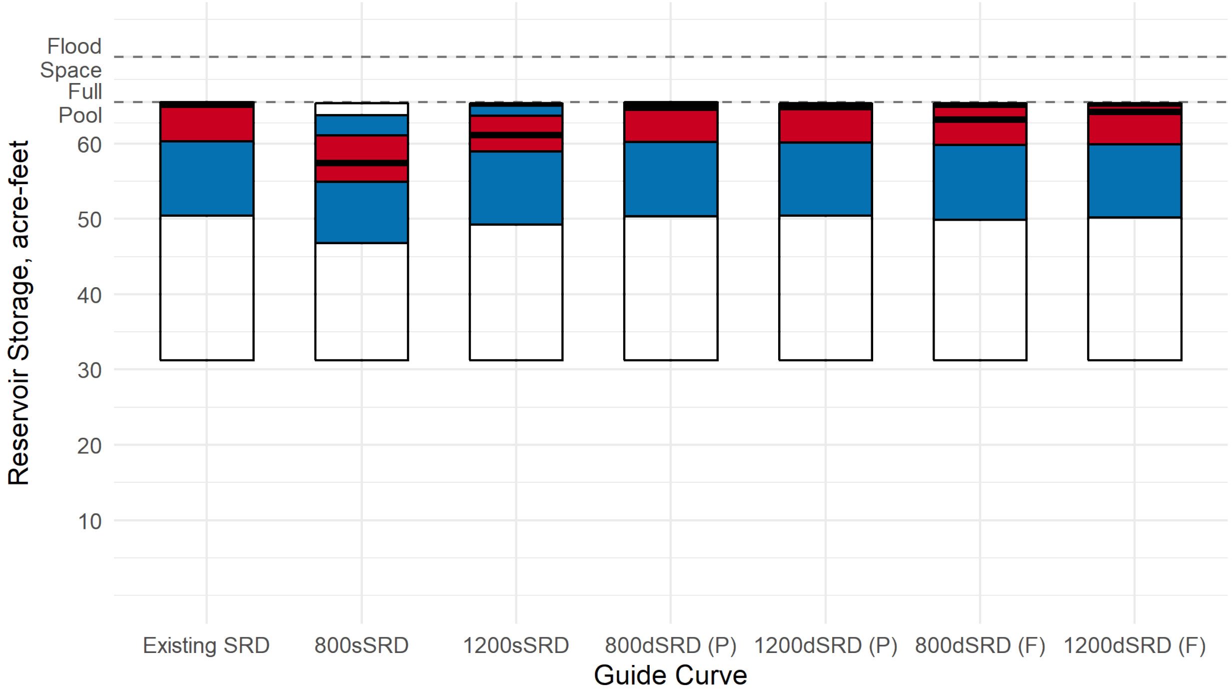


Figure 27. Statistical box plot summary results for the seven different operational scenarios of the Lower Umatilla River Model as they relate to the Max Fill metric

The data can also be found in tabular form in Table 7. Like before, a heat map has been added to the table to help distinguish effectiveness of the scenario in terms of the Max Fill metric. Green colors generally mean the metric is being met and red colors generally mean the metric is not being met. For instance, for the median case, the Existing sSRD results in a maximum content of 65,184 acre-feet, a fill miss of only 350 acre-feet below normal full pool of 65,534 acre-feet, and therefore has been colored green to signal that scenario has nearly filled the reservoir for water supply. Conversely, the 800sSRD results in a maximum content of 57,446 acre-feet in the median case, a fill miss of nearly 8,100 acre-feet. This entry has been colored in a red tone to indicate the scenario resulted in less reservoir fill for water supply.

Table 7. Statistical tabular summary results of maximum reservoir fill (acre-feet) for the seven different operational scenarios of the Lower Umatilla River Model as they relate to the Max Fill metric

Quantile	Existing sSRD	800sSRD	1200sSRD	800dSRD (P)	1200dSRD (P)	800dSRD (F)	1200dSRD (F)
Minimum	31,186	31,185	31,186	31,186	31,186	31,186	31,186
10	50,456	46,806	49,255	50,320	50,386	49,869	50,155
25	60,302	54,916	58,923	60,178	60,134	59,782	59,880
Median	65,184	57,446	61,172	64,773	64,868	63,231	64,235
75	65,251	61,052	63,688	65,195	65,122	64,863	65,013
90	65,326	63,759	65,024	65,350	65,301	65,199	65,195
Maximum	65,482	65,367	65,367	65,467	65,367	65,369	65,367

From these results, several observations can be drawn:

1. In the driest scenario, all curves perform the same since no space would be required by any of the SRDs with reservoir content that low.
2. The 800dSRD (both (P) and (F)), and 1200dSRD (both (P) and (F)) all perform similar up to the 25th percentile. This is likely due to the reservoir being below any forecast informed space requirement during dry type years. However, the 800sSRD and 1200sSRD both result in less fill comparatively (about 5,400 acre-feet and 1,400 acre-feet, respectively). Since the sSRDs do not consider basin conditions, the lower fill in these dry type of years is caused by space being required by the sSRD even though the basin conditions did not support the requirement. Figure 28 shows an example of this effect for the 800sSRD.
3. On the median, the Existing sSRD and the 800dSRD (P) and 1200dSRD (P) perform similarly, with all three resulting in a near full reservoir. The 1200dSRD (F) performs slightly worse, likely due to forecast error which may result in over-forecast events in some cases, requiring more space than needed and causing less fill. The 800dSRD performs slightly worse than that, for the same reason, but an over-forecast results in a bigger miss due to more space being required for the 800dSRD for the same forecast. The 800sSRD and 1200sSRD perform the worst, with fill misses of around 8,000 acre-feet and 4,000 acre-feet, respectively, on the median. This is due to the sSRDs not considering basin conditions and requiring space in years when the basin conditions do not support the requirement.
4. In the wettest 10 percent of years, the water supply availability counteracts any space requirement and allows the reservoirs to fill in most cases, although the 800sSRD still results in some missed fill opportunity at the 90th percentile.

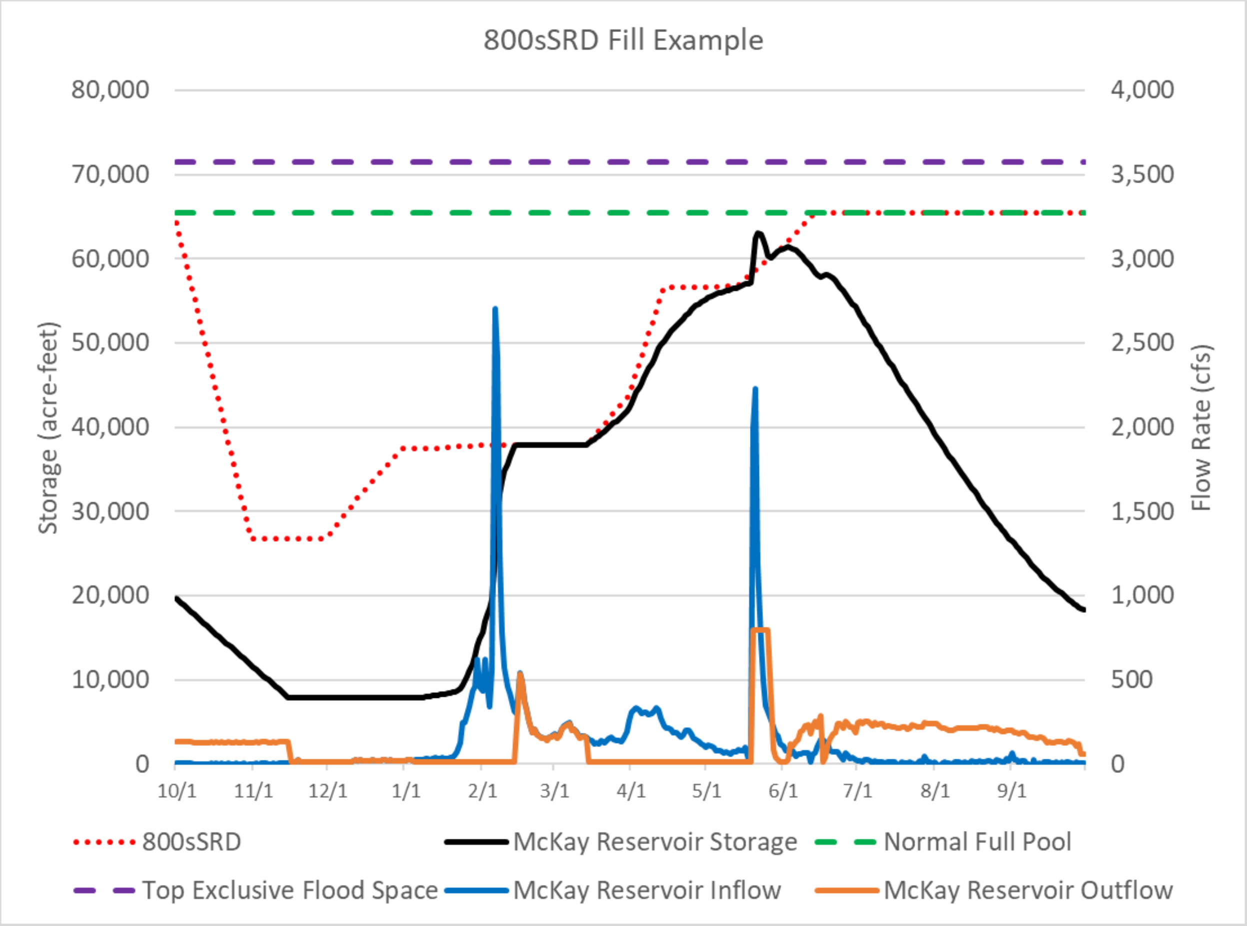


Figure 28. Reservoir fill example of year in which 800sSRD resulted in space being reserved and the reservoir missing fill

Overall, the Existing sSRD provides the best opportunity for reservoir fill. The 800dSRD and 1200dSRD perform very similar to the Existing sSRD when run in perfect forecast mode. In other words, if future runoff can be forecast with a reasonable amount of certainty, the new dynamic curves work well. However, because of forecast uncertainty, the dSRDs sometimes result in less fill due to over-forecast events. The 800sSRD and 1200sSRD perform the worst for this metric due to the curves not accounting for basin conditions and requiring more space than necessary on drier years, with the 1200sSRD performing better than the 800sSRD due to less space required for each day of the season compared to the 800sSRD. In the wettest years, all curves perform nearly the same and fill the reservoir as the water supply counteracts any effects of space requirement.

5.6.3. Max Outflow Metric

Figure 29 summarizes the results from the seven different operational scenarios of the Lower Umatilla River Model as they relate to the Max Outflow metric. The statistics for each scenario are displayed as a box plot. A gray dashed line is shown to represent historical safe channel capacity of 1,200 cfs.

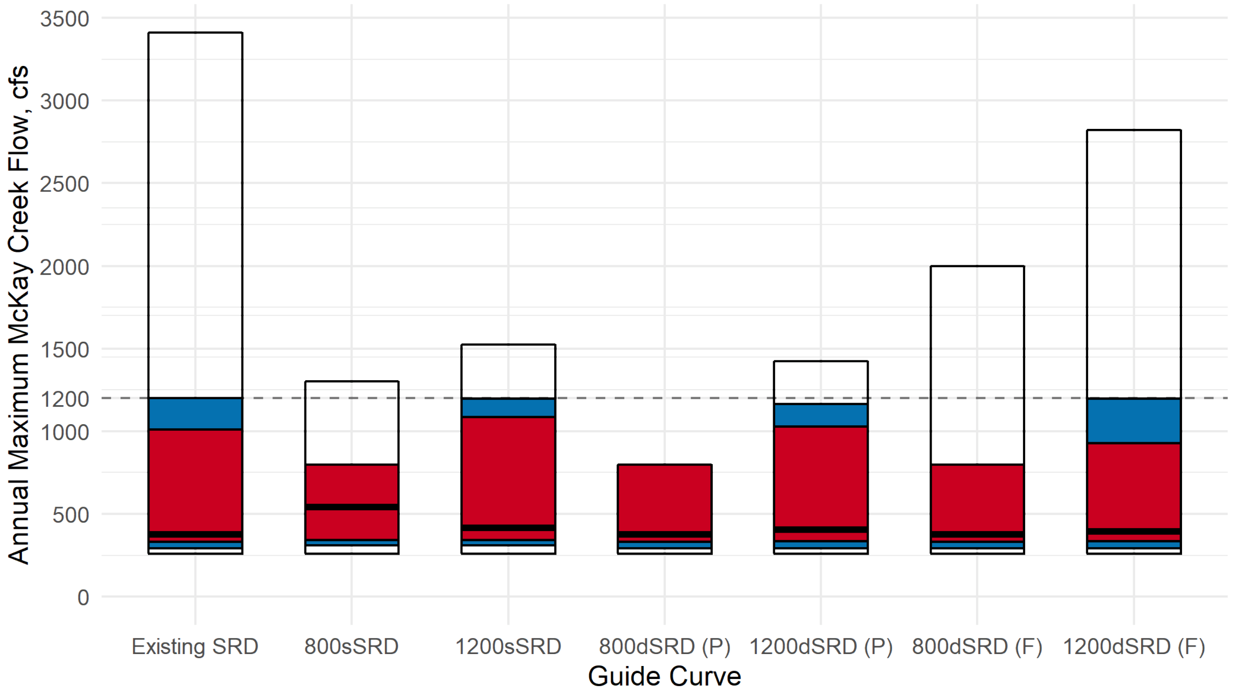


Figure 29. Statistical box plot summary results for the seven different operational scenarios of the Lower Umatilla River Model as they relate to the Max Outflow metric

The data is also presented in tabular form in Table 8. A heat map has been added to the table to help distinguish effectiveness of the scenario in terms of the Max Outflow metric. Green colors generally mean the metric is being met and red colors generally mean the metric is not being met. For instance, for the maximum case, the 800dSRD (P) results in a maximum outflow of 800 cfs and therefore has been colored green to signal that scenario has resulted in a flow less than the channel capacity of 1,200 cfs. Conversely, the Existing sSRD results in a maximum outflow of 3,411 cfs, more than 2,200 cfs higher than the 1,200 cfs safe channel capacity. This entry has been colored in a red tone to indicate that the scenario is not meeting this metric.

Table 8. Statistical tabular summary results for the seven different operational scenarios of the lower Umatilla River Model as they relate to the Max Outflow metric; results in cfs

Quantile	Existing sSRD	800sSRD	1200sSRD	800dSRD (P)	1200dSRD (P)	800dSRD (F)	1200dSRD (F)
Minimum	259	259	259	259	259	259	259
10	293	308	308	293	293	293	293
25	333	342	343	333	335	333	335
Median	377	542	417	377	406	377	395
75	1,012	800	1,087	799	1,030	799	927
90	1,200	800	1,199	800	1,163	800	1,199
Maximum	3,411	1,300	1,523	800	1,423	1,999	2,822

From these results, several observations can be drawn:

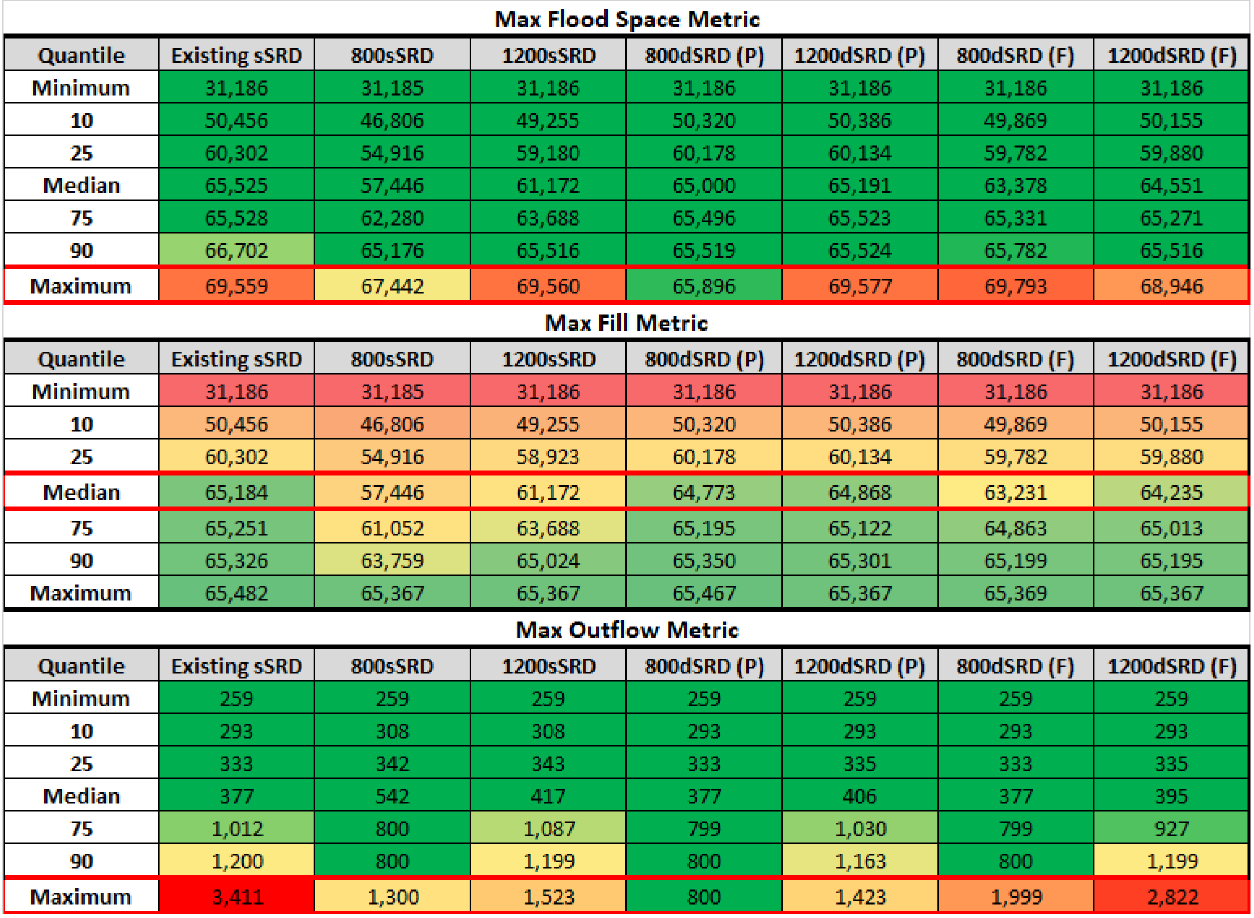
1. All new SRDs result in improvement of maximum Max Outflow when compared to the Existing sSRD, ranging from between around 600 cfs to 2,600 cfs less outflow in the maximum event, as compared to the 3,400 cfs Max Outflow for the Existing sSRD. This type of very large event was the driving force for this Study, and the results show that improvement is possible in terms of Max Outflow through use of a different SRD.
2. The 800dSRD (P) performs the best of all the SRDs, indicating that if forecasts can be made with reasonable level of certainty, it is possible to manage outflows to within safe channel capacity and even provide some buffer. Even when incorporating forecast uncertainty, the 800dSRD (F) still performs better than the Existing sSRD and 1200dSRD (F) but does result in a Max Outflow of around 2,000 cfs, which is more than the 1,200 cfs safe channel capacity.
3. The 800sSRD and 1200sSRD are the best performing SRDs in terms of Max Outflow when forecast uncertainty is considered. Because the sSRD space requirement is independent of future runoff forecast, the sSRDs perform the best in large runoff years because they do not rely on a forecast. However, this benefit comes at the cost of less Max Fill.

Overall, there does appear to be opportunity to provide additional FRM protection downstream through use of an updated SRD, but the suite of metrics needs to be considered when evaluating the effects as more FRM protection may come at the cost of less reservoir fill.

5.7. Discussion

The objective of this analysis was to simulate McKay Reservoir operations using the Existing sSRD (base case) and updated SRDs and WSFs to determine if a reduction to the peak flow downstream of McKay Dam can be achieved without impacting reservoir fill. To understand the full effect, all three metrics must be reviewed in combination to understand cumulative effects. Table 9 shows the statistical results for all three metrics. Red boxes have been drawn around critical ranges to highlight the effects of the different scenarios.

Table 9. Statistical tabular summary results for the seven different operational scenarios of the Lower Umatilla River Model as they relate to the three metrics



Max Flood Space Metric

Quantile	Existing sSRD	800sSRD	1200sSRD	800dSRD (P)	1200dSRD (P)	800dSRD (F)	1200dSRD (F)
Minimum	31,186	31,185	31,186	31,186	31,186	31,186	31,186
10	50,456	46,806	49,255	50,320	50,386	49,869	50,155
25	60,302	54,916	59,180	60,178	60,134	59,782	59,880
Median	65,525	57,446	61,172	65,000	65,191	63,378	64,551
75	65,528	62,280	63,688	65,496	65,523	65,331	65,271
90	66,702	65,176	65,516	65,519	65,524	65,782	65,516
Maximum	69,559	67,442	69,560	65,896	69,577	69,793	68,946

Max Fill Metric

Quantile	Existing sSRD	800sSRD	1200sSRD	800dSRD (P)	1200dSRD (P)	800dSRD (F)	1200dSRD (F)
Minimum	31,186	31,185	31,186	31,186	31,186	31,186	31,186
10	50,456	46,806	49,255	50,320	50,386	49,869	50,155
25	60,302	54,916	58,923	60,178	60,134	59,782	59,880
Median	65,184	57,446	61,172	64,773	64,868	63,231	64,235
75	65,251	61,052	63,688	65,195	65,122	64,863	65,013
90	65,326	63,759	65,024	65,350	65,301	65,199	65,195
Maximum	65,482	65,367	65,367	65,467	65,367	65,369	65,367

Max Outflow Metric

Quantile	Existing sSRD	800sSRD	1200sSRD	800dSRD (P)	1200dSRD (P)	800dSRD (F)	1200dSRD (F)
Minimum	259	259	259	259	259	259	259
10	293	308	308	293	293	293	293
25	333	342	343	333	335	333	335
Median	377	542	417	377	406	377	395
75	1,012	800	1,087	799	1,030	799	927
90	1,200	800	1,199	800	1,163	800	1,199
Maximum	3,411	1,300	1,523	800	1,423	1,999	2,822

By comparing simulations of each scenario to the Baseline, and reviewing results from the three metrics in combination, the following overall conclusions can be drawn:

1. The maximum peak outflow (Max Outflow metric) for the 800sSRD (period peak of 1,300 cfs) and 1200sSRD (period peak of 1,523 cfs) perform better than the Existing sSRD (period peak of 3,411 cfs). However, the median reservoir fill (Max Fill metric) for the 800sSRD (57,446 acre-feet) and 1200sSRD (61,172 acre-feet) perform worse than the Existing sSRD (65,184 acre-feet).
2. When run in perfect (P) forecast mode, the maximum peak outflow for the 800dSRD (P) (period peak of 800 cfs) and 1200dSRD (P) (period peak of 1,423 cfs) perform better than the Existing sSRD (period peak of 3,411 cfs) and for median reservoir fill perform similarly to the Existing sSRD (64,773 acre-feet, 64,868 acre-feet, and 65,184 acre-feet, respectively). However, this result is tempered when forecast error in the system is considered. The purpose of including the perfect forecast scenarios is to illustrate that additional benefit to operations may be possible if forecast performance can be improved in the future as technology improves. This does not imply that a perfect forecast, and therefore optimal operation, can be achieved now or in the future.

3. When run in imperfect (F) forecast mode, the maximum peak outflow for the 800dSRD (F) (period peak of 1,999 cfs) and 1200dSRD (F) (period peak of 2,822 cfs) perform better than the Existing sSRD (period peak of 3,411 cfs) but worse than the 800sSRD (period peak of 1,300 cfs) and 1200sSRD (period peak of 1,523 cfs). The median reservoir fill for the 800dSRD (F) (63,231 acre-feet) and 1200dSRD (F) (64,235 acre-feet) perform worse than the Existing sSRD (65,184 acre-feet), but better than the 800sSRD (57,446 acre-feet) and 1200sSRD (61,172 acre-feet).

In other words, when forecast uncertainty is considered, the additional FRM protection downstream of McKay Reservoir provided by the newly created sSRDs and dSRDs in a rare year may come at the expense of less reservoir fill in a more normal year. However, the possibility for improvement compared to the Existing sSRD remains, especially when considering additional flexibility of real-time operations compared to model simulation. If WSFs can continue to improve in the future with new technology, the full benefit of the dSRD may eventually be realized. Conversely, if WSF becomes more difficult in the future, or the hydrologic regime changes and the past is no longer indicative of the future, the dSRDs as currently designed may not provide the benefits intended. Section 6 discusses the possibilities of future climate change flows.

5.8. Limitations and Uncertainty

River-reservoir models, such as the one used in this study, are designed to replicate current operating criteria along with potential future operating criteria to test potential changes in operations. They use assumptions and simplifications that are required to develop repeatable logic and a suitable test environment for potential future conditions. They are not intended to be predictive in nature, nor are they intended to exactly replicate future operations on a day-to-day basis. Rather, they are intended to be used to understand trends and effects from plausible operations using a range of historical inflow hydrology. Therefore, selecting individual years, months, or days for analysis is not recommended. In addition, statistics from the model output should be used as a guideline for potential future conditions, but it should be recognized that changes to future inflow hydrology or variations in real-time operations could affect the performance of those statistics in the future.

The output from the models presented in this analysis shows the effects of specific operating criteria on key metrics such as reservoir outflow and storage. The uncertainty in the results is represented by a range of outputs presented in the hydrographs and tables.

6. Climate Change

This effort focused on the selection of potential future climate change hydrology in the McKay basin, and the use of that climate change hydrology in the RiverWare model to test the performance of the newly developed SRDs. The potential effects of future climate during the WY2030-WY2059 (i.e., 2040s) and the WY2060-WY2089 (i.e., 2070s) periods were explored. Like the historical hydrology simulations, the

RiverWare model was used to simulate McKay Reservoir operations using the newly developed SRDs under climate change hydrologic conditions to determine the effects to reservoir fill and downstream flow rate. The purpose of this effort was to stress test the existing and newly developed SRD products under perfect forecast simulations to determine how well they may or may not perform into the future.

6.1. Climate Change Hydrology Development

6.1.1. Methodology

Following the methods described in a prior study (Reclamation 2020b), climate change hydrologic inflows were selected from an ensemble of 160 potential future hydrology scenarios for 1950 through 2099 from the River Management Joint Operations Committee (RMJOC-II) Long-Term Planning Studies, Part 1 (RMJOCII 2018). The hydrology scenarios are varying combinations of global climate models (inmcm4; CNRM-CM5; MIROC5; CanESM2; CCSM4; HadGEM2-ES; HadGEM2-CC; GFDL-ESM2M; CSIRO-Mk3-6-0; IPSL-CM5A-MR), global emission scenarios (RCPs 4.5 and 8.5), downscaling techniques (BCSD and MACA), hydrologic routing (VIC and PRMS), and calibration techniques (x3).

The modeled future flows in the Umatilla River near Umatilla and Pendleton were selected (UMAO and PDTO, respectively, in Hydromet). These are the only locations on the Umatilla River provided in the RMJOC-II data. Unlike RMJOC-II data for other sites, this data had not yet been bias-corrected, which is a necessary step after downscaling for adjusting predicted flows for specific locations to remove model bias (e.g., over-/under-predicting base flows). An automated bias-correction was applied using the 'BMorph' bias correction package (Pierce et al. 2015) used by the RMJOC-II. The technique used the historical daily flows at the UMAO and PDTO gages for 1993 through 2019 to apply a quantile-mapping-based daily bias correction to each scenario from 1950 through 2099.

After bias-correction, the resulting flows at Umatilla and Pendleton were spatially disaggregated to estimate the flows at three gages between Umatilla and Pendleton (YOKO, UMUO, and UMDO in Hydromet), Birch Creek, and inflow into McKay Reservoir. These flows were needed for calculating the gains and losses for each reach in the RiverWare model. The live flow at each gage was calculated by applying multiple linear regression equations for each month, which were established from the historical live flow data for 1993 through 2019 between the three additional gages (YOKO, UMUO, and UMDO), Birch Creek, and McKay Reservoir inflow as the response variables and the two RMJOC-II gages (UMAO and PDTO) as the predictor variables. This period was used because this is the historical period that the necessary gage data had been collected and processed for the RiverWare model for the historical period.

Hydrology scenarios were selected using a selection tool developed for RMJOC-II. The selection tool uses an automated approach to choose a set of scenarios that capture a range of variability for specified metrics at specific locations. For specific locations, the tool was set to assess stream flow at the PDTO and UMAO gages. Flow at both gages is important to include for assessing climate impacts to the lower Umatilla Basin. For metrics, the selection tool was set to assess changes in half volume day, winter flow volumes, total annual flow volumes, spring flow volumes, summer flow volumes, and the ratio of winter to spring volume.

Each hydrology scenario was evaluated during the WY2030-WY2059 period (2040s) and the WY2060-WY2089 period (2070s) by its change relative to its respective baseline scenario for the 1975 to 2005 period, as was used in RMJOC-II. Each baseline scenario used the same hydrologic model and calibration as the hydrology scenario being evaluated, but with simulated historical climate (Livneh) rather than future climate to avoid comparing differences due to remaining model bias between measured and modeled inflow. In order to approximate the likely range of future hydrology, the selection tool was set to pick models that produced flows within 5 percent of the 10th and 90th percentiles of the metrics evaluated, representing high and low values for each of the six selection metrics. The tool selects the minimum number of models necessary for meeting the criteria.

The tool was run four times: once for each combination of RCP (4.5 and 8.5) and time period (2040s and 2070s). This allowed separate analyses of each RCP and time period. A total of 19 models were selected. The models that were selected are listed below in the following format: ClimateModel_RCPScenario_DownscalingTechnique_HydrologicModel_Calibration:

RCP 4.5

2040s

- CanESM2_RCP45_BCSD_VIC_P1
- HadGEM2-CC_RCP45_MACA_VIC_P2
- IPSL-CM5A-MR_RCP45_MACA_VIC_P3
- MIROC5_RCP45_BCSD_PRMS_P1

2070s

- CNRM-CM5_RCP45_BCSD_VIC_P3
- CSIRO_Mk3-6-0_RCP45_MACA_VIC_P2
- IPSL-CM5A-MR_RCP45_MACA_VIC_P2
- MIROC5_RCP45_MACA_VIC_P1
- MIROC5_RCP45_MACA_VIC_P3

RCP 8.5

2040s

- CanESM2_RCP85_BCSD_VIC_P2
- CNRM-CM5-RCP85_MACA_VIC_P2
- GFDL-ESM2M_RCP85_MACA_PRMS_P1
- IPSL-CM5A-MR_RCP85_BCSD_VIC_P1
- MIROC5-RCP85_BCSD_PRMS_P1

2070s

- CanESM2_RCP85_BCSD_VIC_P3
- CNRM-CM5_RCP85_MACA_VIC_P2
- CSIRO-Mk3-6-0_RCP85_MACA_VIC_P3
- HadGEM2-CC_RCP85_MCSD_VIC_P2
- inmcm4_RCP85_BCSD_VIC_P3

Inflows and local gains developed for each of the selected climate scenarios were then used as model inputs for simulations with each of the five SRDs described in Section 4. For simulations using a dSRD, perfect forecasts were used. Thus, 100 simulations were analyzed for climate change analysis: 95 simulations using predicted climate change hydrology and 5 simulations using historical hydrology for comparison.

6.1.2. Summary Hydrographs

For each time period (2040s and 2070s) and RCP (4.5 and 8.5), the selected hydrologic sequences were used to develop a range of possible 10th percentile, median, 90th percentile, and maximum McKay Reservoir inflows for each day of the water year. The range of possibilities is used to account for uncertainty in future climate change hydrology. The range of possibilities was then compiled to develop a summary hydrograph for each, with the range represented by a shaded band (RCP4.5 represented by a light red band and RCP8.5 represented by a light blue band). For example, Figure 30 shows the 10th percentile 2040s. The light red RCP4.5 band shows the range of 10th percentile values for the selected hydrologic sequences. The historical hydrology condition, represented by a single line, was then overlain for comparison. The following sections describe the results for each time period.

6.1.2.1. 2040s

The following four figures show a progression of summary hydrographs for McKay Reservoir inflow for the 2040s period, starting with the 10th percentile low flow condition up to the maximum high flow condition. The scale is the same for each of the 10th, median, and 90th percentile graphs (and is also the same as the 2070s hydrographs in Section 6.1.2.2) for ease of relative comparison. The scale for the maximum scenario has been set to capture the maximum flow rate.

Figure 30, 10th percentile 2040s, shows a general shift to slightly earlier and higher magnitude flows in the climate change condition as compared to the historical condition. Flows after the peak are generally similar to the historical condition but vary depending on climate scenarios.

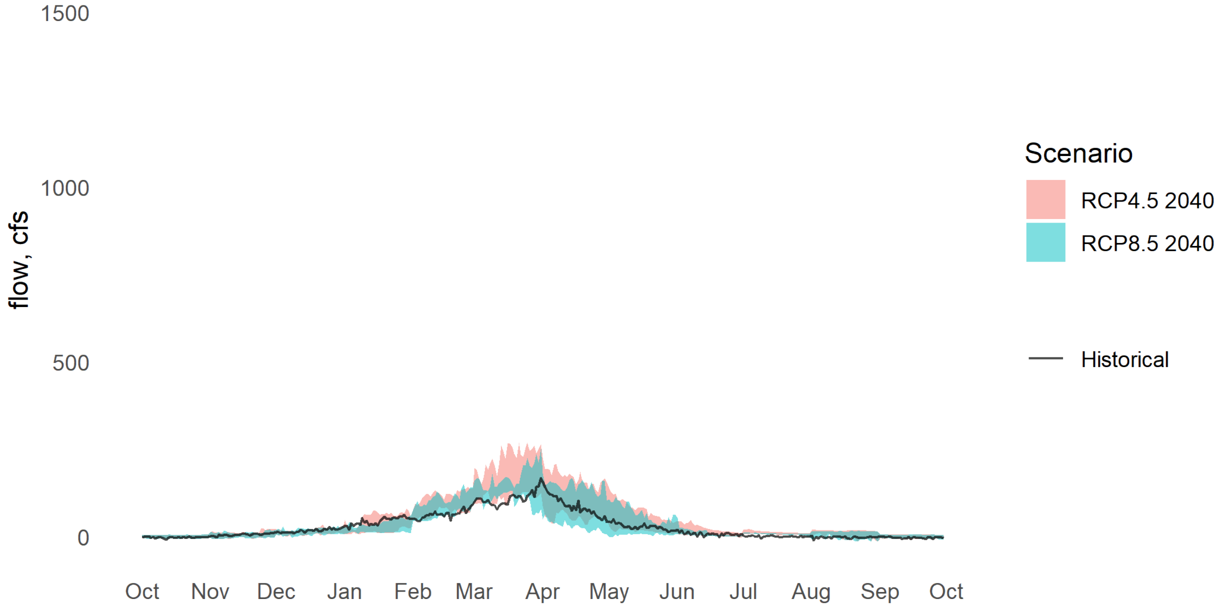


Figure 30. Summary hydrographs of McKay Reservoir Inflow for historical hydrology and 2040s (both RCP 4.5 and 8.5) for the 10th percentile flow for each day of the water year. The RCP4.5 2040s is represented by a light red band, the RCP8.5 2040s is represented by a light blue band, and the historical hydrology is represented by a single black line.

Figure 31, median 2040s, shows similar peak flow timing and magnitude, but with more flow materializing in the late winter February through March time frame and in the late spring May through June timeframe. The higher late winter flows are indicative of more precipitation falling as rain rather than snow during that time frame. The late spring flows are indicative of the potential for an overall wetter climate in the future.

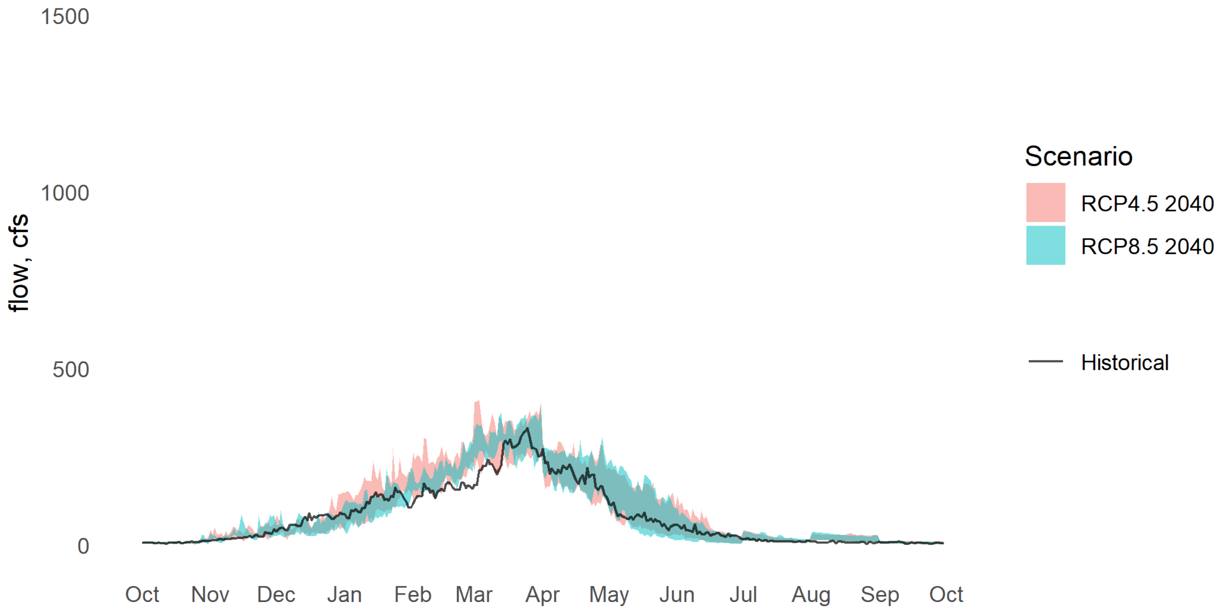


Figure 31. Summary hydrographs of McKay Reservoir Inflow for historical hydrology and 2040s (both RCP 4.5 and 8.5) for the median flow for each day of the water year. The RCP4.5 2040s is represented by a light red band, the RCP8.5 2040s is represented by a light blue band, and the historical hydrology is represented by a single black line.

Figure 32, 90th percentile 2040s, shows a stronger pattern of a shift to earlier timing and larger magnitude inflow events in the winter and early spring, and fewer large inflow events in the late spring and early summer months. This pattern is likely indicative of more rain and rain-on-snow type events during the winter, leading to less snowpack in the spring that historically contributed to high flow events in that time period.

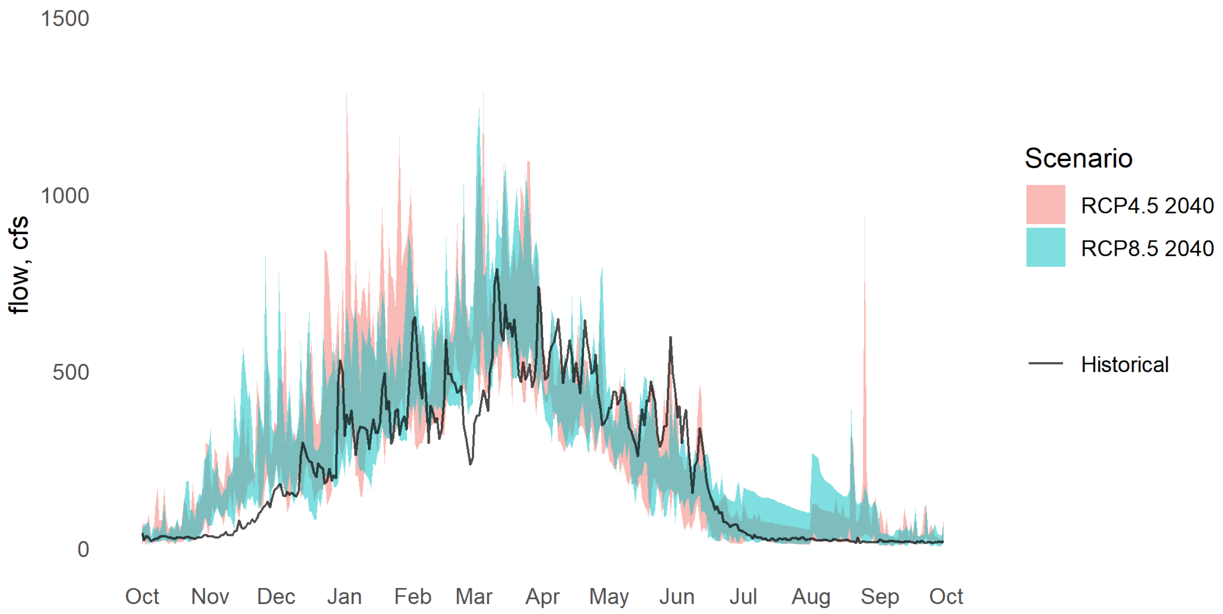


Figure 32. Summary hydrographs of McKay Reservoir Inflow for historical hydrology and 2040s (both RCP 4.5 and 8.5) for the 90th percentile flow for each day of the water year. The RCP4.5 2040s is represented by a light red band, the RCP8.5 2040s is represented by a light blue band, and the historical hydrology is represented by a single black line.

For the same reasons as discussed above for Figure 32, Figure 33, maximum 2040s, shows a similar pattern as the 90th percentile of a shift to earlier timing and larger magnitude inflow events in the winter and early spring, and fewer large inflow events in the late spring and early summer months. The potential for high flow events in late summer and early fall also appears to be a possibility under climate change, although these had little bearing on this Study.

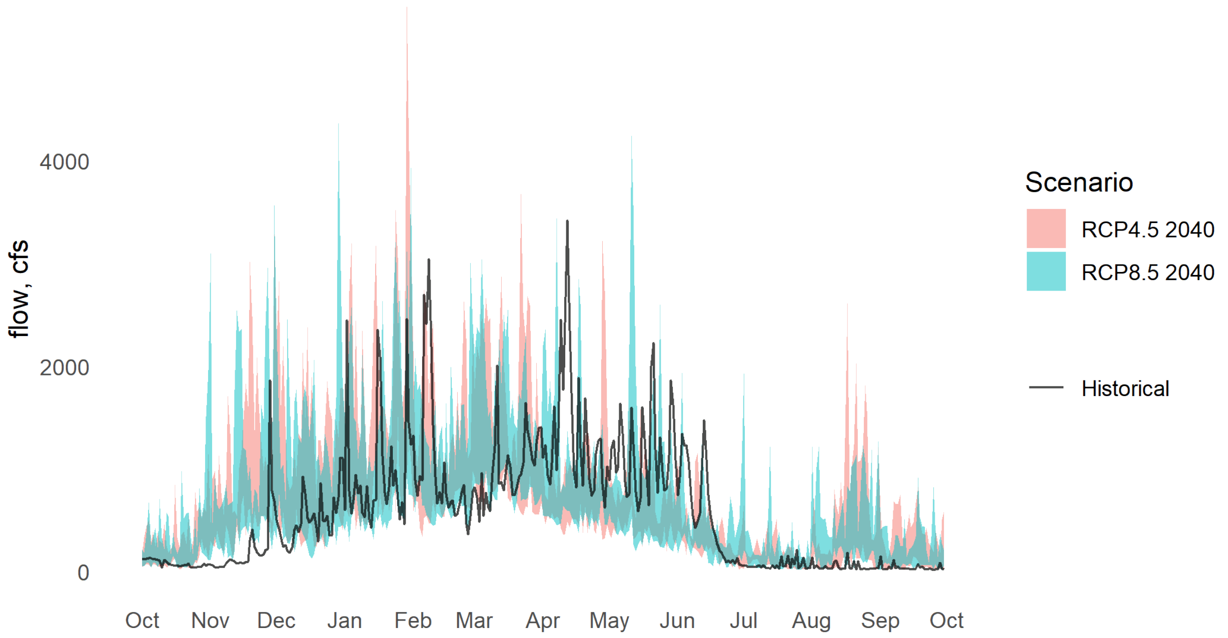


Figure 33. Summary hydrographs of McKay Reservoir Inflow for historical hydrology and 2040s (both RCP 4.5 and 8.5) for the maximum flow for each day of the water year. The RCP4.5 2040s is represented by a light red band, the RCP8.5 2040s is represented by a light blue band, and the historical hydrology is represented by a single black line.

6.1.2.2. 2070s

The following four figures show a similar progression of summary hydrographs for McKay Reservoir inflow for the 2070s period, starting with the 10th percentile low flow condition up to the maximum high flow condition. Figure 34, 10th percentile 2070s, shows a strong shift to earlier and higher peak flows in the climate change condition as compared to the historical condition. Flows after the peak are generally similar to the historical condition.

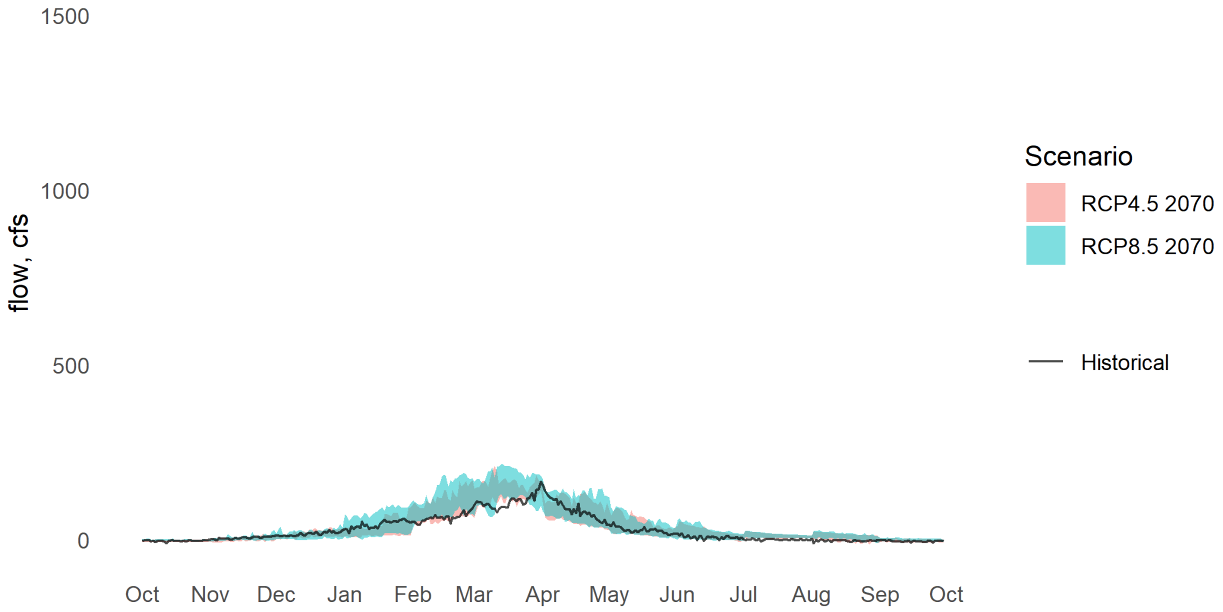


Figure 34. Summary hydrographs of McKay Reservoir Inflow for historical hydrology and 2070s (both RCP 4.5 and 8.5) for the 10th percentile flow for each day of the water year. The RCP4.5 2070s is represented by a light red band, the RCP8.5 2070s is represented by a light blue band, and the historical hydrology is represented by a single black line.

Figure 35, median 2070s, also shows a shift to earlier timing with similar magnitude as the historical condition, with more flow materializing in the late winter February through March time frame. The higher late winter flows are indicative of more precipitation falling as rain rather than snow during that time frame. Interestingly, the higher early summer flows in May through June are not as strong of a pattern in the 2070s as they were in the 2040s.

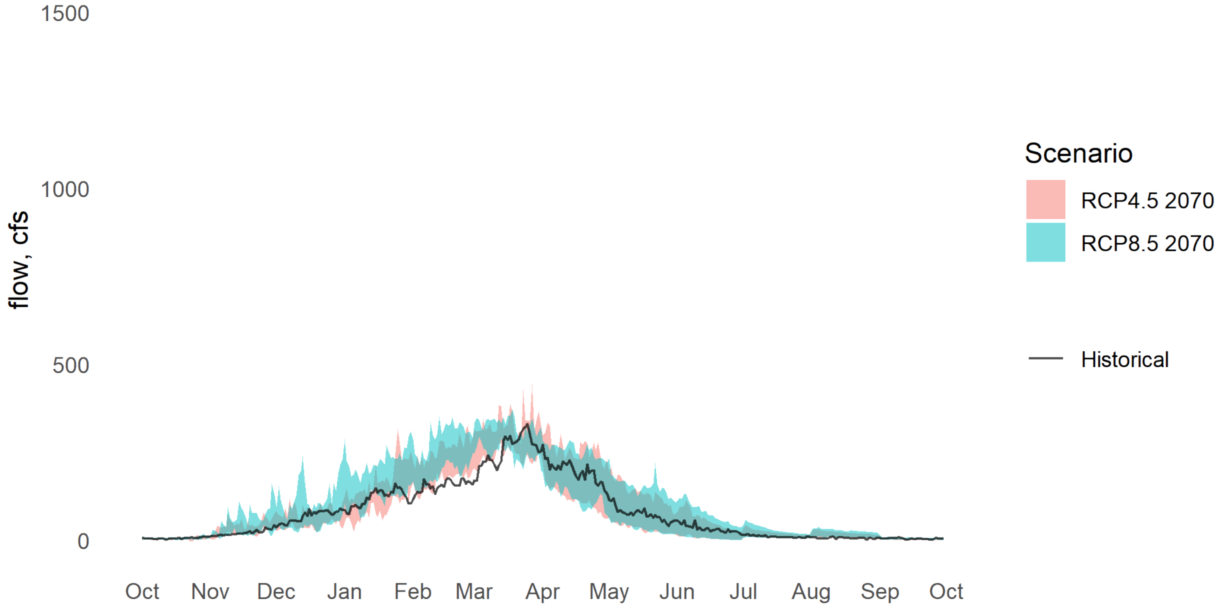


Figure 35. Summary hydrographs of McKay Reservoir Inflow for historical hydrology and 2070s (both RCP 4.5 and 8.5) for the median flow for each day of the water year. The RCP4.5 2070s is represented by a light red band, the RCP8.5 2070s is represented by a light blue band, and the historical hydrology is represented by a single black line.

Figure 36, 90th percentile 2070s, shows a strong pattern of a shift to earlier timing and larger magnitude inflow events in the winter and early spring, and fewer large inflow events in the late spring and early summer months. The magnitude of the winter events is also greater than that seen in the 2040s case. This pattern is indicative of more rain and rain-on-snow type events during the winter, leading to less snowpack in the spring that historically contributed to high flow events in that time period.

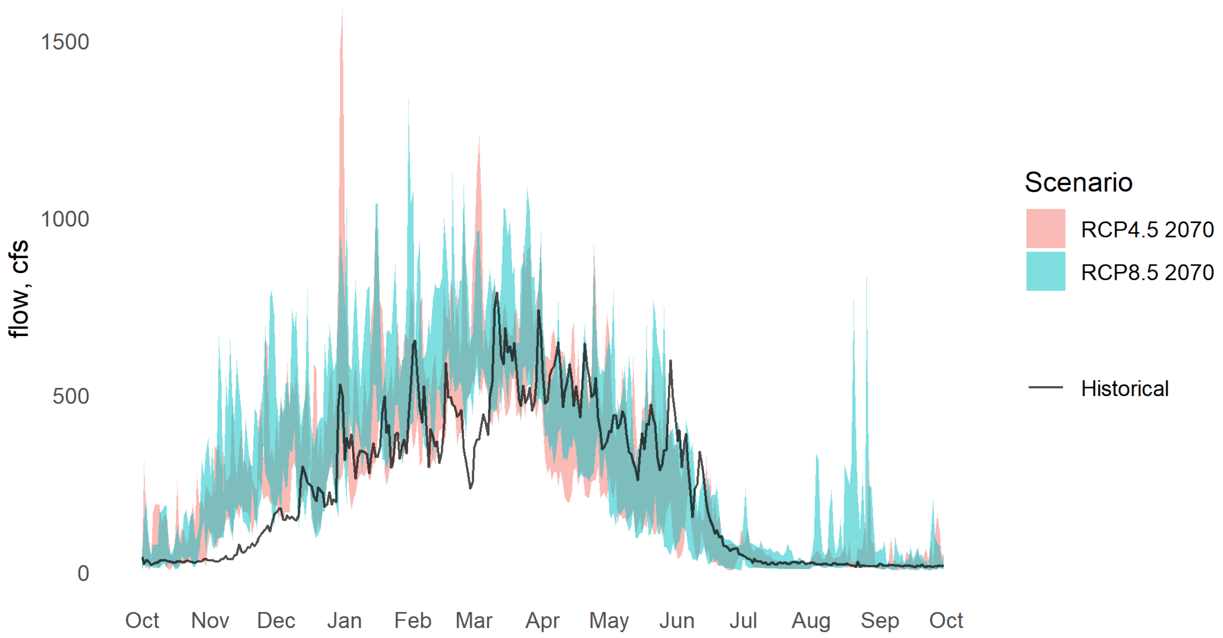


Figure 36. Summary hydrographs of McKay Reservoir Inflow for historical hydrology and 2070s (both RCP 4.5 and 8.5) for the 90th percentile flow for each day of the water year. The RCP4.5 2070s is represented by a light red band, the RCP8.5 2070s is represented by a light blue band, and the historical hydrology is represented by a single black line.

Figure 37, maximum 2070s, for the same reasons described for Figure 36, shows a similar pattern as the 90th percentile of a shift to earlier timing and larger magnitude inflow events in the winter and early spring along with the potential for high flow events in late summer and early fall. The magnitude of the winter and early spring events has the potential to be greater than that seen in the 2040s.

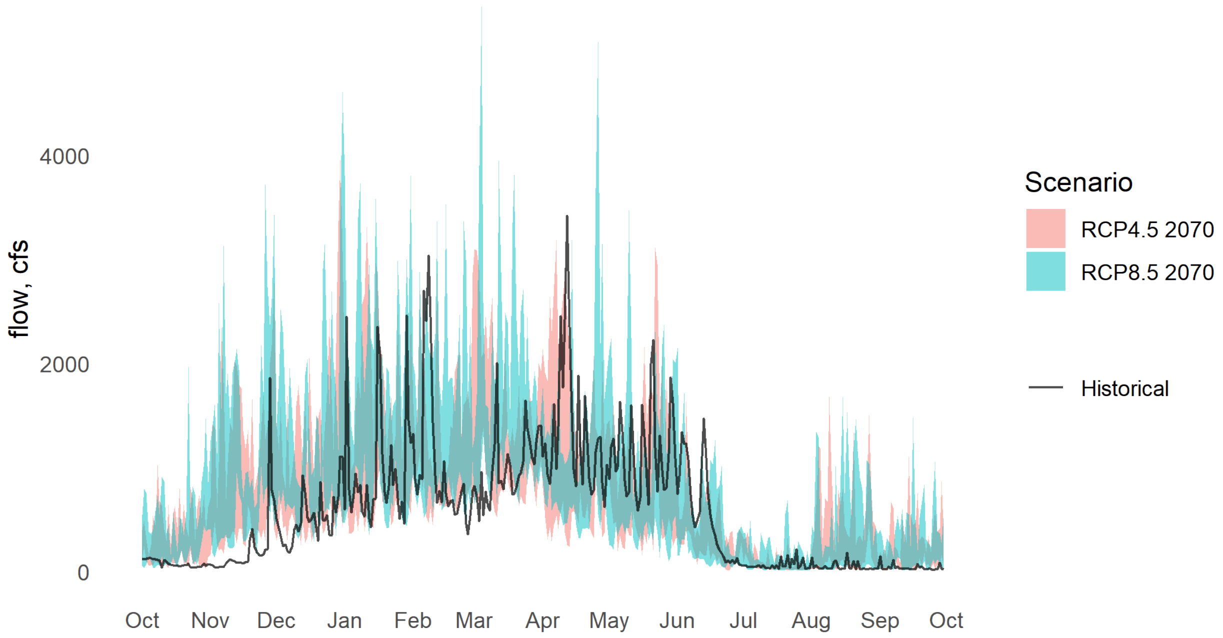


Figure 37. Summary hydrographs of McKay Reservoir Inflow for historical hydrology and 2070s (both RCP 4.5 and 8.5) for the maximum flow for each day of the water year. The RCP4.5 2070s is represented by a light red band, the RCP8.5 2070s is represented by a light blue band, and the historical hydrology is represented by a single black line.

6.1.2.3. 2040s and 2070s Climate Change Hydrology Summary

For both the 2040s and 2070s, a general pattern shift to earlier timing and overall increased water supply is seen in the median condition. For purposes of stress testing the SRDs, the larger 90th percentile and maximum flow events may be of greater concern, with potential for not only earlier timing but also higher magnitude inflows during the winter and early spring months. Section 6.2 describes the simulation results using the climate change hydrology to understand how well the SRDs may or may not perform in the future.

6.2. Simulation Results

The Lower Umatilla River Planning Model was adjusted to utilize the 2040s and 2070s climate change hydrology. Unlike the historical hydrology simulations in which a single historical hydrology sequence was utilized, the climate change simulations include multiple time periods (2040s and 2070s) with multiple RCP levels (4.5 and 8.5) and multiple potential hydrology sequences for each. The result is 19 potential future hydrologic sequences (four RCP 4.5 2040s, five RCP 8.5 2040s, five RCP 4.5 2070s, and five RCP 8.5 2070s). The model was run for each potential hydrologic sequence and was used to simulate five of the previous seven operational scenarios: 1) Existing SRD (Baseline), 2) 800sSRD, 3) 1200sSRD, 4) 800dSRD (P), 5) 1200dSRD (P). The other two scenarios, 800dSRD (F) and 1200dSRD (F), were not utilized for this portion of the Study as the purpose of this analysis is to test the effectiveness of the SRDs under perfect forecast mode to determine how well they may or may not perform under climate change hydrology independent of potential future forecast error. Future forecast uncertainty was not analyzed as part of this Study and would result in additional variability in the performance of the dSRDs under climate change hydrology.

Like the historical hydrology simulations described in Section 5, statistics were compiled for each simulation for each metric 1) Max Flood Space, 2) Max Fill, and 3) Max Outflow. The statistics were evaluated to determine if improvement (or detriment) over baseline (Existing sSRD) was achieved. The statistical results are displayed in a different manner than for the historical hydrology simulations. To account for the range of potential future climate change hydrology, a range of possibilities is shown. For each metric, individual diagrams are shown for the 10th percentile, median, 90th percentile, and maximum case. Each operational scenario includes a point to illustrate the historical hydrology condition and a series of four colored boxes to represent the range of possibilities given a particular climate change timeframe and RCP; the presentation format is explained in more detail in the following sections.

6.2.1. Max Flood Space Metric

Figure 38 displays the climate change simulation results for the 10th percentile of the Max Flood Space metric. Each scenario is represented by a point and four colored bars. The point represents the historical hydrology condition. The light blue bar represents the potential range of 10th percentile outcomes based on the simulations of the four RCP4.5 2040s hydrologic sequences. The dark blue bar is for the RCP8.5 2070s, and so on. Because future climate hydrology is uncertain, this method allows conclusions to be drawn based on a range of possibilities occurring.

For example, when reviewing the data for the Existing sSRD simulations, the 10th percentile Max Flood Space for historical hydrology was 50,456 acre-feet content, shown by the black dot. For the RCP4.5 2040s simulations, the range of 10th percentile Max Flood Space, shown by the light blue bar, was between approximately 35,000 acre-feet and approximately 65,000 acre-feet, meaning it is possible the use of the Existing sSRD in future climate change hydrologic conditions could result in higher or lower Max Flood Space levels in the 10th percentile than under historical hydrologic conditions. In the case of the 10th percentile, this result is of little consequence for this metric as the exclusive flood space is not being used in any case.

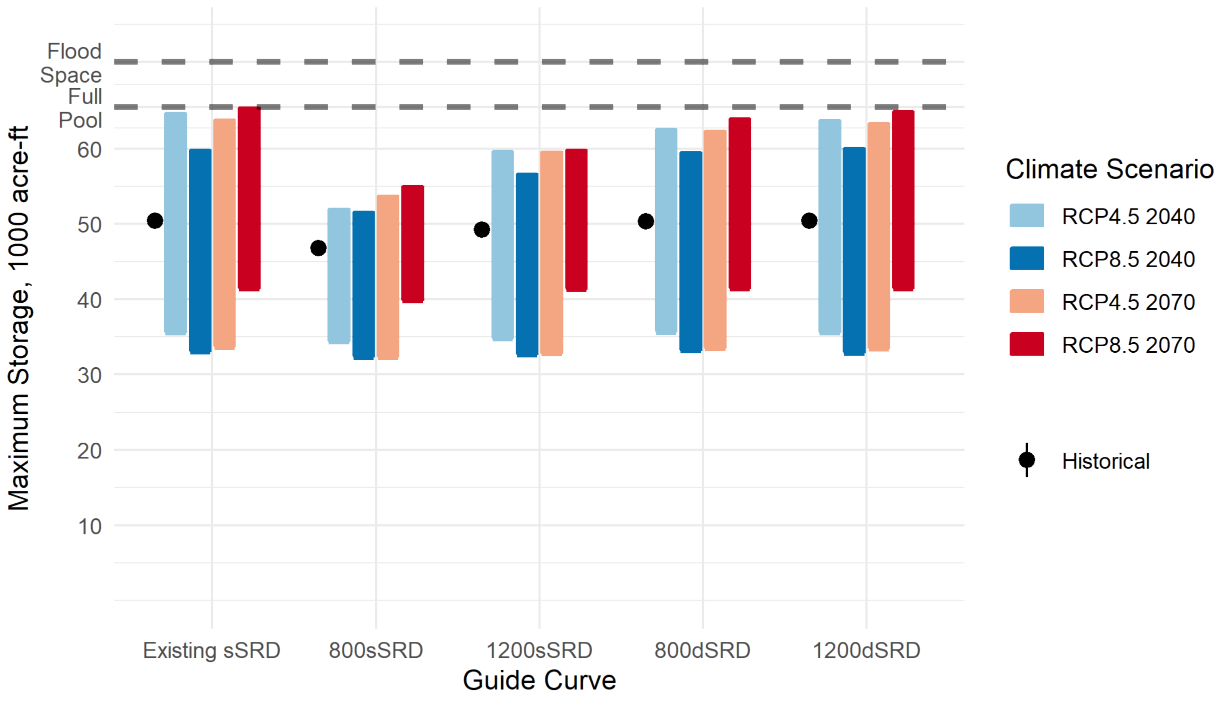


Figure 38. 10th percentile summary results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Flood Space metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential 10th percentile outcomes under potential future climate change hydrology.

Similarly, in the median case (Figure 39) for the Max Flood Space metric, the exclusive flood space is not being utilized in any case, and therefore is of little consequence as to which SRD is used for this particular metric.

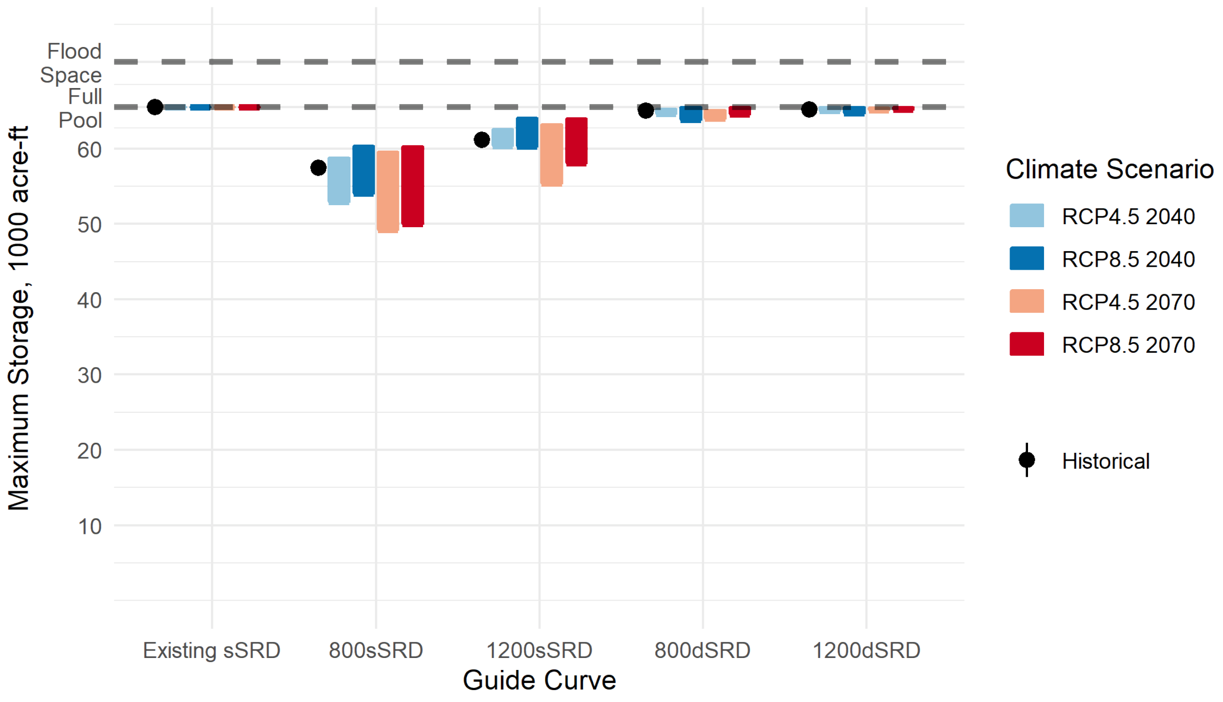


Figure 39. Median results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Flood Space metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential median outcomes under potential future climate change hydrology.

However, in the 90th percentile case (Figure 40) for the Max Flood Space metric, it can be observed that for the Existing sSRD in the RCP8.5 2070s hydrology, it is possible more exclusive flood space may be used than under historical hydrology. This is shown by the top of the red bar extending higher into the exclusive flood space than the black dot. For the other SRDs, no exclusive flood space is needed for this case.

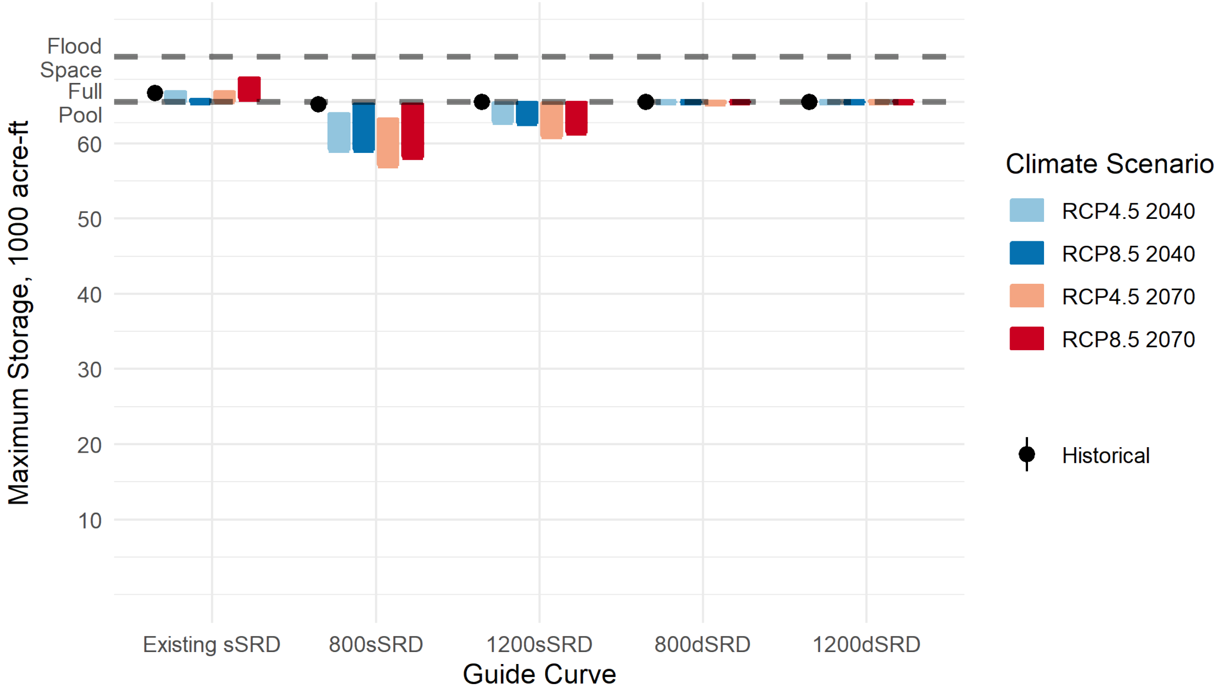


Figure 40. 90th percentile results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Flood Space metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential 90th percentile outcomes under potential future climate change hydrology.

Further, when examining the maximum case (Figure 41) for the Max Flood Space metric, it can be observed that for all SRDs, it is possible with future climate change hydrology that more exclusive flood space may need to be utilized to help manage flows from McKay Dam as compared to historical hydrology – at times, up to the full 6,000 acre-feet.

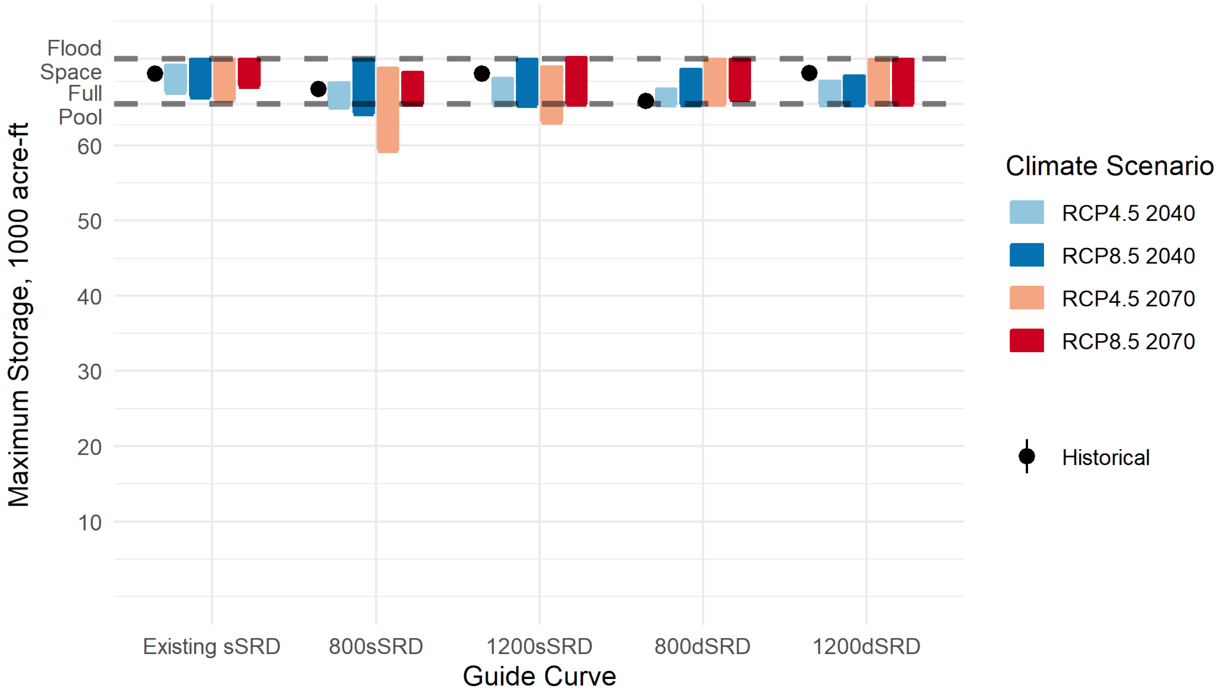


Figure 41. Maximum summary results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Flood Space metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential maximum outcomes under potential future climate change hydrology.

6.2.2. Max Fill Metric

A similar methodology was used to develop the statistical summaries for the Max Fill Metric. In the 10th percentile case (Figure 42), it is possible that all the SRDs in future climate change hydrologic conditions could result in either higher or lower reservoir levels in the 10th percentile than under historical hydrologic conditions. The pattern is generally the same as the historical hydrology simulations in which the 800sSRD and 1200sSRD generally result in lower reservoir levels in the 10th percentile as compared to the other scenarios.

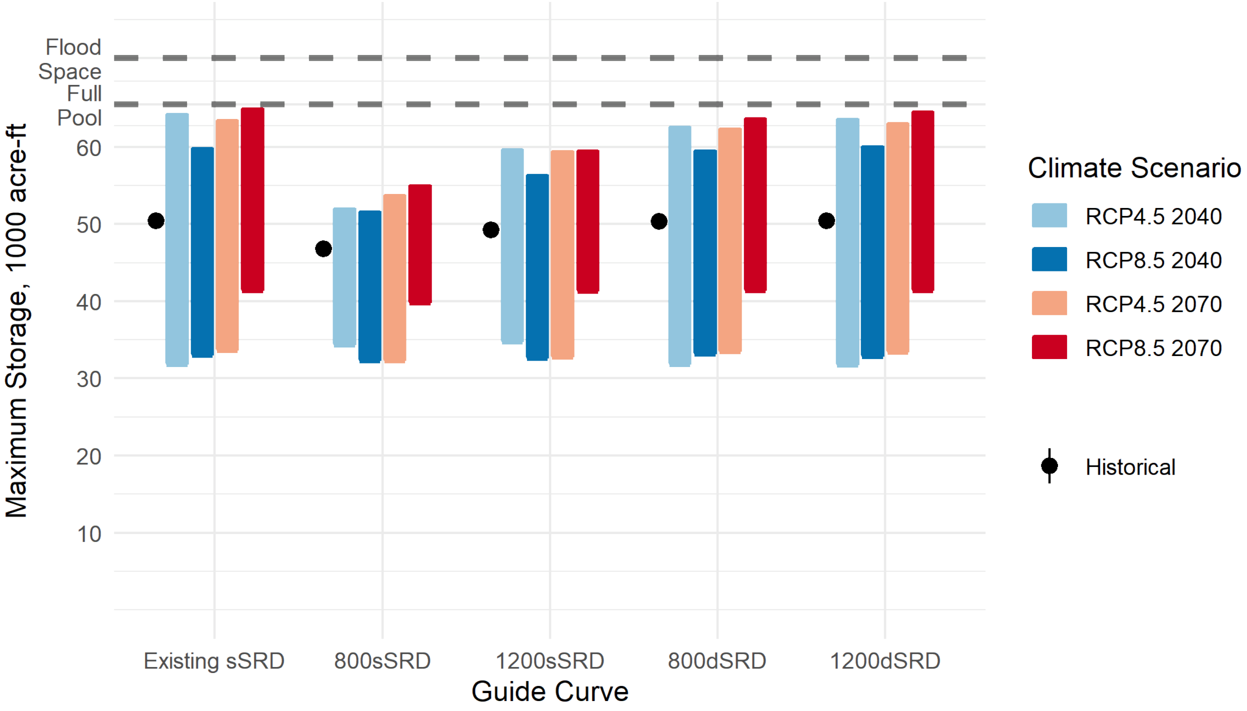


Figure 42. 10th percentile summary results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Fill metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential 10th percentile outcomes under potential future climate change hydrology.

In the median, 90th percentile, and maximum cases (Figure 43, Figure 44, and Figure 45), the pattern is also generally the same as the historical hydrology simulations, with lower storage levels with the 800sSRD and 1200sSRD as compared to the Existing sSRD, 800dSRD and 1200dSRD. However, under climate change, the 800sSRD and 1200sSRD generally have the potential for lower content as compared to historical hydrology. This is likely a result of the runoff timing shifting earlier into period when the sSRD requires space to be reserved in the reservoir regardless of basin conditions. By the time the sSRD allows the reservoir to fill, the runoff is largely complete and the reservoir is unable to reach a level as full as for historical hydrology.

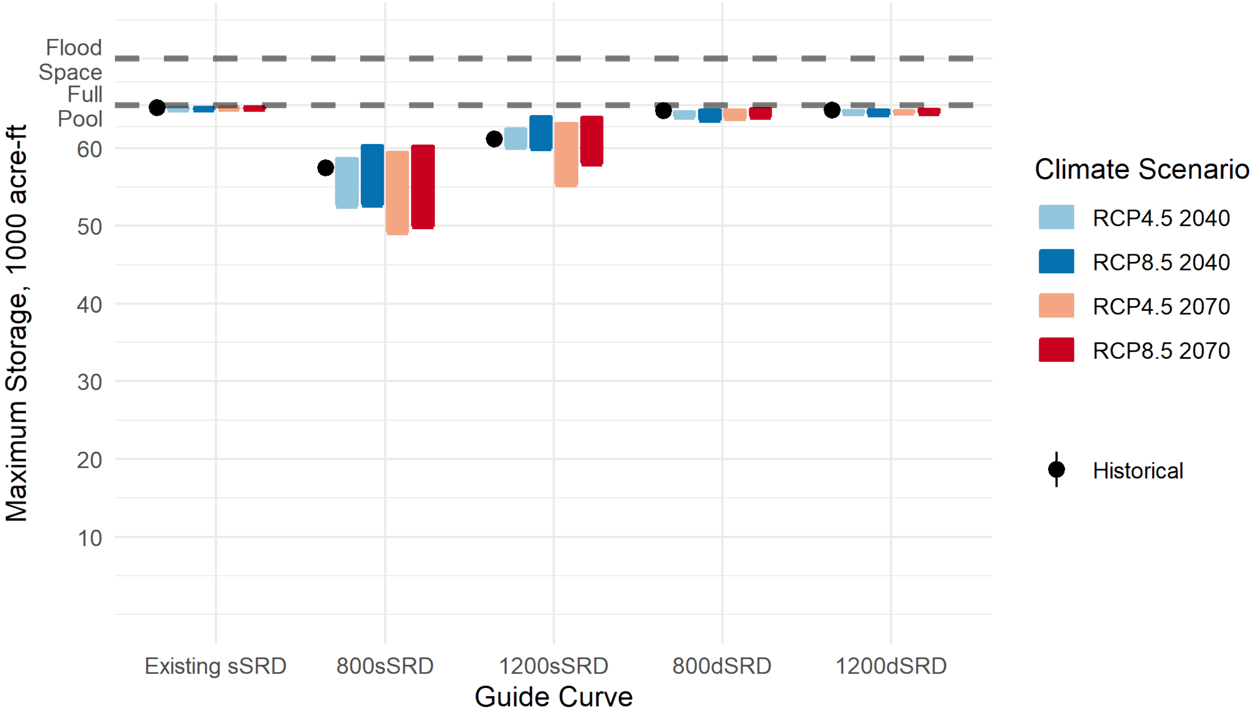


Figure 43. Median summary results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Fill metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential median outcomes under potential future climate change hydrology.

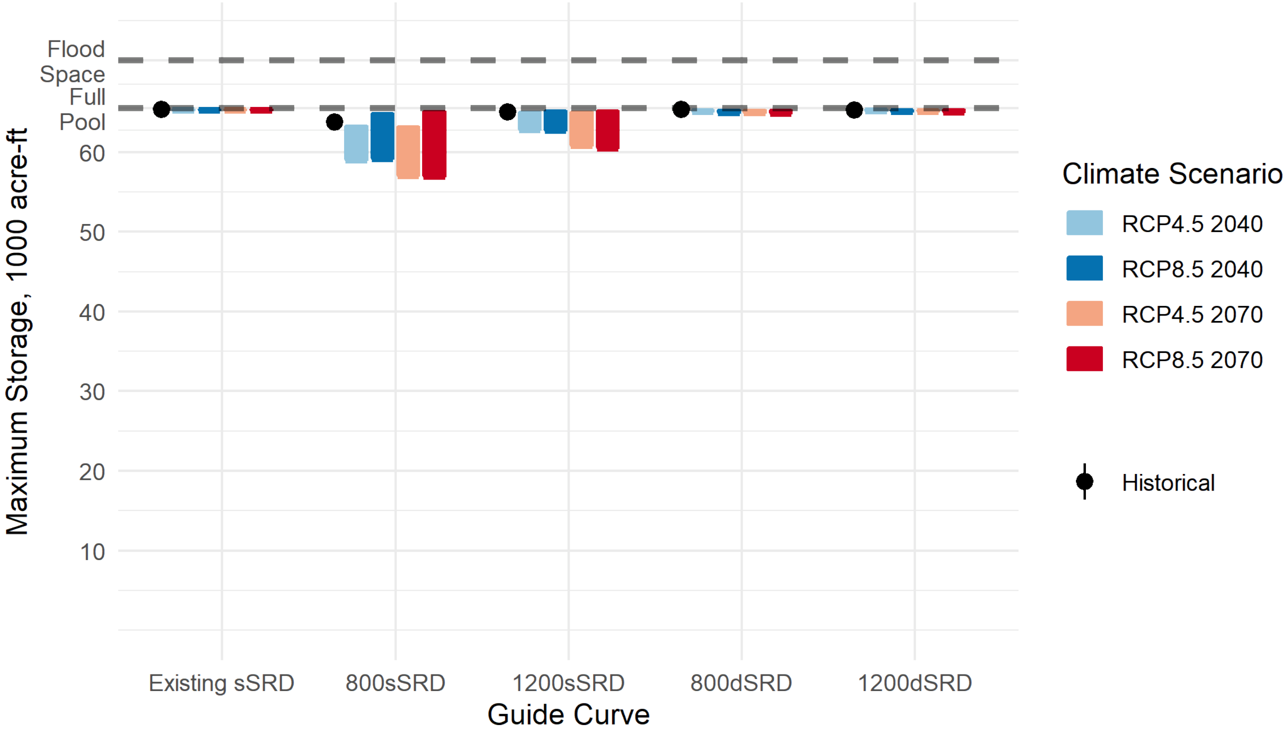


Figure 44. 90th percentile summary results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Fill metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential 90th percentile outcomes under potential future climate change hydrology.

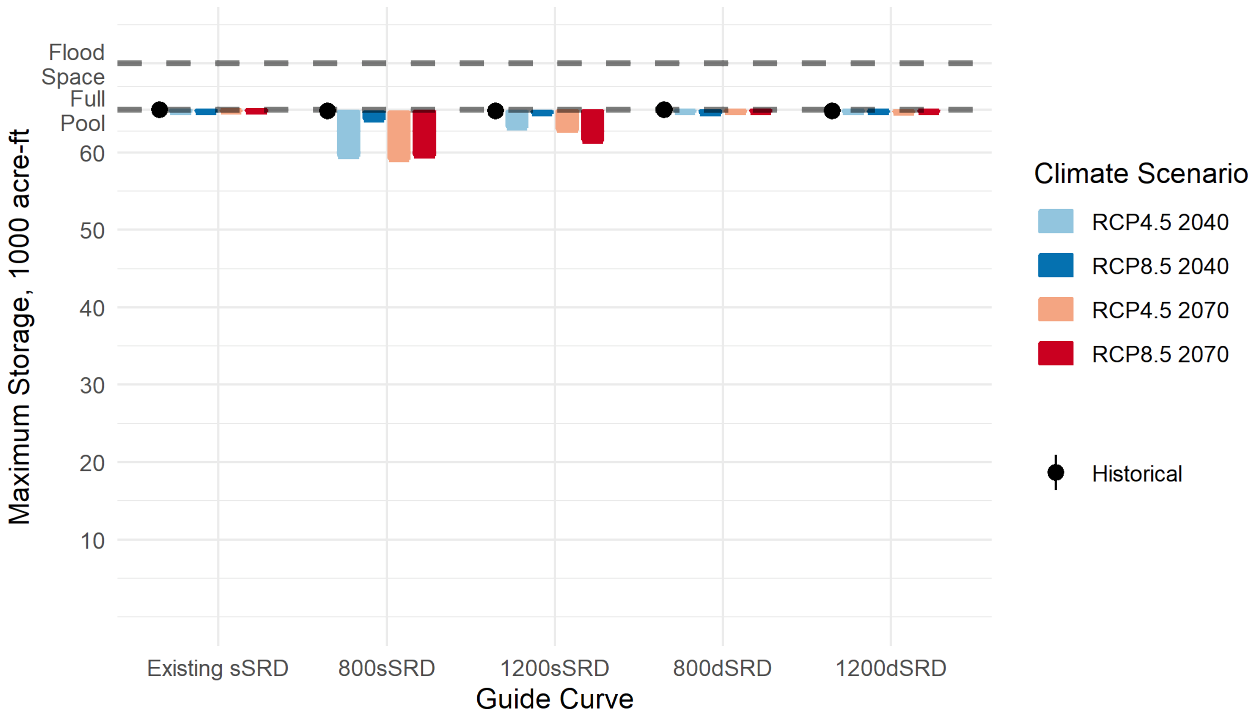


Figure 45. Maximum summary results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Fill metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential maximum outcomes under potential future climate change hydrology.

6.2.3. Max Outflow Metric

A similar methodology was used to develop the statistical summaries for the Max Outflow Metric. In the 10th percentile case (Figure 46), almost all cases result in higher flow than in the historical hydrology case. In the case of the 10th percentile, this result is of little consequence for this metric as the outflow does not exceed safe channel capacity of 1,200 cfs.

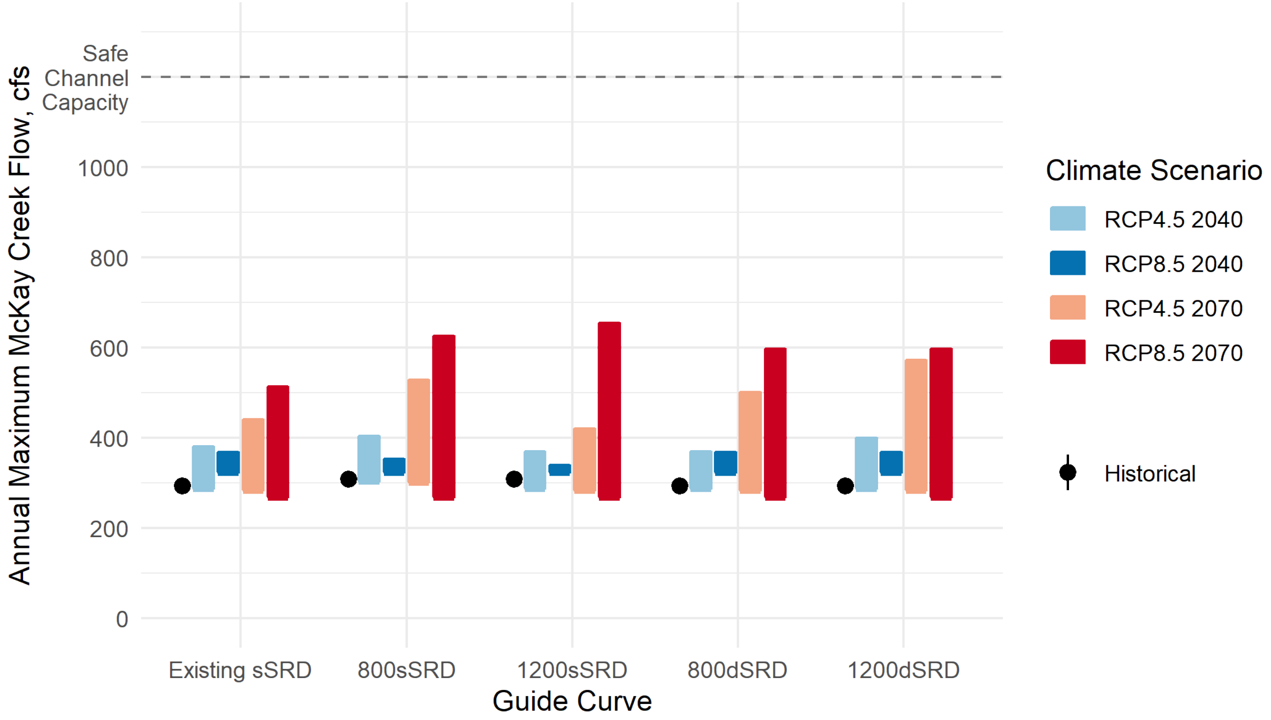


Figure 46. 10th percentile summary results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Outflow metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential 10th percentile outcomes under potential future climate change hydrology.

Similarly, in the median case (Figure 47), all cases result in higher flow than in the historical hydrology case, often resulting in flows near the safe channel capacity. Even though current safe channel capacity is 1,200 cfs, this result could be concerning if safe channel capacity were to be reduced in the future.

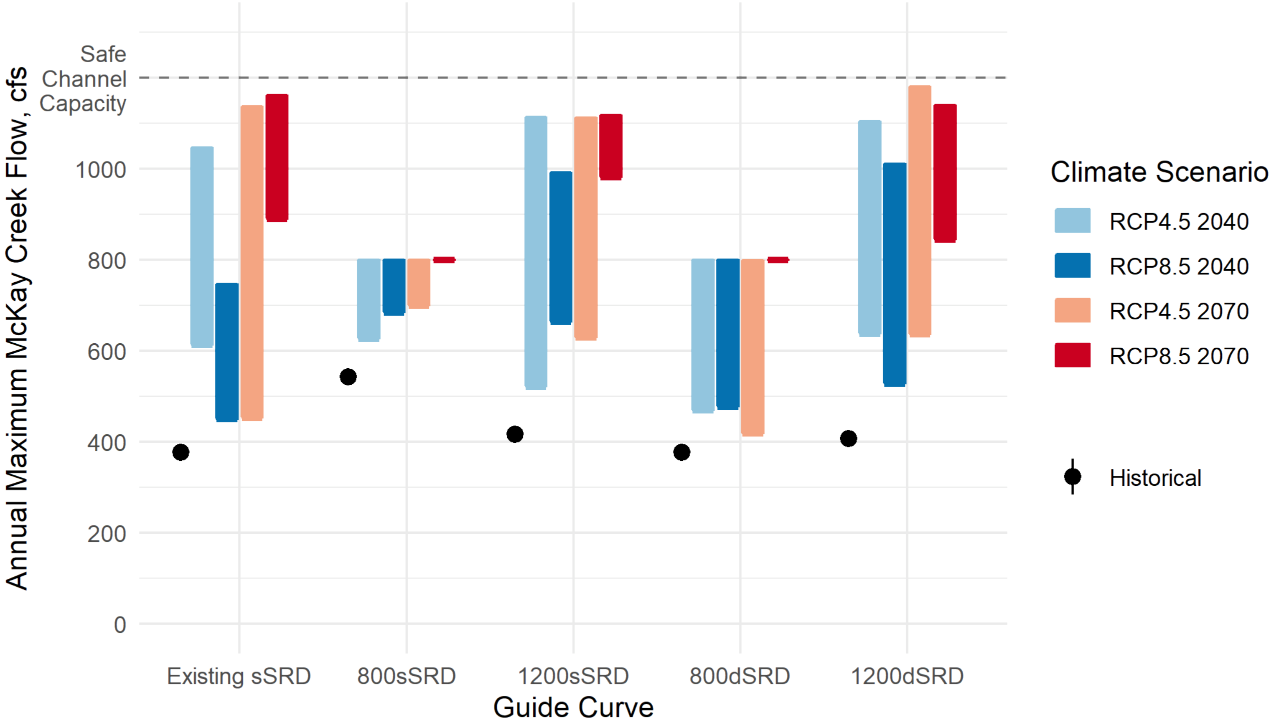


Figure 47. Median summary results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Outflow metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential median outcomes under potential future climate change hydrology.

In the 90th percentile case (Figure 48), the results show generally similar maximum outflow compared to the historical condition occurs for all cases. This result intuitively makes sense, since in high flow years, even under historical hydrology conditions, it is typical for safe channel capacity to be reached regardless of which SRD is used. This also provides confidence that the SRDs continue to maintain flows within safe channel capacity during most years, even as the hydrology regime changes.

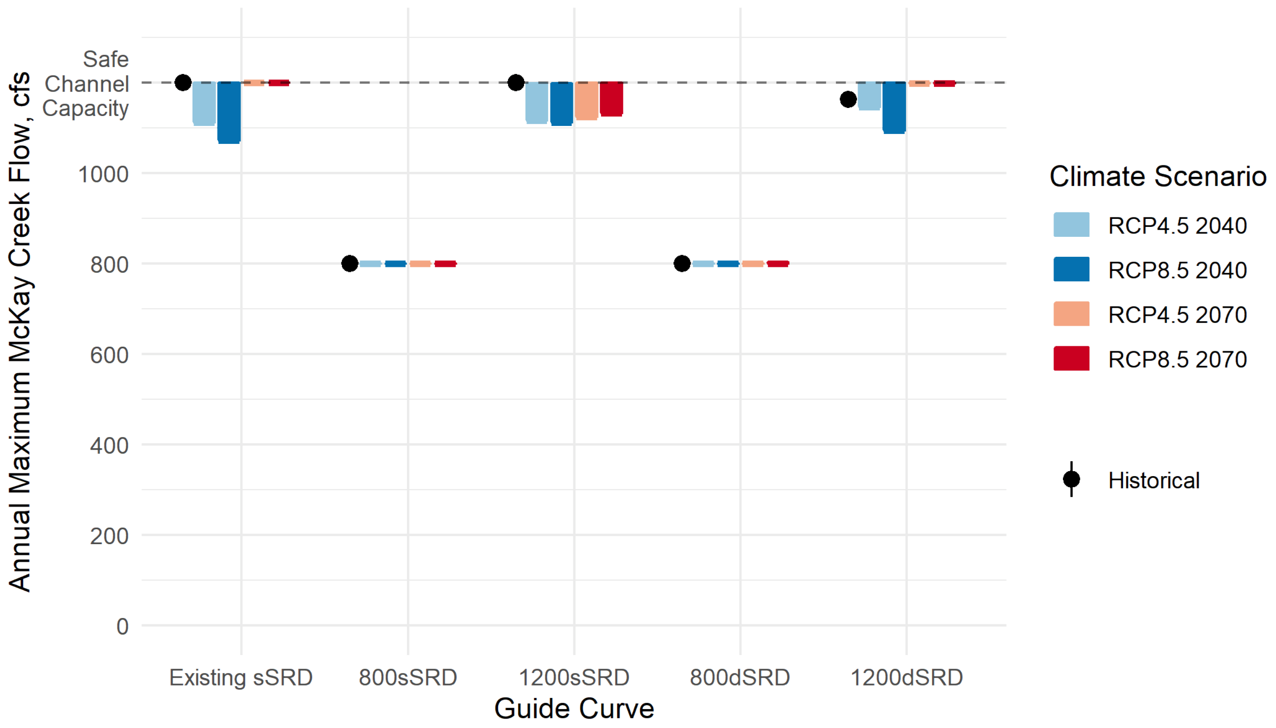


Figure 48. 90th percentile summary results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Outflow metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential 90th percentile outcomes under potential future climate change hydrology.

As with the historical hydrology case, the potential for very high flows downstream of McKay Dam in the climate change scenarios occurs around the same frequency, within the top 10 percent of years as shown by the 90th percentile summary results (Figure 48) resulting in flows at or less than the 1,200 cfs channel capacity and the maximum case (Figure 49) resulting in flows greater than the 1,200 cfs channel capacity in many cases. In the maximum case, the newly developed sSRDs and dSRDs generally result in a lower range of potential outflows than the Existing sSRD, but for the dSRDs, this result would likely be tempered when forecast uncertainty is considered and would need further study.

In most cases, apart from the RCP4.5 2040s, the potential exists for higher flows downstream of McKay Dam for all SRDs under climate change as compared to historical hydrology. For example, for the 1200dSRD scenario, the historical hydrology simulation resulted in a maximum outflow of around 1,450 cfs. However, the RCP8.5 2040s, RCP 4.5 2070s, and RCP 8.5 2070s all resulted in discharges of more than 2,250 cfs. This is an indication that the newly developed SRDs may not perform as intended with future potential climate change hydrology, despite performing better than the Existing sSRD. Section 6.3 provides an analysis of the factors causing this loss of performance.

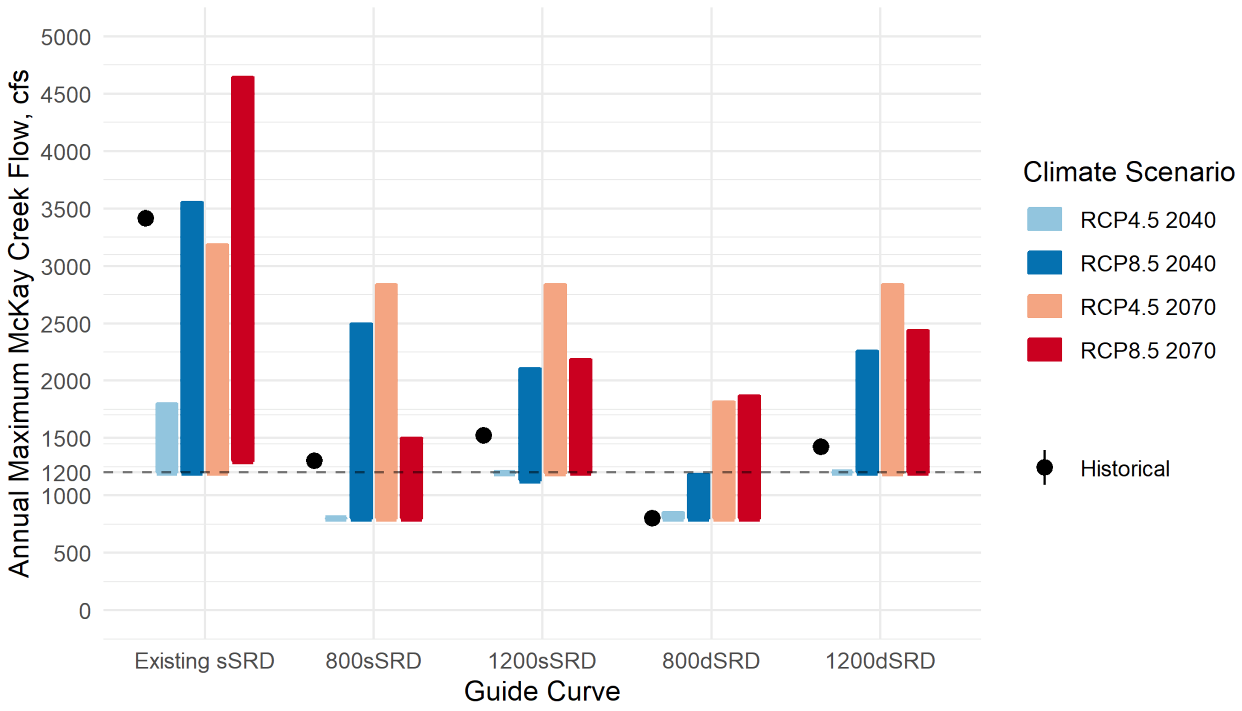


Figure 49. Maximum summary results for the five different operational scenarios of the Lower Umatilla River Model as they relate to the Max Outflow metric and for different hydrology scenarios (Historical, 2040s, and 2070s). The bars represent the range of potential maximum outcomes under potential future climate change hydrology.

6.3. SRD Performance

As described for the Max Outflow Metric, outflows in the climate change scenarios are much higher than in the historical maximum case. This may reflect a combination of influences from climate change as well as model bias (e.g., the models may tend to overpredict peak flows and the bias correction may not completely remove these effects). Regardless, this is an indication that the newly developed SRDs may not perform as intended with future potential climate change hydrology. In other words, the SRDs have been designed with historical observed events that potentially do not capture the range of future climate change hydrology.

Figure 50 shows an individual RCP8.5 2070s water year for the 1200dSRD. The red line represents the 1200dSRD, the black line represents McKay Reservoir Storage, the blue line represents inflow, and the orange line represents outflow. During this event, inflow causes the reservoir to begin to fill above the 1200dSRD in mid-March; outflow is increased to 1,200 cfs, but it quickly needs to be increased to 2,450 cfs as the reservoir approaches the top of the exclusive flood control space in late March. Even with perfect foresight, the model was unable to control this event to the 1,200 cfs control flow to which the 1200dSRD was designed.

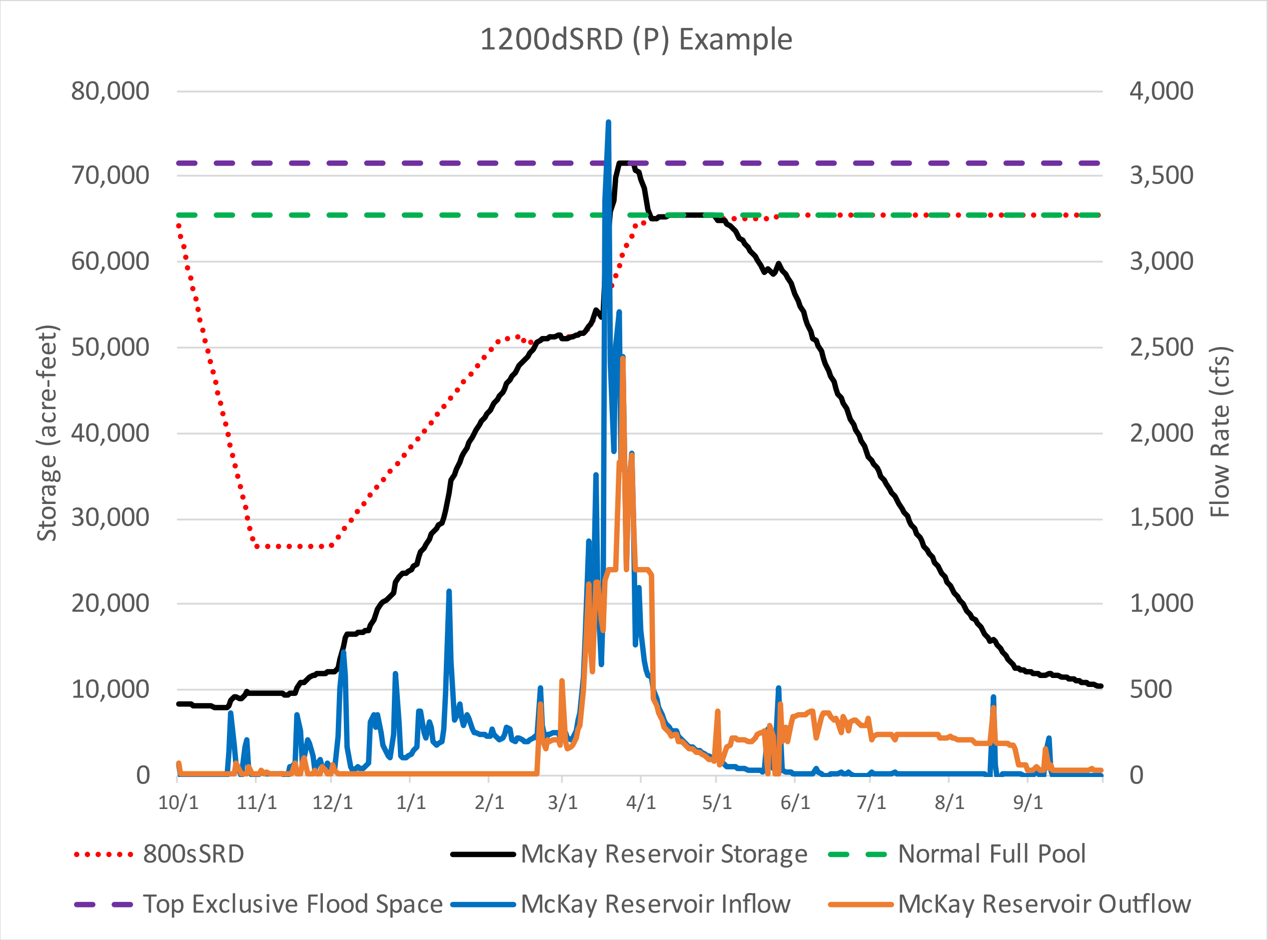


Figure 50. Individual RCP8.5 2070s water year example using the 1200dSRD (P)

An examination of the development of the 1200dSRD explains this result. The procedure described in Section 4 for flow enveloping during SRD development was used to determine the runoff volume to space required relationship for the February 15 through June 30 period for the RCP8.5 2070s year shown above. This RCP8.5 2070s trace had a February 15 through June 30 runoff volume of 109,815 acre-feet, nearly identical to the WY2019 volume of 109,368 acre-feet. However, the shape of the runoff in the RCP8.5 2070s trace is much earlier, as seen in Figure 51.

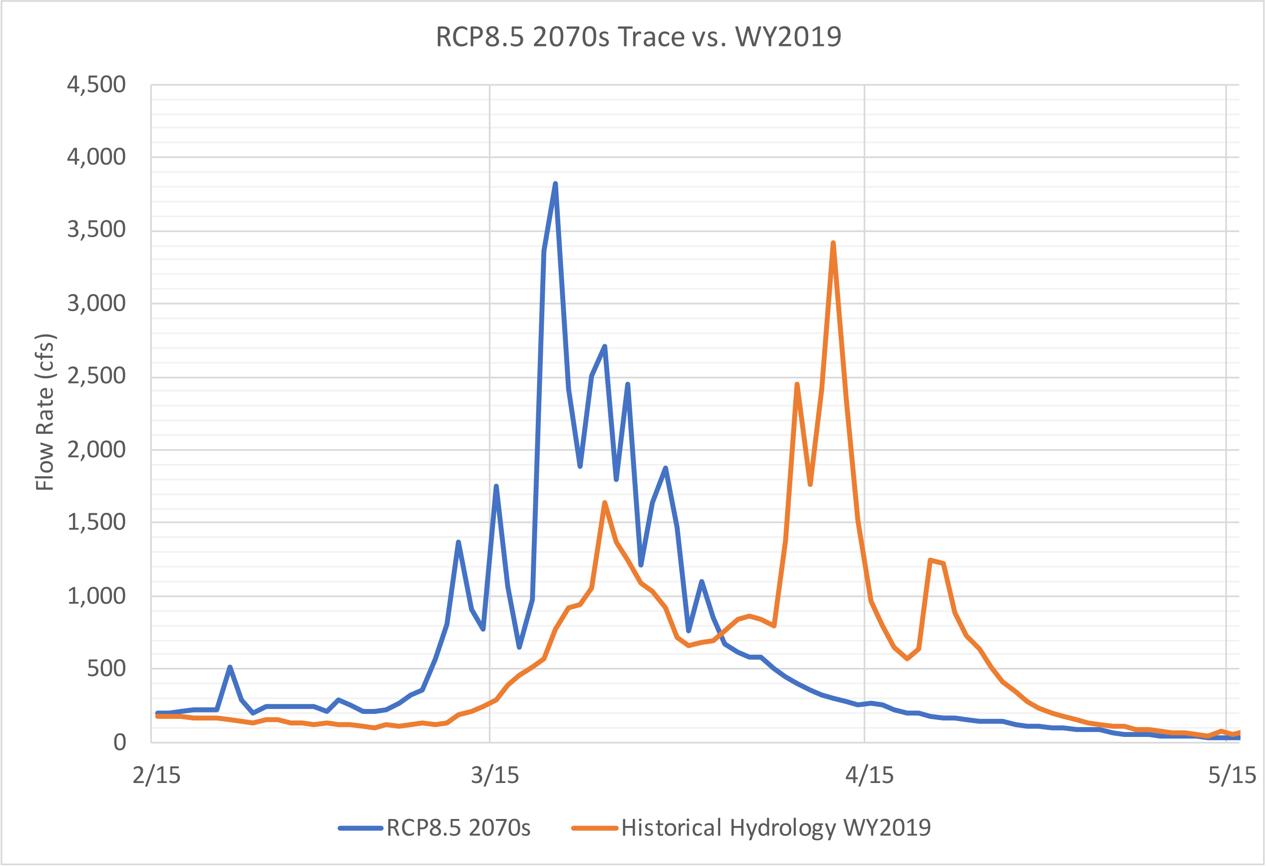


Figure 51. Historical hydrology WY2019 McKay Reservoir Inflow vs. individual RCP8.5 2070s McKay Reservoir inflow trace

The volume of runoff when inflow exceeded the downstream control flow of 1,200 cfs was determined to be 26,777 acre-feet for the RCP8.5 2070s trace, much greater than the 15,059 acre-feet required for WY2019. Figure 52 provides a graphical depiction of this process with reservoir outflow shown as an orange line, inflow shown as a blue line, and cumulative space required shown as a dotted green line.

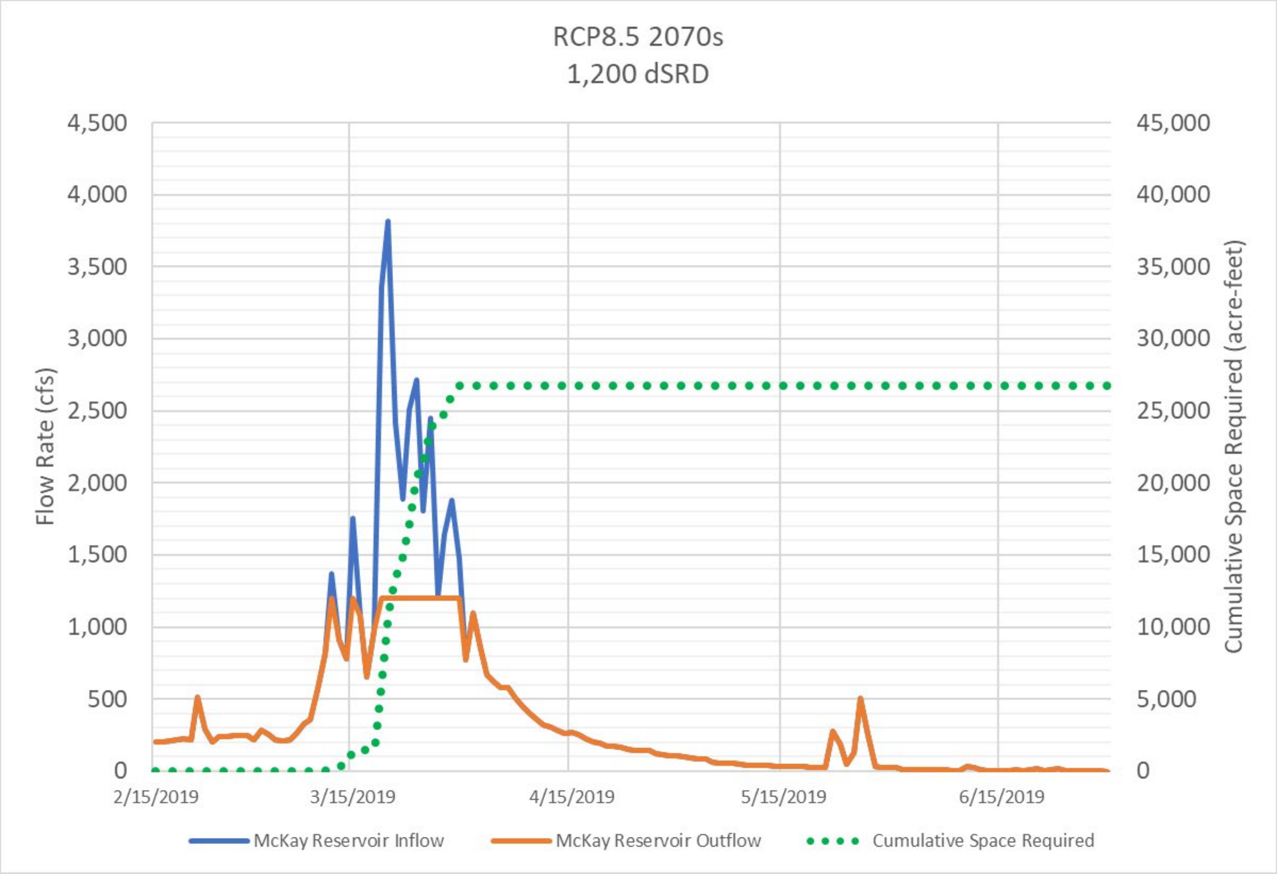


Figure 52. Individual RCP8.5 WY2070s hydrology trace runoff volume to space required development for the February 15 through June 30 period for 1,200 cfs control flow

Figure 53 shows the runoff volume to space required envelope curve that was created previously, which provided sufficient space for all historical water years in the dataset to control outflow to 1,200 cfs. However, this process did not incorporate data for future potential climate change flows that may require more space. The space requirement for the RCP8.5 2070s trace has been shown on the February 15 through June 30 envelope curve as a red star to illustrate that the space requirement for the RCP8.5 2070s trace is much higher than any of the historical observed events.

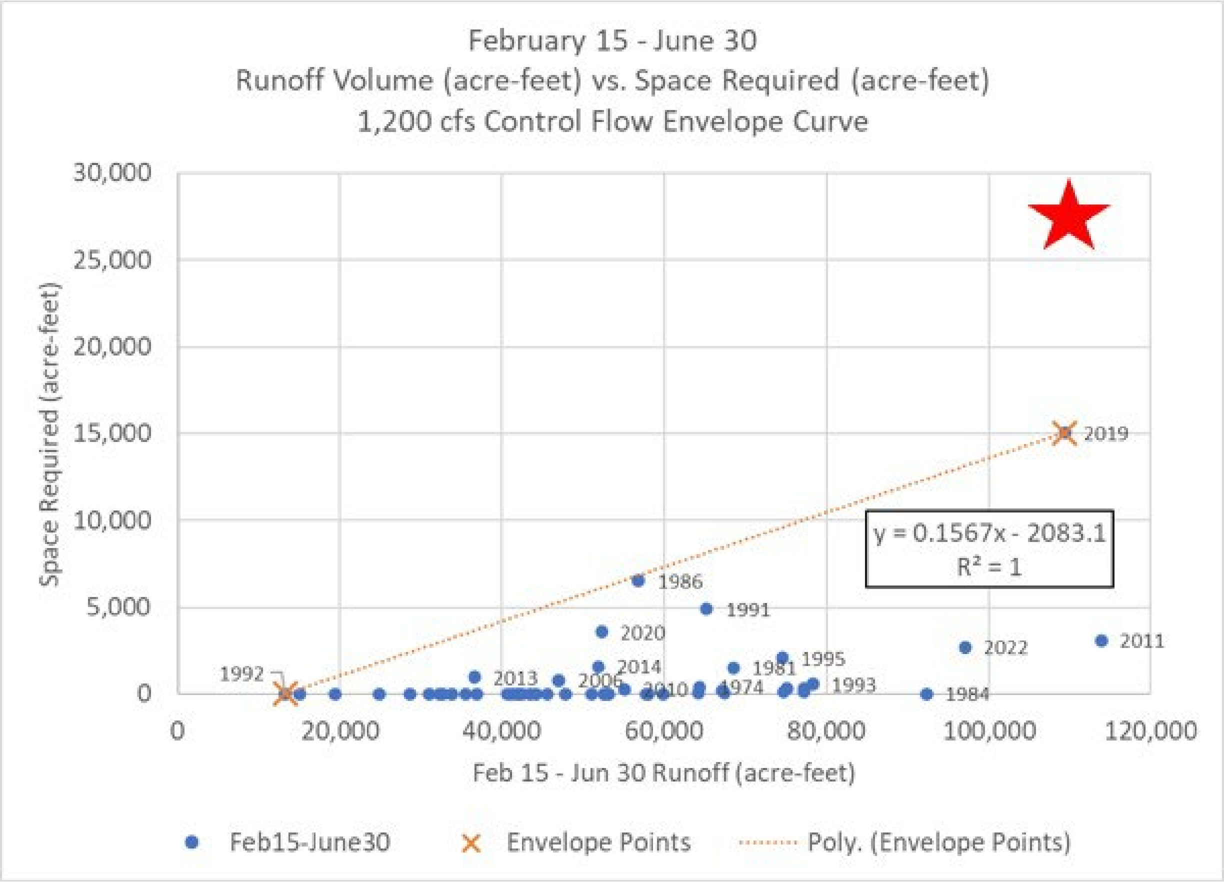


Figure 53. Historical hydrology February 15 through June 30 runoff volume to space required envelope curve for a 1,200 cfs control flow, with individual RCP8.5 WY2070s runoff volume to space required point shown for comparison

The result is that the 1200dSRD (and by way of extension the other newly developed SRDs as well) was not designed for inflows such as this RCP8.5 2070s trace; therefore, it is unable to maintain flows downstream of McKay Dam to less than 1,200 cfs in this case. However, given the uncertainties associated with model biases and the differing probabilities of the different projections of potential future inflows, the probability of such flows occurring in the future is unknown. If the SRDs were re-developed to consider the potential for future climate change flows, the likely outcome would be additional space being required. This would likely exacerbate the effects to reservoir refill as seen with the Max Fill metric in the historical hydrology modeling.

6.4. Discussion

The purpose of this effort was to stress test the existing and newly developed SRD products under perfect forecast simulations to determine how well they may or may not perform into the future independent of potential future forecast error. By comparing simulations of each scenario to historical hydrology simulations, the following observations can be made:

1. Under perfect forecast mode, all scenarios, including the Existing sSRD, may be able to maintain flows downstream to less than the historical 1,200 cfs safe channel capacity more than 90 percent of the time.
2. However, in extreme cases due to climate change hydrology falling outside of the historically observed range, climate change hydrology may result in higher outflows from McKay Reservoir than under historical hydrology when comparing historical and climate change hydrology runs for the same SRD.
3. In the maximum case, the newly developed sSRDs and dSRDs generally result in a lower range of potential outflows than the Existing sSRD; however, for the dSRDs, this result would likely be tempered when forecast uncertainty is considered and would need further study.
4. Like the historical hydrology analysis, the climate change analysis showed that the benefit of lower outflows during extreme events may come at the cost of less fill of the reservoir in the median case.

SRDs created for this exercise were developed based on historical hydrology and therefore do not incorporate potential future extreme events that may need additional space reservation. Future study to develop SRDs based on potential climate change flows (including analysis of the probability of the various climate change scenarios occurring) may provide protection against future extreme events, but will likely exacerbate the effects to reservoir fill seen in the historical hydrology modeling.

6.5. Limitations and Uncertainty

Future climatic and hydrologic conditions are inherently uncertain. The climate scenario selection process attempted to capture this uncertainty using the standardized techniques used by prior studies to attempt to bracket the likely range of hydrologic variability. Given the inherent variability and uncertainties associated with the different global climate models, downscaling techniques, hydrologic models and parameters, bias correction, and spatial disaggregation approaches used to estimate flow at each of the gages, it is possible that actual future hydrologic conditions may fall outside the range of variability captured by the models selected. The climate scenarios should not be considered predictions or forecasts of the most probable future conditions, but rather scenarios bracketing a range of possible future conditions. The estimates of future hydrologic conditions presented herein represent an attempt to use the best available data and most appropriate analyses to summarize the possible range of effects under future hydrologic conditions to help understand climate risks for hydrology and guide decision making. The uncertainty associated with these scenarios should be considered when evaluating possible effects.

7. Conclusions

This Study found that there appears to be opportunity to provide additional FRM protection downstream of McKay Dam through use of updated WSF and SRD products. However, the analysis showed this improvement may come at the risk of less reservoir refill. Even so, the possibility for improvement compared to the Existing sSRD remains, especially when considering additional flexibility of real-time operations compared to model simulation. No formal adoption of a single updated WSF or SRD product is being recommended as part of this study. Rather, the WSF and SRD products developed as part of this study will all provide additional tools to help water managers work within the latitude provided in qualifier in the Existing sSRD which states, "more space will be provided if snow pack so indicates," while the Study itself provides for a better understanding of the trade-offs between peak flows downstream of McKay Dam and fill of McKay Reservoir.

Future studies may provide additional tools for water managers in the basin. This research may include:

- Investigating additional improvements to WSF products, such as:
  - Improvements in weather forecasting, both in terms of rainfall amount prediction and longer lead time
  - Determining locations for additional SNOwpack TELemetry Network (SNOTEL) sites in the basin to capture lower elevation snowpack conditions, and use of those sites in future iterations of WSF updates
  - Utilizing remote sensing datasets (such as snow water equivalent, soil moisture, etc.) in future iterations of WSF updates
- Additional climate change hydrology analysis, such as:
  - Developing SRDs based on potential climate change flows
  - Examining WSF uncertainty under future climate change hydrology conditions
  - Modeling analysis using this information to analyze potential effects to flows downstream of McKay Dam and fill of McKay Reservoir under imperfect forecast mode
- Investigating infrastructure flexibilities in the managed system, such as:
  - Examining downstream channel capacity flexibilities to provide for additional operational flexibility

If WSFs can continue to improve in the future with new technology, the full benefit of the updated dSRDs may eventually be realized. However, if water supply forecasting becomes more difficult in the future, or if the hydrologic regime changes such that the past is no longer a good indicator of the future, the updated sSRDs and dSRDs as currently assessed may need to be reviewed.

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Appendix A

WSF McKay Reservoir Inflow Hindcasts, Date-June 30 (kaf)

	ACTUAL						MLR trained to 1981-2021					
WY	1-Jan	1-Feb	1-Mar	1-Apr	1-May	1-Jun	1-Jan	1-Feb	1-Mar	1-Apr	1-May	1-Jun
1981	74.0	70.5	53.6	35.5	21.0	10.5	52.4	40.6	25.9	10.6	-8.8	-16.5
1982	104.3	81.7	54.2	26.0	7.8	0.6	79.1	75.2	39.5	16.5	-7.1	-26.5
1983	84.0	68.2	51.8	20.5	13.0	1.5	82.3	63.2	47.7	25.5	15.4	0.2
1984	119.9	97.6	83.9	49.2	25.6	10.4	86.3	49.4	42.3	19.2	-1.7	-19.9
1985	49.4	45.4	36.7	22.5	3.3	0.5	82.9	64.9	56.2	49.5	22.2	9.4
1986	72.2	63.2	30.9	10.0	3.8	-0.7	59.2	48.5	30.5	0.5	-14.5	-23.7
1987	49.0	43.6	29.0	8.1	2.4	0.9	72.3	66.5	53.8	26.3	10.2	5.2
1988	36.4	32.2	25.9	18.3	7.1	1.2	38.1	36.8	26.4	15.1	15.4	6.6
1989	98.3	81.5	69.4	33.1	9.2	0.6	70.3	71.2	61.6	24.2	-0.4	-9.4
1990	38.9	35.9	30.8	20.0	14.8	5.9	35.2	26.4	28.2	13.8	12.1	7.3
1991	79.0	67.4	56.4	43.7	28.0	3.5	46.5	31.5	10.2	2.9	-16.1	-15.8
1992	19.2	15.9	8.3	2.9	-0.4	0.8	83.1	68.4	55.0	34.2	30.8	13.6
1993	89.2	81.4	76.0	44.8	20.1	3.2	73.1	69.7	65.5	33.0	21.5	3.3
1994	43.1	31.7	29.6	14.5	9.2	1.7	44.4	32.7	38.3	12.7	1.4	9.3
1995	101.7	87.6	65.4	47.3	36.0	2.3	86.9	71.4	42.0	27.2	28.5	-7.0
1996	96.0	80.6	43.2	23.9	11.4	1.6	76.0	68.3	35.1	12.1	0.6	-3.9
1997	88.0	70.1	52.7	24.4	6.1	0.8	116.4	92.4	71.8	39.8	27.3	13.4
1998	58.6	46.3	39.0	21.7	14.7	3.0	55.7	52.4	40.5	20.9	14.2	8.2
1999	61.9	46.3	37.5	18.0	6.7	0.6	84.7	58.4	64.4	38.6	20.0	10.1
2000	69.6	62.6	47.4	16.5	5.2	2.7	64.8	62.7	54.7	32.8	14.4	14.5
2001	56.0	50.7	43.2	27.2	5.4	1.0	68.6	56.1	45.7	24.7	7.2	-7.5
2002	44.1	39.1	30.7	16.3	2.0	0.6	61.2	56.2	43.5	26.6	14.6	5.3
2003	78.9	68.0	47.8	19.9	6.3	0.6	47.6	35.2	18.3	-10.8	-19.1	-28.0
2004	96.5	74.5	56.7	38.4	31.3	8.9	66.2	54.0	43.6	14.2	7.9	-6.5
2005	28.9	25.8	24.0	21.0	14.9	1.3	46.3	30.8	21.1	11.4	3.4	10.4
2006	66.0	51.7	45.4	35.2	7.1	5.0	58.1	60.5	46.5	46.1	24.3	23.7
2007	42.4	35.1	24.7	10.8	2.9	1.0	69.7	52.9	43.5	23.8	14.2	2.5
2008	62.1	56.8	47.6	30.0	15.3	7.1	74.2	77.5	64.2	55.1	32.7	27.6
2009	85.2	69.5	64.6	43.9	16.3	1.0	60.3	44.8	39.1	39.4	10.7	-8.9
2010	63.4	58.9	51.7	45.4	33.7	17.0	60.7	53.6	38.8	33.3	29.2	26.7
2011	153.2	119.3	106.9	82.3	43.6	13.3	99.4	56.5	44.7	37.8	1.2	-9.6
2012	56.5	50.1	41.4	27.5	9.5	3.6	44.6	41.8	37.7	30.6	21.7	8.0
2013	46.2	41.3	34.0	22.1	3.8	2.1	73.8	59.4	46.8	31.3	12.8	9.6
2014	63.5	58.0	42.6	14.3	3.6	1.2	55.0	44.4	33.1	8.8	-0.7	-13.2
2015	38.0	20.1	12.1	6.5	2.7	0.8	98.1	57.5	46.8	30.3	17.2	19.6
2016	46.8	38.3	21.7	4.9	1.4	0.1	83.9	68.3	48.3	41.6	30.9	30.7
2017	90.3	85.8	65.9	30.4	6.6	-0.1	82.9	72.6	61.7	39.6	33.9	20.9
2018	71.1	53.5	37.7	18.6	1.7	-0.4	73.8	53.2	40.7	25.4	19.1	14.5
2019	130.2	116.2	105.1	72.2	10.6	1.1	75.7	59.1	69.6	36.2	-0.6	-1.6
2020	83.1	75.4	44.8	35.0	21.7	3.2	48.0	45.7	30.4	20.9	-0.4	13.1
2021	51.3	42.6	34.5	16.0	1.6	-0.3	69.7	53.2	56.5	37.0	12.6	0.2
2022	112.6	99.2	94.3	75.6	61.4	29.2	74.5	57.6	51.1	31.8	33.4	37.4

	ACTUAL						NWRFC ESP0					
WY	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**
1981	74.0	70.5	53.6	35.5	21.0	10.5	61.5	36.5	35.4	22.9	6.7	2.4
1982	104.3	81.7	54.2	26.0	7.8	0.6	81.1	84.5	65.4	32.4	11.9	4.1
1983	84.0	68.2	51.8	20.5	13.0	1.5	79.1	57.2	45.5	30.1	11.8	4.5
1984	119.9	97.6	83.9	49.2	25.6	10.4	92.6	68.6	53.1	33.3	13.3	4.8
1985	49.4	45.4	36.7	22.5	3.3	0.5	104.9	77.4	71.6	48.6	14.0	3.9
1986	72.2	63.2	30.9	10.0	3.8	-0.7	66.9	58.6	50.3	23.9	8.6	2.9
1987	49.0	43.6	29.0	8.1	2.4	0.9	62.1	55.4	37.6	16.5	4.8	1.7
1988	36.4	32.2	25.9	18.3	7.1	1.2	41.9	36.1	20.2	14.1	6.2	1.9
1989	98.3	81.5	69.4	33.1	9.2	0.6	76.7	94.1	79.9	46.0	15.6	5.2
1990	38.9	35.9	30.8	20.0	14.8	5.9	43.7	36.4	22.8	11.1	6.0	2.6
1991	79.0	67.4	56.4	43.7	28.0	3.5	61.7	43.6	25.5	15.4	6.1	5.3
1992	19.2	15.9	8.3	2.9	-0.4	0.8	80.5	53.5	31.2	10.5	3.5	1.1
1993	89.2	81.4	76.0	44.8	20.1	3.2	76.2	74.8	55.2	30.5	16.5	5.9
1994	43.1	31.7	29.6	14.5	9.2	1.7	46.5	35.7	31.7	12.3	4.0	2.1
1995	101.7	87.6	65.4	47.3	36.0	2.3	75.9	63.5	40.3	22.4	15.3	5.7
1996	96.0	80.6	43.2	23.9	11.4	1.6	83.1	78.7	59.4	28.4	11.9	4.3
1997	88.0	70.1	52.7	24.4	6.1	0.8	102.6	83.3	49.0	25.3	14.0	4.6
1998	58.6	46.3	39.0	21.7	14.7	3.0	54.2	49.4	26.6	13.4	3.8	1.7
1999	61.9	46.3	37.5	18.0	6.7	0.6	78.2	56.3	50.9	21.3	7.6	2.8
2000	69.6	62.6	47.4	16.5	5.2	2.7	57.4	52.1	39.4	26.0	8.1	3.2
2001	56.0	50.7	43.2	27.2	5.4	1.0	64.8	53.3	28.4	14.4	7.5	2.0
2002	44.1	39.1	30.7	16.3	2.0	0.6	50.9	46.6	25.7	14.4	4.8	1.7
2003	78.9	68.0	47.8	19.9	6.3	0.6	44.7	40.9	31.6	21.4	8.4	2.7
2004	96.5	74.5	56.7	38.4	31.3	8.9	80.9	94.4	72.5	28.9	11.5	7.9
2005	28.9	25.8	24.0	21.0	14.9	1.3	59.3	35.6	20.6	10.9	3.6	2.2
2006	66.0	51.7	45.4	35.2	7.1	5.0	63.0	59.1	33.3	21.8	10.0	3.7
2007	42.4	35.1	24.7	10.8	2.9	1.0	76.2	49.9	38.8	17.7	4.7	1.6
2008	62.1	56.8	47.6	30.0	15.3	7.1	76.0	73.4	48.3	25.8	8.6	3.2
2009	85.2	69.5	64.6	43.9	16.3	1.0	78.3	64.4	44.7	40.9	14.0	5.2
2010	63.4	58.9	51.7	45.4	33.7	17.0	54.3	40.4	22.3	11.7	5.5	2.9
2011	153.2	119.3	106.9	82.3	43.6	13.3	104.5	82.6	61.5	34.2	17.5	8.5
2012	56.5	50.1	41.4	27.5	9.5	3.6	47.1	42.9	29.4	16.4	10.6	2.6
2013	46.2	41.3	34.0	22.1	3.8	2.1	68.8	55.3	32.6	11.6	6.4	2.3
2014	63.5	58.0	42.6	14.3	3.6	1.2	67.0	50.9	40.4	25.5	9.4	3.2
2015	38.0	20.1	12.1	6.5	2.7	0.8	81.5	54.1	35.0	16.2	3.8	1.5
2016	46.8	38.3	21.7	4.9	1.4	0.1	74.8	56.5	36.5	20.4	6.1	2.3
2017	90.3	85.8	65.9	30.4	6.6	-0.1	88.4	76.8	60.5	34.2	15.9	5.0
2018	71.1	53.5	37.7	18.6	1.7	-0.4	66.6	53.3	48.6	22.1	10.0	3.5
2019	130.2	116.2	105.1	72.2	10.6	1.1	62.7	42.8	53.3	25.8	13.9	5.1
2020	83.1	75.4	44.8	35.0	21.7	3.2	46.9	52.6	51.5	31.3	9.5	6.6
2021	51.3	42.6	34.5	16.0	1.6	-0.3	75.7	50.1	66.7	28.2	7.1	2.6

	ACTUAL						NWRFC ESPHEFS					
WY	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**
1981	74.0	70.5	53.6	35.5	21.0	10.5						
1982	104.3	81.7	54.2	26.0	7.8	0.6						
1983	84.0	68.2	51.8	20.5	13.0	1.5						
1984	119.9	97.6	83.9	49.2	25.6	10.4						
1985	49.4	45.4	36.7	22.5	3.3	0.5						
1986	72.2	63.2	30.9	10.0	3.8	-0.7						
1987	49.0	43.6	29.0	8.1	2.4	0.9						
1988	36.4	32.2	25.9	18.3	7.1	1.2						
1989	98.3	81.5	69.4	33.1	9.2	0.6	76.1	90.0	81.4	48.8	16.8	5.1
1990	38.9	35.9	30.8	20.0	14.8	5.9	46.8	35.9	21.5	9.1	5.1	2.5
1991	79.0	67.4	56.4	43.7	28.0	3.5	62.2	39.7	28.9	17.5	5.6	5.3
1992	19.2	15.9	8.3	2.9	-0.4	0.8	79.7	44.6	24.3	8.1	3.3	1.0
1993	89.2	81.4	76.0	44.8	20.1	3.2	76.4	67.2	50.8	35.6	24.0	6.0
1994	43.1	31.7	29.6	14.5	9.2	1.7	49.2	34.1	26.2	11.5	3.7	2.1
1995	101.7	87.6	65.4	47.3	36.0	2.3	75.7	63.7	45.5	21.5	21.2	5.8
1996	96.0	80.6	43.2	23.9	11.4	1.6	85.4	75.2	63.6	22.4	12.3	4.2
1997	88.0	70.1	52.7	24.4	6.1	0.8	106.4	82.1	55.1	25.9	13.3	4.6
1998	58.6	46.3	39.0	21.7	14.7	3.0	59.6	45.3	27.9	15.0	4.1	1.7
1999	61.9	46.3	37.5	18.0	6.7	0.6	85.0	58.5	52.0	23.0	8.0	2.8
2000	69.6	62.6	47.4	16.5	5.2	2.7	68.0	52.5	40.8	24.9	8.6	3.2
2001	56.0	50.7	43.2	27.2	5.4	1.0	69.7	54.5	29.3	13.9	6.5	2.1
2002	44.1	39.1	30.7	16.3	2.0	0.6	51.7	48.2	26.7	14.3	4.8	1.6
2003	78.9	68.0	47.8	19.9	6.3	0.6	43.6	38.7	28.9	25.0	9.6	2.7
2004	96.5	74.5	56.7	38.4	31.3	8.9	89.4	95.7	70.3	24.7	10.9	7.9
2005	28.9	25.8	24.0	21.0	14.9	1.3	61.2	32.2	18.6	12.1	6.6	2.3
2006	66.0	51.7	45.4	35.2	7.1	5.0	66.5	56.2	34.2	27.3	10.0	3.8
2007	42.4	35.1	24.7	10.8	2.9	1.0	76.3	46.7	39.0	16.6	4.9	1.7
2008	62.1	56.8	47.6	30.0	15.3	7.1	76.8	76.2	45.8	23.4	8.3	3.3
2009	85.2	69.5	64.6	43.9	16.3	1.0	79.6	62.4	43.6	46.7	17.4	5.3
2010	63.4	58.9	51.7	45.4	33.7	17.0	57.7	38.6	22.2	12.7	6.7	4.3
2011	153.2	119.3	106.9	82.3	43.6	13.3	102.6	79.6	64.8	34.4	20.2	8.7
2012	56.5	50.1	41.4	27.5	9.5	3.6	46.0	39.5	27.5	17.0	10.5	2.7
2013	46.2	41.3	34.0	22.1	3.8	2.1	67.8	48.6	30.2	12.5	6.4	2.2
2014	63.5	58.0	42.6	14.3	3.6	1.2	63.5	50.4	44.0	25.6	8.8	3.1
2015	38.0	20.1	12.1	6.5	2.7	0.8	82.0	57.6	26.5	16.2	3.8	1.5
2016	46.8	38.3	21.7	4.9	1.4	0.1	71.2	54.0	40.2	21.1	6.1	2.3
2017	90.3	85.8	65.9	30.4	6.6	-0.1	95.6	79.2	63.0	30.0	15.7	5.0
2018	71.1	53.5	37.7	18.6	1.7	-0.4	71.2	49.1	48.6	29.5	9.7	3.5
2019	130.2	116.2	105.1	72.2	10.6	1.1	61.4	45.7	51.6	26.3	13.8	5.1
2020	83.1	75.4	44.8	35.0	21.7	3.2						
2021	51.3	42.6	34.5	16.0	1.6	-0.3						

	ACTUAL						PyCast Top PCA trained to 1981-2021					
WY	1-Jan	1-Feb	1-Mar	1-Apr	1-May	1-Jun	1-Jan	1-Feb	1-Mar	1-Apr	1-May	1-Jun
1981	74.0	70.5	53.6	35.5	21.0	10.5	55.3	40.9	36.9	25.3	8.1	2.7
1982	104.3	81.7	54.2	26.0	7.8	0.6	95.1	90.6	63.3	36.6	16.7	4.0
1983	84.0	68.2	51.8	20.5	13.0	1.5	91.8	65.7	44.5	30.8	18.1	0.8
1984	119.9	97.6	83.9	49.2	25.6	10.4	112.5	79.3	65.3	49.4	23.1	6.1
1985	49.4	45.4	36.7	22.5	3.3	0.5	91.8	57.7	47.5	38.2	9.8	-1.0
1986	72.2	63.2	30.9	10.0	3.8	-0.7	67.9	57.5	52.5	27.2	11.7	1.4
1987	49.0	43.6	29.0	8.1	2.4	0.9	58.4	53.9	36.9	21.6	6.3	-0.5
1988	36.4	32.2	25.9	18.3	7.1	1.2	49.0	48.8	30.1	17.9	10.6	4.2
1989	98.3	81.5	69.4	33.1	9.2	0.6	80.2	85.1	66.7	44.7	14.7	3.9
1990	38.9	35.9	30.8	20.0	14.8	5.9	32.8	30.5	24.9	15.1	5.6	4.0
1991	79.0	67.4	56.4	43.7	28.0	3.5	54.4	41.3	23.6	20.7	7.6	7.5
1992	19.2	15.9	8.3	2.9	-0.4	0.8	54.1	30.6	21.5	7.7	4.5	-0.5
1993	89.2	81.4	76.0	44.8	20.1	3.2	74.0	69.6	58.1	32.3	14.9	2.7
1994	43.1	31.7	29.6	14.5	9.2	1.7	51.6	43.4	40.7	16.7	6.9	2.1
1995	101.7	87.6	65.4	47.3	36.0	2.3	71.9	65.9	42.5	23.8	17.3	5.5
1996	96.0	80.6	43.2	23.9	11.4	1.6	66.9	63.3	51.4	24.0	12.8	5.1
1997	88.0	70.1	52.7	24.4	6.1	0.8	105.7	83.1	54.8	28.9	15.4	2.5
1998	58.6	46.3	39.0	21.7	14.7	3.0	55.7	61.1	40.8	24.4	14.0	4.5
1999	61.9	46.3	37.5	18.0	6.7	0.6	67.0	49.9	56.6	31.5	11.7	2.6
2000	69.6	62.6	47.4	16.5	5.2	2.7	63.5	65.5	62.5	35.1	14.0	1.3
2001	56.0	50.7	43.2	27.2	5.4	1.0	56.0	47.1	31.9	17.2	9.5	1.1
2002	44.1	39.1	30.7	16.3	2.0	0.6	59.2	48.4	37.7	22.1	8.2	2.2
2003	78.9	68.0	47.8	19.9	6.3	0.6	67.7	57.4	46.4	21.7	14.1	4.7
2004	96.5	74.5	56.7	38.4	31.3	8.9	87.9	91.1	67.2	26.4	14.0	3.4
2005	28.9	25.8	24.0	21.0	14.9	1.3	53.0	31.7	20.1	13.5	5.2	4.0
2006	66.0	51.7	45.4	35.2	7.1	5.0	80.0	76.7	50.9	35.4	15.5	2.1
2007	42.4	35.1	24.7	10.8	2.9	1.0	61.9	40.5	31.5	14.0	7.8	-0.1
2008	62.1	56.8	47.6	30.0	15.3	7.1	75.9	72.3	54.4	40.2	11.9	3.5
2009	85.2	69.5	64.6	43.9	16.3	1.0	87.1	67.8	52.2	39.8	15.9	3.0
2010	63.4	58.9	51.7	45.4	33.7	17.0	64.6	54.7	37.5	22.0	11.6	8.9
2011	153.2	119.3	106.9	82.3	43.6	13.3	105.8	73.0	60.4	46.5	19.1	7.1
2012	56.5	50.1	41.4	27.5	9.5	3.6	46.9	43.9	37.1	28.5	11.0	3.7
2013	46.2	41.3	34.0	22.1	3.8	2.1	54.4	46.5	32.5	16.4	6.9	2.4
2014	63.5	58.0	42.6	14.3	3.6	1.2	59.3	46.4	40.6	23.4	11.2	3.1
2015	38.0	20.1	12.1	6.5	2.7	0.8	83.5	56.4	38.1	10.3	7.6	0.9
2016	46.8	38.3	21.7	4.9	1.4	0.1	82.7	68.1	42.7	21.6	9.5	-0.3
2017	90.3	85.8	65.9	30.4	6.6	-0.1	89.7	73.1	66.3	29.8	18.4	4.4
2018	71.1	53.5	37.7	18.6	1.7	-0.4	62.7	58.8	44.0	23.5	10.0	1.1
2019	130.2	116.2	105.1	72.2	10.6	1.1	80.2	74.2	73.2	43.1	17.7	4.4
2020	83.1	75.4	44.8	35.0	21.7	3.2	51.9	70.0	61.0	34.6	10.6	2.5
2021	51.3	42.6	34.5	16.0	1.6	-0.3	76.3	58.5	58.0	36.6	7.5	-1.5
2022	112.6	99.2	94.3	75.6	61.4	29.2	79.6	65.5	43.6	16.8	9.2	9.7

	ACTUAL						PyCast Top Z trained to 1981-2021					
WY	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**
1981	74.0	70.5	53.6	35.5	21.0	10.5	56.8	46.2	32.1	24.3	9.1	3.1
1982	104.3	81.7	54.2	26.0	7.8	0.6	94.1	89.6	61.9	35.4	20.8	2.3
1983	84.0	68.2	51.8	20.5	13.0	1.5	83.1	59.5	40.7	31.9	21.4	0.5
1984	119.9	97.6	83.9	49.2	25.6	10.4	112.3	79.7	66.7	50.0	25.0	5.3
1985	49.4	45.4	36.7	22.5	3.3	0.5	88.8	53.0	53.3	35.7	9.8	-1.4
1986	72.2	63.2	30.9	10.0	3.8	-0.7	71.7	61.1	49.4	25.7	11.1	1.0
1987	49.0	43.6	29.0	8.1	2.4	0.9	50.0	47.7	42.9	21.2	5.0	-0.6
1988	36.4	32.2	25.9	18.3	7.1	1.2	52.1	49.7	27.8	17.3	8.1	5.3
1989	98.3	81.5	69.4	33.1	9.2	0.6	81.3	78.9	69.2	41.6	14.5	4.1
1990	38.9	35.9	30.8	20.0	14.8	5.9	36.1	30.4	25.9	13.9	5.6	4.5
1991	79.0	67.4	56.4	43.7	28.0	3.5	57.3	40.4	24.3	20.3	11.1	7.5
1992	19.2	15.9	8.3	2.9	-0.4	0.8	50.4	28.5	19.9	7.2	3.9	-0.6
1993	89.2	81.4	76.0	44.8	20.1	3.2	87.3	74.6	65.4	31.8	16.8	3.6
1994	43.1	31.7	29.6	14.5	9.2	1.7	47.7	43.9	40.6	16.4	5.5	2.8
1995	101.7	87.6	65.4	47.3	36.0	2.3	73.0	63.8	30.9	24.4	15.9	5.4
1996	96.0	80.6	43.2	23.9	11.4	1.6	63.5	65.6	46.3	23.5	11.3	5.0
1997	88.0	70.1	52.7	24.4	6.1	0.8	102.4	85.4	50.3	27.9	13.0	2.0
1998	58.6	46.3	39.0	21.7	14.7	3.0	50.9	57.0	41.6	24.9	12.0	4.3
1999	61.9	46.3	37.5	18.0	6.7	0.6	73.4	57.2	52.1	28.1	14.4	1.9
2000	69.6	62.6	47.4	16.5	5.2	2.7	65.0	67.1	57.2	35.2	11.1	1.6
2001	56.0	50.7	43.2	27.2	5.4	1.0	55.7	44.3	35.1	15.5	8.1	1.6
2002	44.1	39.1	30.7	16.3	2.0	0.6	61.2	48.3	36.9	20.0	10.4	2.5
2003	78.9	68.0	47.8	19.9	6.3	0.6	70.4	62.7	46.6	23.8	14.2	4.1
2004	96.5	74.5	56.7	38.4	31.3	8.9	87.5	88.2	61.9	26.7	12.1	3.8
2005	28.9	25.8	24.0	21.0	14.9	1.3	50.7	29.8	19.8	12.0	4.4	4.6
2006	66.0	51.7	45.4	35.2	7.1	5.0	75.9	80.0	50.2	36.4	15.8	2.6
2007	42.4	35.1	24.7	10.8	2.9	1.0	60.7	39.7	32.1	14.8	6.1	-0.1
2008	62.1	56.8	47.6	30.0	15.3	7.1	81.0	75.6	58.1	39.6	15.9	2.7
2009	85.2	69.5	64.6	43.9	16.3	1.0	89.2	72.7	55.2	38.8	13.6	2.6
2010	63.4	58.9	51.7	45.4	33.7	17.0	66.2	56.2	39.9	20.9	13.4	9.4
2011	153.2	119.3	106.9	82.3	43.6	13.3	110.2	81.3	65.0	46.2	22.2	6.9
2012	56.5	50.1	41.4	27.5	9.5	3.6	46.3	43.7	39.8	26.9	10.4	4.1
2013	46.2	41.3	34.0	22.1	3.8	2.1	56.7	45.4	39.9	14.5	6.4	2.4
2014	63.5	58.0	42.6	14.3	3.6	1.2	54.0	43.0	39.8	23.5	12.4	2.5
2015	38.0	20.1	12.1	6.5	2.7	0.8	86.0	57.9	37.8	15.0	5.9	1.2
2016	46.8	38.3	21.7	4.9	1.4	0.1	80.0	67.0	37.5	25.3	6.8	-0.3
2017	90.3	85.8	65.9	30.4	6.6	-0.1	99.0	77.4	70.0	32.9	16.7	4.3
2018	71.1	53.5	37.7	18.6	1.7	-0.4	65.2	58.6	45.6	26.4	8.7	1.5
2019	130.2	116.2	105.1	72.2	10.6	1.1	75.5	70.4	76.9	48.4	17.7	4.6
2020	83.1	75.4	44.8	35.0	21.7	3.2	49.8	64.5	58.6	38.3	11.7	3.0
2021	51.3	42.6	34.5	16.0	1.6	-0.3	67.5	54.0	59.7	36.4	8.4	-1.9
2022	112.6	99.2	94.3	75.6	61.4	29.2	77.9	63.2	51.5	19.1	9.1	10.0

	ACTUAL						PyCast Forced PCA trained to 1981-2021					
WY	1-Jan	1-Feb	1-Mar	1-Apr	1-May	1-Jun	1-Jan	1-Feb	1-Mar	1-Apr	1-May	1-Jun
1981	74.0	70.5	53.6	35.5	21.0	10.5	49.3	39.7	31.2	23.1	8.2	2.6
1982	104.3	81.7	54.2	26.0	7.8	0.6	85.5	83.7	62.9	38.4	17.8	1.3
1983	84.0	68.2	51.8	20.5	13.0	1.5	92.4	67.0	49.4	28.7	18.7	1.5
1984	119.9	97.6	83.9	49.2	25.6	10.4	103.9	70.9	63.5	44.0	22.7	3.8
1985	49.4	45.4	36.7	22.5	3.3	0.5	101.8	70.7	59.2	39.0	9.3	-0.9
1986	72.2	63.2	30.9	10.0	3.8	-0.7	72.4	58.1	46.4	24.1	10.8	1.0
1987	49.0	43.6	29.0	8.1	2.4	0.9	60.7	58.3	47.6	26.2	5.6	0.1
1988	36.4	32.2	25.9	18.3	7.1	1.2	51.9	54.6	33.4	20.6	9.3	4.4
1989	98.3	81.5	69.4	33.1	9.2	0.6	87.3	90.0	73.0	46.5	14.0	3.3
1990	38.9	35.9	30.8	20.0	14.8	5.9	38.9	40.3	32.7	17.2	6.0	3.9
1991	79.0	67.4	56.4	43.7	28.0	3.5	60.0	51.6	27.8	19.7	9.4	6.5
1992	19.2	15.9	8.3	2.9	-0.4	0.8	60.4	41.3	24.4	11.0	4.4	-0.3
1993	89.2	81.4	76.0	44.8	20.1	3.2	90.4	83.3	62.9	34.1	15.9	3.7
1994	43.1	31.7	29.6	14.5	9.2	1.7	54.1	50.0	43.1	19.5	6.1	3.5
1995	101.7	87.6	65.4	47.3	36.0	2.3	78.0	59.0	35.5	21.5	16.0	4.9
1996	96.0	80.6	43.2	23.9	11.4	1.6	56.5	59.7	40.5	22.6	11.6	4.0
1997	88.0	70.1	52.7	24.4	6.1	0.8	92.4	67.9	50.4	27.1	14.6	2.4
1998	58.6	46.3	39.0	21.7	14.7	3.0	60.3	61.9	44.7	23.0	12.3	3.4
1999	61.9	46.3	37.5	18.0	6.7	0.6	67.8	53.8	54.7	30.3	12.3	1.6
2000	69.6	62.6	47.4	16.5	5.2	2.7	69.4	64.0	52.8	33.8	12.1	1.9
2001	56.0	50.7	43.2	27.2	5.4	1.0	56.0	49.1	34.4	17.2	8.9	1.4
2002	44.1	39.1	30.7	16.3	2.0	0.6	71.5	63.2	43.1	26.4	8.8	2.3
2003	78.9	68.0	47.8	19.9	6.3	0.6	64.0	43.5	38.0	21.7	13.4	3.5
2004	96.5	74.5	56.7	38.4	31.3	8.9	79.0	70.3	57.8	28.0	12.7	3.8
2005	28.9	25.8	24.0	21.0	14.9	1.3	51.1	36.2	24.5	14.2	5.1	5.2
2006	66.0	51.7	45.4	35.2	7.1	5.0	69.2	67.4	47.7	32.6	15.3	3.3
2007	42.4	35.1	24.7	10.8	2.9	1.0	62.5	48.3	32.6	15.4	7.1	0.7
2008	62.1	56.8	47.6	30.0	15.3	7.1	79.6	77.0	57.1	37.5	13.3	2.3
2009	85.2	69.5	64.6	43.9	16.3	1.0	83.2	64.0	49.4	36.8	14.1	2.2
2010	63.4	58.9	51.7	45.4	33.7	17.0	66.2	55.8	39.1	20.9	11.6	7.3
2011	153.2	119.3	106.9	82.3	43.6	13.3	98.1	63.1	54.3	41.1	20.3	6.2
2012	56.5	50.1	41.4	27.5	9.5	3.6	50.7	52.3	39.8	26.3	10.0	3.4
2013	46.2	41.3	34.0	22.1	3.8	2.1	63.1	59.0	42.4	18.0	6.3	2.4
2014	63.5	58.0	42.6	14.3	3.6	1.2	57.9	51.8	41.7	23.3	11.9	1.8
2015	38.0	20.1	12.1	6.5	2.7	0.8	73.2	44.7	30.5	14.8	8.2	1.5
2016	46.8	38.3	21.7	4.9	1.4	0.1	81.7	64.9	39.3	21.1	9.5	1.2
2017	90.3	85.8	65.9	30.4	6.6	-0.1	89.1	71.7	58.1	31.0	18.9	4.8
2018	71.1	53.5	37.7	18.6	1.7	-0.4	59.3	48.0	41.6	25.1	11.7	2.8
2019	130.2	116.2	105.1	72.2	10.6	1.1	73.5	62.6	72.0	43.4	20.1	6.8
2020	83.1	75.4	44.8	35.0	21.7	3.2	53.4	63.0	60.2	35.5	13.0	4.9
2021	51.3	42.6	34.5	16.0	1.6	-0.3	70.7	58.8	65.1	37.9	9.2	-0.8
2022	112.6	99.2	94.3	75.6	61.4	29.2	72.5	57.6	44.6	20.8	11.0	11.3

	ACTUAL						**PyCast Forced Z trained to 1981-2021**					
WY	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**
1981	74.0	70.5	53.6	35.5	21.0	10.5	50.3	37.0	31.2	23.5	7.9	2.9
1982	104.3	81.7	54.2	26.0	7.8	0.6	90.4	88.2	63.0	37.4	20.5	1.9
1983	84.0	68.2	51.8	20.5	13.0	1.5	89.1	62.5	48.7	30.7	20.5	0.7
1984	119.9	97.6	83.9	49.2	25.6	10.4	107.0	76.6	65.3	47.2	25.1	4.9
1985	49.4	45.4	36.7	22.5	3.3	0.5	99.3	61.0	56.3	38.1	11.3	-1.4
1986	72.2	63.2	30.9	10.0	3.8	-0.7	71.6	58.6	48.8	24.2	10.8	0.9
1987	49.0	43.6	29.0	8.1	2.4	0.9	58.4	52.1	45.2	24.6	5.4	-0.4
1988	36.4	32.2	25.9	18.3	7.1	1.2	49.7	51.1	31.7	19.5	8.6	5.1
1989	98.3	81.5	69.4	33.1	9.2	0.6	86.6	87.4	71.3	44.4	15.1	3.9
1990	38.9	35.9	30.8	20.0	14.8	5.9	35.4	30.0	28.8	15.4	6.2	4.3
1991	79.0	67.4	56.4	43.7	28.0	3.5	58.2	44.6	25.9	19.8	10.7	7.3
1992	19.2	15.9	8.3	2.9	-0.4	0.8	55.8	31.1	22.0	9.3	4.7	-0.7
1993	89.2	81.4	76.0	44.8	20.1	3.2	85.9	76.6	61.8	32.8	16.9	3.7
1994	43.1	31.7	29.6	14.5	9.2	1.7	49.7	44.9	42.6	18.1	5.7	3.1
1995	101.7	87.6	65.4	47.3	36.0	2.3	71.8	60.3	35.4	22.8	16.2	5.4
1996	96.0	80.6	43.2	23.9	11.4	1.6	59.8	64.2	42.9	22.7	11.2	4.7
1997	88.0	70.1	52.7	24.4	6.1	0.8	96.4	79.0	51.3	27.0	14.5	2.1
1998	58.6	46.3	39.0	21.7	14.7	3.0	55.2	58.8	44.4	24.4	13.1	4.0
1999	61.9	46.3	37.5	18.0	6.7	0.6	68.4	51.8	53.8	28.8	14.9	1.8
2000	69.6	62.6	47.4	16.5	5.2	2.7	67.8	65.3	55.5	34.5	10.5	1.7
2001	56.0	50.7	43.2	27.2	5.4	1.0	55.2	45.0	32.7	15.8	9.1	1.5
2002	44.1	39.1	30.7	16.3	2.0	0.6	63.6	50.3	39.6	23.8	10.4	2.4
2003	78.9	68.0	47.8	19.9	6.3	0.6	65.9	55.2	41.3	22.7	12.1	4.0
2004	96.5	74.5	56.7	38.4	31.3	8.9	85.6	87.7	61.1	27.3	11.3	3.8
2005	28.9	25.8	24.0	21.0	14.9	1.3	49.0	28.4	21.3	13.0	5.5	4.9
2006	66.0	51.7	45.4	35.2	7.1	5.0	72.0	74.9	48.9	34.6	15.0	2.9
2007	42.4	35.1	24.7	10.8	2.9	1.0	61.0	40.5	32.3	15.2	6.1	0.1
2008	62.1	56.8	47.6	30.0	15.3	7.1	78.8	76.3	56.7	38.7	15.6	2.5
2009	85.2	69.5	64.6	43.9	16.3	1.0	88.6	69.8	51.1	37.9	13.8	2.5
2010	63.4	58.9	51.7	45.4	33.7	17.0	66.2	56.3	39.3	20.6	12.1	8.9
2011	153.2	119.3	106.9	82.3	43.6	13.3	108.6	76.1	58.0	43.2	21.5	6.8
2012	56.5	50.1	41.4	27.5	9.5	3.6	48.4	47.9	39.3	26.4	9.2	3.9
2013	46.2	41.3	34.0	22.1	3.8	2.1	59.0	50.6	40.1	16.2	7.0	2.4
2014	63.5	58.0	42.6	14.3	3.6	1.2	58.3	46.7	40.5	23.0	12.0	2.2
2015	38.0	20.1	12.1	6.5	2.7	0.8	78.4	53.7	32.2	15.0	6.2	1.2
2016	46.8	38.3	21.7	4.9	1.4	0.1	81.1	68.3	39.9	23.0	7.2	0.1
2017	90.3	85.8	65.9	30.4	6.6	-0.1	95.9	76.9	61.9	31.3	16.0	4.6
2018	71.1	53.5	37.7	18.6	1.7	-0.4	62.8	54.9	41.9	25.3	9.1	1.9
2019	130.2	116.2	105.1	72.2	10.6	1.1	75.6	71.3	75.0	46.4	17.3	5.4
2020	83.1	75.4	44.8	35.0	21.7	3.2	51.5	68.3	61.1	37.0	11.8	3.7
2021	51.3	42.6	34.5	16.0	1.6	-0.3	73.8	60.2	64.5	37.4	8.8	-1.7
2022	112.6	99.2	94.3	75.6	61.4	29.2	75.8	64.8	45.8	19.4	8.3	10.3

	ACTUAL						4 PyCast Average					
WY	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**
1981	74.0	70.5	53.6	35.5	21.0	10.5	52.9	40.9	32.8	24.1	8.3	2.8
1982	104.3	81.7	54.2	26.0	7.8	0.6	91.3	88.0	62.8	37.0	19.0	2.4
1983	84.0	68.2	51.8	20.5	13.0	1.5	89.1	63.7	45.8	30.5	19.7	0.9
1984	119.9	97.6	83.9	49.2	25.6	10.4	108.9	76.6	65.2	47.7	23.9	5.0
1985	49.4	45.4	36.7	22.5	3.3	0.5	95.4	60.6	54.1	37.8	10.1	-1.2
1986	72.2	63.2	30.9	10.0	3.8	-0.7	70.9	58.8	49.3	25.3	11.1	1.1
1987	49.0	43.6	29.0	8.1	2.4	0.9	56.9	53.0	43.1	23.4	5.6	-0.3
1988	36.4	32.2	25.9	18.3	7.1	1.2	50.7	51.0	30.8	18.8	9.2	4.7
1989	98.3	81.5	69.4	33.1	9.2	0.6	83.8	85.4	70.1	44.3	14.6	3.8
1990	38.9	35.9	30.8	20.0	14.8	5.9	35.8	32.8	28.1	15.4	5.8	4.2
1991	79.0	67.4	56.4	43.7	28.0	3.5	57.5	44.5	25.4	20.1	9.7	7.2
1992	19.2	15.9	8.3	2.9	-0.4	0.8	55.2	32.9	22.0	8.8	4.4	-0.5
1993	89.2	81.4	76.0	44.8	20.1	3.2	84.4	76.0	62.1	32.7	16.1	3.4
1994	43.1	31.7	29.6	14.5	9.2	1.7	50.8	45.6	41.8	17.7	6.1	2.9
1995	101.7	87.6	65.4	47.3	36.0	2.3	73.7	62.2	36.1	23.1	16.4	5.3
1996	96.0	80.6	43.2	23.9	11.4	1.6	61.7	63.2	45.3	23.2	11.7	4.7
1997	88.0	70.1	52.7	24.4	6.1	0.8	99.2	78.8	51.7	27.7	14.4	2.3
1998	58.6	46.3	39.0	21.7	14.7	3.0	55.5	59.7	42.9	24.2	12.9	4.0
1999	61.9	46.3	37.5	18.0	6.7	0.6	69.2	53.2	54.3	29.7	13.3	2.0
2000	69.6	62.6	47.4	16.5	5.2	2.7	66.4	65.5	57.0	34.6	11.9	1.6
2001	56.0	50.7	43.2	27.2	5.4	1.0	55.7	46.4	33.5	16.4	8.9	1.4
2002	44.1	39.1	30.7	16.3	2.0	0.6	63.9	52.5	39.3	23.1	9.5	2.3
2003	78.9	68.0	47.8	19.9	6.3	0.6	67.0	54.7	43.1	22.5	13.4	4.1
2004	96.5	74.5	56.7	38.4	31.3	8.9	85.0	84.3	62.0	27.1	12.5	3.7
2005	28.9	25.8	24.0	21.0	14.9	1.3	50.9	31.5	21.4	13.2	5.0	4.7
2006	66.0	51.7	45.4	35.2	7.1	5.0	74.3	74.8	49.4	34.8	15.4	2.7
2007	42.4	35.1	24.7	10.8	2.9	1.0	61.5	42.2	32.1	14.8	6.7	0.1
2008	62.1	56.8	47.6	30.0	15.3	7.1	78.8	75.3	56.6	39.0	14.2	2.8
2009	85.2	69.5	64.6	43.9	16.3	1.0	87.0	68.6	52.0	38.3	14.3	2.6
2010	63.4	58.9	51.7	45.4	33.7	17.0	65.8	55.8	39.0	21.1	12.2	8.6
2011	153.2	119.3	106.9	82.3	43.6	13.3	105.7	73.4	59.4	44.2	20.8	6.8
2012	56.5	50.1	41.4	27.5	9.5	3.6	48.1	46.9	39.0	27.0	10.2	3.8
2013	46.2	41.3	34.0	22.1	3.8	2.1	58.3	50.4	38.7	16.3	6.6	2.4
2014	63.5	58.0	42.6	14.3	3.6	1.2	57.4	46.9	40.6	23.3	11.9	2.4
2015	38.0	20.1	12.1	6.5	2.7	0.8	80.3	53.2	34.7	13.8	7.0	1.2
2016	46.8	38.3	21.7	4.9	1.4	0.1	81.4	67.1	39.9	22.7	8.3	0.2
2017	90.3	85.8	65.9	30.4	6.6	-0.1	93.4	74.8	64.1	31.2	17.5	4.5
2018	71.1	53.5	37.7	18.6	1.7	-0.4	62.5	55.0	43.3	25.1	9.8	1.9
2019	130.2	116.2	105.1	72.2	10.6	1.1	76.2	69.6	74.3	45.3	18.2	5.3
2020	83.1	75.4	44.8	35.0	21.7	3.2	51.6	66.4	60.2	36.3	11.8	3.5
2021	51.3	42.6	34.5	16.0	1.6	-0.3	72.1	57.9	61.8	37.1	8.5	-1.5
2022	112.6	99.2	94.3	75.6	61.4	29.2	76.4	62.8	46.4	19.0	9.4	10.3

Appendix B

McKay Creek near Pendleton, OR PyForecast WSF Development

The dependent variable of the McKay Reservoir inflow WSF is the daily Unregulated Streamflow at the McKay Creek near Pendleton, OR gage (MCKO QU). MCKO QU is based on data collected by the Oregon Water Resources Department (OWRD) at the McKay Creek near Pendleton, OR gage (MCKO QD), approximately 1/4 mile downstream of McKay Dam. This gage has a long period of record, with average daily flow data available starting in WY1919. From this data, Reclamation calculates a daily unregulated streamflow at the site, considering changes in storage at McKay Reservoir (MCK) upstream (which inherently incorporates reservoir losses such as evaporation). Irrigation diversions are believed to be minimal upstream of the gage and historically have not been considered in the calculation. The formula for calculating MCKO QU is as follows:

MCKO QU = MCKO QD + DstoMCK

Where:

- MCKO QU = Daily Unregulated Streamflow at the McKay Creek near Pendleton, OR gage (cfs)
- MCKO QD = Daily Observed Streamflow at the McKay Creek near Pendleton, OR gage (cfs)
- DstoMCK = Change in Storage at McKay Reservoir (acre-feet)/1.98347

Predictor Inventory

Data availability in the McKay basin is fair, with multiple sites having long periods of record. This provides a pool of potential predictors to use in the development of the WSF. It should be noted PyForecast is not yet able to process gridded SWE data, which may provide a better representation of snowpack in the basin. Instead, PyForecast is limited to utilizing SNOTEL sites for purposes of determining basin snowpack, which, as described previously, only represents around 20 percent of the basin. Future development of this feature may provide additional benefits to PyForecast WSFs. During predictor selection, sites within two HUC-8 basins of the McKay basin were considered to ensure sufficient coverage while maintaining similar basin characteristics. The potential predictor pool consisted of the following and can be found in Table B-1:

- Twenty-two NRCS SNOTEL sites
- Three Agrimet/Hydromet/National Weather Service precipitation sites
- One Antecedent Streamflow
- Two Climatic Indices

Table B-1. Potential predictor pool

Snow Water Equivalent		
Site	Considered	Potential Predictors
Aneroid Lake #2	X	
Arbuckle Mtn	X	X
Beaver Reservoir	X	
Bourne	X	X
Bowman Springs	X	X
County Line	X	
Eilertson Meadows	X	
Emigrant Springs	X	X
Gold Center	X	
High Ridge	X	X
Lucky Strike	X	
Madison Butte	X	X
Milk Shakes	X	
Moss Springs	X	
Mt. Howard	X	X
Schneider Meadows	X	
Sourdough Gulch	X	
Spruce Springs	X	
Taylor Green	X	X
Tipton	X	
Touchet	X	
Wolf Creek	X	X
Precipitation		
Site	Considered	Potential Predictors
La Grande, OR	X	
Pendleton E OR Rgnl Ap, OR	X	X
Pilot Rock 11E, OR	X	X

Antecedent Streamflow		
Site	Considered	Potential Predictors
MCKO QU	X	
Climatic Indices		
Site	Considered	Potential Predictors
ONI	X	
SOI	X	X

Data Quality Control

No data cleanup was required for the sites considered for the MCKO WSF.

Predictor Culling

Predictors were culled (selected) using the process outlined in the PyForecast development documentation. In general, predictors with the best linear regression fit (i.e., r^2 values) were considered the best indicators and were placed into the final predictor pool for input into the PyForecast software program for further analysis. However, professional judgement was also used to include predictors in the final pool that provide for sufficient spatial representativeness, even though they may not have the highest correlation. The potential predictor pool was analyzed and culled (selected), as seen in Table B-2 and Figure B-1, and includes the following:

- Nine NRCS SNOTEL sites
- Two Agrimet/Hydromet/National Weather Service precipitation sites
- One Climatic Index

Table B-2. Culled (selected) predictor list for use in MCKO WSF. Notice r^2 values are much lower than purely snow dominated basins.

Site	Period of Record	Elevation	Jan-Jun		Feb-Jun		Mar-Jun		Apr-Jun		May-Jun		Jun-Jun	
			Data Date	r^2	Data Date	r^2	Data Date	r^2	Data Date	r^2	Data Date	r^2	Data Date	r^2
Snow Water Equivalent														
Arbuckle Mtn	Oct-1978	5770	1-Jan	0.13	1-Feb	0.12	1-Mar	0.14	1-Apr	0.06	--	--	--	--
Bourne	Oct-1978	5850	1-Jan	0.16	1-Feb	0.18	1-Mar	0.13	1-Apr	0.14	--	--	--	--
Bowman Springs	Oct-1978	4530	1-Jan	0.24	1-Feb	0.19	1-Mar	0.19	1-Apr	0.14	--	--	--	--
Emigrant Springs	Jan-1979	3800	1-Jan	0.22	1-Feb	0.11	1-Mar	0.21	1-Mar	0.09	--	--	--	--
High Ridge	Oct-1978	4920	1-Jan	0.13	1-Feb	0.14	1-Mar	0.12	1-Apr	0.07	--	--	--	--
Madison Butte	Oct-1980	5150	1-Jan	0.10	1-Feb	0.05	1-Mar	0.22	1-Apr	0.28	--	--	--	--
Mt. Howard	Oct-1980	7910	--	--	--	--	--	--	--	--	--	--	1-Jun	0.15
Taylor Green	Oct-1979	5740	1-Jan	0.14	1-Feb	0.21	1-Mar	0.20	1-Apr	0.23	1-May	0.19	--	--
Wolf Creek	Oct-1978	5630	1-Jan	0.18	1-Feb	0.25	1-Mar	0.22	1-Apr	0.12	1-May	0.14	--	--
Precipitation														
Pendleton, OR	Jan-1928	1485	Dec-Dec	0.25	Dec-Jan	0.29	Dec-Feb	0.27	Dec-Mar	0.15	Dec-Apr	0.08	Apr-May	0.30
Pilot Rock, OR	Nov-1908	1920	Dec-Dec	0.18	Dec-Jan	0.18	Dec-Feb	0.14	Dec-Mar	0.12	Dec-Apr	0.01	Apr-May	0.06
Climatic Indices														
Southern Oscillation Index	Jan-1951	N/A	Prev Aug	0.15	Prev Aug	0.15	Prev Aug	0.15	Prev Aug	0.10	--	--	--	--

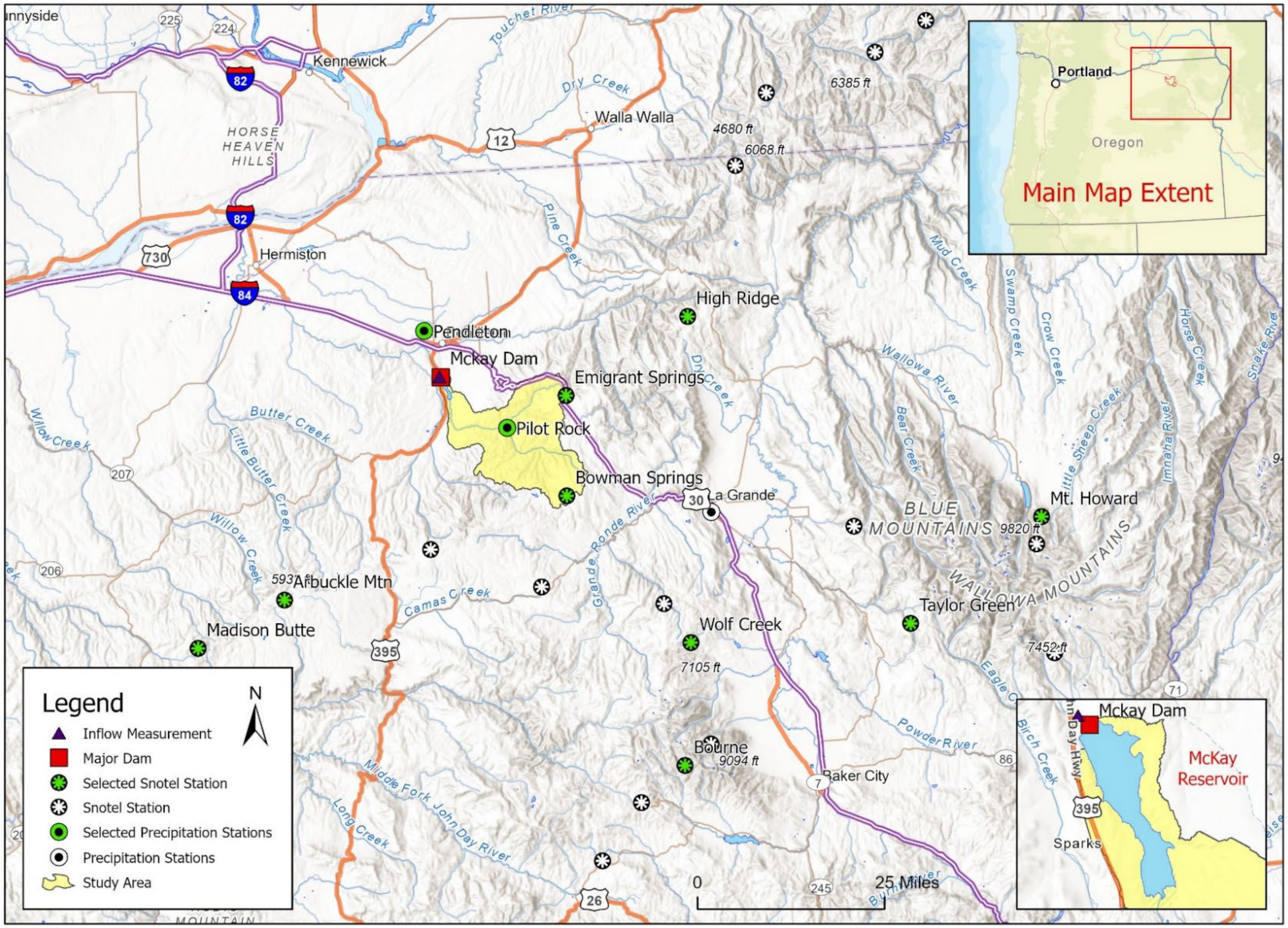


Figure B-1. Map of culled (selected) predictor sites for use in MCKO WSF

Training Period Determination

For the McKay WSF, snowpack data was the limiting factor in determining the start of the training period. SNOTEL data was available for most sites in the basin starting in WY1981, while other potential predictor data such as precipitation and climatic data was available prior to WY1981. Therefore, the start of the training period was chosen as WY1981. For the end of the training period, data was available through WY2022; however, the ESP0 forecasts provided by the NWRFC utilize meteorological forcings from the WY1981-WY2021 period. Therefore, to be consistent, the end of the training period was chosen to be WY2021.

The chosen training period was compared to the historical period of record to gain understanding of how well the training period encompasses the range of historical runoff volumes and to determine the events that fall outside of the range. On the wet end, it was found that the WY1981-WY2021 period includes the top three highest January through June runoffs on record (WY2011, WY2019, WY1984), which provides confidence that large runoff events are captured in the training period. This is an important consideration given that one of the main purposes of this updated WSF is to inform operations during high runoff years. On the dry end, one of the three lowest annual runoffs on record (WY1992) was found to fall within the WY1981-WY2021 period, which provides confidence that low runoff events are captured in the training period. The McKay WSF becomes less consequential in extreme drought years as FRM operations generally become unnecessary and the WSF is not directly used in allocating water in the basin. However, the WSF does help to inform water users of the potential for dry conditions. WY1992 was considered an extreme drought year in the basin, and its inclusion in the training period provides confidence that drought years are also captured even though the driest years (WY1966 and WY1973) fall outside the training period.

The blue box-and-whisker plots in Figure B-2 and Figure B-3 represent the range of runoff volumes for the period of record (WY1928-WY2022), with the box representing the interquartile range (between the 25th and 75th percentile). The orange box-and-whisker plots represent the training period (WY1981-WY2021). The gray box-and-whisker plots represent the data not included in the training period (WY1928-WY1980). The green box-and-whisker plots represent the most recent 30-year averaging period (WY1991-WY2020). Overall, the WY1981-WY2021 training period generally captures the range of both wet and dry conditions as described above. The interquartile range of the WY1981-WY2021 training period encompasses a larger range than the WY1928-WY1980 period, indicating the data in the training period is more dispersed than the data not in the training period. This indicates more variability in the training period data. Also, the median value for the WY1981-WY2021 training period was found to be 14 percent higher than the WY1928-WY1980 period for the January-to-June period. This might weight the model towards wet years, relative to the full record, but these changes might also reflect the effects of a changing climate, with the training period better representing what we might anticipate in the future. Conversely, the median value for the WY1981-WY2021 training period for the April-to-June period was found to be 4 percent lower than the WY1928-WY1980 period, indicating that overall the training period may be skewed wetter, but runoff has shifted earlier into the January through March period. Overall, these differences are not anticipated to cause major sources of error in the forecasts, and the chosen WY1981-WY2021 period generally captures the historical period well and is more representative of the more recent 30-year averaging period of WY1991-WY2020.

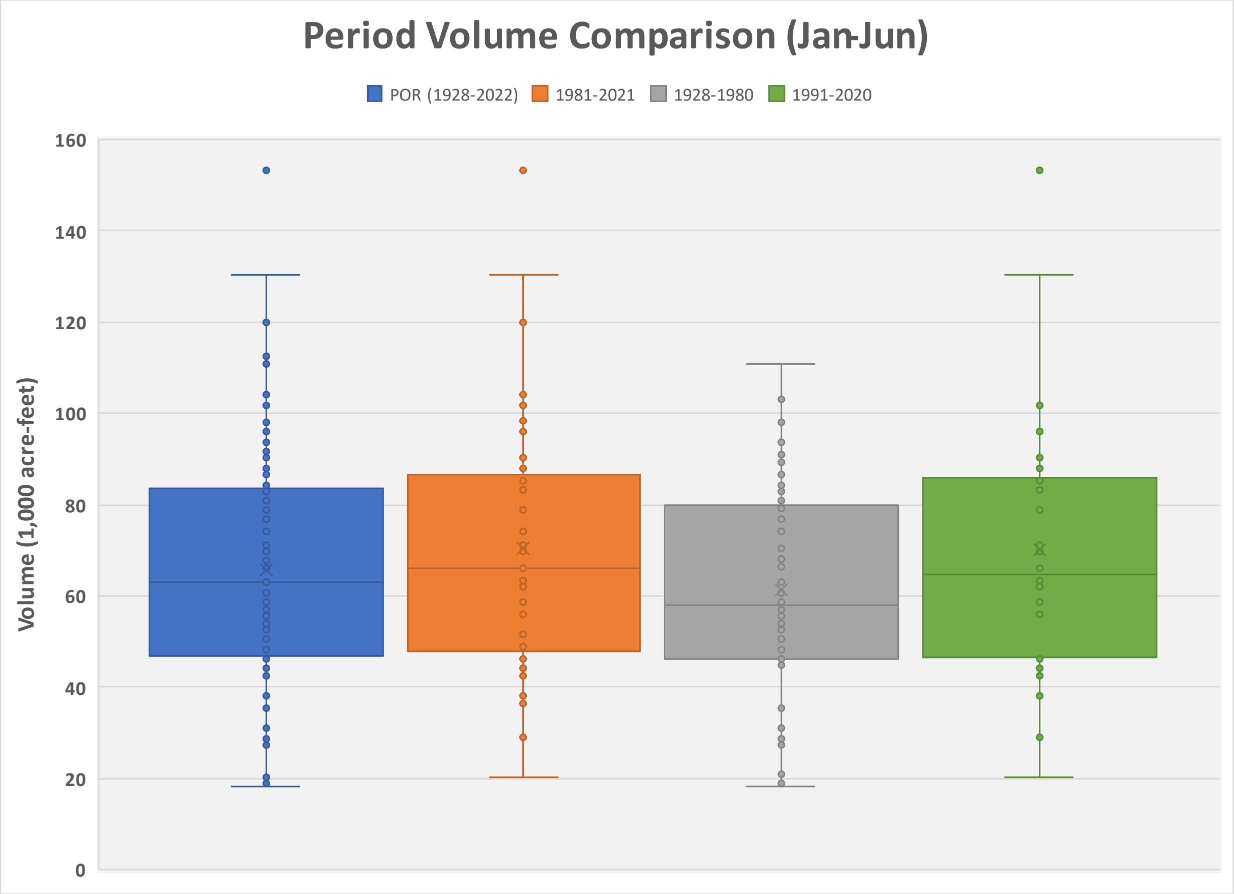


Figure B-2. January through June MCKO QU volume range for the WY1981-WY2021 training period used in the forecast update vs. other historical periods

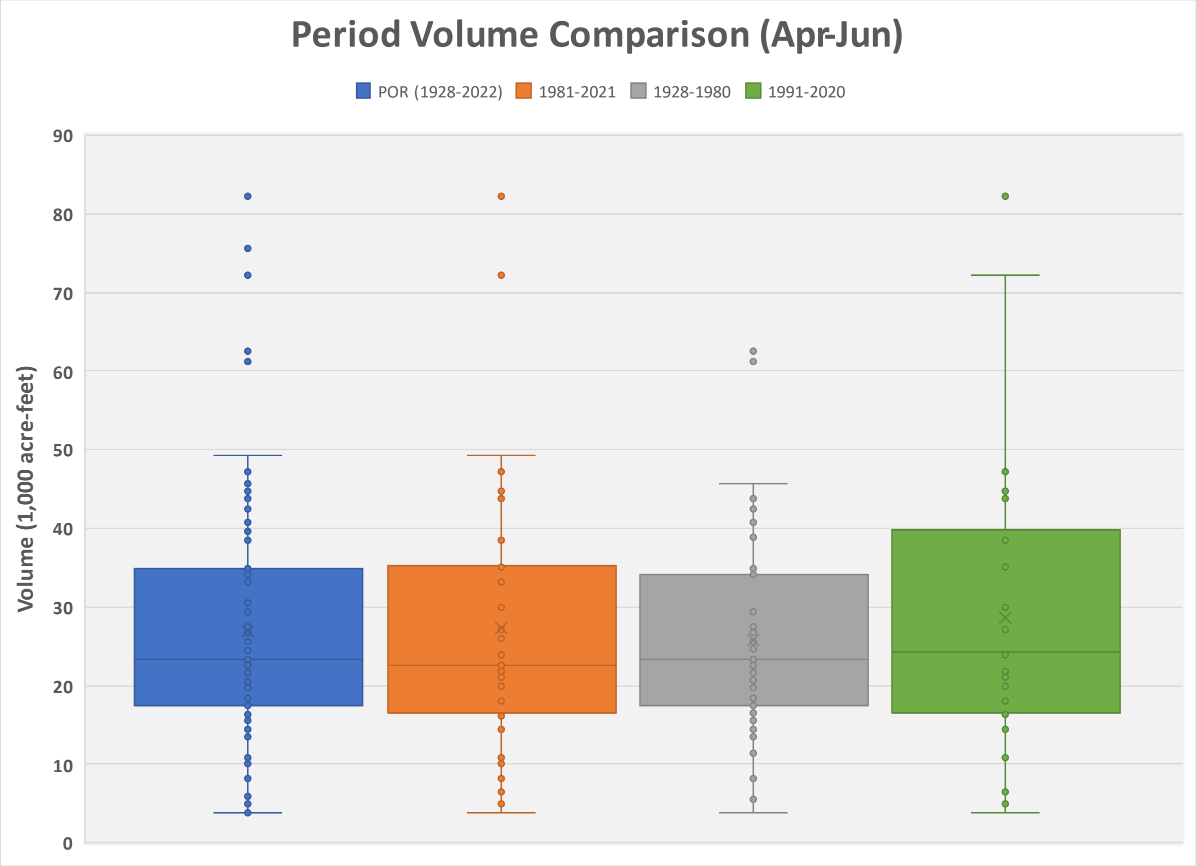
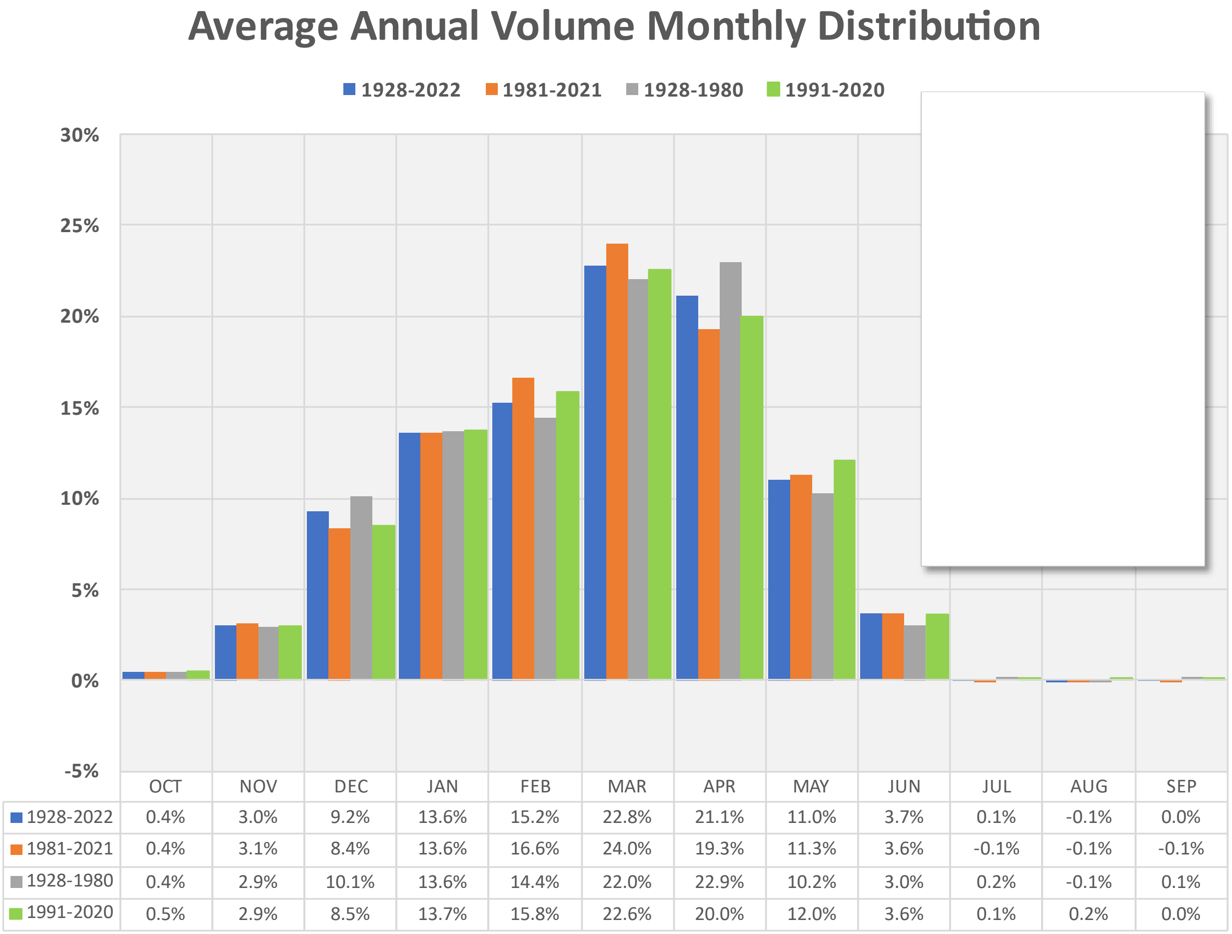


Figure B-3. April through June MCKO QU volume range for the WY1981-WY2021 training period used in the WSF update vs. other historical periods

The chosen training period was also compared to the historical period of record to gain understanding of runoff timing in the basin and how it has changed over time. Figure B-4 shows the monthly runoff volumes for the WY1928-WY2022 period of record (blue bars), the WY1981-WY2021 training period (orange bars), the WY1928-WY1980 period that is not included in the training period (gray bars), and the WY1991-WY2020 most recent 30-year averaging period (green bars). In general, there has not been a major shift in runoff timing in the basin, as illustrated by similar monthly runoff distributions for all the periods and by both the WY1928-WY2022 and the WY1991-WY2020 period having around 64 percent of the annual runoff occurring in the October-March period. This effect may be due to the basin already being within the rain-snow transition zone which historically has resulted in large runoff events occurring anytime during the months of November through June.



	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
■ 1928-2022	0.4%	3.0%	9.2%	13.6%	15.2%	22.8%	21.1%	11.0%	3.7%	0.1%	-0.1%	0.0%
■ 1981-2021	0.4%	3.1%	8.4%	13.6%	16.6%	24.0%	19.3%	11.3%	3.6%	-0.1%	-0.1%	-0.1%
■ 1928-1980	0.4%	2.9%	10.1%	13.6%	14.4%	22.0%	22.9%	10.2%	3.0%	0.2%	-0.1%	0.1%
■ 1991-2020	0.5%	2.9%	8.5%	13.7%	15.8%	22.6%	20.0%	12.0%	3.6%	0.1%	0.2%	0.0%

Figure B-4. Summary hydrograph showing the McKay Creek near Pendleton unregulated monthly volume for the WY1981-WY2021 training period used in the WSF update vs. other historical periods. Note: negative values during July-September account for reservoir evaporation.

Top PyForecast Equations

The Top PyForecast equations were developed using the procedure described in the PyForecast development documentation.

Top PyForecast Models

The Top PyForecast PCR (Principal Component Regression) and Z-Score equations were chosen based on the best root-mean-square error (RMSE). The variables included in each WSF along with their coefficients can be found in Table B-3 and Table B-4.

Table B-3. MCKO Top PyForecast PCR coefficients

Regression Variables		Forecast Issue Date					
Type	**Variable Name**	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**
Snow Water Equivalent (inches)	Arbuckle Mtn	--	--	--	--	--	--
	Bourne	--	--	--	--	--	--
	Bowman Springs	3.43860	2.00320	--	--	--	--
	Emigrant Springs	--	--	0.88636	--	--	--
	High Ridge	--	--	--	--	--	--
	Madison Butte	--	--	--	1.23605	--	--
	Mt. Howard	--	--	--	--	--	0.21803
	Taylor Green	--	--	--	0.63301	--	--
	Wolf Creek	2.12788	1.52975	1.14944	--	0.37408	--
Precipitation (inches)	Pendleton, OR	7.22376	4.61907	3.26064	1.60764	1.40310	1.52040
	Pilot Rock, OR	5.53722	3.65390	1.99605	--	--	--
Climatic Index	SOI	1.65632	1.39230	2.07245	1.93383	--	--
Constant	Constant (in kaf)	23.04672	6.18409	3.08914	2.46877	-0.54220	-2.49806

Table B-4. MCKO Top PyForecast Z-Score coefficients

Regression Variables		Forecast Issue Date					
Type	**Variable Name**	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**
Snow Water Equivalent (inches)	Arbuckle Mtn	--	--	--	--	--	--
	Bourne	--	--	--	--	--	--
	Bowman Springs	--	--	--	--	--	--
	Emigrant Springs	2.31059	0.74798	0.99167	--	--	--
	High Ridge	--	--	--	--	--	--
	Madison Butte	--	--	1.48410	1.35985	--	--
	Mt. Howard	--	--	--	--	--	0.14646
	Taylor Green	--	--	--	0.52975	0.49556	--
	Wolf Creek	1.93358	1.72014	--	--	--	--
Precipitation (inches)	Pendleton, OR	8.40574	6.49806	4.15778	1.47551	0.93037	2.01510
	Pilot Rock, OR	5.07410	3.55058	1.56713	0.85310	--	--
Climatic Index	SOI	3.07905	2.64833	2.39288	1.19340	--	--

Regression Variables		Forecast Issue Date					
Type	Variable Name	1-Jan	1-Feb	1-Mar	1-Apr	1-May	1-Jun
Constant	Constant (in kaf)	29.22381	7.32832	9.93553	-0.45602	0.53780	-3.24485

Forced PyForecast Equations

The forced PyForecast equations were developed using the procedure described in the PyForecast development documentation.

Forced PyForecast Models

The Forced PyForecast PCR and Z-Score equations were chosen based on the best RMSE. The variables included in each WSF along with their coefficients can be found in Table B-5 and Table B-6.

Table B-5. MCKO Forced PyForecast PCR coefficients

Regression Variables		Forecast Issue Date					
Type	Variable Name	1-Jan	1-Feb	1-Mar	1-Apr	1-May	1-Jun
Snow Water Equivalent (inches)	Arbuckle Mtn	--	--	--	--	--	--
	Bourne	--	--	--	--	--	--
	Bowman Springs	2.12892	1.26398	0.84264	0.46431	--	--
	Emigrant Springs	1.44336	0.87660	0.64116	0.43584	--	--
	High Ridge	--	--	--	--	--	--
	Madison Butte	1.98976	1.20477	0.88926	0.63820		
	Mt. Howard	--	--	--	--	--	0.07977
	Taylor Green	1.19432	0.88385	0.59702	0.31408	0.18002	--
	Wolf Creek	--	--	--	--	0.22173	--
Precipitation (inches)	Pendleton, OR	3.07135	1.28394	1.21845	0.71947	0.74361	1.05472
	Pilot Rock, OR	2.32070	0.83569	0.82561	0.47379	0.40829	0.62233
Climatic Index	SOI	0.86480	0.82608	1.18858	0.98271	--	--
Constant	Constant (in kaf)	33.66718	24.02919	12.82373	7.13750	-0.01441	-2.66311

Table B-6. MCKO Forced PyForecast Z-Score coefficients

Regression Variables		Forecast Issue Date					
Type	**Variable Name**	**1-Jan**	**1-Feb**	**1-Mar**	**1-Apr**	**1-May**	**1-Jun**
Snow Water Equivalent (inches)	Arbuckle Mtn	--	--	--	--	--	--
	Bourne	--	--	--	--	--	--
	Bowman Springs	2.68635	1.46842	0.69427	0.33578	--	--
	Emigrant Springs	1.62896	0.59631	0.62614	0.23141	--	--
	High Ridge	--	--	--	--	--	--
	Madison Butte	1.11002	0.40267	0.93706	0.99733	--	--
	Mt. Howard	--	--	--	--	--	0.12726
	Taylor Green	0.83930	1.11988	0.54646	0.38852	0.29637	--
	Wolf Creek	--	--	--	--	0.29637	--
Precipitation (inches)	Pendleton, OR	5.92602	5.18036	2.62523	1.08216	0.55640	1.75084
	Pilot Rock, OR	3.57723	2.83058	0.98949	0.62567	0.06746	0.22281
Climatic Index	SOI	2.17072	2.11129	1.51087	0.87525	--	--
Constant	Constant (in kaf)	29.73869	6.78562	8.19347	3.63161	2.36981	-3.27217

Appendix C

Summary Statistics Definitions

The performance of the WSF equations developed for this study were compared with six statistical relationships: root mean squared error (RMSE), standard deviation (SD), standard error (SE), coefficient of determination (r^2), max error, and Nash-Sutcliffe Efficiency (NSE).

Root Mean Squared Error (RMSE)

RMSE is a measure of accuracy, to compare forecasting errors of different models for a particular dataset. A value of 0 would indicate a perfect fit to the data. Attaining a lower RMSE indicates improvement.

Standard Deviation (SD)

The SD is a measure of the amount of variation or dispersion of a set of values. The standard deviation of the sample is the degree to which individuals within the sample differ from the sample mean. A low SD indicates that the values tend to be close to the mean of the set, while a high SD indicates that the values are spread out over a wider range. For this process, the SD of the forecast error was taken. Attaining a lower SD indicates improvement.

Standard Error (SE)

The SE is the standard deviation of its sampling distribution. The standard error of the sample mean is an estimate of how far the sample mean is likely to be from the population. The SE was calculated based on the forecast error. Attaining a lower SE indicates improvement.

Coefficient of Determination (r^2)

The r^2 is the proportion of the variance in the dependent variable that is predictable from the independent variable. The r^2 provides a measure of how well observed outcomes are replicated by the model. Attaining a higher r^2 indicates improvement.

Max Error

The maximum absolute error that resulted from the hindcasts was compared. The max error can be used to indicate the performance of an equation in predicting years where the final predicted volume had limited predictability in the forecast season from January through June. This can occur in extreme dry or wet sequences later in the spring or summer. Attaining a lower max error indicates improvement.

Nash-Sutcliffe Efficiency (NSE)

The NSE is used to assess the predictive skill of hydrological models. The NSE is calculated as 1 minus the ratio of the error variance of the modeled time-series divided by the variance of the observed time-series. In the situation of a perfect model with an estimation error variance equal to zero, the resulting NSE equals 1. Attaining a higher NSE indicates improvement.

Appendix D

Tabular SRDs

Existing sSRD

11/1	11/15	12/1	12/15	1/1	1/15	2/1	2/15	3/1	3/15	4/1	4/15	5/1	5/15	6/1	6/15
38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	3,300	0	0	0	0	0	0

800sSRD

11/1	11/15	12/1	12/15	1/1	1/15	2/1	2/15	3/1	3/15	4/1	4/15	5/1	5/15	6/1	6/15
38,800	38,800	38,800	33,500	28,029	28,029	27,660	27,660	27,660	27,660	21,713	8,953	8,953	8,618	4,378	0

1200sSRD

Space Required on Date															
11/1	11/15	12/1	12/15	1/1	1/15	2/1	2/15	3/1	3/15	4/1	4/15	5/1	5/15	6/1	6/15
38,800	38,800	38,800	33,500	27,500	22,400	16,300	15,059	15,059	15,059	13,758	4,892	4,892	4,892	584	0

800dSRD

	Space Required on Date															
Date-Jun30 Runoff (ac-ft)	11/1	11/15	12/1	12/15	1/1	1/15	2/1	2/15	3/1	3/15	4/1	4/15	5/1	5/15	6/1	6/15
0	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	3,300	0	0	0	0	0	0
10,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	3,300	0	0	1,767	2,738	0	0
20,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	3,300	1,369	3,222	5,302	5,977	2,228	0
30,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	3,633	5,263	7,161	8,837	9,216	4,561	0
40,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	7,009	9,157	11,101	12,372	12,455	6,894	0
50,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	8,883	10,386	13,050	15,041	15,906	15,694	9,228	0
60,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	13,447	12,293	13,762	16,944	18,981	19,441	18,933	11,561	0
70,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	16,326	15,703	17,138	20,837	22,921	22,976	22,173	13,894	0
80,000	38,800	38,800	38,800	33,500	27,500	22,400	17,680	19,205	19,113	20,515	24,731	26,861	26,510	25,412	16,228	0
90,000	38,800	38,800	38,800	33,500	27,500	22,400	20,438	22,084	22,523	23,891	28,625	30,801	30,045	28,651	18,561	0
100,000	38,800	38,800	38,800	33,500	27,500	22,400	23,197	24,963	25,932	27,268	32,518	34,740	33,580	31,890	20,894	0
110,000	38,800	38,800	38,800	33,500	27,500	23,709	25,955	27,841	29,342	30,644	36,412	38,680	37,115	35,129	23,227	0
120,000	38,800	38,800	38,800	33,500	27,500	26,287	28,713	30,720	32,752	34,021	40,305	42,620	40,649	38,368	25,561	0
130,000	38,800	38,800	38,800	33,500	27,975	28,866	31,471	33,599	36,162	37,397	44,199	46,560	44,184	41,607	27,894	0
140,000	38,800	38,800	38,800	33,500	30,501	31,445	34,229	36,478	39,572	40,774	48,093	50,500	47,719	44,846	30,227	0
150,000	38,800	38,800	38,800	33,500	33,026	34,023	36,987	39,357	42,982	44,150	51,986	54,440	51,254	48,085	32,561	0
160,000	38,800	38,800	38,800	33,500	35,552	36,602	39,745	42,236	46,392	47,527	55,880	58,380	54,788	51,325	34,894	0
170,000	38,800	38,800	38,800	33,500	38,077	39,180	42,504	45,115	49,802	50,903	59,773	62,319	58,323	54,564	37,227	0
180,000	38,800	38,800	38,800	33,500	40,603	41,759	45,262	47,993	53,212	54,280	63,667	65,534	61,858	57,803	39,561	0
190,000	38,800	38,800	38,800	33,500	43,128	44,337	48,020	50,872	56,622	57,656	65,534	65,534	65,392	61,042	41,894	0
200,000	38,800	38,800	38,800	33,500	45,654	46,916	50,778	53,751	60,032	61,033	65,534	65,534	65,534	64,281	44,227	0

1200dSRD

	Space Required on Date															
Date-Jun30 Runoff (ac-ft)	11/1	11/15	12/1	12/15	1/1	1/15	2/1	2/15	3/1	3/15	4/1	4/15	5/1	5/15	6/1	6/15
0	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	3,300	0	0	0	0	0	0
10,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	3,300	0	0	1,107	1,207	74	0
20,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	3,300	679	1,643	3,210	3,620	339	0
30,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	3,300	2,609	3,699	5,312	6,034	605	0
40,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	3,816	4,539	5,754	7,415	8,448	870	0
50,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,100	5,654	6,470	7,809	9,518	10,861	1,136	0
60,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	6,689	7,493	8,400	9,864	11,621	13,275	1,401	0
70,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	8,546	9,331	10,330	11,919	13,724	15,689	1,667	0
80,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	11,200	10,404	11,169	12,261	13,974	15,827	18,102	1,932	0
90,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	12,023	12,261	13,008	14,191	16,029	17,930	20,516	2,198	0
100,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	13,591	14,118	14,846	16,121	18,085	20,033	22,930	2,463	0
110,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	15,158	15,976	16,684	18,051	20,140	22,136	25,343	2,729	0
120,000	38,800	38,800	38,800	33,500	27,500	22,400	16,300	16,726	17,833	18,523	19,982	22,195	24,238	27,757	2,994	0
130,000	38,800	38,800	38,800	33,500	27,500	22,400	17,134	18,293	19,690	20,361	21,912	24,250	26,341	30,171	3,260	0
140,000	38,800	38,800	38,800	33,500	27,500	22,400	18,636	19,860	21,548	22,199	23,842	26,305	28,444	32,584	3,525	0
150,000	38,800	38,800	38,800	33,500	27,500	22,400	20,138	21,428	23,405	24,037	25,772	28,360	30,547	34,998	3,791	0
160,000	38,800	38,800	38,800	33,500	27,500	22,400	21,639	22,995	25,263	25,876	27,703	30,415	32,650	37,412	4,056	0
170,000	38,800	38,800	38,800	33,500	27,500	22,400	23,141	24,562	27,120	27,714	29,633	32,471	34,753	39,825	4,322	0
180,000	38,800	38,800	38,800	33,500	27,500	22,435	24,643	26,130	28,977	29,552	31,563	34,526	36,856	42,239	4,587	0
190,000	38,800	38,800	38,800	33,500	27,500	23,821	26,144	27,697	30,835	31,391	33,494	36,581	38,959	44,653	4,853	0
200,000	38,800	38,800	38,800	33,500	27,500	25,206	27,646	29,265	32,692	33,229	35,424	38,636	41,062	47,066	5,118	0