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Managing Water in the West

RiverWare Modeling Review of Bighorn Lake Operating Criteria

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Introduction and Objectives

Reclamation implemented changes to its Bighorn Lake/Yellowtail Dam operating criteria in water year 2010. These changes followed an extensive effort in which Reclamation formed the Bighorn River Issues Group, comprised of Yellowtail Dam/Bighorn Lake stakeholders to obtain input on operating criteria. This effort followed a prolonged drought, from 2000 through 2007, and was intended to improve water supply reliability, improve transparency, improve lake and river fisheries and recreation, increase hydropower generation, and enhance flood control benefits.

At the request of the Montana Area Office, Reclamation's Great Plains Regional Office reviewed the operating criteria for Bighorn Lake. The goals of the review were to: 1) document differences between current and past operations of Bighorn Lake; 2) determine if significant differences exist between the realized and anticipated benefits of the operating criteria; 3) determine potential causes for any differences in operations and between realized and anticipated benefits; and 4) propose potential operational improvements for future examination.

The first component of the operating criteria review was a graphical and statistical analysis comparing operations under current and past operating criteria, and across different historical periods. The investigation also examined seasonal forecast skill, comparing NRCS and Reclamation forecasts to observed reservoir inflow. The analysis found significant differences between hydrology and operations across time periods and during different operating criteria. The analysis also found differences between expected (based on Reclamation's 2012 Draft Yellowtail Unit Operating Criteria Evaluation Study & Report) peak flows and duration. Forecasting error was also identified as a possible cause of differences in operations.

The methods used in the aforementioned study could not control variables to isolate the cause of the differences between the periods. It was therefore not possible to determine the causes for the differences in operations and realized and anticipated benefits. This study uses a modeling framework to isolate potential causes for differences in operations, and to identify potential operational improvements for future examination and refinement.

Methods

The modeling approach for this study uses RiverWare, a river and reservoir modeling tool, to represent current basin physical attributes and basin policy. The Bighorn Lake model is composed of model objects, including: water users, river reaches, stream gages, canals, and reservoirs. The daily timestep model uses hydrologic data including inflows and water use demands for Bighorn Canal. The model also includes physical parameters such as reservoir area-capacity-elevation tables and hydropower generation tables.

The model represents Bighorn Lake operations for two distinct types of studies: forward-looking operations mode and planning mode. Operations mode represents Bighorn Lake operations under future conditions and is used to inform future operational decisions such as near-term changes in releases from Yellowtail Dam. Planning mode, which is the focus of this effort, uses historical or long-term projections of water supply and demands to inform operational policy. Policy refers to a set of independent river system objectives that drive reservoir releases and other control actions.

Using a RiverWare model in planning mode allows for the comparison of alternative operational policies over the same hydrologic conditions. This allows us to isolate the impacts of operational criteria on river releases, pool elevations, and hydropower generation. Similarly, we can isolate the impacts of forecasting by comparing modeled operations under perfect forecasts (perfect advanced knowledge of reservoir inflows) to historical Reclamation monthly forecasts used to operate the dam. The model can be used to isolate hydrologic impacts by comparing modeled operational metrics under current policy with perfect forecasts across time periods.

Scenarios and Results

The study generally examined model results comparing operations under 2000 Standard Operating Procedures ("2000 SOP operations") to 2010 operating criteria, and 2010 operating criteria with perfect forecasts to historical most probable forecasts.

Comparisons between 2000 SOP operations and 2010 operating criteria using perfect forecasts showed higher pool elevations and lower peak river releases during flood control under 2000 SOP operations, and lower river releases during periods of drought. While the lower peak river releases would be preferable, this is likely an artifact of representing the two scenarios with perfect forecasts.

Rule curves used by the 2010 operating criteria provide a heuristic technique providing adequate guidance for operations in the face of uncertain inflow volume and timing. Rule curves also provide transparency to operations and a well-defined balance between competing interests. The 2000 SOPs lack transparency and result in undesirably low river releases in dry years. For these reasons, we do not consider the 2000 SOPs preferable to the 2010 operating criteria. Recommendations therefore focus on enhancing the 2010 operating criteria.

The comparison between operations with 2010 operating criteria and perfect forecasts to operations with 2010 operating criteria with historical most probable forecasts showed that forecast error was a significant component of observed, higher-than-expected pool elevations in Bighorn Lake. However, comparing these model runs to historical operations showed additional differences not due to forecasting.

Further examination of operations with 2010 operating criteria with historical most probable forecasts for individual water years for the period 2010 through 2017 showed differences between expectations and historical operations. The differences resulted from an array of reasons as further discussed.

Hydrology in the Wind/Bighorn Basin above Bighorn Lake/Yellowtail Dam was a key driver of high flows. The period examined contained two record-setting high April through July Bighorn Lake inflows (2011 and 2017), with water year 2018 resulting in the third-highest inflow on record. Operating criteria seems to have a smaller impact on pool elevations and releases in these high water years, as the available space for flood control is quite small in comparison to runoff volume. Additionally, the shape of the inflow hydrograph impacted the peak river release rate. Inflows with short duration, high peak flow rates will likely require higher releases than the same inflow volume with a longer duration, lower peak inflow rate.

Forecasting errors impact pool elevations, particularly when setting winter releases and during normal and lower water years. Forecasts below the minimum fill volume resulted in operators cutting releases to preserve storage. Several years (2010, 2011, 2015, and 2016) were dry in early spring followed by late spring/early summer precipitation resulting in high inflows. This pattern resulted in higher-than-anticipated pool elevations and peak river releases.

Differences in expected and observed operations are also partially attributable to operating criteria. First, forecasts below the minimum fill threshold allow operators sole discretion to determine “a properly balanced operation between the lake and the river.” Under these circumstances, releases were typically cut to conserve storage in anticipation of the onset of drought conditions. High releases and encroachment into the exclusive flood control pool were required after these conservation efforts were implemented and followed by above-average precipitation.

Second, rule curves were developed based on anticipated inflow timing based on expected upstream reservoir operations according to April through July runoff volume. The rule curves do not consider any advance knowledge of runoff timing, as Yellowtail Dam operators receive through coordination with Boysen and Buffalo Bill Reservoir operators. Model simulations show, particularly for higher inflow years, historical inflow timing does not match expected inflow timing. This results in higher than anticipated river releases and encroachment into the exclusive flood control pool.

Seven scenarios preliminarily examined potential changes to operating criteria. One scenario lowered the March 31 target to examine the impacts of evacuating more storage in anticipation of snowmelt inflow. The second scenario modified existing rule curves to target elevation 3,620 ft. by May 31 to ensure lake recreational access. The third scenario increased the minimum drawdown of existing rule curves to allow evacuation of more space for flood control. One scenario raised the top of joint use pool five feet, one lowered the top of joint use pool five feet, and two removed the dependence of winter release rates from pool elevations. Modeling results showed none of the potential scenarios improved operations, particularly considering the balance between river and lake recreation interests, hydropower, and flood control.

Conclusions

No single factor caused deviations from anticipated pool elevations and river releases. Observed operations are a result of the combination of factors including hydrology, forecasting, operating criteria, and operators' decisions. External factors also impact operations, such as USACE system flood control orders. The anticipated benefits of implementing the 2010 operating criteria may also have been overstated during rule curve development by performing analysis at a monthly time step and by underestimating the impact of forecast error.

The nine water years following implementation have included several extremely wet years and two very dry years. Releases have been much higher than anticipated, as have Bighorn Lake pool elevations, resulting in calls to reexamine the operating criteria. However, deviations from anticipated operations are attributable to several factors:

- Record high April through July inflows and a small reservoir flood control volume compared to runoff volume are likely the largest cause of higher than average river releases.
- Forecasts tended to under-predict inflows, resulting in less evacuation of flood control storage space than anticipated by the operating criteria and therefore higher river releases.
- Rule curves were built using an assumed inflow hydrology and maximum inflow volume. Deviations from the assumed inflow hydrograph in both timing and magnitude result in operational inefficiencies such as higher peak river releases or not filling to the top of joint use pool.
- The 2010 operating criteria does not explicitly define operations when dry conditions are forecast. Operators tended to act to conserve storage in these cases, and when followed by a wet spring and early summer, releases were greater than anticipated by the operating criteria and flood control space was used.

Recommendations

Recommendations address both the 2010 operating criteria and Yellowtail operations overall. The 2010 operating criteria is an important subset of Yellowtail operations but does not completely determine how Bighorn Lake and River are operated.

Preliminary exploration of modifications to the operating criteria show operations with the 2010 operating criteria using perfect forecasts are relatively balanced between competing uses authorized for Yellowtail Dam: Flood control, water supply, hydropower, fisheries and wildlife, and recreation. The pool elevation targets for winter flows and rule curves do not appear to favor one party over another. However, the operating criteria lacks critical guidance on operations in several areas, including generating forecasts, operations during periods of low runoff forecasts, and adjusting releases when forecasts are in error.

Reclamation and stakeholders endured a long process developing the 2010 operating criteria. Potential improvements should not attempt to mitigate the high flows observed over the last nine years at the expense of operations for water supply during dry years and should maintain the agreed-upon balance between interests. It is important to incorporate only those improvements that benefit all parties, rather than improvements coming at the expense of a competing interest. Several potential improvements to the operating criteria were identified which do not benefit one stakeholder group at the expense of another.

Recommendations were developed based on the modeling results showing potential improvements to forecasting, and operating criteria. General recommendations for operations, not directly related to the operating criteria, and transparency are also included. As described above, there is no single cause for the observed deviations from expected operations. Likewise, there is no single solution which will provide the benefits that stakeholders desire. However, several changes can provide incremental improvements to Bighorn Lake operations.

Forecasting Recommendations

Potential forecast improvements are intended to reduce forecast error and better define uncertainty bounds, which aid in operations. Likewise, the statistical analysis showed Reclamation forecasts leaned toward under-forecasting April through July inflows. Correcting this imbalance may improve adherence to the operating criteria.

Table 1 displays a list of forecasting improvements. Frequently, the difference between forecasts and observed runoff is due to precipitation during the spring/early summer runoff season, when the basin receives its highest months of precipitation. Snow-based forecasts are unable to predict this precipitation, and weather forecasting is only skillful over short periods. As such, there is a limit to how much Reclamation's forecasts can be improved.

Table 1: Forecasting Recommendations

Recommendation	Narrative Description
Examine skill of forecast components	Develops an understanding of forecast component skill metrics, providing a baseline for recommendation on "evaluate improvements to statistical forecasts."
Evaluate improvements to statistical forecasts	Potential for some forecast skill improvements and elimination of the observed forecast bias. The better representation of forecast uncertainty will provide stakeholders a better understanding of future conditions.
Study enhanced resolution snowmelt runoff modeling	May provide advance knowledge of early spring runoff event volume, allowing operators to mitigate these events through reservoir drawdown.
Evaluate skill of NWS and other forecast ensembles	Provides forecast ensemble skill metrics, allowing for potential inclusion of ensembles into operations.

Operating Criteria and Rule Curve Recommendations

The largest observed area of operating criteria improvement is due to the lack of guidance during low inflow water years and the assumption of fixed inflow timing. Frequently during the period operating under the 2010 operating criteria, dry early spring conditions resulted in forecasts below the minimum fill volume. Operating criteria provided no guidance as to operations in these conditions. These forecasts were subsequently followed by spring and early summer precipitation resulting in higher than average inflows. Table 2 describes each of the recommendations.

Table 2: Operating Criteria and Rule Curve recommendations.

Recommendation	Narrative Description
Model and evaluate explicit low-flow rules	Low flow rules would provide guidance to operators when forecasts are below the minimum fill threshold and provide transparency to stakeholders. This would potentially avoid high releases observed historically when dry forecasts followed by wet spring conditions resulted in higher-than-necessary releases.
Examine frequency of elevation targeting	Will provide explicit guidance on how frequently to adjust winter releases. Could result in less reaction to drier forecasts.
Remove encroachment into flood pool	Brings fill side of operating criteria in line with Reclamation's legal authorities regarding exclusive flood pool (i.e. does not represent curve entering flood pool.)
Update rule curves to anticipate higher inflow volumes	May result in greater or earlier drawdown in years very high snowpack. However, WY 2011 and 2017 both resulted in USACE flood control orders; it is likely that system flood control will supersede in such big water years.
Explicitly define relationship between flood pool and releases	Provides stakeholders transparency as to why certain releases are soft caps (i.e., 15,000 cfs release from Afterbay)
Examine variable drawdown timing	May result in more efficient operations by develop a methodology in which the peak drawdown timing and rate of fill would vary based on the forecasted inflow hydrograph. May provide reductions in peak river releases during high water events.

General Operations Recommendations

Several recommendations address how operations are conducted and are not specific to the 2010 operating criteria (Table 3).

The most impactful general operations recommendations come about from modeling and incorporating ensembles into operational decision-making. Incorporating a daily operations model will eliminate calculation errors associated with monthly timestep simplifying assumptions. Implementing a Wind/Bighorn River Basin-wide operations model will allow operators to more easily transfer information and examine a wide array of potential inflow scenarios while explicitly representing upstream depletions.

Table 3: General operations recommendations.

Recommendation	Narrative Description
Avoid hedging operations using uniform release factor	May avoid operators unnecessarily hedging toward filling or drafting.
Implement Daily Time-step Operations Model	The daily timestep model will increase efficiency of model runs, allowing operators to examine a wider range of potential future inflow scenarios. The model will also result in daily timestep calculations for monthly plans, increasing numerical accuracy.
Implement basin-wide operations model	Provides operators with a better understanding of range of operating conditions. Improves coordination efficiency between offices. Explicitly represents local inflows, potentially improving forecast skill.
Incorporate ensemble inflow forecasts	If proven to be skillful, provides operators a better understanding of future inflow uncertainty, based on current basin conditions. Allows for inclusion of risk-informed decision making for operations.

Introduction

Reclamation implemented changes to its operating criteria in 2010. These changes followed an extensive effort in which Reclamation formed the Bighorn River Issues Group, assembling Yellowtail Dam/Bighorn Lake stakeholders to obtain input on operating criteria. This effort followed a prolonged drought, from 2000 through 2007, and was intended to improve water supply reliability, improve lake and river fisheries and recreation, increase hydropower generation, and enhance flood control benefits.

On behalf of the Montana Area Office, Reclamation's Great Plains Regional Office reviewed the Bighorn Lake operating criteria. The goals of the review are to: 1) document differences between current and past operations of Bighorn Lake; 2) determine if significant differences exist between the realized and anticipated benefits of the operating criteria; 3) determine potential causes for any differences in operations and realized and anticipated benefits; and 4) propose potential operational improvements for future examination.

The first component of the criteria review consisted of a statistical analysis of Bighorn Lake operational data (Appendix A). The statistical analysis documented significant differences between operations before and after implementation of the 2010 operating criteria in all operational metrics examined. Releases tended to be greater in the post-criteria period, particularly for the spring and summer runoff months. Releases were also greater than anticipated by the criteria based on April through July inflow volume. Pool elevations were also significantly greater for the post-criteria period, and elevations were higher than anticipated by the criteria based on inflow volume. Hydropower generation was also higher during the post-criteria period than the period from 1993-2009 and lower than the period 1966-1992, with one of the four turbines inoperable for nearly half the 2010 operating criteria timeframe.

Additionally, the statistical review examined historical Reclamation forecasts. Forecast error appears to have significantly impacted observed reservoir operations. Reclamation forecasts appear biased, in the statistical sense, toward under-predicting April through July inflows. Both Natural Resources Conservation Service (NRCS) and Reclamation forecasts significantly under-predicted inflows in four above-average runoff years, likely resulting in inadequate Bighorn Lake drawdown prior to snowmelt runoff. Reclamation forecasts showed somewhat greater skill than NRCS forecasts.

The statistical review determined differences between expected and observed operations following implementation of the 2010 operating criteria. However, it also identified four key potential causes for these differences: hydrologic differences from the period analyzed to create the criteria; forecasting error and bias; differences in operating criteria; and operating criteria implementation.

River systems modeling allows us to isolate the impacts of the variables on pool elevations, river releases, and hydropower generation by comparing operations while maintaining three of the four variables and altering one at a time. As such, we developed a daily timestep model of Bighorn Lake in RiverWare software to examine the relative impacts.

Based on personal communication with the Western Area Power Administration (Grubbs, 2018), much of the hydropower generation is used for purposes such as load balancing. This occurs on a sub-daily timestep and is dependent on variables outside the scope of this study. The issue of the system being operated in a way that did not take advantage of power generation opportunities was discussed within the Technical Working Group reviewing Reclamation's operational review, and the complexities under which spilling must occur are related to hydrology, load balancing and power units off-line. The interrelationship of these factors is numerous and, as such, this study does not examine hydropower generation in detail. The model can represent mean daily hydropower generation, but only limited analysis appears in this report.

The following sections describe model development, modeling results, and conclusions and recommendations.

Model Development

Modeling Background

A river system model was developed using the RiverWare™ software. RiverWare was developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) of Boulder, Colorado, with substantial support from Reclamation, the U.S. Army Corps of Engineers (USACE), and the Tennessee Valley Authority. The software allows reservoir operators to develop and run detailed, site-specific simulations. It includes an extensive library of modeling algorithms, several solvers, and a language for the expression of operating policy. Its graphical interface facilitates model construction, execution, and analysis of results. Federal and state agencies across the United States have developed RiverWare models to resolve a wide range of operational and planning problems.

The modeling approach for this study uses RiverWare to represent current basin physical attributes and basin policy. The Bighorn Lake model is composed of model objects, including: water users, river reaches, stream gages, canals, and reservoirs. The daily-timestep model uses hydrologic data including inflows and water use demands for Bighorn Canal. The model also includes physical parameters such as reservoir area-capacity-elevation tables and hydropower generation tables.

The model represents Bighorn Lake operations for two distinct types of studies: forward-looking operations mode and planning mode. Operations mode represents Bighorn Lake operations under future conditions and is used to inform future operational decisions such as near-term changes in releases from Yellowtail Dam. Planning mode, which is the focus of this effort, uses historical or long-term projections of water supply and demands to inform operational policy.

Policy refers to a set of independent river system objectives that drive reservoir releases and other control actions. Examples of policy driving operational decisions for Bighorn Lake include the **2010 operating criteria** and U.S. Army Corps of Engineers safe channel capacities. The operating criteria defined within the **2000 Standard Operating Procedures (SOPs)** is an example of alternative operating policy and was also represented for comparison to the **2010 operating criteria**.

Using a RiverWare model in planning mode allows for the comparison of alternative operational policies over the same hydrologic conditions. This allows us to isolate the impacts of operational criteria on river releases, pool elevations, and hydropower generation. Similarly, we can isolate the impacts of forecasting by comparing modeled operations under perfect forecasts to historical Reclamation forecasts used to operate the dam. The model can be used to isolate hydrologic impacts by comparing modeled operational metrics under current policy with perfect forecasts across time periods.

Planning models must represent how operators would make decisions under varying hydrologic conditions. The model therefore represents policy through a series of "if-then" statements. Due to insufficient detail within the **2010 operating criteria** documentation, and where the operating criteria defines operator flexibility, the model must make certain decisions without strict guidance. The model was therefore developed using certain assumptions which impact the results of this study. These assumptions are further detailed below.

Modeling Assumptions

Modeling assumptions fall into two categories: Assumptions on physical parameterization and forcing data, and policy assumptions.

Water Supply Data

The RiverWare model required several forcing data assumptions. First, water supply, or inflows to the model, were described using two sources. The model used Hydromet calculated inflows for reservoir inflows (Bureau of Reclamation, 2018a). Hydromet calculates inflows to Bighorn Lake through a mass-balance approach, where inflows are equal to the daily average reservoir outflow plus the 24-hour change in reservoir storage. This sometime results in day-to-day fluctuations due to measurement errors in the reservoir stage, which is used to calculate storage from a rating table. Bighorn Lake stage can frequently be impacted by wind, which can nullify the assumption of a level reservoir pool. Small differences in reservoir stage can result in large volumetric changes in storage in comparison to the release volume, resulting in these swings in calculated inflow. Over longer periods of time there is no impact to the calculated inflows.

It is also necessary to represent inflows below Yellowtail Dam. Significant ungaged accretions enter the Yellowtail Afterbay. These are estimated as a constant 70 cfs year-round.

Demands Data

Because inflows are calculated through a mass-balance approach, evaporation is accounted for in storage changes and therefore is not explicitly represented in the RiverWare model. The only demands represented in the model are Bighorn Canal diversions. The model uses Hydromet gaged diversions for Bighorn Canal for the available period (water year 1985-2017) and mean daily gaged diversions for water years 1967-1984.

Forecasting Data

Bighorn Lake operations are dependent on forecasts throughout the year. Two types of forecasts were used to drive the model: perfect forecasts and historical forecasts from Reclamation’s monthly plans. Perfect forecasts are those forecasts which contain exact advance knowledge of reservoir inflows. These forecasts simply sum the reservoir inflows. Perfect forecasts are useful for isolating the effects of operating criteria on operations.

Minimum, most probable, maximum plan historical forecasts exist for Reclamation monthly plans from 1990-present. Four monthly plans were not available within this period, so missing forecasts were filled with the previous month’s forecast.

We assumed that the most probable forecast represents the forecast used for operations. While operations during the runoff season use more frequent forecasts, there is no record of these intra-monthly forecasts. Operators refine the inflow forecasts as the peak inflows are more apparent. The modeled operations using historical forecasts therefore exaggerate the impacts of forecast error during the months of May through July. It is likely that, as the peak of the hydrograph approaches, forecasts become more accurate because both weather and snowmelt forecasts improve. Maintaining the first of the month forecast, which has little foresight on upcoming weather, will result in over-filling when under-forecasting and under-filling the reservoir when over-forecasting. To mitigate this, pool elevation forecasts are updated daily in the model using the first of the month forecast. This provides some daily adjustment as pool elevations diverge from predictions due to forecast error. Using the erroneous forecasts with current pool elevations mitigates some of the issues with using a static forecast during the snowmelt runoff.

Policy Assumptions

Policy for Bighorn Lake and Yellowtail Dam operations is derived from numerous authorities. The Yellowtail Unit was initially authorized by the Flood Control Act of 1944 (“1944 FCA”) (United States Code, 1944). The 1944 FCA approved the general comprehensive plans set forth in House Document 475 (78th Congress, 2d Session, 1944a) and Senate Document 191 (78th Congress, 2d Session, 1944b). The 1944 FCA, and by incorporation, Senate Document 191, are Reclamation’s authority for operation of Yellowtail Dam, along with Reclamation Law generally, including the Reclamation Acts of 1902 (United States Code, 1902) and 1939 (United States Code, 1939). The1944 FCA provide Reclamation and USACE responsibility for operations for water supply and flood control, respectively. Additional guidance is provided in the Definite Plan Report of 1950 (Bureau of Reclamation, 1950) and 1962 revision with new summary sheets, transmitted in 1965 (Bureau of Reclamation, 1965), Bighorn Canyon National Recreation Act (United States Code, 1966), Streamflow and Lake Level Management Plan, and the Claims Settlement Act of 2010 (United States Code, 2010).

Reclamation’s guiding operating document is the Yellowtail Unit Operating Criteria Evaluation Study and Report from April 2012 (Bureau of Reclamation, 2012c). General guidance of this operating criteria is provided in Chapter IV of Yellowtail Dam’s Standing Operating Procedures (SOP) (Bureau of Reclamation, 2012b). Development of the SOPs considered the numerous authorities. This study necessarily assumes that Reclamation accurately considered its legal authorizations when developing SOPs. It is not within the scope of this study to examine the relevant legal authorities.

USACE’s guiding operational document is its Report on Reservoir Regulations for Flood Control for Yellowtail Dam and Bighorn Lake (“Flood Control Manual”) (U.S. Army Corps of Engineers, 1974). This document describes how Bighorn Lake is to be operated for flood control within the exclusive flood control and joint use pools.

Because the joint use pool is operated by Reclamation for water supply and USACE for flood control, coordination of operations in this pool may be required. The Flood Control Manual states that “…to provide for maximum effectiveness of this space for flood control, fill at all times will be limited to the level which will provide a reasonable assurance of subsequent fill.” (U.S. Army Corps of Engineers, 1974) In practice, Reclamation draws down the joint use pool further than specified by the Flood Control Manual, which provides for 90% probability of filling Bighorn Lake to make reasonable assurance of fill. Therefore, the USACE joint use requirements are not explicitly represented in this model. The potential exists, however, that an alternative scenario could be designed where Reclamation would not draw down the joint use pool as much as required by the Flood Control Manual. Should such an alternative be analyzed, it would be important to add the ability of the model to represent USACE's joint use pool rules.

The USACE also has responsibility for local (i.e., Bighorn River) flood control and system (the entirety of the Missouri River Basin) flood control. It is not possible to represent system flood control as it would require modeling the entire Missouri River Basin. This is far outside the scope of this project.

Finally, water rights are governed by the doctrine of prior appropriation ("first in time, first in right") within the States of Montana and Wyoming. Two key authorities describe water rights in Bighorn Lake and below Yellowtail Dam. First, the Yellowstone River Compact (Yellowstone River Compact, 1950) describes Bighorn River allocations between the States of Montana and Wyoming. This study assumes that the intrastate allocation was properly followed and that historical inflows to Bighorn Lake represent Montana's allocation of the Bighorn River. Second, the Crow Water Rights Settlement (United States Code, 2010) allocates water within the State of Montana and storage in Bighorn Lake to the Crow Tribe. The settlement states:

"…the Tribe shall enact a tribal water code, that provides for—

> *(A) the management, regulation, and governance of all uses of the tribal water rights in accordance with the Compact; and*
> *(B) establishment by the Tribe of conditions, permit requirements, and other limitations relating to the storage, recovery, and use of the tribal water rights in accordance with the Compact."*

Reclamation and the Crow Tribe finalized a Storage Allocation Agreement in 2016 (Bureau of Reclamation, 2016a) which identified Tribal use of their reserved water rights. However, the Tribe has not yet added additional water use to its continued use of the Bighorn Canal. Water use demands downstream of Yellowtail Dam by senior water right holders are currently met through releases to the Bighorn Canal or through releases as described in the standard operating procedures. Therefore, no water rights allocation under the doctrine of prior appropriation is necessary for this study, and the model does not represent water right priority dates.

2010 Operating Criteria Assumptions

General **2010 operating criteria** operations, using the following assumptions, for a sample water year are shown in Appendix B.

Assumptions regarding operating criteria were necessary for target elevations both **2010 operating criteria** and **2000 SOP operations**. These are summarized in Table 4 and Table 5.

Table 4: Summary of Operations pool elevation targets.

	2000 SOP	2010 operating criteria
Pool Elevation Targets		
March 31 Target (ft.)	3,614	3,617
March 31-July 31 Operations	July 31 target	Rule curves
July 31 Target (ft.)	3,640	3,640
October 15 Target (ft.)	3,635	No target
October 31 Target (ft.)	No target	3,635
November 30 Target (ft.)	3,630	No target

Table 5 shows a summary of assumptions for **2000 SOP operations** and **2010 operating criteria** during flood control operations.

Table 5: Summary of flood control operations assumptions.

Flood Control Operations		
	2000 SOP	**2010 Operating Criteria**
Frequency of updating target flow calculations	1st of month and after peak pool elev.	1st of month, after minimum drawdown, after peak pool elev.
January and February Operations	If AJ Volume is in top quartile, go into flood operations	If AJ Volume is in top quartile, go into flood operations
January and February Flood target	July 31 target	April 30 rule curve
January and February winter flows target	March 31 target	March 31 target
March flood target	July 31 target	April 30 rule curve
April through July flood target	July 31 target	Max rule curve drawdown or End-of-month rule curve target
Flood minimum drawdown pool elev. (ft.)	3600	3591.5
Allowable release rate before entering flood pool	15,000 cfs	15,000 cfs

Rule Curve Targeting

The **2010 operating criteria** (Bureau of Reclamation, 2012c) states that:

> *Some flexibility and judgment should be exercised in determining how close the actual operations follow the rule curves as making operations strictly follow the rule curve could result in a number of significant and frequent release adjustments. Normally, adjustments to the lake releases should be*

> *based on looking several days or a week ahead to allow time for the lake level to come back on track with the rule curve.*

The model targets end of April rule curve elevations from January through April and adjusts releases on the first of the month. May 1 release decisions target the minimum rule curve drawdown elevation, which occurs in mid-May. The model re-targets the end of May rule curve elevation after passing the minimum rule curve drawdown elevation. June and July operations target either the end-of-month rule curve elevation or the minimum flow rate that just fills the reservoir to the greater of the top of joint use or the maximum rule curve elevation. Most rule curves encroach somewhat into the exclusive flood control pool.

Should the flow rate targeting the end-of-month rule curve result in drawing the reservoir below the minimum flood control drawdown elevation specified in Reclamation (Bureau of Reclamation, 2012c), the release is set to the rate that just draws the reservoir down to the minimum flood control elevation. Likewise, the model checks to ensure releases do not fill into the exclusive flood control pool before and after filling the reservoir. This might otherwise occur due to differences between peak runoff timing and the assumed inflow hydrograph. If actual inflows are lower than the assumed inflow hydrograph while drawing down to the lowest rule curve elevation, the actual pool elevation may drop below the minimum flood control drawdown elevation. Likewise, if the inflow hydrograph has an earlier peak than assumed, the constant release rate targeting the maximum rule curve elevation will result in flood pool encroachment.

February Operations in High Forecasted Inflow Years

The **2010 operating criteria** allows for flood control operations to start in February in water years with high forecasted April through July runoff (Bureau of Reclamation, 2012c):

> *Once the February 1 spring runoff forecasts become available, the March 31 lake level target may be allowed to vary somewhat dependent on the forecast amount. In years with a forecast for very low spring runoff, it may be beneficial to reduce the February and March river release rate to prevent the need for larger release reductions later in the spring. In years with a well above normal spring runoff forecast, it may be beneficial to increase the February and March release rate to draft the lake sufficiently to meet desired lake levels for flood control based on the use of the Rule Curve which begins on April 1.*

Because the documentation did not quantify “well above normal spring runoff forecast,” we used a threshold of the upper quartile (as defined by the rule curves) of April through July runoff as defined in (Bureau of Reclamation, 2012c). Beginning in February, operations will target the April 30 rule curve in years in which forecasted runoff is greater than 1,584,000 acre-feet.

Operations Below "Min Fill" Volume

The **2010 operating criteria** specifies a minimum fill April through July runoff volume, above which rule curves are implemented. The minimum fill runoff volume was calculated as the volume below which 2,000 cfs could not be maintained and still fill Bighorn Lake to the top of joint use pool. The "min fill" volume was 26 percent exceedance at the time that the rule curves were developed. The **2010 operating criteria** does not specify how to set releases in years with runoff forecasted below the minimum fill volume, and no rule curves exist for these years:

> *For years with forecasted April-July Inflow falling below a 26 percentile year (April-July inflow less than 727,000 acre-feet) rule curves were not developed, as it was found that these are years when the lake will need to be managed to provide a careful balance between the need for a minimum river release for the river fishery flows (2,000 cfs or less) and sufficient storage to provide adequate longer term water supply for all users. In these years the lake is not expected to fill to its normal full level at elevation 3640. The goal, in these low runoff years should initially be that of holding a river release near 2,000 cfs through the end of the following March if this will allow the lake to end up near its desired March 31 target elevation of 3617. The ROMS Access model should be used along with the November through March operating criteria and forecasted inflows to determine if this is probable. If this is not probable then a decision will be needed to determine when and to what degree river flows are reduced below 2,000 cfs. Reducing the river release below 1,500 cfs should only be considered when needed to prevent full depletion of the active conservation pool. Decisions to reduce releases below 2,000 cfs and especially 1,500 cfs are not decisions that can or should be spelled out in this report. Flexibility should be left to Reclamation to address the needs of each of the interests in Bighorn Lake in determining a properly balanced operation between the lake and the river under these situations. (Bureau of Reclamation, 2012c)*

Because the RiverWare model must make decisions on releases, it was necessary to clearly define logic determining releases below the minimum fill volume. The following logic is used to determine releases in these years:

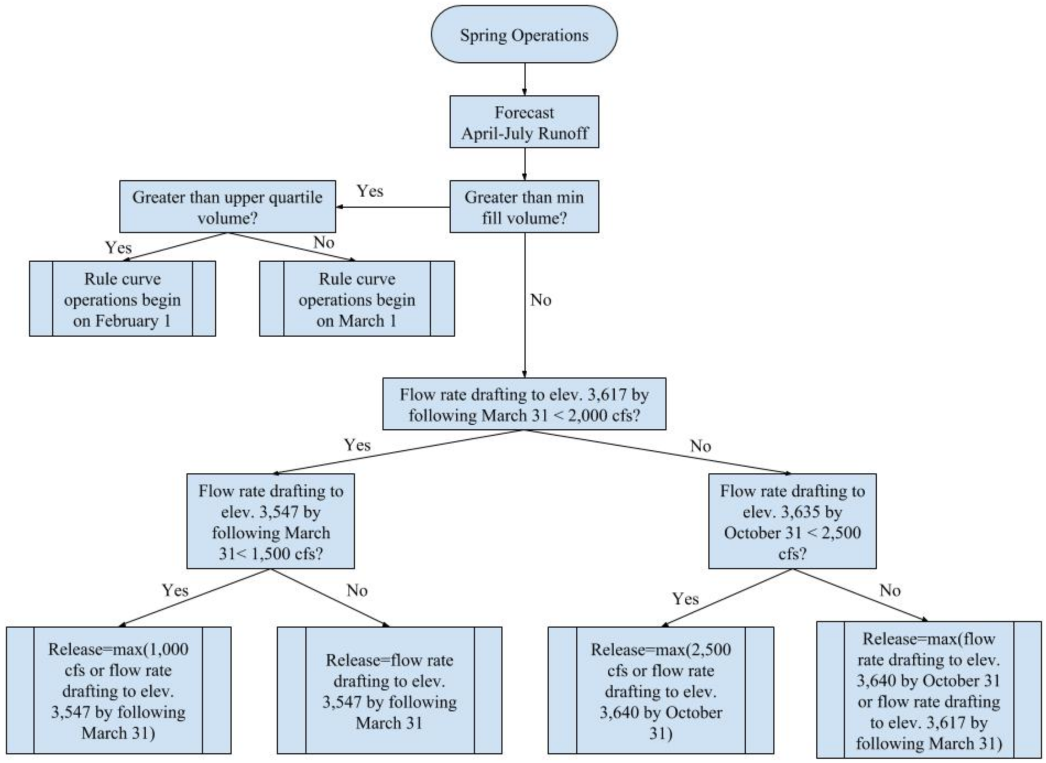

Figure 1: Flow chart describing modeled spring Bighorn Lake operations.

Turbine Capacity

Yellowtail hydropower facilities are undergoing an extended period of maintenance due to generator rewinds. The facilities also undergo periodic maintenance. The model does not represent these outages and assumes that all turbines (and turbine release capacity) are always available.

Rule curve and target changes

Operating criteria were modified in 2012 and 2015. Throughout the report, modeled operations represent the current version of the **2010 operating criteria**, which updated the March 31 target elevation for setting winter flows and rule curve minimum pool elevation drawdown. The exception is the analysis of each individual water year comparing historical operations to modeled operations with perfect forecasts and most probable forecasts. In these years, actual rule curves and targets were used for 2010-2012.

2000 SOP Criteria Assumptions

2000 SOP operations assumptions were based on the 2000 SOPs (Bureau of Reclamation, 2000). Because the 2000 SOPs are not extremely detailed, certain assumptions were required. First, the March 31 elevation target under **2000 SOP operations** was a range from 3,610 to 3,614 ft. For modeling purposes, winter releases were calculated based on an end of March target elevation of 3,614 ft. Second, 2000 SOPs do not contain guidance on setting low flow releases. The 2000 SOPs (Bureau of Reclamation, 2000) state:

> *Whenever an adequate water supply is available, releases from Bighorn Lake will be maintained at rates to sustain flows in the Bighorn River at 2,500 cfs or higher. This is normally required to protect the quality and quantity of the river fishery and protect lake and river recreation activities. When there is not an adequate water supply available, it may be necessary to reduce releases to the Bighorn River to 2,000 cfs or the absolute minimum flow of 1,500 cfs required to protect the river fishery.*

2000 SOP operations used the same logic as **2010 operating criteria**, described above.

Scenarios and Results

Reclamation examined several scenarios to meet the goals of the study. These scenarios compare different operating criteria, hydrology, or model timesteps to determine relative impacts of individual variables. The scenarios are further detailed below. Significant events in the history of Yellowtail Dam define the time periods used for the study:

- Yellowtail Dam was closed and filled beginning in water year 1967, and is the start of calculated inflow records;
- Buffalo Bill storage expansion was completed beginning in water year 1993;
- **2010 operating criteria** were first implemented in water year 2010. Operating criteria were modified in water year 2012 (Bureau of Reclamation, 2011a) and 2015 (Bureau of Reclamation, 2015)

Table 6: Description of modeled scenarios.

Study goals	Compare	Keep Constant	Period (Water Year)
Determine if benefits were realized/Isolate impacts of operational criteria	2010 operating criteria to 2000 SOP	Perfect forecasts	1967-2018
Determine if benefits were realized/Isolate impacts of forecasting	Perfect forecasts to historical (Reclamation) forecasts	2010 operating criteria	2010-2018
Determine if benefits were realized/Isolate impacts of operators	2010 operating criteria to historical observations	historical forecasts	2010-2018
Determine if benefits were realized/Isolate hydrologic impacts	2010-2017 to 1967-1992 and 1993-2009	2010 operating criteria with perfect forecasts	1967-2018
Isolate impacts of monthly timestep operations model	Daily timestep to monthly timestep	2010 operating criteria with perfect forecasts	1967-2018

General Results

The statistical analysis (Bureau of Reclamation, 2018b) examined the question as to whether the anticipated operating criteria benefits were realized. A major conclusion of the statistical analysis was that some benefits were realized, and some were not. The statistical analysis conclusions are excerpted below:

- River releases and fisheries targets: Anticipated changes by flow category were mostly realized and flows below 1,500 cfs were eliminated. Flows greater than 6,000 cfs increased greatly but no estimate of change existed.
- Flood control: Observed peak flow rate and duration for each water year were compared to anticipated peak flow rate and duration. In general, the observed peak outflow was greater than the expected peak outflow described in the revised operating criteria report.
- Lake Levels: Lake levels, on average, were greater than anticipated by the operating criteria (Bureau of Reclamation, 2011a) for the period 2010-2017.
- Hydropower: Power generation also changed significantly after criteria implementation. Generation increased when compared to the drier period from 1993-2009 and decreased when compared to the period 1967-1992. As with releases, timing of hydropower generation also significantly

changed. Much like pool elevation and releases, hydropower is dependent on several mitigating factors. The post-criteria period had a significant time in which one of the four hydropower units was inoperable due to a generator rewind, further complicating comparisons. As such, we cannot attribute differences in hydropower to any one factor.

The statistical analysis lacks clear results regarding whether implementation of the **2010 operating criteria** resulted in the anticipated benefits. The number of influencing variables makes determining the cause of differences difficult. The study identified forecasting, hydrologic conditions, operating error, and operating criteria as potential factors impacting Bighorn Lake operations. However, statistical and graphical comparisons between the historical periods cannot determine the relative impact of each of the factors on resultant operations. Accordingly, a river systems model can be used to isolate each of the factors. The following sections detail each of the individual factors impacting operations.

The first scenario compares modeled operations under the **2010 operating criteria** to **2000 SOP operations** using perfect forecasts. By using perfect forecasts, impacts due to forecasting error and operator decisions under uncertainty are eliminated and only the impacts of operating criteria are compared. Because historical forecasts are not used, the complete inflow period of record can be compared.

Model results for the two alternative operating criteria were compared for the period of record of Bighorn Lake inflows (water years 1967-2017). Primary comparisons were between pool elevation and river releases. Historical, observed operations were not compared as the intent is to determine the impacts of changing operating criteria.

Pool Elevations

Differences in pool elevations can be quickly compared using daily average plots for the two scenarios. The mean daily pool elevation is higher throughout the year, as shown in Figure 2.

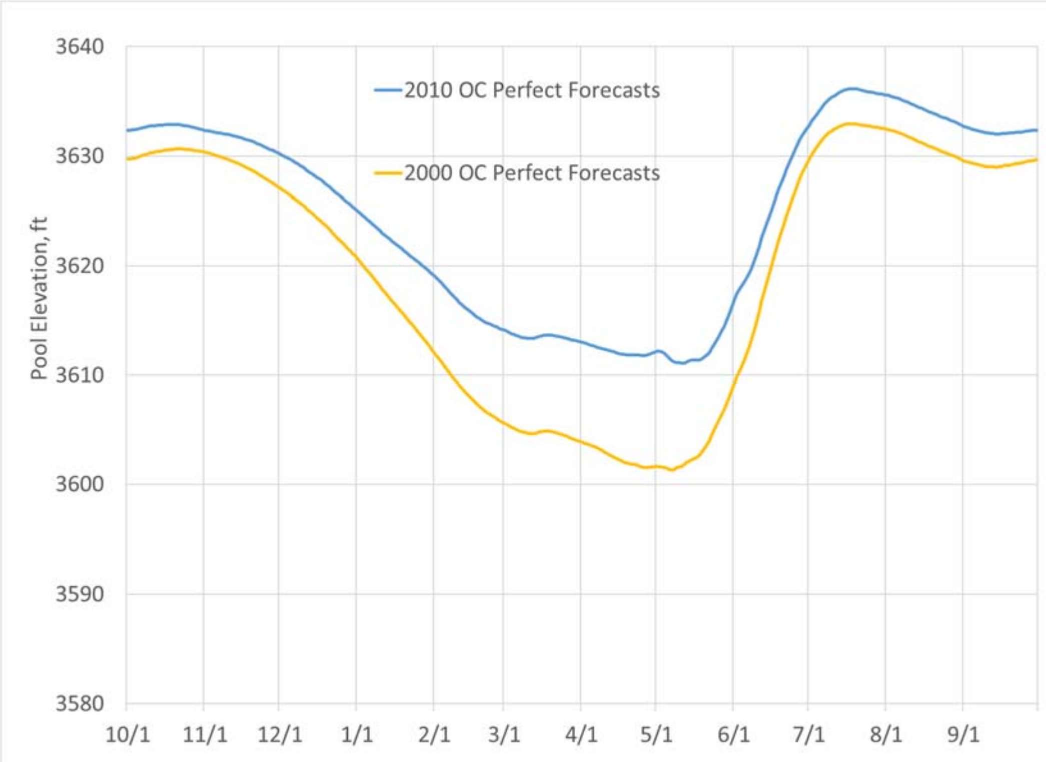

Figure 2: Daily mean pool elevation for Bighorn Lake for the period of record (1967-2018).

While the model allows us to conclude that **2010 operating criteria** results in higher pool elevations, the cause is not clear. There are three viable explanations. First, the higher March 31 target under **2010 operating criteria** may result in higher pool elevations during winter periods than **2000 SOP operations**. Second, releases in low-flow years could result in greater summer drawdown. Third, differences in flood control drawdown could result in lower spring/early summer pool elevations. Figure 2 shows that the larger differences occur at low pool elevations.

Pool elevations for the period from water year 2000 through 2018 provide insight as to the causes of lower pool elevations under **2000 operating criteria** (Figure 3). This period contains both an extended drought (2000-2007) and an extended wet period (2010-2018). As such, it is useful to examine performance over a wide range of hydrologic conditions. Modeled **2000 SOP operations** result in lower pool elevations during drought periods, with pool elevations dropping below elevation 3,560 ft.

In most wet years 2000 SOP operations also draws Bighorn Lake down further in anticipation of snowmelt runoff than does the **2010 operating criteria**. This is because, as modeled, **2000 SOP operations** release the minimum average flow which fills Bighorn Lake without entering exclusive flood control space. The model representation calculates this release based on actual inflow timing rather than the assumed inflow timing used to create the rule curves of the **2010**

operating criteria. The **2010 operating criteria**, however, has a lower minimum flood control drawdown (3,591.5 ft.) than the **2000 SOP operations** (3,600 ft.). In higher water years when rule curves require drawdown below elevation 3,600 ft., the **2010 operating criteria** draws down Bighorn Lake more than **2000 SOP operations**.

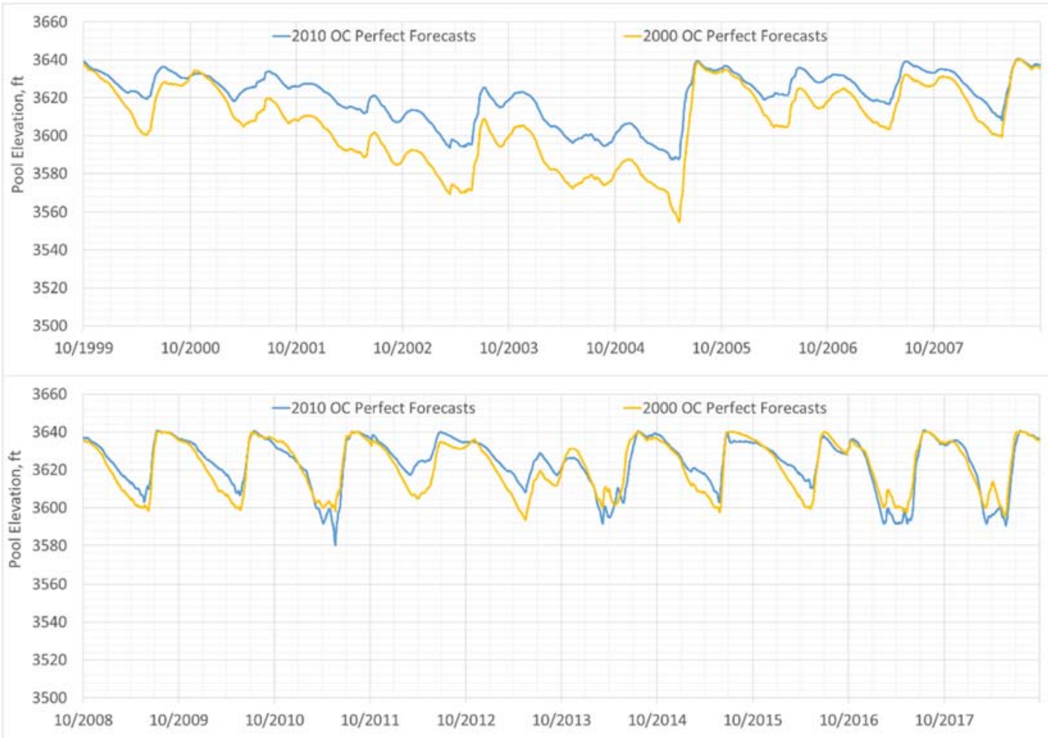

*Figure 3: Modeled pool elevations for **2010 operating criteria** and **2000 SOP operations** from 1999-2018.*

River Release

Comparing mean daily river releases for the two scenarios shows seasonal differences in river releases (Figure 4). Modeled **2000 SOP operations** and perfect forecasts shows higher releases during winter months, aiming for the lower end of March target (elevation 3,614 ft.) than under the **2010 operating criteria** (elevation 3,617 ft.). Because the end of March target used to set winter flows is lower, the calculated winter release rate is higher for **2000 operating criteria**. The **2010 operating criteria** results in higher releases in October to meet the end of October target, and higher releases in June than the **2000 SOP operations**.

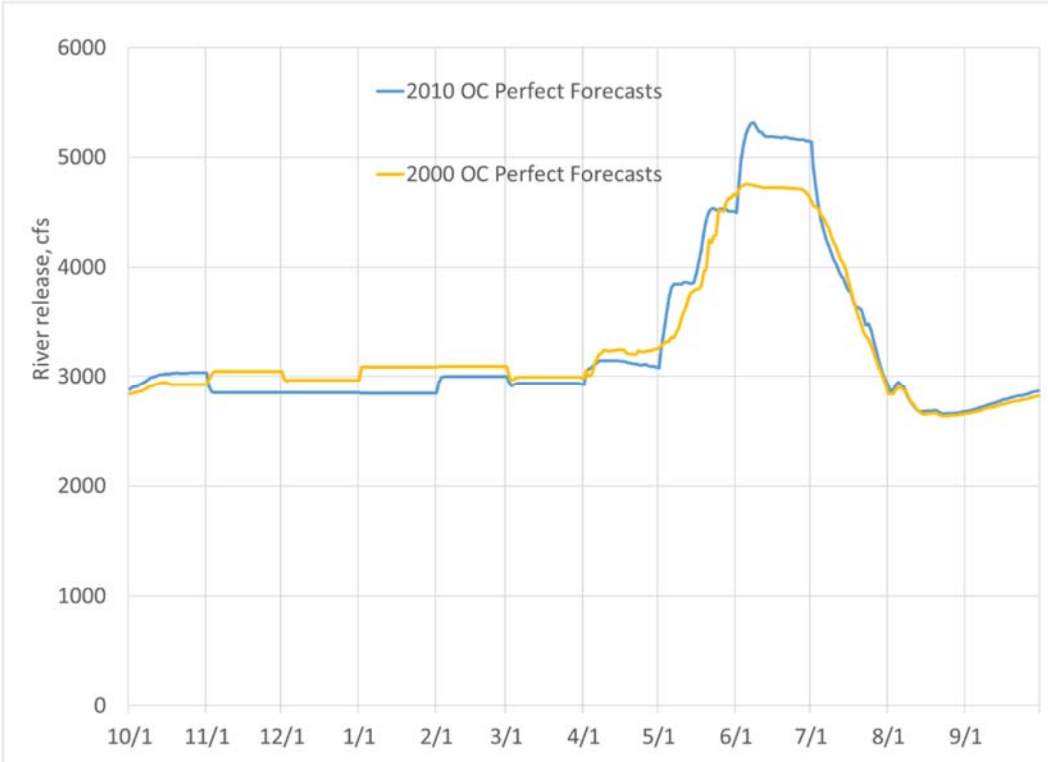

Figure 4: Mean daily river releases for 2010 Operating Criteria and 2000 SOP operations using perfect forecasts from 1967-2018.

Examining river releases in Figure 5 over the 2000-2017 period shows two interesting results. During the extended drought period, operations under **2000 SOPs** resulted in releases below 1,500 cfs, whereas **2010 operating criteria** modeled operations maintained a minimum of 1,500 cfs throughout the model run.

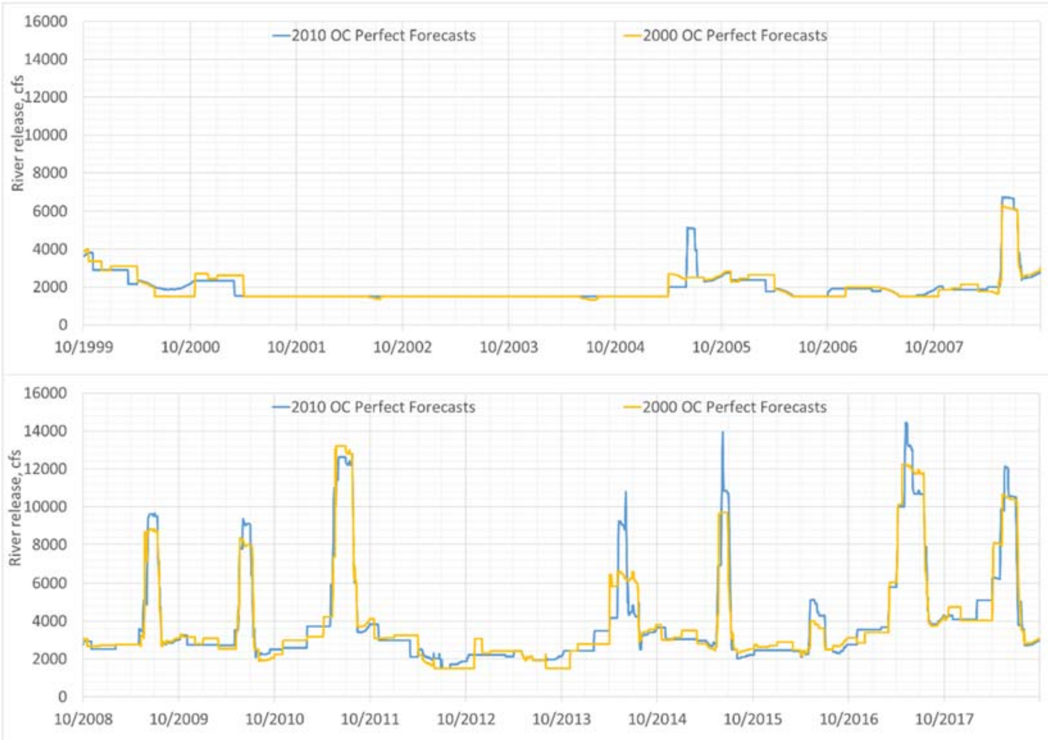

Figure 5: Modeled river releases comparing 2010 operating criteria to 2000 operating criteria with perfect forecasts for the period WY 2000-2018. Years are labeled at the end of the water year (October 1).

From 2000 through 2004, both operating criteria modeled with perfect forecasts failed to fill Bighorn Lake. For the most part, both criteria maintained river releases at 1,500 cfs through this drought period. A few short periods under the **2000 SOP operations** resulted in releases below 1,500 cfs, when releases were reduced to avoid drafting below the top of inactive conservation.

Most years in which April through July runoff was below the minimum fill threshold show lower river releases under **2000 SOP operations** due to three factors. First, the lower March 31 target results in lower pool elevations under **2000 SOP operations** entering the April through July runoff period, allocating greater storage space for runoff. Second, timing differences between the assumed inflow hydrograph for the **2010 operating criteria** and the actual hydrograph result in higher river releases. For example, when inflows are later than assumed, releases will be lower than assumed to meet drawdown targets. The reservoir fills faster than expected and requires short-term higher releases to meet the rule curve elevations at the end of the month or at a peak drawdown or maximum fill level. Rule curves also have minimum drawdown limitations associated with lower inflow volumes. Modeled **2000 SOP operations** are not limited to a minimum drawdown, and with perfect advance knowledge of runoff timing can find a more optimal drawdown elevation and river release.

2010 operating criteria operations show a "spike" in river releases, or a rapid increase followed by a rapid decrease. An example of this occurs in water year 2015. This is an artifact of how rule curves were modeled. Releases are calculated to hit rule curve pool elevation targets at the end of the month, at the low point of the rule curve, and the high point of the rule curve. When peak inflows occur around the end of the month, when releases are targeting a pool elevation, the model may have to rapidly increase releases to meet the next target or avoid entering exclusive flood control space.

In the water year 2015 case, releases were set to meet the May 31, 2015 target and then rapidly ramped up to avoid entering exclusive flood control space. Inflows were roughly twice the magnitude of inflows expected when the rule curves were developed, meaning the rule curves as designed could not handle the inflow without entering exclusive flood space or increasing releases. Releases then ramped down to meet the end of June target. However, the rule curves expected high inflows to continue into July (approximately 11,000 cfs), whereas actual inflows were about 6,100 cfs. Therefore, the reservoir failed to fill in July, even though inflow was greater than the minimum fill volume.

Hydropower Generation

The mean daily hydropower generation for the two scenarios shows seasonal differences (Figure 6) closely related to those in river releases (Figure 4). Modeled **2000 SOP operations** and perfect forecasts shows higher generation during winter months, with higher releases due to aiming for the lower end of March target than under the **2010 operating criteria**. The **2010 operating criteria** results in higher releases, and therefore generation, in October to meet the end of October target, and higher releases in June than the **2000 SOP operations**. On average, neither scenario reaches the approximate daily average turbine capacity of about 6,200 cfs, which varies based on WAPA's need for reserve and regulation. Mean modeled annual generation for the period 1967-2018 was 37,899 MWH/month for **2010 operating criteria** and 37,795 MWH/month for **2000 SOP operations**. This represents an increase of 0.3% due to changed operations. However, timing of generation increases in spring and early summer and decreases in winter from the **2000 SOP operations**.

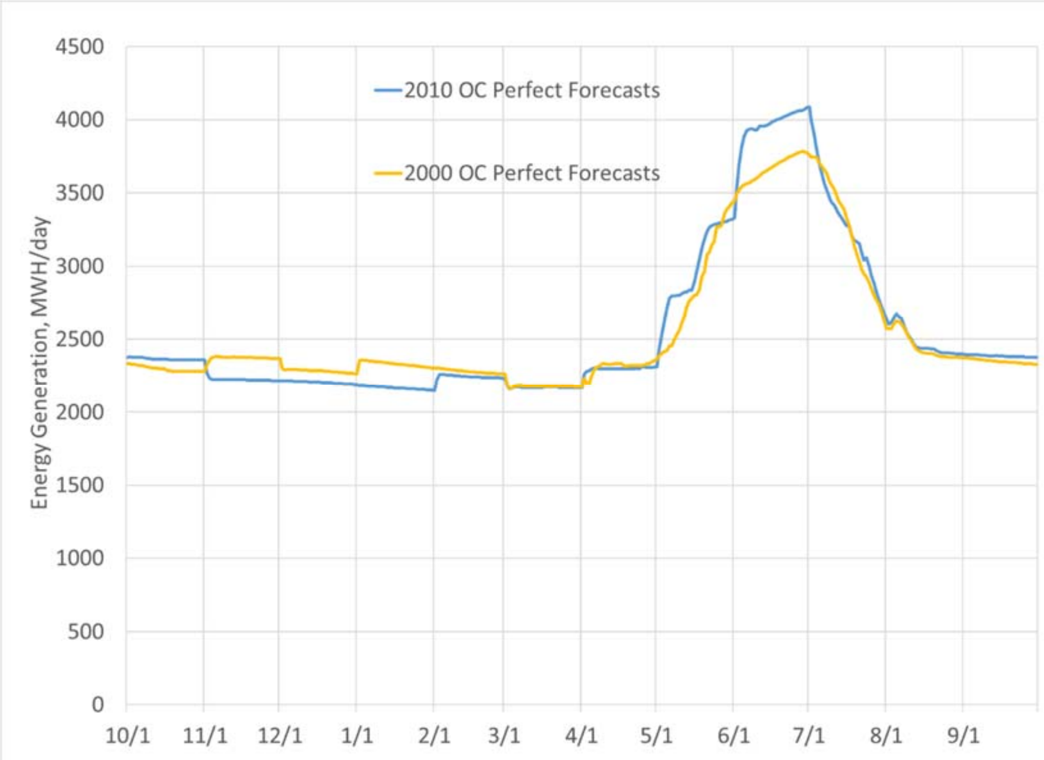

Figure 6: Mean daily hydropower generation for 2010 Operating Criteria and 2000 SOP operations using perfect forecasts from 1967-2018.

Impacts of Hydrology

Two analyses investigated the impacts of hydrology on operations. First, operations were represented using **2010 operating criteria** with perfect forecasts to directly compare the periods analyzed with historical data in the statistical analysis (Reclamation, 2018). Second, operations during the highest April through July runoff year, 2017, were examined using idealized operations as a best-case scenario focusing only on river releases. This analysis was performed in response to stakeholder comments that increasing drawdown in high flow years could reduce the magnitude and duration of river releases.

Comparison of historical periods

To isolate the impacts of hydrologic regime over the period of record modeled operations with **2010 operating criteria** and perfect forecasts are compared across different periods. As with the statistical analysis, the first period runs from reservoir filling in 1967 to the 1993 expansion of Buffalo Bill Reservoir. We can reasonably assume this impacted Bighorn Lake operations, as greater upstream storage should alter inflow timing and magnitude. The second period runs from 1993 through the implementation of the new operating criteria in 2010. The final period is from 2010 through the end of water year 2018.

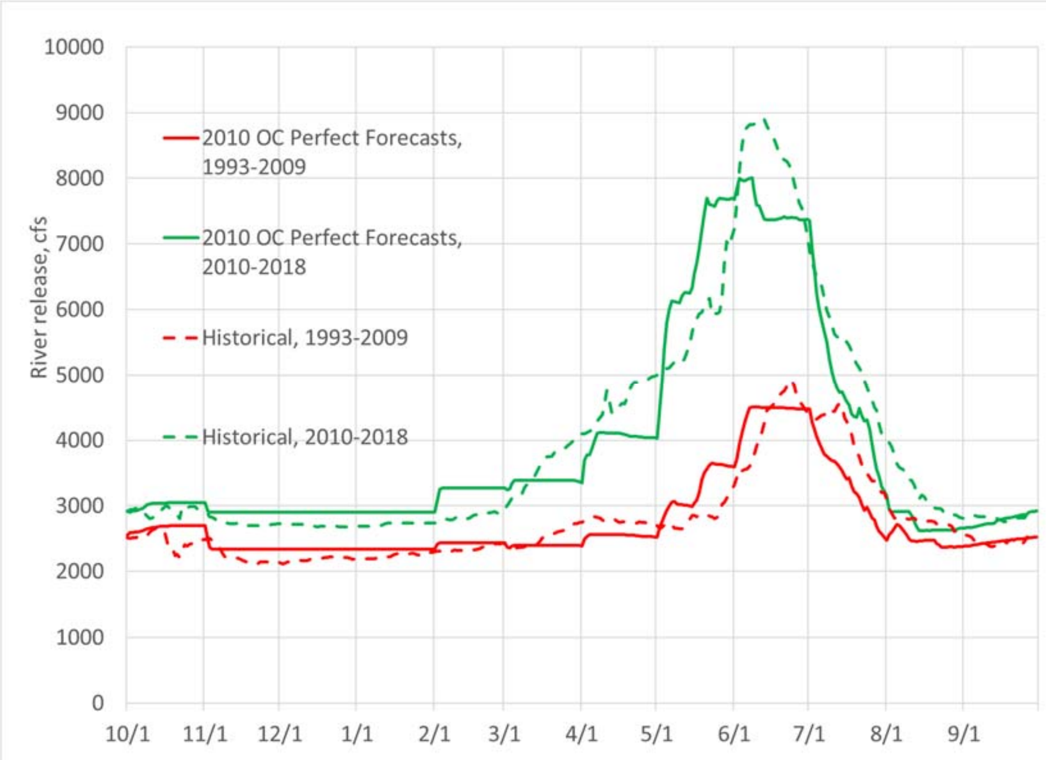

*Figure 7: Mean daily river releases for modeled **2010 operating criteria** and **historical** operations compared across two time periods.*

Figure 7 shows mean daily **historical** and **2010 operating criteria** modeled river releases using perfect forecasts for the periods 2010-2018 and 1993-2009. Peak mean daily releases are significantly greater for both modeled perfect forecast operations and **historical** operations for the period 2010-2018 than the period 1993-2009. A much smaller difference exists between peak river release for **historical** operations (8,894 cfs) and **modeled** operations (8,009 cfs). This shows that much of the differences between the two periods is attributable to hydrology rather than operations or forecasting. If hydrologic conditions were less of a factor, the two solid lines representing perfect forecasts would be more closely related. This comparison does not provide insight as to the impacts of forecasting.

Idealized operations to minimize river releases during record inflows

A simple mass balance comparison between inflow volume, reservoir flood control storage volume, and the release rate can be used to examine minimum physically possible releases. Ideal simplified conditions (for minimizing the magnitude of peak river release) would be represented by the following:

- Bighorn Lake is fully drawn down to the relevant target (i.e., elevation 3,591.5 ft.) on April 1;
- Inflows and releases are constant throughout the April through July period;
- Bighorn Lake is completely full on July 31;

- No Yellowtail Afterbay accretions or Bighorn Canal diversions occur.

Clearly, this scenario is not balancing competing uses for the active conservation and joint use pools and focuses solely on flood control. Such an event would have significant detrimental impact on lake recreation and hydropower.

Using these assumptions, we can see minimum potential releases based on runoff volume in Figure 8. River release is simply based on the average inflow minus the average change of storage flow rate.

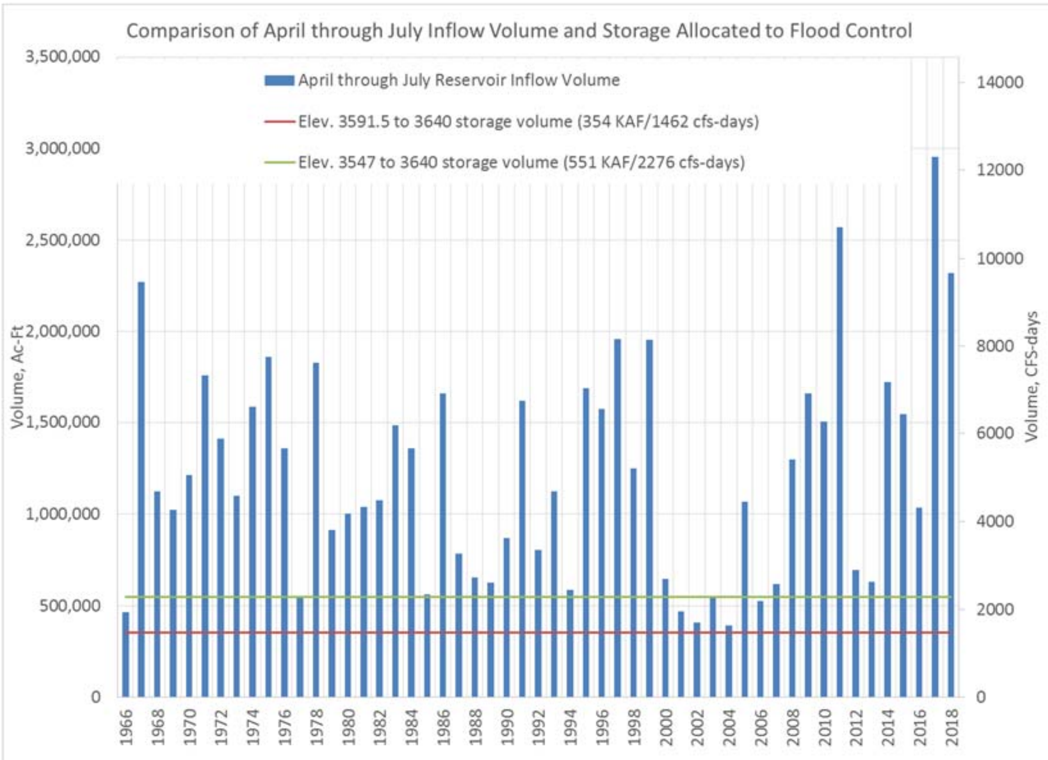

Figure 8: Historical runoff volume compared to the idealized peak flow reduction attributable to filling flood control storage.

Accordingly, the minimum possible release when managing only for flood control for each water year can be calculated. The difference between the blue bar and the relevant storage line indicates the minimum potential release for that year, assuming idealized inflow timing. For example, if Bighorn Lake were drawn down to elevation 3,547 ft. on April 1, 2017, and inflow was evenly distributed through July 31, 2017, Yellowtail Dam release would be 9,928 cfs for the entire period to avoid entering flood control space. If Bighorn Lake were drawn down to elevation 3,591.5 ft., filling Bighorn Lake to elevation 3,640 ft. from April 1 to July 31 would reduce river releases over the same period by 1,462 cfs. Under this condition, the minimum achievable release would be 10,742 cfs and the joint use storage space allocated to flood control reduces river releases by about 12%. Actual April through July 2017 inflows ranged from 4,839 cfs to 18,344 cfs, peaking on June 11. The assumption of even inflow timing is clearly not accurate, and the theoretical minimum possible release in 2017 must be greater than the estimate of 10,742 cfs.

The RiverWare model allows us to examine this concept in further detail. Using the water year 2017 record April through July inflow volume as a test case, the model can be run using current operating criteria; drawing the reservoir down to elevation 3,591.5 ft. by April 1; and drawing the reservoir down to elevation 3,547 ft. by April 1. These scenarios use the **2000 SOP operations** rules with altered end of March targets, which ignores the rule curves. This model configuration solves the average river release from April l which would peak at elevation 3,640 ft., or effectively the “best case” scenario for minimizing the magnitude of peak releases while considering actual inflow timing. These scenarios do not represent turbine outages or other maintenance limitations, providing the full design release capacity for Yellowtail Dam.

Figure 9 shows pool elevations, Figure 10 shows river releases and Figure 11 shows power generation for these two scenarios, as well as historical operations and operations under **2010 operating criteria** with perfect forecasts. It should be noted that Unit 1 was offline during water year 2017, limiting hydropower generation to just three units. Modeled scenarios utilized all four units as needed.

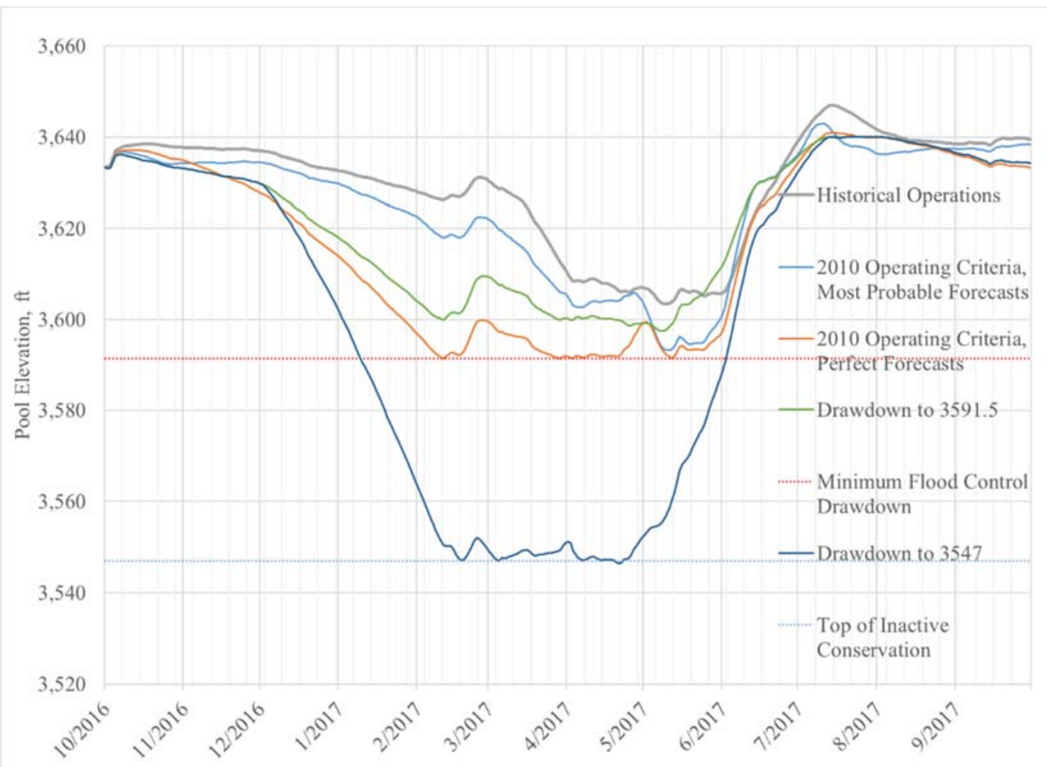

Figure 9: Pool elevation under scenarios minimizing average river release for flood control in water year 2017.

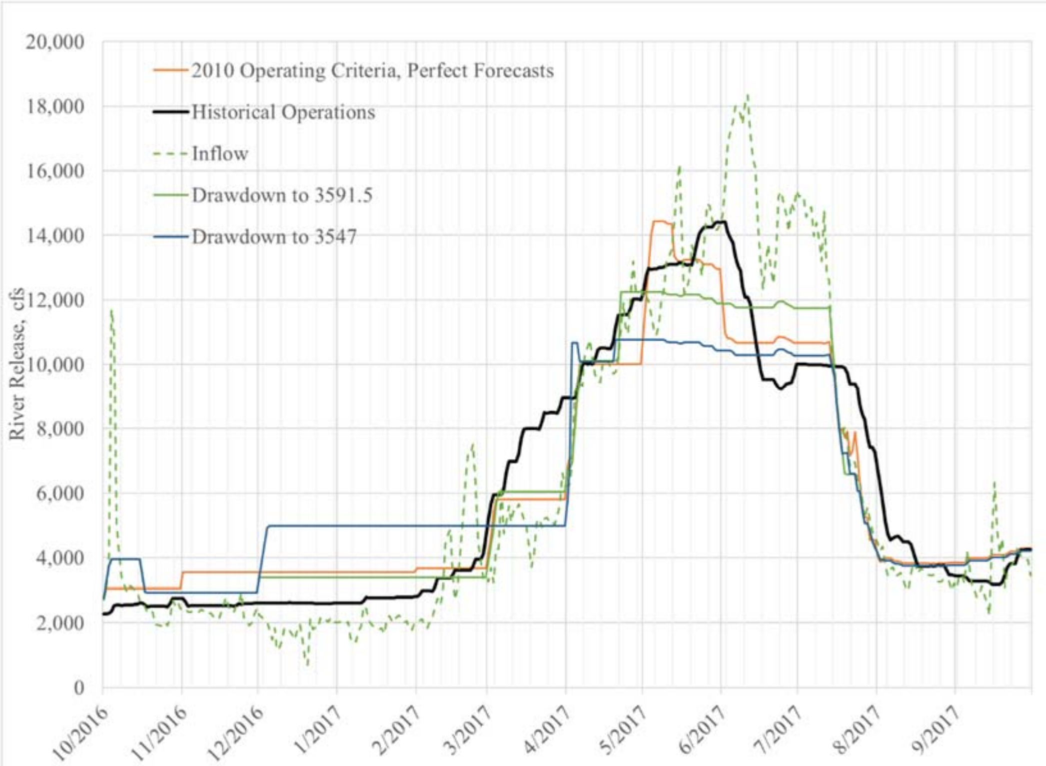

Figure 10: River releases for operations minimizing average river release in water year 2017.

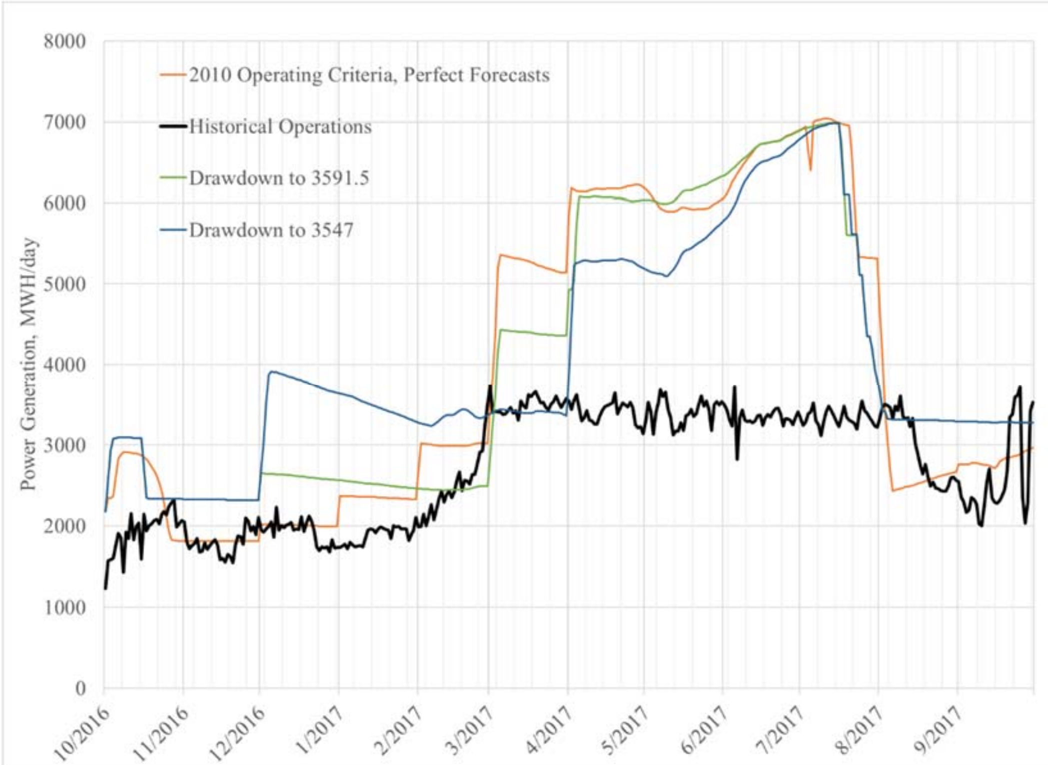

Figure 11: Power generation for operations minimizing average river release in water year 2017.

The scenarios show widely varying drawdown by April 1, with historical operations at 3,607 ft. and both **2010 operating criteria** and the scenario without rule curves drawing down to elevation 3,591.5 ft.

Peak releases for all scenarios are greater than 11,000 cfs. The **2010 operating criteria** peak release reaches 14,376 cfs; drawdown to 3,591.5 ft. scenario reached 12,244 cfs; and drawdown to elevation 3,547 ft. (top of inactive conservation) scenario peaked at 10,770 cfs. The duration of releases greater than 10,000 cfs was the same for the **2010 operating criteria** scenario and elevation 3,591.5 ft. drawdown scenario.

Fully drawing down the reservoir to reduce outflows has limited effects during high inflow volume water years. All scenarios have extended periods of high river releases, and the most aggressive drawdown scenario only reduces the period of flows greater than 10,000 cfs by about two weeks, largely due to physical limitations. These exaggerated drawdown scenarios would likely have considerable impacts on hydropower generation due to extended periods of low head. Lake recreation would also likely be impacted due to excessive drawdown.

Water year operations review

To further examine the causes for differences between anticipated operations and historical operations, each water year since implementation of the **2010 operating**

criteria was examined. Modeled scenarios included **2010 operating criteria** with perfect and most probable forecasts and are compared to historical pool elevations and river releases. These comparisons allow inferences regarding the relative impacts of hydrology, forecasting, operating criteria, and operators' decisions.

The hydrologic variability observed within the 2010-2017 period allows for examination of hydrologic impacts on pool elevations and river releases. This period contained both wet and dry years, providing a range of hydrologic conditions under which to examine operating criteria.

Comparing model runs for perfect forecasts against historical, monthly plan forecasts for the **2010 operating criteria** provides insight as to the impacts of forecast error on pool elevations and river releases. Comparing model runs with historical forecasts provides insight to the impact of operator decisions and any potential deviation from the **2010 operating criteria**.

It should be noted that the historical forecast model runs will not exactly represent historical operations as operators update forecasts on a much more frequent basis, particularly during spring and summer when conditions change rapidly due to snowmelt. However, these intramonth forecasts are not currently documented and were not available for modeling. Therefore, the model re-checks to see if forecasted pool elevations will exceed the top of joint use pool throughout June and July using the historical forecast. For example, if the modeled pool elevation diverges from the planned pool elevation based on first of the month operations due to under-forecasting and the forecasted pool elevation is greater than top of joint use, the model will recalculate the new release based on the historical (erroneous) forecast and current reservoir storage. This brings modeled operations with historical forecasts more in line with the historical operations, in which operators observe trends in pool elevation and inflows and update operations accordingly throughout the month. As such, the comparison is not ideal, but can still provide general observations as to the impact of forecasting, particularly in periods such as winter and early spring when decisions are not made daily.

As with forecasting, there is no direct comparison that can completely determine the impacts of operators' decision-making. However, annual operations reviews, which Reclamation publishes each year, and monthly operating plans provide insight regarding the decision-making process. Also, comparing modeled operations with monthly most probable forecasts to historical operations can highlight periods of interest and for further examination of the monthly plans and flood control orders from the USACE. Generally, flood control orders intending to control Missouri Basin system flooding (2011, 2018) were represented by overriding releases in the model. USACE flood control orders resulting only from encroachment on flood control space were not represented in this exercise.

Water Year 2010 Operations

Water year 2010 (October 1, 2009 through September 30, 2010) was the first year in which the **2010 operating criteria** were implemented. Pool elevations were at the top of joint use pool during October 2009, and winter flows were set with a March 31 target of 3,620.62 ft. (Bureau of Reclamation, 2011b). This was the top of the March 31 target range as per the operating criteria in 2010 and 2011 (Bureau of Reclamation, 2011a). Modeled simulations for water year 2010 used a March 31 target of 3,620.6 ft. because operating criteria do not provide guidance on what elevation within the range should be used. Modeled simulations also used 2010 rule curves (Bureau of Reclamation, 2011c) rather than the updated rule curves, first implemented in 2012 (Bureau of Reclamation, 2012a). Updates resulted in rule curves drawing down Bighorn Lake about 0.4 ft. more than the 2010 rule curves. Finally, the model runs used elevation 3,603 ft. as the minimum drawdown elevation, as was defined by the operating criteria in 2010 prior to 2012 updates.

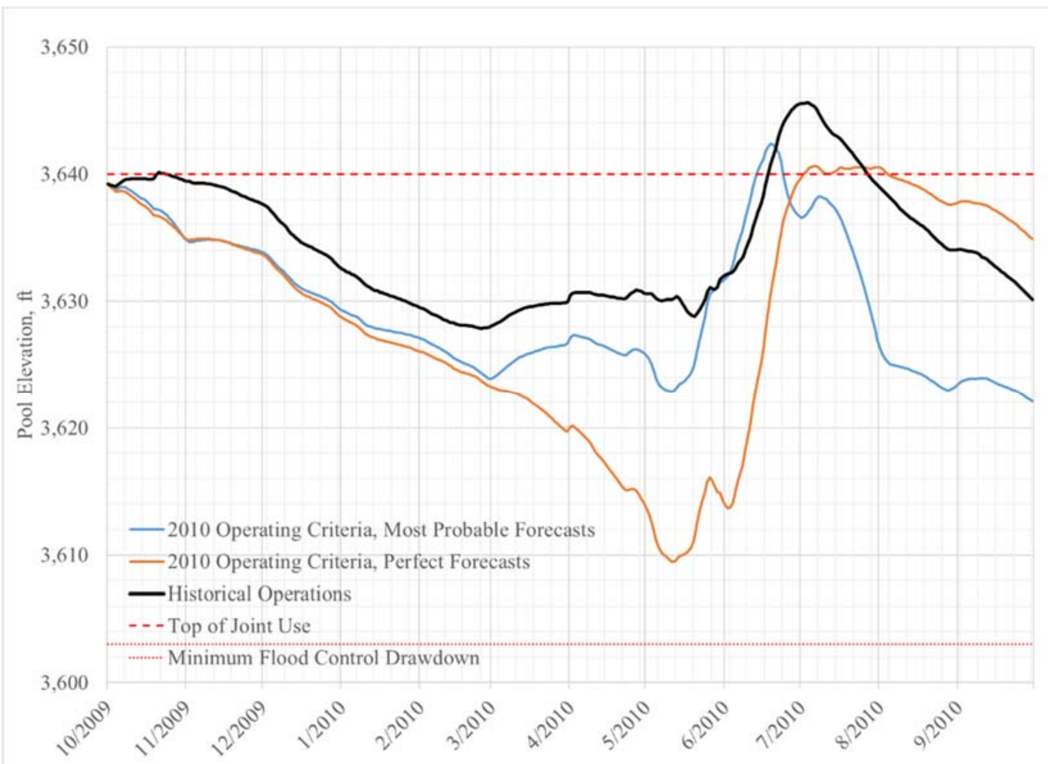

Figure 12: Modeled and historical water year 2010 operations.

Figure 12 shows modeled and historical pool elevations for water year 2010. Historical pool elevations were significantly higher than either modeled scenario, with pool elevations almost 20 feet greater at the end of April. Modeled operations with most probable forecasts and historical operations both encroach on exclusive flood control space, with less encroachment in the most probable scenario due to much greater June reservoir releases. Historically, river releases decreased in February 2010 which caused higher pool elevations.

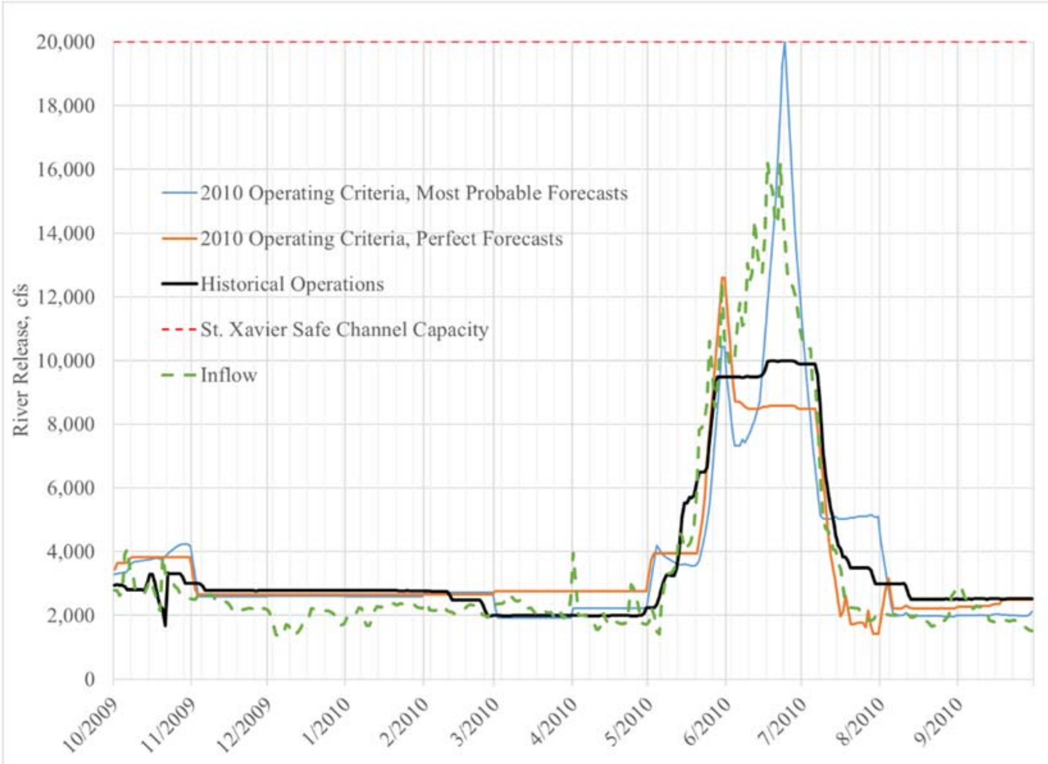

Figure 13: River releases for modeled 2010 water year operations.

Historical operations reduced the peak flows below Yellowtail Afterbay Dam by greater than 5,000 cfs, with peak flows for the perfect forecast model nearly reaching the same peak as historical operations, albeit for a shorter duration.

Modeled peak flows for the most probable forecast scenario rapidly increased and decreased in the months of May and June due to strict adherence to rule curve targets and forecasting errors. As the model neared the end of May and was significantly above target pool elevations, it released more water to try to meet the target. On June 1, the model recalculated releases using a low forecast, and attempted to cut releases. Because the forecast was low releases had to once again increase to try to meet the end of June target. Releases reached nearly 20,000 cfs when the model attempted to avoid entering exclusive flood control space due to under-forecasting of July inflows. This is a result of strictly following operating criteria while lacking updated inflow forecasts during runoff periods. Because the modeled operations with most probable forecasts avoided entering the flood control pool, river releases in June and July are not exactly comparable to determine the impacts of forecasting.

Impact of hydrology

Hydrology was likely the largest cause of river releases much greater than historical means. Inflows were 135.6 percent of the 1966-2017 median for the April through July runoff period. Peak flows were similar for modeled operations with perfect forecasts and historical operations, indicating that much of the high peak flows resulted from high inflows. The magnitude of peak river releases was reduced for historical operations in comparison to modeled operations with perfect forecasts due to greater use of the exclusive flood pool.

Impact of forecasting

Water year forecasts by both Reclamation and NRCS (Table 7) under-predicted Bighorn Lake inflows. However, forecasting does not appear to have caused all the differences in pool elevation between historical operations and modeled operations, as the modeled pool elevation with both the most probable and perfect forecasts is significantly lower than the historical pool elevation until mid-May. Forecasts were under the minimum fill volume until May, meaning rule curves did not apply in March and April. Forecasts are hereafter referenced in thousands of acre-feet, or KAF.

Table 7: Water year 2010 forecasts.

Date	Forecasted Period	Reclamation Forecast (KAF)	NRCS Forecast (KAF; Adjusted for holdback)	Observed Inflow (KAF)
1/2010	April-July	757.9	569	1,505
2/2010	April-July	634.2	359	1,505
3/2010	April-July	590.8	289	1,505
4/2010	April-July	625.0	439	1,505
5/2010	May-July	779.0	661	1,383
6/2010	June-July	801.1	660	1,042

Low forecasts were likely due to lower-than-average mountain snow water equivalent (SWE) until higher-than-average precipitation in the month of May, as shown by Figure 14.

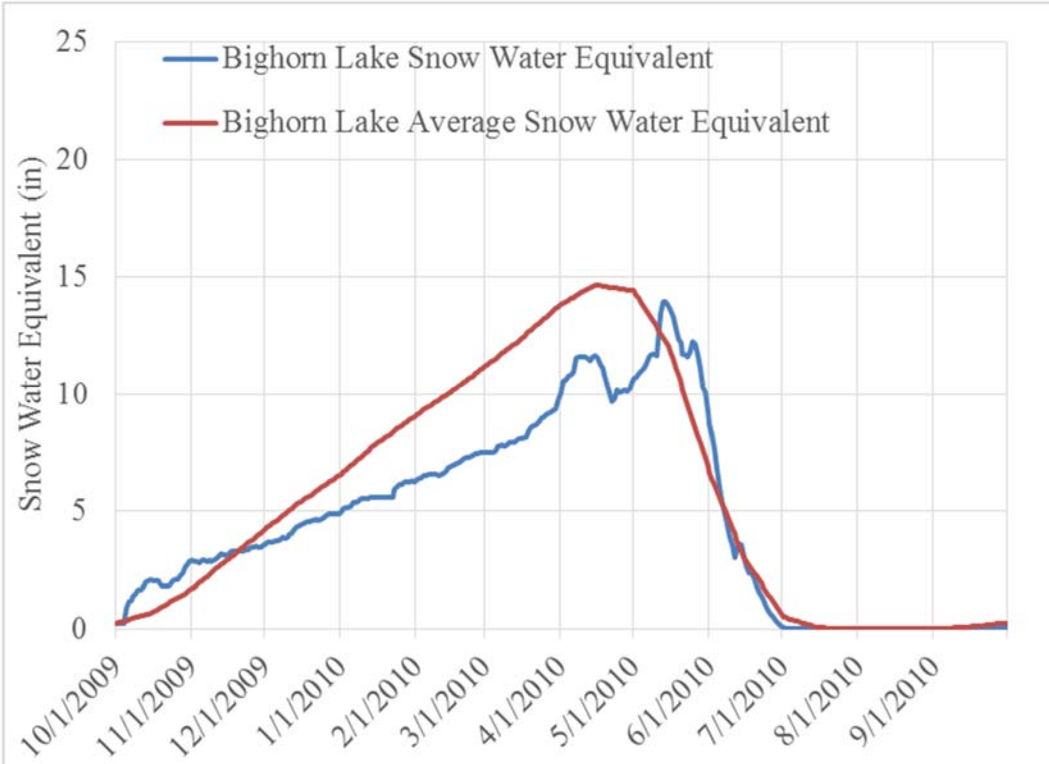

Figure 14: Basin average snow water equivalent for water year 2010.

Runoff was subsequently much greater than forecasted, with Bighorn Lake inflows about 880 KAF greater than the April forecast. Accordingly, Bighorn Lake elevations were higher than average entering the runoff season and releases increased rapidly in May. The magnitude of peak releases was not substantially greater than the modeled releases using perfect forecasts, but the duration was considerably longer (approximately one week longer before and after peak runoff) and the reservoir encroached into flood control space.

Comparing modeled releases and pool elevations with most probable and perfect forecasts shows much greater releases and encroachment into the exclusive flood control space due to forecasting. It appears that forecasting was a significant factor determining pool elevations and river releases but was not the sole factor determining operations for water year 2010.

Impact of operating criteria

According to the Annual Operating Plan (Bureau of Reclamation, 2011b) "…because of the unusually low water supply forecast, the decision was made to reduce the releases out of Bighorn Lake to the Bighorn River" in February from 2,775 cfs to 2,000 cfs "in an effort to conserve storage in Bighorn Lake." This is allowable under the operating criteria, which states "In years with a forecast for very low spring runoff, it may be beneficial to reduce the February and March river release rate to prevent the need for larger release reductions later in the spring." (Bureau of Reclamation, 2012c) However, the model does not represent any reductions in river releases due to low forecasts; it only draws the model down due to high forecasts. This is largely due to the use of exclusive flood control space.

Impact of operators

Based on model results, forecasts, and the Annual Operating Plan, it appears that the operators followed the **2010 operating criteria**. In hindsight, using the flexibility to reduce river releases when pool elevations were 10 feet below the top of joint use pool and forecasting inflows just below the minimum fill volume may have been overly conservative toward filling and future water supply.

Water Year 2011 Operations

Water year 2011 saw the largest recorded April through July Bighorn Lake inflow of 2,572 KAF, since exceeded in 2017. Historical river releases reached levels greater than 15,000 cfs and pool elevations reached 3,655.03 ft., within two feet of the top of exclusive flood control pool and five feet from the dam crest (elevation 3,660 ft.).

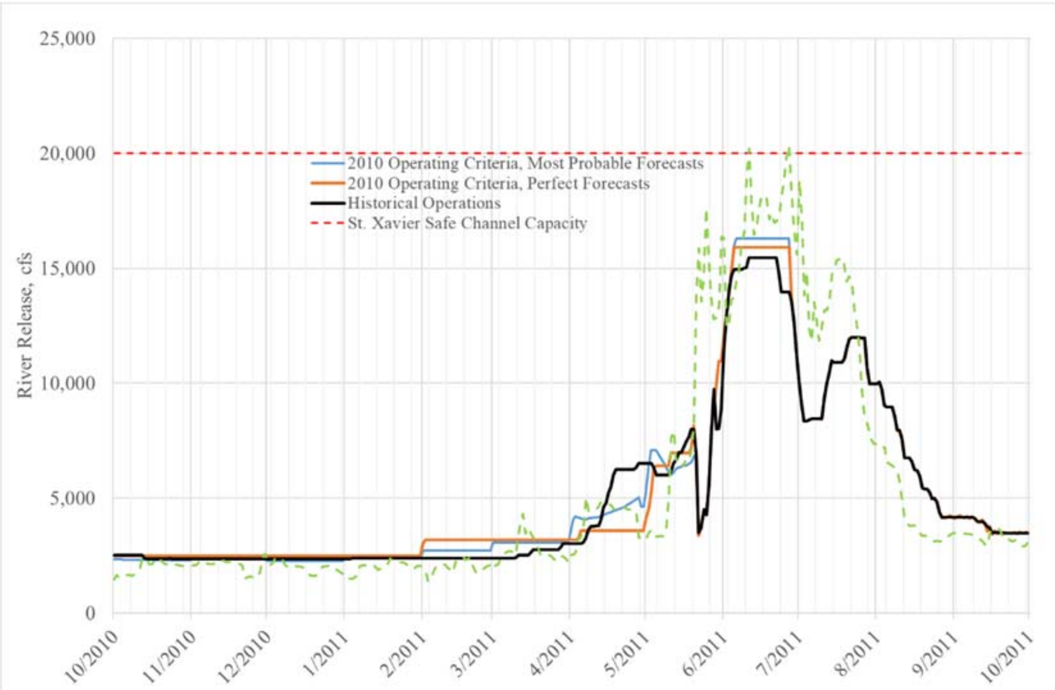

Figure 15: Modeled and historical river releases for water year 2011.

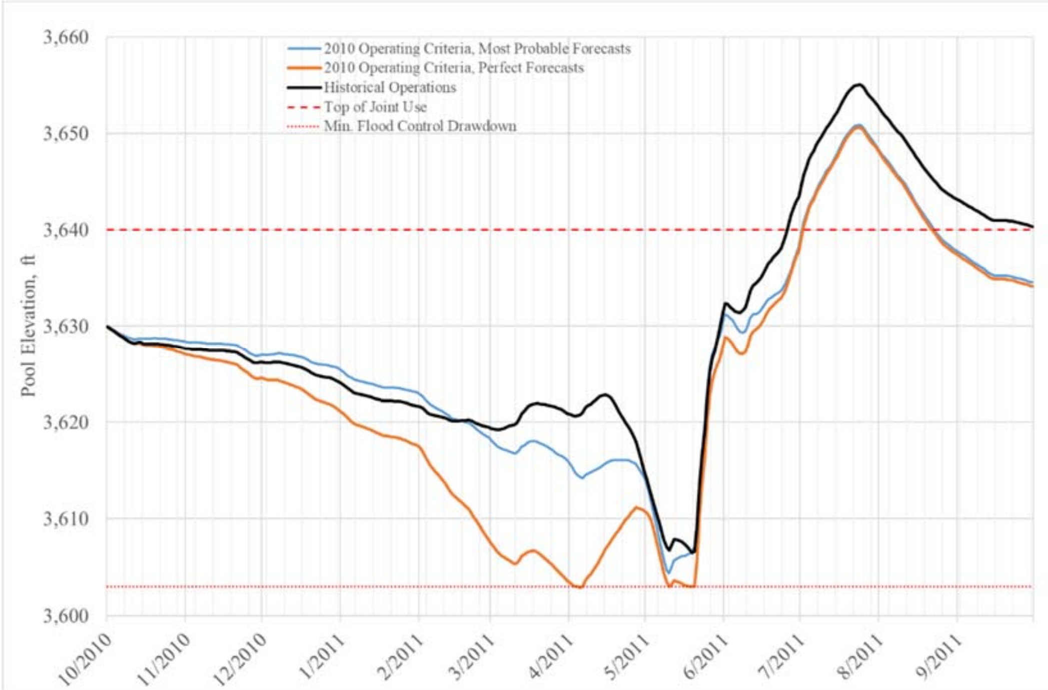

Figure 16: Modeled and historical pool elevations for water year 2011.

As shown in Figure 15, modeled and historical peak river releases were of a similar magnitude, with modeled releases slightly greater than historical. The lower historical releases came with the greater flood storage use, as both modeled scenarios limited pool elevations to the top of joint use pool (Figure 16). Historical operations encroached nearly 15 feet into the exclusive flood pool. The encroachment largely resulted from cutting releases in late June and early July prior to peak inflows.

Reservoir operations reduced the peak river releases by about 5,000 cfs, and significantly reduced the duration of flows greater than 10,000 cfs when compared to reservoir inflows.

Modeled scenarios used the same releases as historical operations from May 21, 2011 through May 27, 2011. Bighorn Lake was under USACE flood control orders during this period to reduce flows in the Bighorn and Yellowstone Rivers due to intense precipitation in late May. Downstream local inflows caused flooding, requiring release reductions. Using historical releases approximates the USACE required releases over this period. USACE flood control orders for Missouri River flow reductions were also represented from June 28 through the end of the water year, as described in (U.S. Army Corps of Engineers, 2018).

Similar to 2010, modeled scenarios used the 2010 rule curves defined in the rule curve spreadsheet from 2011 (Bureau of Reclamation, 2011c), the March 31 target of 3,617 ft. in this spreadsheet, and the minimum flood control drawdown elevation of 3,603 ft. The target in 2011 was a range from 3,616.7 to 3,620.6

(Bureau of Reclamation, 2011a), and November 2010 most probable monthly plans used a winter release of 2,300 cfs, which targeted a lower pool elevation of 3,614.73.

Impact of hydrology

As described above, the April through July inflow was the highest recorded inflow at that time. The runoff volume of 2,572 KAF is 2,218 KAF greater than the allotted joint use space for flood control under the **2010 operating criteria**, or an average of 9,183 cfs over the 122-day period from April through July.

As shown in Figure 17, measurements on April 1 showed slightly above average snowpack in the basin above Bighorn Lake. As with water year 2010, significant spring precipitation resulted in high SWE accumulation from April 1 through the end of May as well as high local runoff.

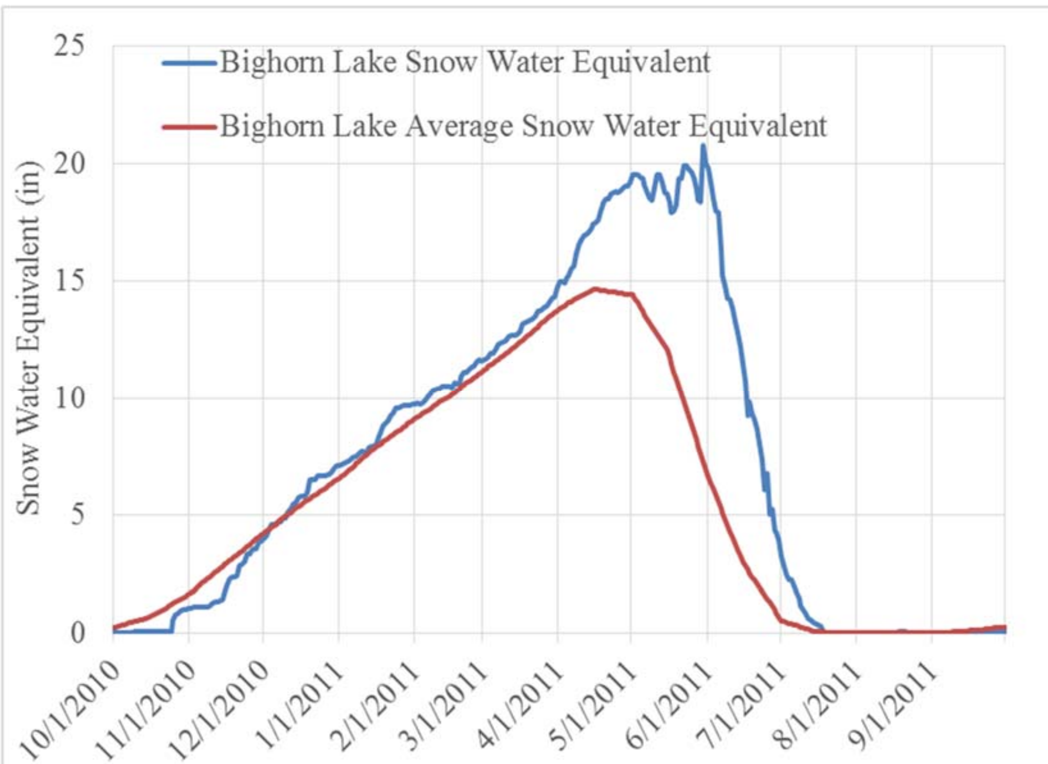

Figure 17: Snow water equivalent above Bighorn Lake in Water Year 2011.

Operations were also significantly impacted by a May rainstorm. According to Reclamation (Bureau of Reclamation, 2012d),

> *…southeastern Montana and northeastern Wyoming reported receiving from 2.50 inches of rain up to 7.75 inches. At one location in the Wolf Mountains near Lodge Grass, Montana, amounts of nearly 11 inches was reported. The record precipitation created ravaging floods along the Bighorn and Yellowstone River Basins downstream of Yellowtail Dam.*

Reclamation and USACE accordingly reduced releases in response to this precipitation event to mitigate downstream flooding on the Bighorn and Yellowstone Rivers (Bureau of Reclamation, 2012d).

Both hydrologic volume and timing therefore had a significant impact on operations. Record runoff clearly resulted in high pool elevations and river releases, and later snowpack accumulation resulted in under-forecasting and therefore less drawdown for flood storage. Hydrology throughout the Missouri Basin also resulted in USACE system flood control orders.

Impact of forecasting

Reclamation forecasts were again significantly below the eventual April through July runoff of 2,572 KAF, with January through April forecasts under the observed inflow by more than one million acre-feet (Table 8). Forecasts were likely low due to average snowpack on April 1, followed by dramatically increasing SWE through the end of May (Figure 17). Modeled operations were able to avoid exclusive flood pool encroachment by releasing as much as 20,000 cfs to the river.

Table 8: Water year 2011 Reclamation most probable and NRCS median forecasts.

Date	Forecasted Period	Reclamation Forecast (KAF)	NRCS Forecast (KAF; Adjusted for holdback)	Observed Inflow (KAF)
1/2011	April-July	1,128	1,257	2,572
2/2011	April-July	1,161	1,177	2,572
3/2011	April-July	1,204	1,187	2,572
4/2011	April-July	1,400	1,297	2,572
5/2011	May-July	1,660	1,631	2,326
6/2011	June-July	1,801	1,559	1,797

While forecasts were significantly lower than observed, it does not appear that under-forecasting greatly impacted peak river releases during the spring runoff period. Historical releases were somewhat below that of the perfect forecast scenario from January through March, resulting in a greater modeled drawdown of about 17 feet on April 1. However, June most probable forecast releases (15,897 cfs) quickly compensated for much of the perfect forecast drawdown and peak releases were not significantly different from the perfect forecast scenario (15,458 cfs). Both modeled scenarios did not use exclusive flood control space until flood control orders went into place in late June, slightly later than historical operations.

Examining river releases and pool elevations in 2011 shows historical and modeled operations significantly encroaching on the flood pool and releases peaking above 15,000 cfs. However, 2011 was an extreme flood year throughout the Missouri Basin and operations were driven mostly by USACE orders for system flood control.

Impact of operating criteria

Due to the minimal joint use flood control space available compared to April through July runoff, it is unlikely that changes to operating criteria would make a significant impact on peak flows or pool elevations without additional drawdown. It should be noted that the inflow for 2011 was greater than the “maximum” April through July inflow from the assumed inflow hydrology used to develop the rule curves. Updates in 2012 served to drop the minimum flood control drawdown elevation from 3,603 to 3,591.5 ft. Modeled scenarios represent the historical rule curves and associated minimum drawdown elevation.

Impact of operators

As described above, Reclamation operators worked in conjunction with USACE to provide Missouri Basin flood control (Bureau of Reclamation, 2012d); (U.S. Army Corps of Engineers, 2018):

> *The Corps made a special request to Reclamation to store a significant amount of floodwaters in Bighorn Lake to help alleviate the severe flooding that was already along the Missouri River in the Dakotas. Reclamation and the Corps coordinated a release plan necessary to balance the local flood risk and benefits to the downstream flooding. The most immediate need was to decrease flows in the Missouri River near Williston, North Dakota, to reduce pressures and large seepage that was occurring on levies in the Williston area.*

Except for the periods under which flood control efforts were coordinated with USACE, historical operations closely match modeled operations with most probable forecasts. It therefore appears that operators followed operating criteria in water year 2011.

Water Year 2012 Operations

Following two years of high inflows, water year 2012 was a relatively dry one. April through July runoff totaled only 693 KAF, or 71.7% exceedance based on the period water year 1966 through 2017. Exceedance is defined as the probability that runoff in any given year would be greater than the runoff volume.

Storage started the water year at the top of joint use pool, and winter releases were set at around 3,000 cfs. Peak inflows during an October event reached 11,689 cfs while the maximum spring runoff inflow was 6,527 cfs.

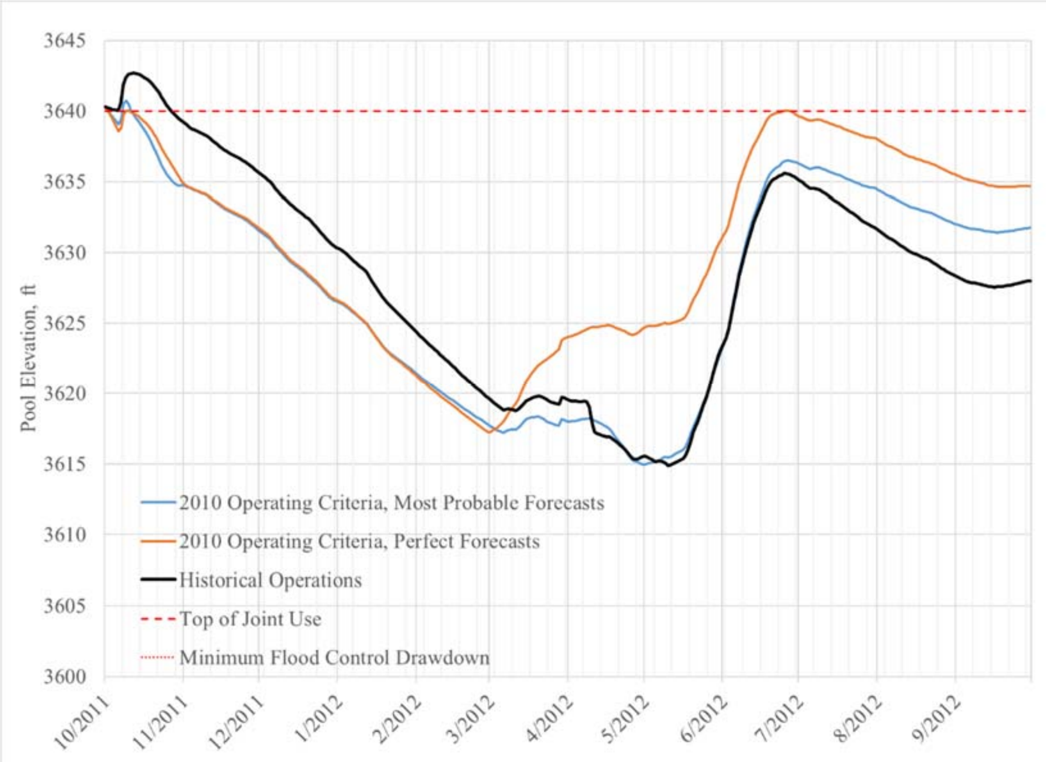

Figure 18: Modeled and historical pool elevations for water year 2012.

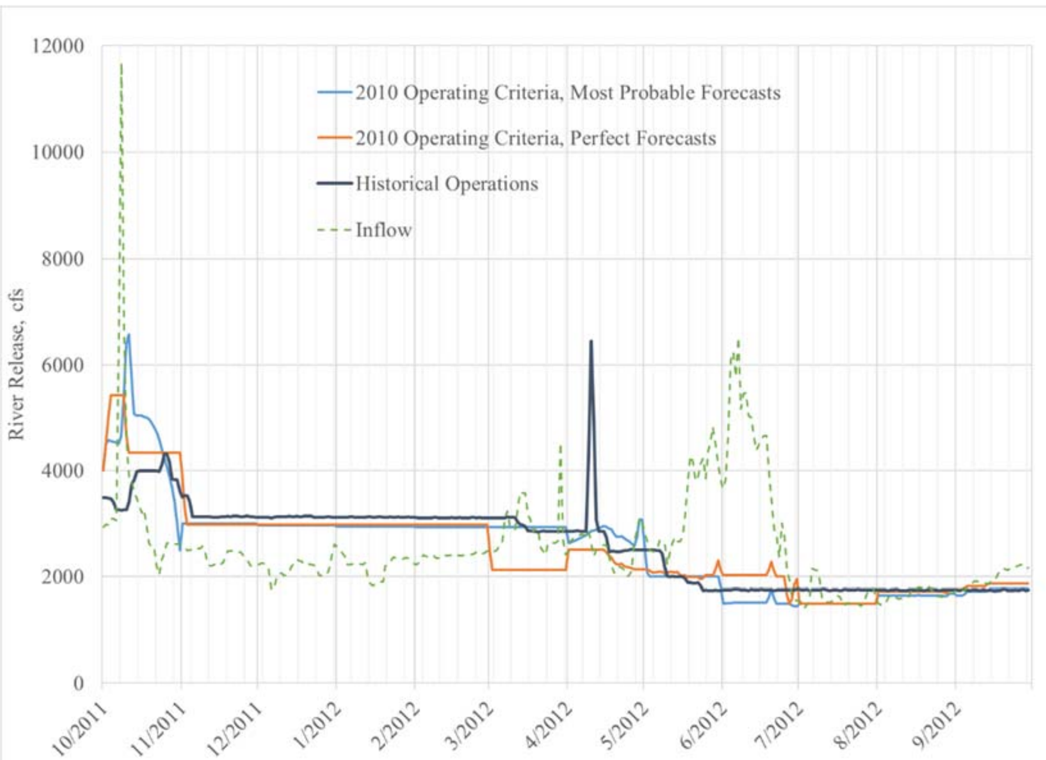

Figure 19: Modeled and historical river releases for water year 2012.

Impact of hydrology

High initial storage resulted in releases around 3,000 cfs for all scenarios. Dry winter and spring conditions resulted in inflows below the minimum fill volume. As described previously, the minimum fill volume of April through July forecast runoff of 727 KAF is the threshold over which rule curves are used. While the inflows were below the minimum fill volume, the perfect forecast scenario still fills to the top of joint use because releases are reduced to target the March 31, 2013 pool elevation of 3,617 ft.

Impact of forecasting

Basin SWE was around average until April (Figure 20), resulting in forecasts greater than the eventual observed inflow (Table 9).

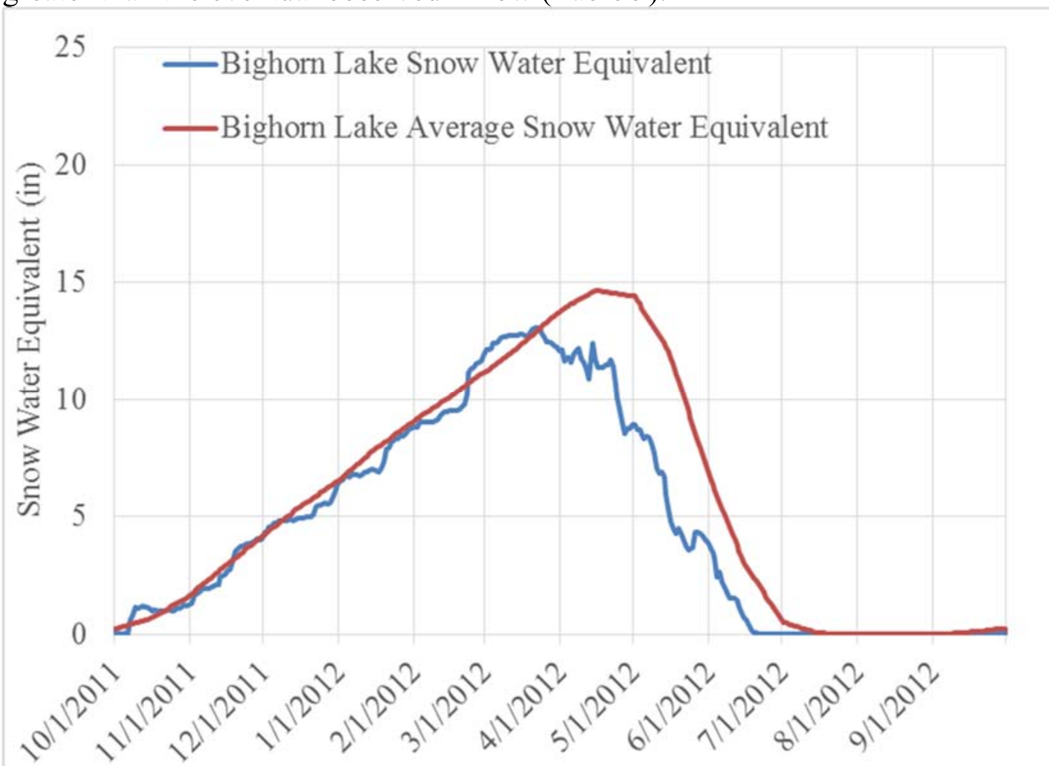

Figure 20: Water year 2012 snow water equivalent.

Table 9: Reclamation most probable and NRCS median forecasts in water year 2012.

Date	Forecasted Period	Reclamation Forecast (KAF)	NRCS Forecast (KAF; Adjusted for holdback)	Observed Inflow (KAF)
1/2012	April-July	1,131	1,397	693
2/2012	April-July	1,212	1,327	693
3/2012	April-July	1,345	1,517	693
4/2012	April-July	1,064	1,057	693
5/2012	May-July	600	685	543
6/2012	June-July	336	411	339

Because forecasts were greater than the minimum fill volume for January through April, rule curves applied to the historical and most probable forecast modeled scenario. These two scenarios drew Bighorn Lake down in anticipation of greater runoff, resulting in lower summer pool elevations than with perfect forecasts. Forecasting did not appear to influence late summer and early fall releases, as the modeled scenarios with most probable and perfect forecasts were similar.

Whereas Reclamation's most probable forecast under-predicted April through July reservoir inflow in water years 2010 and 2011, the most probable forecast over-predicted inflows in 2012. Because the most probable forecast was under the upper quartile threshold for starting drawdown in February, modeled operations with most probable and perfect forecasts were nearly identical through the end of February. Beginning in March, modeled operations with perfect forecasts cut releases to conserve water supply. Historical and modeled most probable operations maintained higher March releases and further drew down Bighorn Lake. Historical operations and modeled most probable operations did not reach the top of joint use pool. The lower releases from the modeled operations with perfect forecasts resulted in a full joint use pool in June.

Modeled operations with perfect and most probable forecasts reduced river releases to 1,500 cfs in July, where historical operations maintained river releases of 1,750 cfs. This resulted in historical lower end-of-water year pool elevations.

Impact of operating criteria

Modeled operations using perfect forecasts fill Bighorn Lake while reducing flows below the 2,000 cfs minimum fisheries flow. This decision is based on the calculated average release to meet the following March 31 target elevation of 3,617.0 ft. Modeled operations with perfect forecasts are less desirable than historical operations for river fisheries due to lower releases in late summer and fall. It should again be noted that operating criteria does not provide adequate guidance to accurately determine releases.

Impact of operators

Bighorn Lake historical pool elevations track very closely to the modeled pool elevations for spring and summer 2012. Releases diverged in late summer and early fall, as the most probable forecast scenario reduced river releases to 1,500 cfs whereas historical releases were maintained at 1,750 cfs. This was allowable under the operating criteria due to May through July and June through July forecasts less than the minimum fill volume. As described previously, operating criteria allow flexibility in dry year releases and modeled operations in these conditions are a best guess as to the intent of the operating criteria.

Water Year 2013 Operations

Due to dry conditions in late 2012 and the previously described operator decisions to maintain 1,750 cfs, water year 2013 began with low Bighorn Lake storage, beginning the year at about elevation 3,628 ft., well below the target elevation of 3,635 ft. April through July reservoir inflow was 628 KAF (77.4% exceedance).

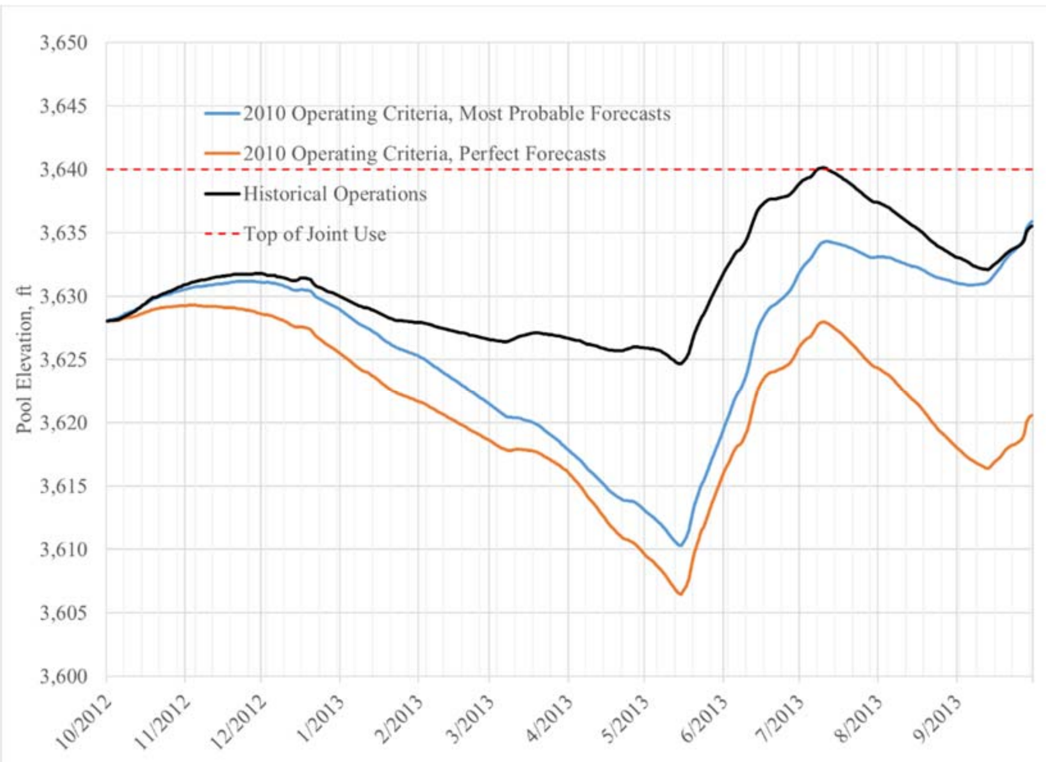

Figure 21: Water year 2013 historical and modeled pool elevations.

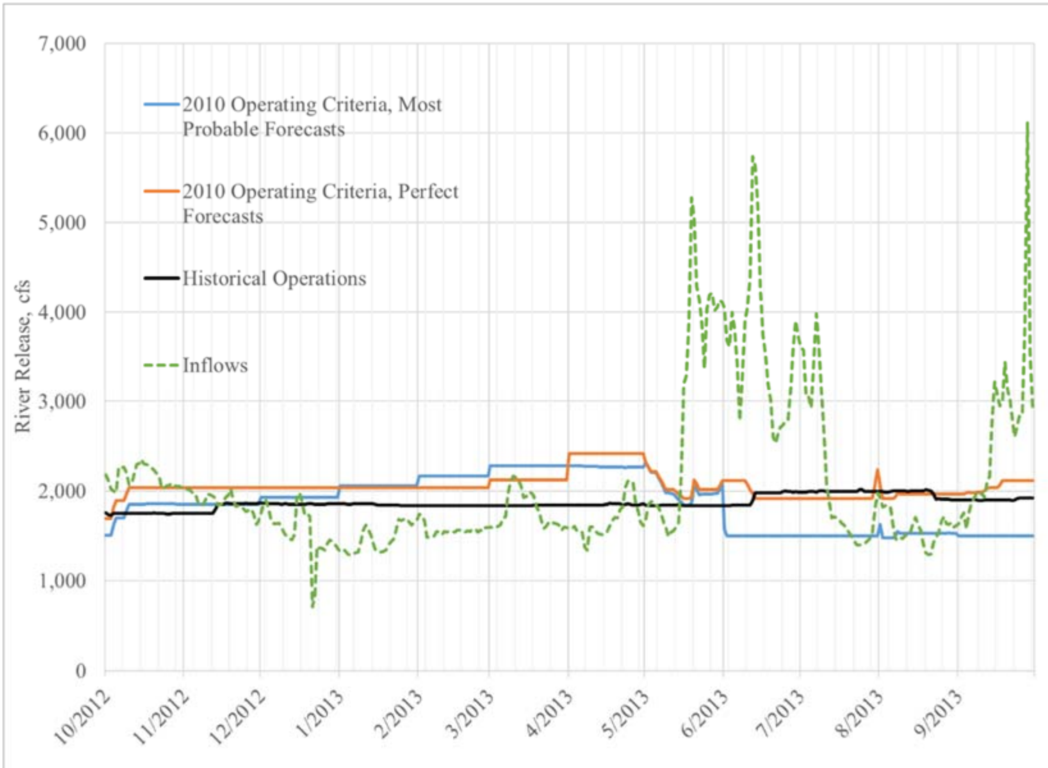

Figure 22: Water year 2013 historical and modeled river releases.

Significant differences exist between historical and the two modeled scenarios, as shown in Figure 21 and Figure 22. **Historical operations** were defined by lower winter releases than both modeled operations scenarios, and filling of the reservoir in mid-July. **Most probable** and **perfect forecast** modeled scenarios both released more water in winter. Neither filled to the top of joint use, and the **most probable** scenario dropped river releases to 1,500 cfs in late summer and fall. **Historical** and **perfect forecast** scenarios resulted in higher summer and fall flows of around 2,000 cfs.

Impact of hydrology

Dry conditions certainly impacted operations in 2013. Low inflows combined with the low reservoir starting pool elevation required reduced releases to balance river and reservoir recreational uses for all scenarios. The observed April through July inflow volume was nearly 100 KAF below the minimum fill volume.

Impact of forecasting

Figure 21 shows that releases were considerably different between the **perfect forecast** scenario and the **most probable** forecast scenario. Winter releases for the **perfect forecast** scenario were set at 2,000 cfs, and forecasts were lower until January for the most probable scenario. Due to winter inflow under-forecasting, releases for the **most probable** scenario increased through the end of May. **Historical** operations had conserved water in spring and filled Bighorn Lake as allowed by the 2010 operating criteria when forecasts are below the minimum fill threshold. P**erfect forecasting** allowed that scenario to release a greater amount of water in anticipation of an October 2013 runoff event. **Most probable** forecasts were drier and resulted in operations limiting fall river releases to 1,500 cfs.

Table 10: Water year 2013 Reclamation and NRCS forecasts.

Date	Forecasted Period	Reclamation Forecast (KAF)	NRCS Forecast (KAF; Adjusted for holdback)	Observed Inflow (KAF)
1/2013	April-July	812	1,131	628
2/2013	April-July	788	981	628
3/2013	April-July	688	901	628
4/2013	April-July	661	801	628
5/2013	May-July	579	782	529
6/2013	June-July	351	559	348

Table 10 shows historical Reclamation and NRCS forecasts. Forecasts were initially above the minimum fill threshold in January and February due to nearly average snowpack (Figure 23), but SWE did not accumulate as fast as the average basin SWE. Forecasts by April 1 were nearly the same as the eventual observed inflow.

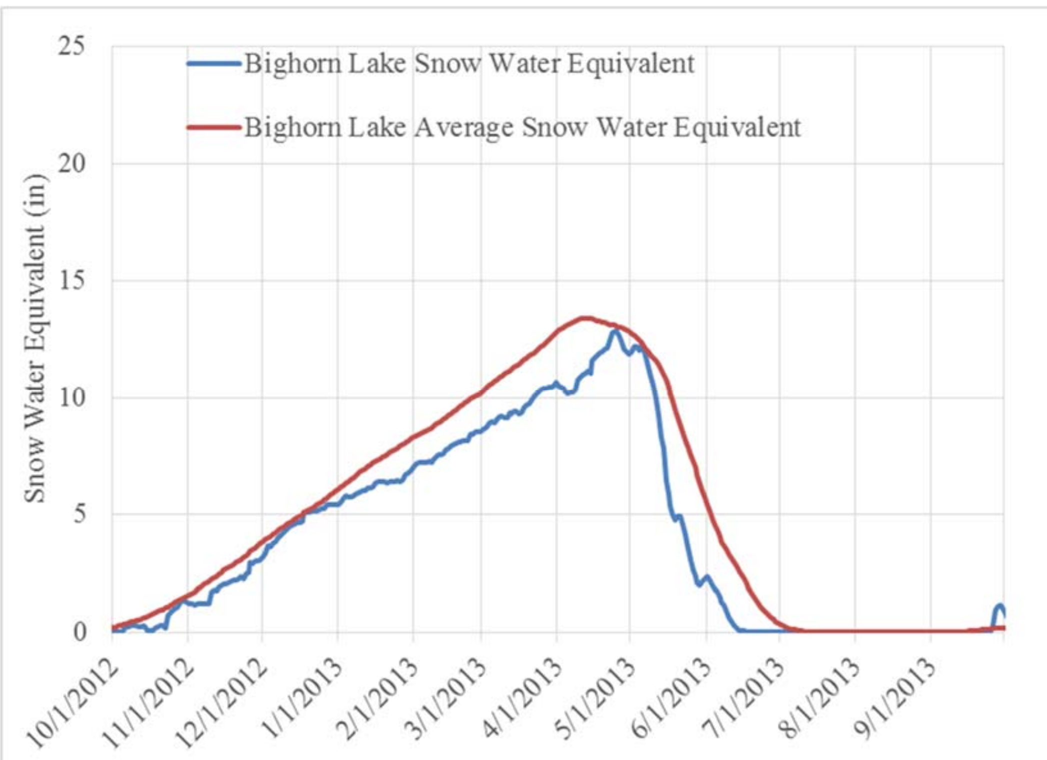

Figure 23: Water year 2013 snow water equivalent.

Impact of operating criteria

The **2010 operating criteria** allowed for discretion during setting low flows during March 2013. This discretion and other deviation allowed for filling of Bighorn Lake. Conditions where pool elevations were significantly higher than 3,617 ft. at the end of March were not contemplated by the operating criteria. The operating criteria therefore provides no guidance on setting flows or changing the minimum fill volume, which was based on the minimum volume to maintain 2,000 cfs and still fill from 3,617 ft. on March 31.

Impact of operators

Figure 21 shows differences of almost 500 cfs between the modeled **most probable** forecast scenario and the **historical** operations in February 2013. Historical monthly plans can be used to determine the cause of these differences. Because the period in question is during winter, flows are unlikely to change more frequently than monthly.

By initializing operations using historical pool elevations, this analysis does not examine the trade-offs of historical operations releasing more water at the end of 2012 than either modeled scenario. Carry-over storage may be an important component of dry year operations.

Table 11: Historical forecasts for Bighorn Lake inflow from November 2012 through April 2013.

		Forecast, KAF						Elev., ft.
		11/2012	**12/2012**	**1/2013**	**2/2013**	**3/2013**	**A-J Vol.**	**March 31 Target**
Forecast Date	**11/2012**	92.9	72.5	76.7	76.4	106.6	1056.3	3617
	12/2012		72.4	76.7	76.3	106.5	1047	3617
	1/2013			76.7	76.3	106.6	812.1	3622.06
	2/2013				76.3	106.5	788	3622.97
	3/2013					106.6	687.6	3623.81
	4/2013						660.7	

Table 12: Planned releases from monthly plans from November 2012 through April 2013.

		Planned Release, cfs				
		11/2012	**12/2012**	**1/2013**	**2/2013**	**3/2013**
Forecast Date	**11/2012**	1760	1,781	1,781	1,779	1,852
	12/2012		1,781	1,781	1,779	2,186
	1/2013			1,781	1,779	1,927
	2/2013				1,779	2,033
	3/2013					1,781
	4/2013					

The monthly plans in Table 11 and Table 12 show that the planned releases were not the average release to reach the March 31 target. Rather, the plans set a higher release in the final month of each monthly plan for the forecast dates from November through February. This in turn reduced the release in earlier months, resulting in higher pool elevations than anticipated by the model under the 2010 operating criteria. All forecasts were greater than the minimum fill volume, but still relatively low, so transition to the rule curves should not have occurred until the March 1, 2013 plan.

The March 31 targeted pool elevation for January and February monthly plans was greater than the pool elevation of 3,617.0 specified by the operating criteria. Operating Criteria in place prior to 2015 used a March 31 target range from 3,615 to 3619. When calculated mean release was less than 2,000 cfs, the target was lowered to 3,615 ft. (Bureau of Reclamation, 2012c). January targets were therefore nearly 8 ft. greater than called for by the **2010 operating criteria**.

Ultimately, Reclamation deviated from the operating criteria when setting winter releases, which was described in (Bureau of Reclamation, 2014):

> *On November 8 Reclamation hosted a public meeting in Billings, Montana to discuss the water supply outlook and projected fall and winter operations of the Bighorn River Basin. With the below average releases from Boysen Reservoir and Buffalo Bill Reservoir and very dry conditions leading up to the meeting, the winter release from Yellowtail Dam was set at 1,850 cfs on November 13. This was a slight deviation from the operating criteria. For winter releases below 2,000 cfs, the end of March elevation target should be 3615.0. However, with the well below normal precipitation since March 2012, the end of March elevation target was kept at 3617.0. There were no objections with setting a lower winter release and keeping the end of March target at 3617.0 feet. This release rate was 72 percent of average.*

While the target was adjusted with input, there was no discussion in (Bureau of Reclamation, 2014) of weighting releases toward March and further conserving water.

The only flexibility described by the **2010 operating criteria** during winter releases is the aforementioned target adjustment, since removed in 2015 (Bureau of Reclamation, 2017). Reclamation operated the reservoir higher than the criteria called for, with lower winter releases. These deviations would have been allowed by the operating criteria during March, as described above. In this month, the forecast was below the minimum fill value and releases can be adjusted to conserve flow.

April through July forecasts were greater than the eventual runoff of 628 KAF. The conservative winter releases of about 1,780 cfs resulted in additional storage, allowing for greater summer releases than the 1,500 cfs modeled releases. Deviations in this year appear to have benefited both lake and river recreation by increasing pool elevations and summer low-flow releases, and stakeholders appeared to have agreed with the deviation in the fall public meeting.

Water Year 2014 Operations

Water year 2014 operations saw an early March runoff event with inflow peaking at 8,470 cfs due to melt of low elevation snowpack (Reclamation, 2015). Runoff remained at high levels through mid-July after peak runoff, resulting in high pool elevations through the end of the water year. Runoff for the April through July period was 1,725 KAF, or 17% exceedance. Pool elevations for all scenarios (Figure 24) were nearly drawn down to elevation 3,600 ft., and river releases for all scenarios reached peaks greater than 8,000 cfs.

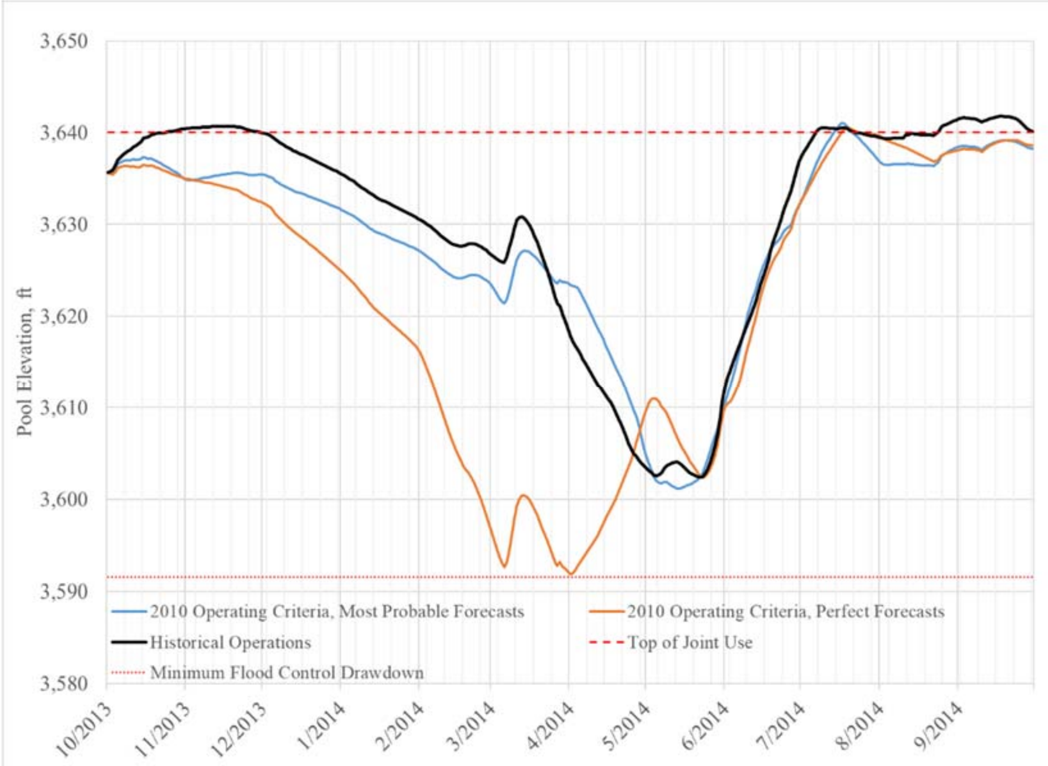

Figure 24: Water year 2014 modeled and historical pool elevations.

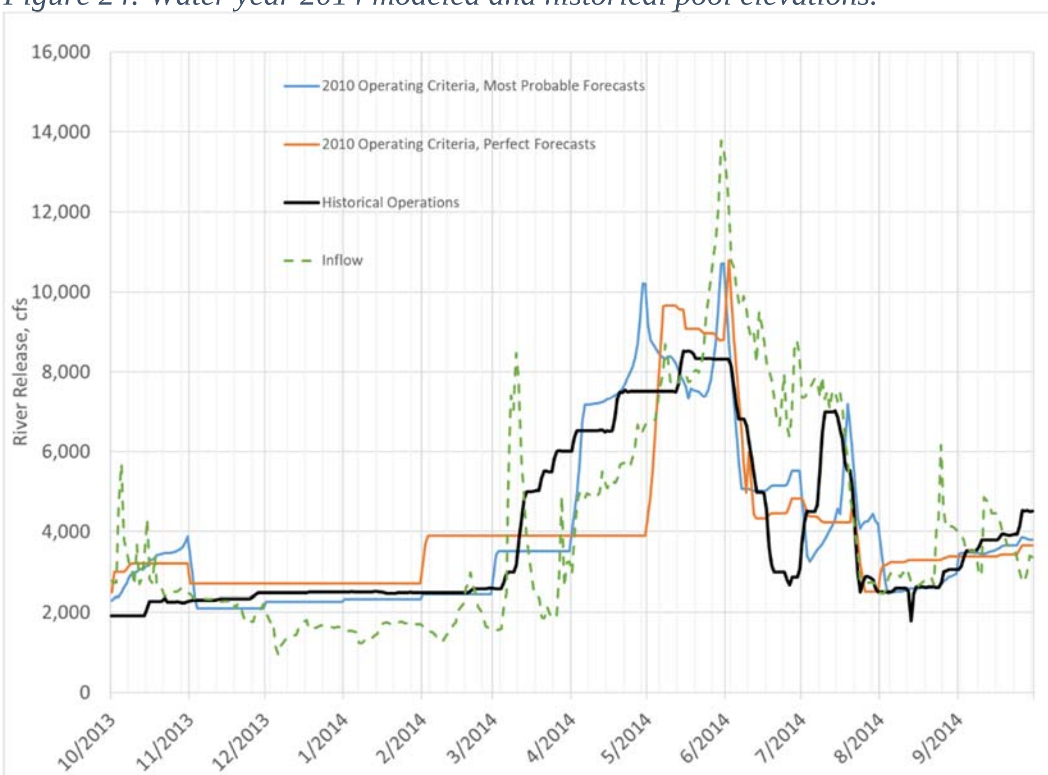

Figure 25: Water year 2014 modeled and historical river releases.

Impact of hydrology

Runoff events in October 2013 and March 2014 increased pool elevations for the **historical** and **most probable** forecast scenarios. As described above, high inflows significantly impacted peak releases and runoff timing also impacted pool elevations. Inflows were relatively evenly distributed through the April through July period, resulting in lower peak releases for historical and modeled operations.

Impact of forecasting

Forecasts were considerably below average in January and February, resulting in high pool elevations for the **historical** operations and **most probable** forecast modeled scenario. The basis for the low forecasts is not clear, as mean basin SWE was above average on January 1 and February 1 (Figure 26), and NRCS' forecast was nearly 500 KAF greater than Reclamation's (Table 13). However, without a retrospective analysis of forecasts we cannot determine the cause of under-forecasting.

Reclamation forecasts increased by 439 KAF in March and 321 KAF from March to April. These increases moved the forecast above the minimum fill threshold; however, because the low forecasts were in January and February, the winter flow should have been maintained until March 1. Historical operations show Reclamation increased releases following the March low elevation snowmelt runoff event; the April 1 forecast was 280 KAF lower than the observed inflow.

Table 13: Water year 2014 Reclamation most probable and NRCS median forecasts.

Date	Forecasted Period	Reclamation Forecast (KAF)	NRCS Forecast (KAF; Adjusted for holdback)	Observed Inflow (KAF)
1/2014	April-July	726	1,215	1,725
2/2014	April-July	685	1,135	1,725
3/2014	April-July	1,124	1,685	1,725
4/2014	April-July	1,445	1,975	1,725
5/2014	May-July	1,203	1,300	1,409
6/2014	June-July	467	824	874

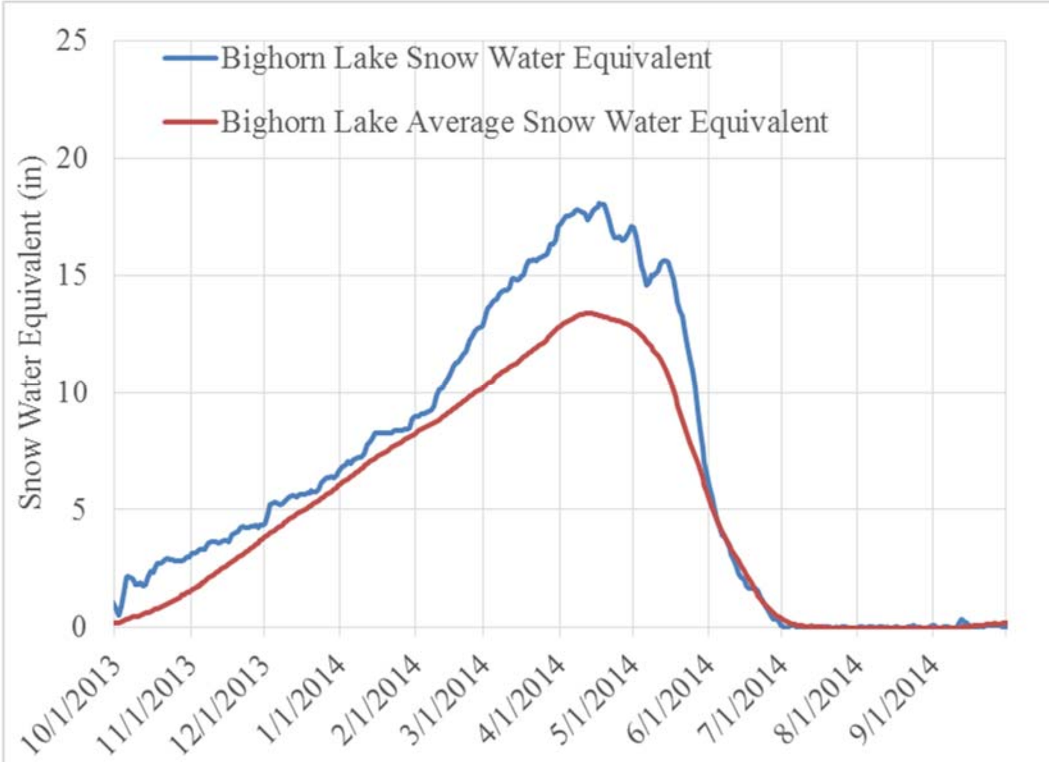

Figure 26: Water year 2014 snow water equivalent.

Historical and modeled operations with the **most probable** and **perfect** forecasts all reached about the same level of drawdown by the peak drawdown date in mid-May. Modeled operations with **perfect** forecasts show Bighorn Lake drawn down almost to the minimum flood control drawdown elevation of 3,591.5 ft. in March to mitigate the high March runoff event. The perfect forecast April through July inflow was greater than the upper quartile volume, and the model initiated flood control releases on February 1 targeting the end of April rule curve. Because of a high inflow event in March, and rapidly increasing inflows in April, the model evacuated storage below the April 30 rule curve elevation to the minimum flood control drawdown elevation of 3,591.5 ft. This allowed the reservoir to fill to the end of April target when April flows ramped up and maintained the minimum possible release to meet the end of April target.

All three scenarios had similar peak river releases above 8,000 cfs. **Historical** operations had a longer period with flows greater than 6,000 cfs due to high pool elevations in March. Modeled operations with **perfect forecasts** had a much shorter period of river releases above 6,000 cfs due to the March and April drawdown. Neither modeled nor historical operations reached elevation 3,617 ft. by the end of May.

Impact of operating criteria

Differences between the assumed rule curve inflow timing and actual inflow hydrograph resulted in inefficiencies for the modeled scenarios. The peak of the inflow hydrograph occurred on May 31. The rapidly increasing inflows at the end of May combined with a strict pool elevation target at the end May, as in the modeled operations, resulted in spikes in river releases.

Impact of operators

Pool elevations were slightly higher than anticipated due to winter flow maintenance during an October 2013 runoff event. Flows were increased rapidly during the March 2014 runoff event, bringing pool elevations in line with expected rule curve elevations. This resulted in less ramping required to meet the higher releases required by high inflows when compared to the modeled scenarios with most probable and perfect forecasts. Operators deviated slightly from rule curves at the end of May; likely this was due to recognizing peak inflows and adjusting the timing of reservoir fill. In this case, deviating from the rule curves in May and June allowed operators to avoid high river releases.

Water Year 2015 Operations

Water year 2015 operations were defined by high flows, with April through July runoff of 1,543 KAF. January, February, and March forecasts predicted greater than 1,000 KAF, but little snow accumulation after March 1 resulted in forecasts below the minimum fill volume in April and May. River releases in the historical and most probable forecast scenarios were reduced at this point due to decreasing forecasts. Late May precipitation resulted in higher than average inflows (Bureau of Reclamation, 2016b). River releases for all three scenarios were greater than 10,000 cfs.

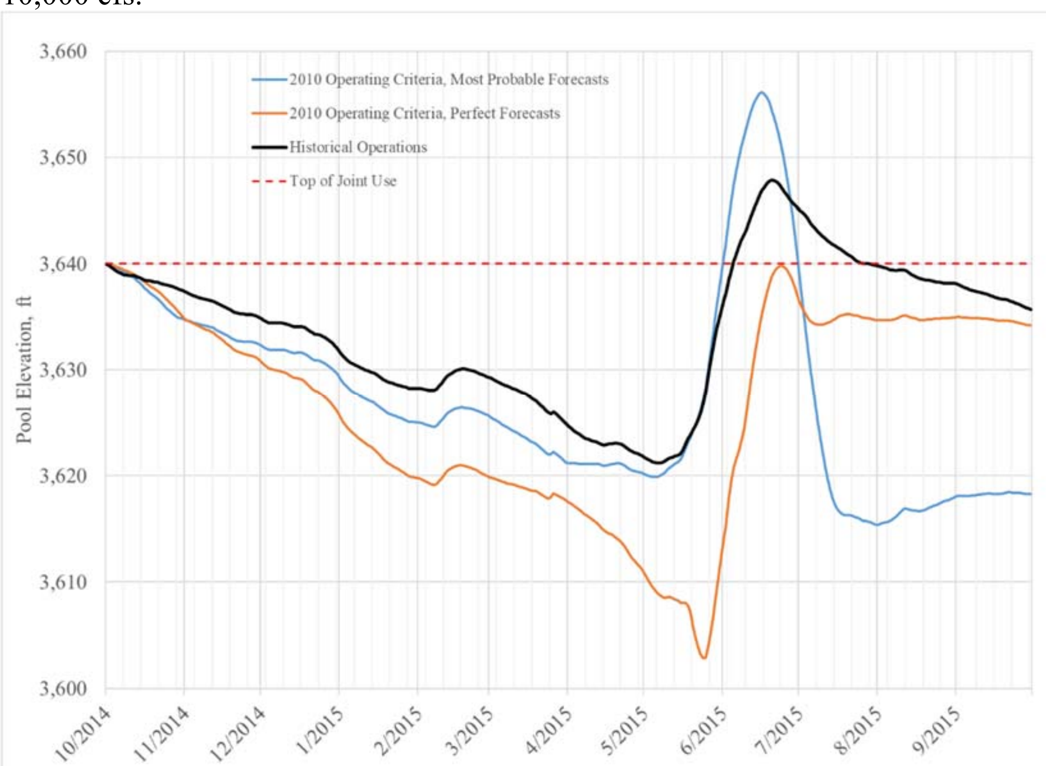

Figure 27: Water year 2015 historical and modeled pool elevations.

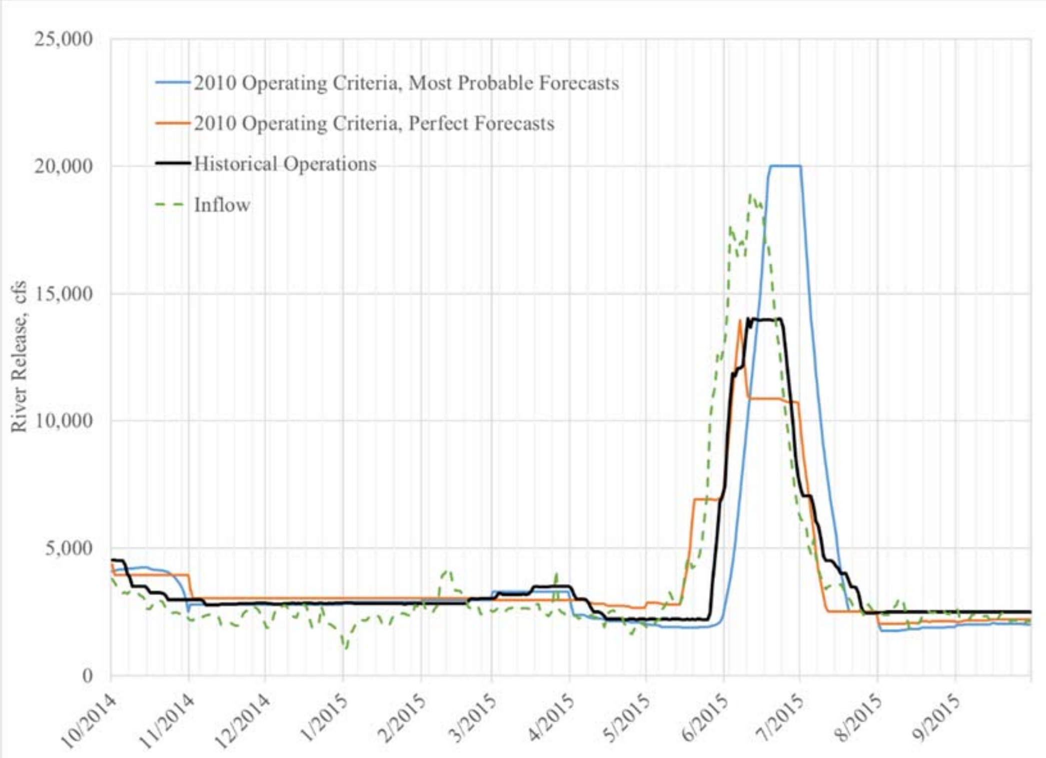

Figure 28: Water year 2015 historical and modeled river releases.

Impact of hydrology

Runoff, as described above, was greater than average and resulted in much greater than average flows. Inflows were low until mid-May, after which high inflows were sustained throughout the month of June. **Historical** river releases and modeled releases with **perfect** forecasts peaked at nearly 14,000 cfs, with flows greater than 10,000 cfs sustained under both from early June through early July. This indicates hydrologic conditions resulted in much of the flow magnitude and duration. Modeled operations with **perfect** forecasts drew the reservoir down to nearly elevation 3,600 ft., but concentrated inflow in June still required an extended period with releases greater than 10,000 cfs.

Impact of forecasting

Table 14 shows NRCS and Reclamation forecasts for water year 2015. Reclamation and NRCS forecasts were similar in magnitude for the periods forecasted, and all forecasts under-predicted inflow. April and May forecasts were particularly low, likely due to dry conditions in March and April, with declining snowpack relative to the median (Figure 29).

Table 14: Water year 2015 Reclamation most probable and NRCS median forecasts.

Date	Forecasted Period	Reclamation Forecast	NRCS Forecast (KAF; Adjusted for holdback)	Observed Inflow (KAF)
1/2015	April-July	1,095.6	1,214.6	1,542.8
2/2015	April-July	1,015.9	1,114.6	1,542.8
3/2015	April-July	1,065.5	1,194.6	1,542.8
4/2015	April-July	675.5	704.6	1,542.8
5/2015	May-July	506.8	448.0	1,415.3
6/2015	June-July	1,027.0	723.7	1,100.5

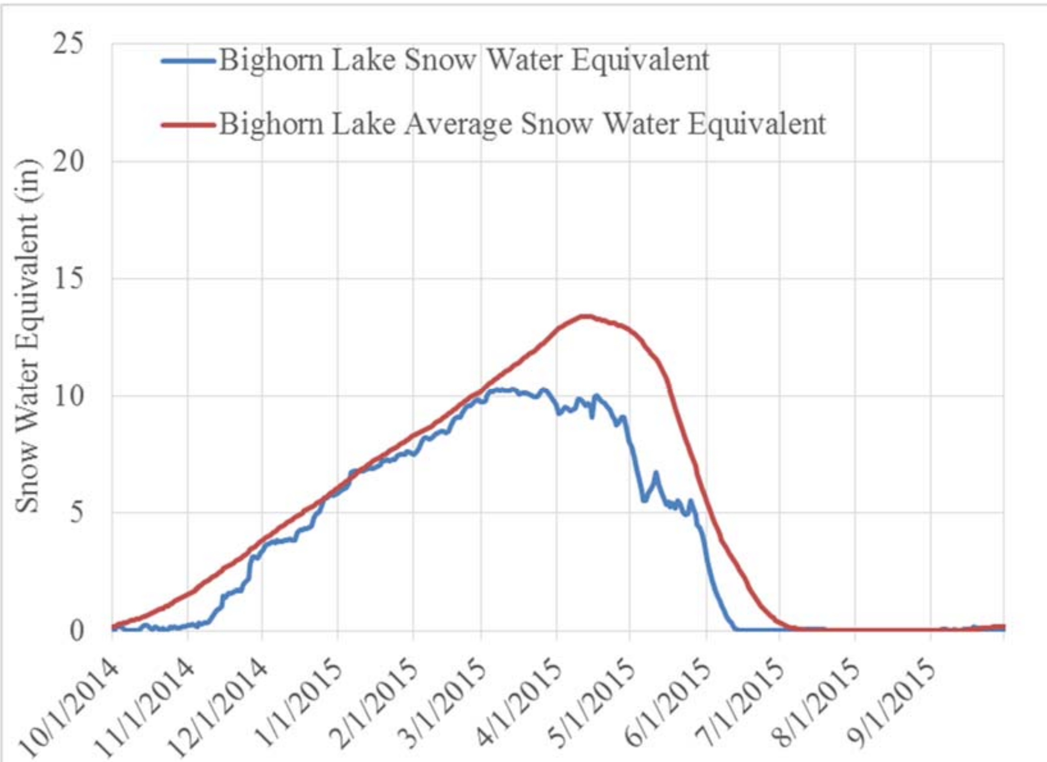

Figure 29: Water year 2015 snow water equivalent.

Forecasts in water year 2015 significantly impacted operations. Modeled operations with **perfect** forecasts show a much greater drawdown of Bighorn Lake to evacuate space for the April through July runoff of 1,542 KAF (Figure 27). Both **historical** operations and modeled operations with **most probable** forecasts do not draw down the reservoir due to forecasted inflow volume.

According to the Water Year 2015 Annual Operating Plan (Bureau of Reclamation, 2016b):

> *In the May 2015 reservoir and river operating plan, Bighorn Reservoir was expected to fill only to approximately 3630.0 feet. Inflow was coming a little lower than expected for the first half of May 2015. However, a steady weather system from the south resulted in much above average precipitation for the second half of May 2015. The mountain precipitation ended up being 157 percent of average and valley precipitation ended up being 189 percent of average in May 2015. Most of the precipitation was rainfall with little to no accumulation to the snowpack. The greatest amount of precipitation occurred above Boysen Reservoir and the Bighorn Mountains. Several release increases were made from Boysen and Buffalo Bill Reservoirs due to the precipitation and snowmelt runoff. Releases from Yellowtail Dam were increased several times in May 2015 starting on May 26, 2015. The river release was 7,000 cfs by the end of May 2015.*

Historical pool elevations entered the spring runoff season higher than modeled pool elevations. Historical pool elevations ultimately encroach on flood storage more than either of the modeled operations scenarios. Modeled operations with **perfect** forecasts show a spike in river releases. The **perfect** forecasts scenario spike is likely due to differences between assumed inflow hydrograph peak timing and actual inflow hydrograph timing. Both modeled scenarios result in rapidly declining pool elevations after filling as the inflow hydrograph declines more rapidly than the ramping rates allow river releases to be cut. Had the **perfect forecast** scenario attempted to meet the fixed rule curve timing or entered flood control space to avoid rapidly increasing river releases, it is possible the peak releases could be 3,000 cfs less than historical.

It appears that this is due to operator recognition of much higher than predicted runoff about a week before June 1, as described in the Annual Operating Plan, whereas the model's **most probable** forecast does not update until June 1. This additional week delay results in later river release increases, higher peak river releases, and greater encroachment into flood space. The release ramping rate appears to be lower for the **most probable** scenario when compared to **historical** operations, further expanding the exclusive flood control space intrusion.

Impact of operating criteria

As described above, differences between the assumed rule curve inflow timing and actual inflow hydrograph resulted in inefficiencies for the modeled scenarios. The **2010 operating criteria** rule curves were based upon an inflow hydrograph with a lower peak (12,557 cfs) than the actual inflow hydrograph (18,947 cfs). Peak inflow was also several weeks earlier than the rule curves anticipate (Figure 30). As described by (Bureau of Reclamation, 2011a), the operating criteria anticipated a peak release rate for inflow of 1,543 KAF of only 7,500 cfs. Based upon modeled operations with **perfect** forecasts, it is likely that the assumed inflow hydrograph shape causes overly optimistic estimates of the peak river release rate. A steeper inflow hydrograph requires higher release rates, as there is less time over which to average the release of the same volume of water.

Figure 30: Water year 2015 actual and expected Bighorn Lake inflow.

Impact of operators

Historical pool elevations deviated from modeled operations with **most probable** forecasts, largely due to earlier recognition of high inflows in May. Operators ramped up releases quickly when recognizing heavy May precipitation.

Historically, operators did go into the flood space by about 7.8 feet while limiting river releases to around 14,000 cfs. This does seem to deviate from the operating criteria in that exclusive flood control space is utilized prior to exceeding safe channel capacity. However, these release decisions were closely coordinated with USACE (U.S. Army Corps of Engineers, 2018), as Bighorn Lake encroached on the flood pool space.

Water Year 2016 Operations

April through July runoff totaled 1,032 KAF, or slightly below the median inflow. **Historical** operations and the two **modeled** scenarios had similar pool elevations but widely differing river release patterns, as shown in Figure 31. While the April through July inflow was nearly 50 percent greater than the minimum fill volume, Bighorn Lake did not fill under any of the scenarios.

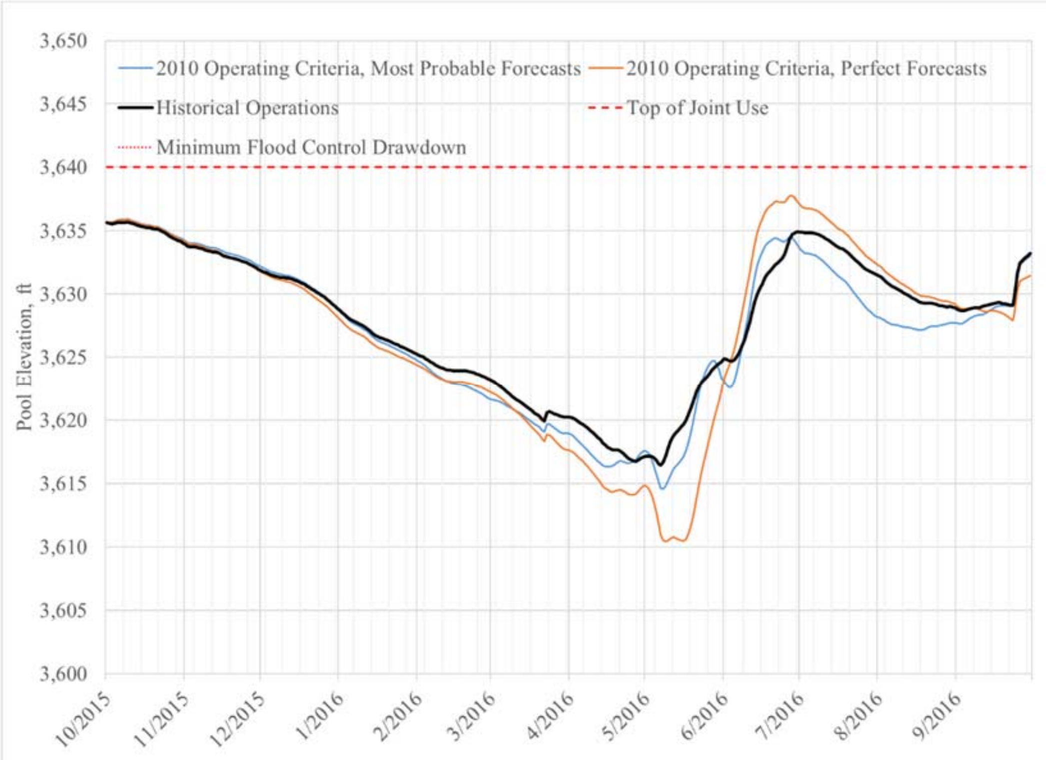

Figure 31: Water year 2016 historical and modeled pool elevations.

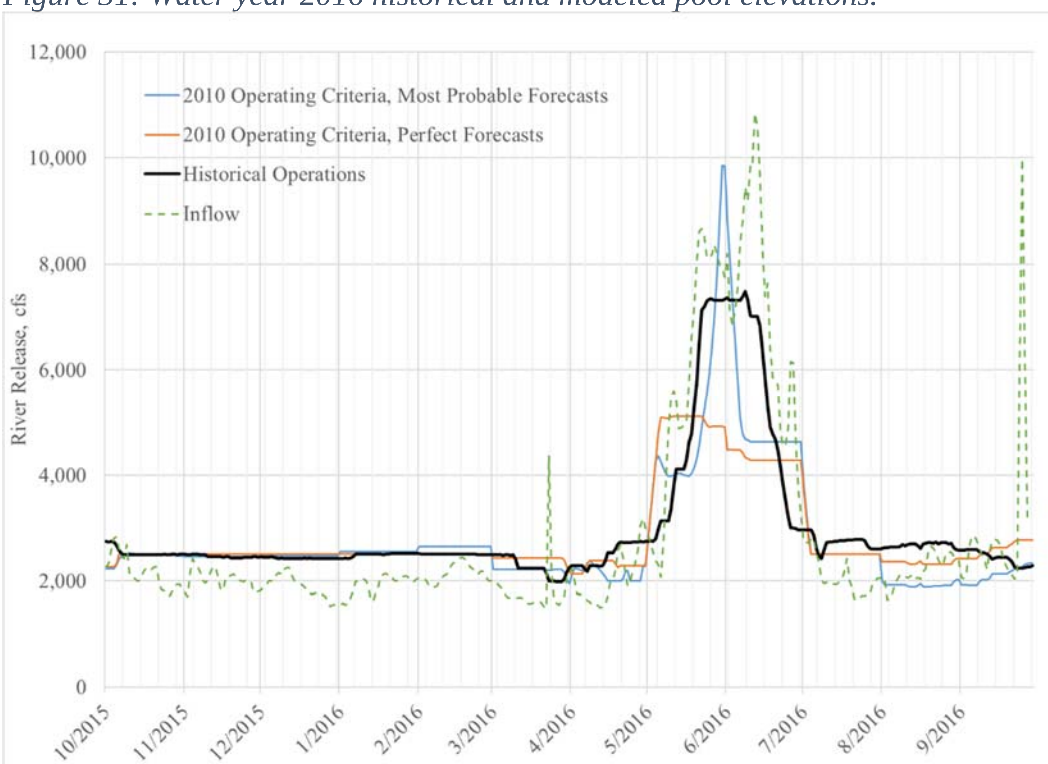

Figure 32: Water year 2016 historical and modeled river releases.

Impact of hydrology

As hydrologic conditions were not extreme, hydrology did not impact river releases or pool elevations significantly. April through July runoff was near average and there were not significant unexpected runoff events in the fall, winter, or spring.

Impact of forecasting

As shown in Table 15, forecasts from January through March were below the minimum fill level, meaning releases should have targeted a pool elevation of 3,617.0 ft. on March 31. Releases under the perfect forecast scenario target the April 30 rule curve, which results in a March 31 elevation of 3,617.65 ft. The **most probable** forecast scenario resulted in a pool elevation of 3,616 ft. on March 31. Forecasts were likely low due to lower-than-median snowpack followed by heavy April and May precipitation (Figure 33).

Table 15: Water year 2016 Reclamation most probable and NRCS median forecasts.

Date	Forecasted Period	Reclamation Forecast (KAF)	NRCS Forecast (KAF; Adjusted for holdback)	Observed Inflow (KAF)
1/2016	April-July	711	765	1,032
2/2016	April-July	596	615	1,032
3/2016	April-July	626	765	1,032
4/2016	April-July	873	1,145	1,032
5/2016	May-July	933	1,164	910
6/2016	June-July	608	986	552

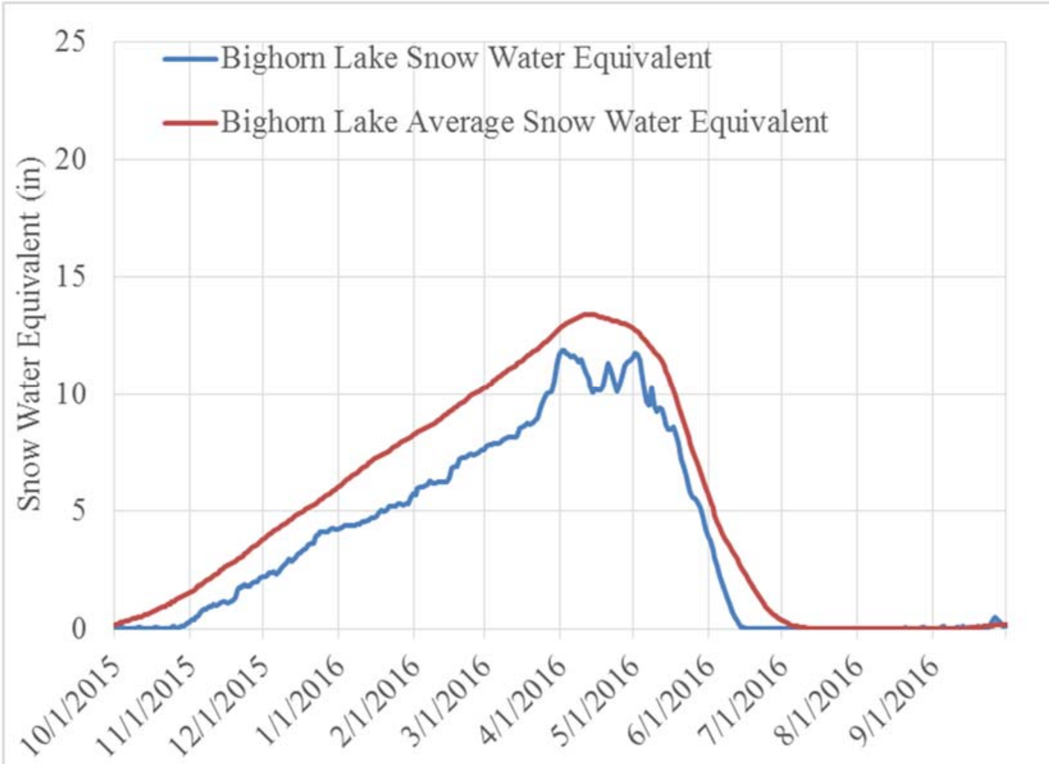

Figure 33: Water year 2016 snow water equivalent.

Modeled operations with **most probable** forecasts resulted in pool elevations similar to the **perfect** forecast scenario through the end of April. May under-forecasting resulted in lower peak releases early in the month and a significant release increase when the model attempted to meet the end of May pool elevation target. Forecasting therefore impacted peak release rates, although the magnitude under modeled operations with **most probable** forecasts is likely high due to model assumptions of a hard end-of-month target. **Historical** operations also show river release increases due to under-forecasting.

Impact of operating criteria

While the April through July inflow volume was greater than the minimum fill volume, the assumed inflow hydrograph used to shape the rule curves did not match the actual inflow hydrograph (Figure 34). This most likely resulted in Bighorn Lake not filling and higher releases than expected under the operating criteria. However, river releases did not have a significant peak and the deficit from the top of joint use pool at peak was not substantial.

Figure 34: Assumed and actual Bighorn Lake inflow hydrograph for Water year 2016.

Modeled operations with **perfect** forecasts were defined by the targeted elevations within the rule curve. First, the model targeted the mid-May maximum rule curve drawdown. Because early May inflows were much greater than the rule curve anticipated flows shown in Figure 34, releases ramped up after hitting the end of April target to hit the minimum rule curve elevation. Subsequently the model targeted the end of May and end of June rule curve elevations. However, the inflow hydrograph used to develop rule curves expected a significantly greater portion of the April through July inflow in July than actually arrived. Ramping rates, or the maximum change in release rate, prevented the model from cutting July flows quickly enough to fill the reservoir.

As described above, the operating criteria also allowed operational flexibility due to forecasts below the minimum fill threshold. Operators utilized this flexibility to reduce releases and conserve storage, which resulted in higher spring pool elevations. The exact difference in peak river releases is not clear due to the model's lack of intra-monthly forecasts and guidance on low-flow periods. Likely **historical** higher river releases were due to higher pool elevations when snowmelt began, combined with uncertainty of runoff volume during daily flood control operations. In particular, the June 1 **most probable** forecast was 278 KAF higher than inflow. Operators released water in anticipation of higher inflow volumes and then were unable to fill due to the inflow shortfall.

Impact of operators

Historically, forecasts below the minimum fill runoff volume in March allowed operators flexibility to adjust flows. Accordingly, Reclamation reduced flows to 2,000 cfs in reaction to a warm, dry March (Reclamation, 2017). Pool elevations were therefore much higher than the **most probable** forecast scenario and resulted and in an April 1 pool elevation of 3,620.24 ft. Higher pool elevations in May subsequently caused higher peak releases than the perfect forecast scenario.

Water Year 2017 Operations

Water year 2017 was defined by the highest April through July inflows on record, with 2,953 KAF flowing into Bighorn Lake. Releases for all scenarios analyzed peaked at around 14,000 cfs and river releases were greater than 6,000 cfs for all from March through July. Wide variations in pool elevations exist between the modeled scenarios, however modeled perfect forecast scenario draws the reservoir down to the minimum flood control drawdown elevation by mid-May and maintains low pool elevations through the beginning of June. **Most probable** forecast modeled operations draws the reservoir down to nearly the minimum flood control drawdown elevation, but not until mid-May.

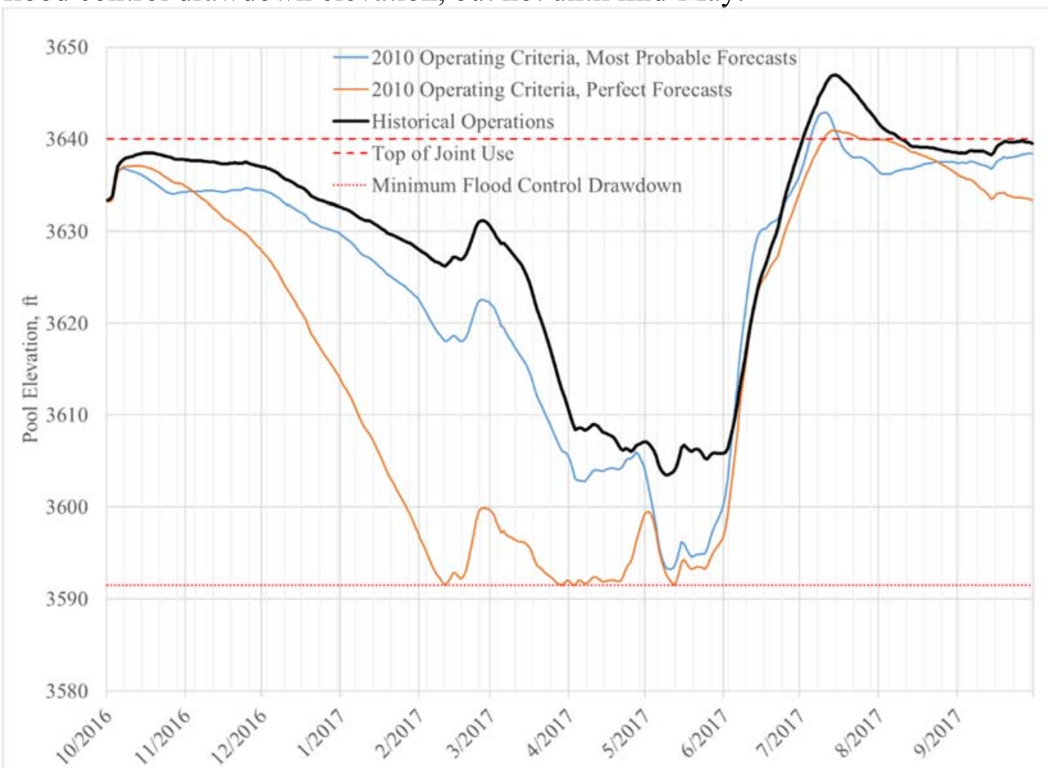

Figure 35: Water year 2017 historical and modeled pool elevations.

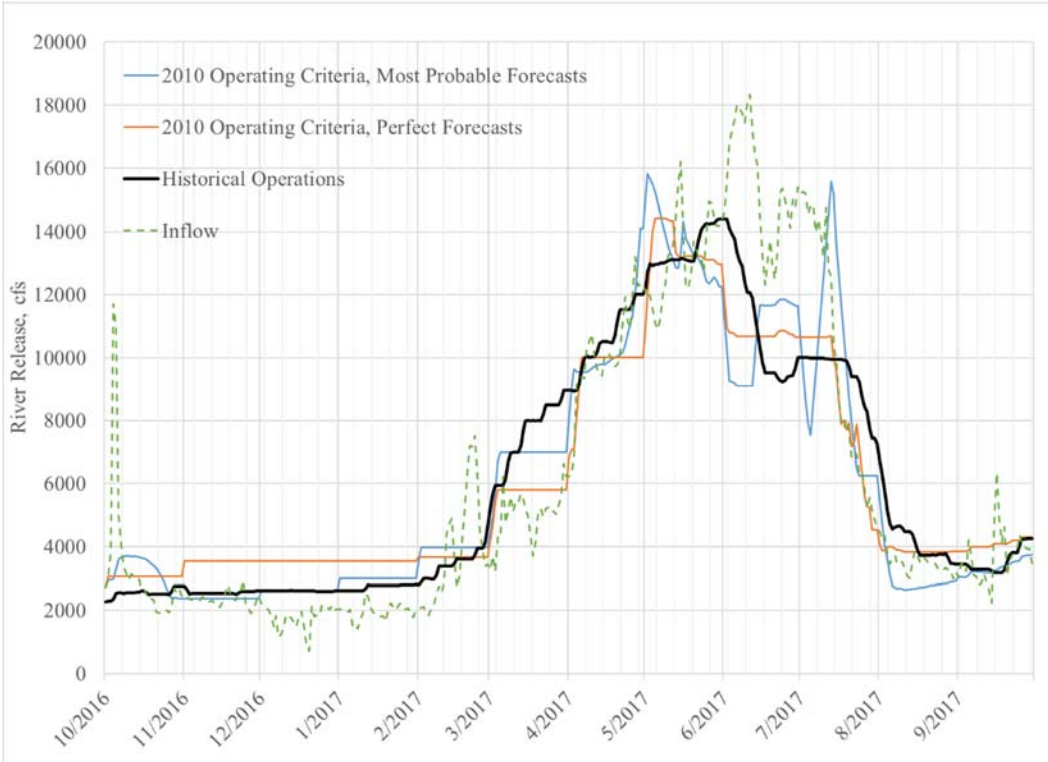

Figure 36: Water year 2017 historical and modeled river releases.

Impact of hydrology

As Bighorn Lake inflows were the highest on record, hydrology clearly impacted operations. Based on the modeled scenarios, months-long releases greater than 10,000 cfs were unavoidable. Runoff timing and magnitude was also important. While the flows were significantly higher than average, the volume arrived at Bighorn Lake for an extended period. This may have prevented much higher river releases and shows the impact of operations in Boysen and Buffalo Bill Reservoirs which assisted in controlling the rate of fill in Bighorn Lake.

Impact of forecasting

Forecasts developed on January 1 and February 1 were more than 1,000 KAF below the ultimate April through July runoff of 2,953 KAF. The **perfect** forecast scenario set winter releases high, primarily due to advance knowledge of high February and March inflows. The **perfect** forecast scenario draws down Bighorn Lake to the minimum flood control drawdown elevation by mid-February as the high February and March inflows would bring the pool up to elevation 3,617 ft. by the end of March. This resulted in much higher pool elevations for the most probable forecast compared to perfect forecasts from November through June.

Table 16: Water year 2017 Reclamation most probable and NRCS median forecasts.

Date	Forecasted Period	Reclamation Forecast (KAF)	NRCS Forecast (KAF; Adjusted for holdback)	Observed Inflow (KAF)
1/2017	April-July	1,384	1,545	2,953
2/2017	April-July	1,654	1,775	2,953
3/2017	April-July	2,099	2,355	2,953
4/2017	April-July	2,232	2,675	2,953
5/2017	May-July	2,454	2,451	2,350
6/2017	June-July	1,084	1,658	1,537

As shown below in Figure 37, basin snowpack steadily increased away from the mean snow water equivalent trendline as the accumulation season progressed. Forecasts increased with the increasing snowpack, predicting far above average inflows (Table 16).

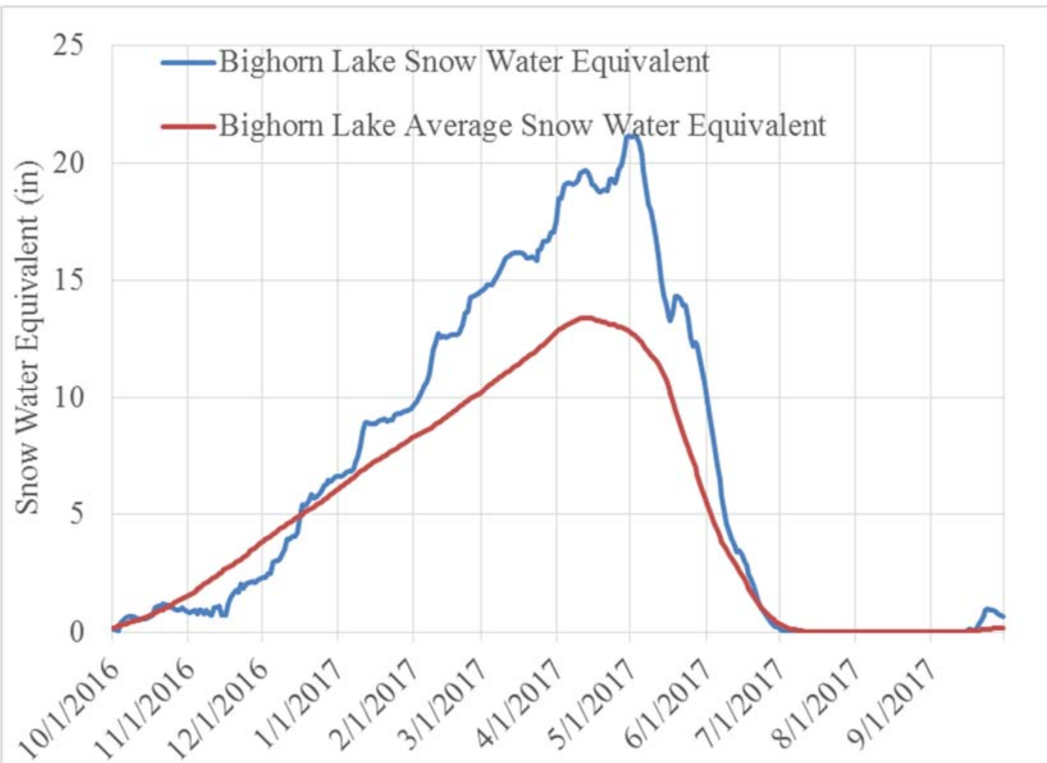

Figure 37: Water year 2017 snow water equivalent

Ultimately, forecasting impacted pool elevations, with higher pool elevations in the modeled scenario with **most probable** forecasts compared to modeled operations with **perfect** forecasts. However, the impact of forecasting seems to be considerably smaller on river releases and pool elevations than does hydrology for water year 2017. This is likely because the inflow volume was far greater than the volume of flood control space available to control inflows.

Impact of operating criteria

The operating criteria limited drawdown in the active conservation pool to elevation 3,591.5 ft. for the **perfect forecast** scenario. The 2012 update to the **2010 operating criteria** developed a new maximum rule curve which reduced minimum drawdown from elevation 3,603 ft. to elevation 3,591.5 ft. (Reclamation, 2012). The minimum drawdown elevation was based on the prior historical record inflow volume, observed in 2011. The operating criteria's arbitrary minimum drawdown elevation based on historical maximum inflow, rather than anticipating higher inflow volumes and preparing associated rule curves, may have impacted operations.

Impact of operators

Based on comparisons between modeled operations with **most probable** forecasts and **historical** operations, it appears that operators deviated somewhat from operating criteria in January and February. However, both ice conditions in the Yellowstone River and limited turbine release capacity due to generator rewinds, combined with pool elevations below the spillway gate elevation, limited the release rate and drawdown in Bighorn Lake. Modeled scenarios did not represent the limited turbine release capacity and did not encounter any physical release rate limitation.

Modeled operations with **most probable** forecasts increased river releases in April and May in response to high inflow forecasts. The deviation in pool elevations between **historical** operations and modeled operations with **most probable** forecasts is likely the physical limitations experienced in May. As described within the impacts from forecasting section, the impact due to operational decisions was dwarfed by hydrologic conditions. This is apparent from the similar magnitude of releases for all three scenarios.

Water Year 2018 Operations

Water year 2018 inflows were again much greater than average and would have been greater than the record when the **2010 operating criteria** were developed. Late spring and early summer precipitation was a large driver of the high inflow volumes. Because operations were heavily impacted by USACE Missouri Basin flood control orders, from May 23 through July 3, operations were represented using both model calculated releases and USACE releases for this period.

Water year 2018 operations started with much higher pool elevations due to hydrologic conditions in 2017. An October 2017 inflow event kept pool elevations high for historical operations, whereas both modeled scenarios increased releases to meet the end of October target. Winter flows were higher for **perfect** forecast scenario than the **most probable** forecast modeled scenario and **historical** operations. Interestingly, the **perfect** forecast scenario reduced releases in February and March when the model began targeting the end of April rule curve due to the high inflow forecasts.

Historically, operators began ramping up releases in February and March to recover from high pool elevations. Inflows increased greatly in April and May, and storage troughed two weeks before the low point in the rule curves.

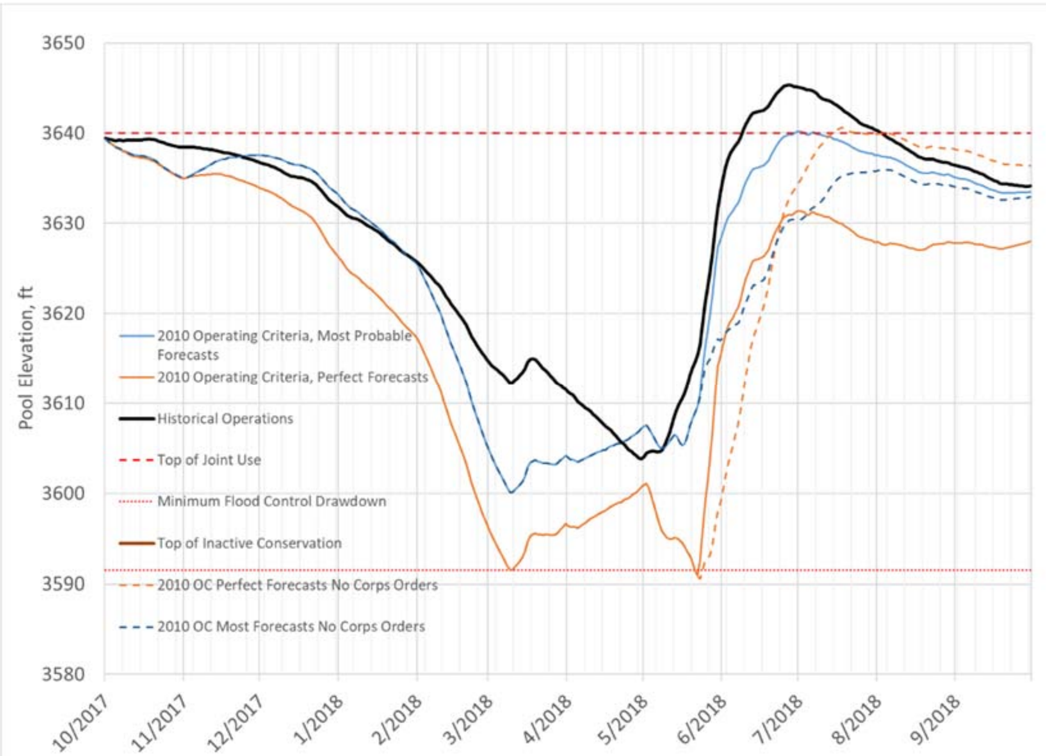

Figure 38: Water year 2018 Bighorn Lake pool elevations.

Peak river releases for all scenarios exceeded 12,000 cfs. Modeled operations under all scenarios resulted in more than a month of flows greater than 10,000 cfs, with **historical** operations having the shortest period greater than 10,000 cfs (Table 17). All scenarios had greater than three months exceeding 6,000 cfs releases. Only **historical** operations utilized the exclusive flood control pool. Timing of the assumed rule curve inflow was once again an issue, as the **most probable** and **perfect** forecast scenarios without USACE orders drew the reservoir down greatly to meet end of May targets but could not cut releases quickly enough due to ramping restrictions to fill.

Table 17: Summary of selected river release statistics for water year 2018.

	Days with river release:			
	>=6,000 cfs	>=8,000 cfs	>=10,000 cfs	Peak release (cfs)
2010 OC Most Probable Forecasts	98	63	41	14,735
2010 OC Perfect Forecasts	96	62	45	12,131
2010 OC Most Probable Forecasts, No Corps Orders	97	64	39	14,751
2010 OC Perfect Forecasts, No Corps Orders	96	62	45	12,318
Historical	113	39	31	14,197

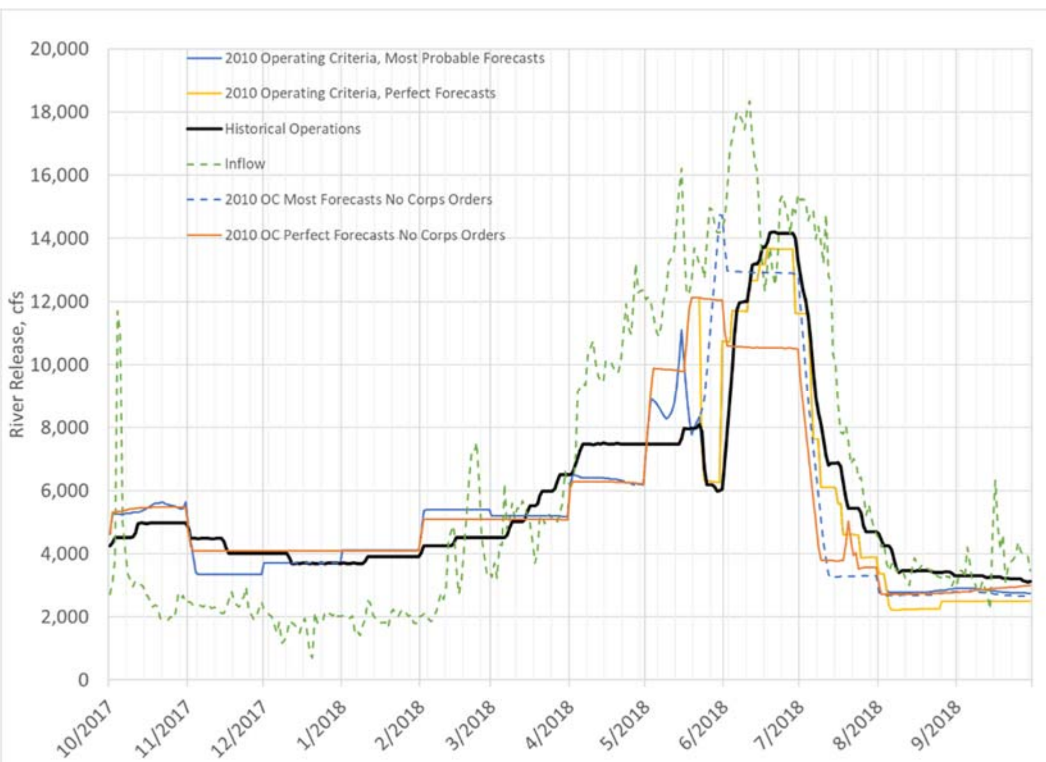

Figure 39: Water year 2018 Bighorn Lake river releases.

Impact of hydrology

Reservoir operations were impacted by prior year high inflows through the end of September as well as an October runoff event. High April through July runoff volume resulted in high releases for all scenarios. Inflow was defined by a longer period of high inflows. This results in an extended period of high modeled river releases. The **2010 operating criteria** anticipated peak river releases of 12,000 cfs for 58 days for an April through July runoff volume of 2,300 KAF. All scenarios examined resulted in fewer than 58 days over 10,000 cfs.

Impact of forecasting

Table 18 shows both Reclamation most probable and NRCS median forecasts for water year 2018.

Table 18: Water year 2018 Reclamation most probable and NRCS median forecasts.

Date	Forecasted Period	Reclamation Forecast (KAF)	Est. NRCS Forecast (KAF; Adjusted for holdback)	Est. Observed Inflow (KAF)
1/2018	April-July	1,669	1,652	2,318
2/2018	April-July	1,772	1,482	2,318
3/2018	April-July	1,841	1,552	2,318
4/2018	April-July	1,865	1,562	2,318
5/2018	May-July	1,349	1,129	1,927
6/2018	June-July	1,126	972	1,270

While forecasts predicted above-average inflows, both NRCS and Reclamation forecasts under-predicted runoff. The basin had average snow water equivalent (Figure 40) throughout the water year. Spring and early summer precipitation also resulted in high runoff and increasing SWE in April.

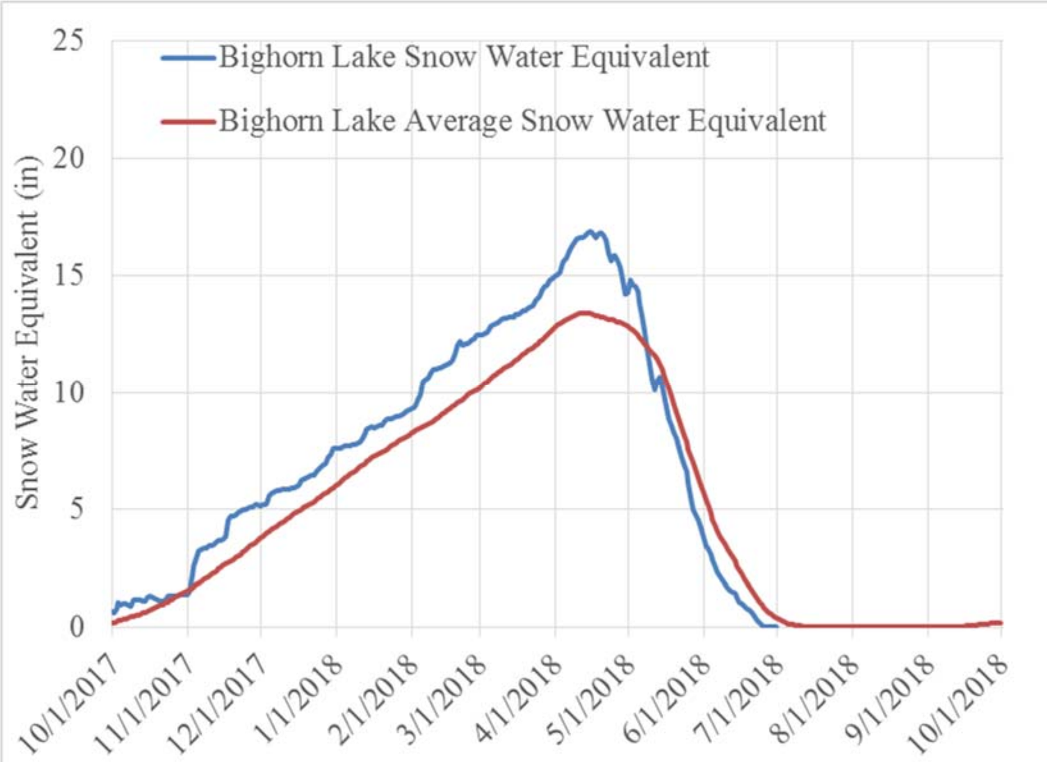

Figure 40: Water year 2018 snow water equivalent.

Impact of operating criteria

Modeled operations with **perfect** forecasts resulted in relatively low peak river releases (when compared to similar high inflow water years and operating criteria expectations) for an extended period.

Impact of operators

Operators appear to have maintained higher releases than expected by the modeled **most probable** forecast scenario in April and May. This ended on May 23 when USACE flood control orders required release reductions for flooding on the Yellowstone River (U.S. Army Corps of Engineers, 2018). This potentially mitigated under-forecasting, as shown by differences in peak releases between modeled operations with **most probable** forecasts and **historical** operations.

Impacts of Monthly Timestep Models

Reclamation currently uses two methods to perform operational calculations. Monthly and annual plans are based on monthly timestep calculations using the Reservoir Operations Modeling System (ROMS) access database programs. As runoff begins, operators also use daily timestep spreadsheet operations models during snowmelt runoff in spring and summer. The ROMS model uses mean monthly average forecasted inflows and outflows. Monthly averages can obscure the impacts of both timing and magnitude of peak flows, and operational decisions would be different using daily calculations rather than monthly calculations.

Two scenarios were developed to determine the relative impact of using monthly timestep operations models. One scenario used the RiverWare model with historical, daily inflows to Bighorn Lake and perfect forecasts **("daily average")**. The second scenario used the same model with the mean monthly inflows for each day of the month, also with perfect forecasts (**"monthly average"**). Calculations were performed daily for both scenarios; however, because the **monthly average** scenario used the same inflow for each day in the month, operational decisions were effectively made monthly with the exception of targeting the minimum rule curve elevation in mid-May and the peak pool elevation in July.

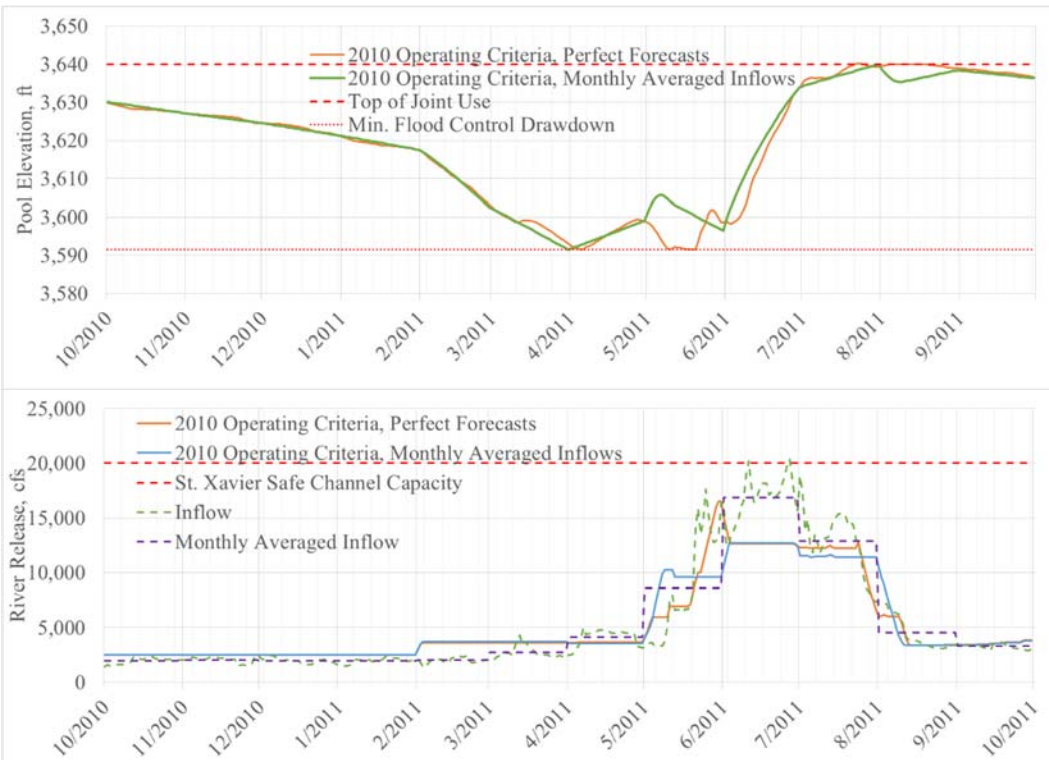

Figure 41: Modeled operations for water year 2011 with daily inflows and monthly averaged inflows.

Figure 41 shows water year 2011 modeled **daily** and **monthly** average operations without representing USACE system flood control requirements. Releases are identical and pool elevations are very similar for the period from October through April during the period when release decisions within the model are made on a monthly timestep. Starting in May, release decisions increase in frequency as the model targets the minimum rule curve drawdown elevation in mid-May. At this point, the two modeled releases diverge, as do pool elevations. Because inflows immediately step up to the May monthly average, releases increase under the **monthly** average scenario. Releases increase less rapidly to meet the minimum drawdown elevation for the daily inflow scenario. However, modeled operations under the **daily average** scenario increase rapidly to a peak river release of 16,876 cfs to meet the end of May target, whereas the **monthly average** scenario does not require a significant release increase to meet the target.

The water year 2011 case study shows issues associated with **monthly average** modeling. Monthly averaging of inflows ignores the timing and peak magnitude of releases and simplifies reservoir operations. However, releases frequently change mid-month. Ultimately, this can result in underestimation of peak releases within monthly plans, particularly in peak runoff months. Because the 2010 operating criteria were developed using the monthly timestep ROMS model, it is also possible that peak releases described in (Bureau of Reclamation, 2011a) were underestimated due to modeling timestep.

It should be noted that MTAO performs actual operations during snowmelt runoff season using a daily spreadsheet model and these errors will not apply to periods in which Reclamation makes operational decisions on a daily and sub-daily time step.

Sample Model Applications

Three alternative operating scenarios for Yellowtail Dam were initially examined for potential improvements to the **2010 operating criteria**. Four additional scenarios were recommended by the Technical Working Group following initial report review and were also represented with RiverWare.

Scenarios were run using the period 1990 through 2017. This period was selected as it includes both a severe drought period (2000-2004) and an extremely wet period (2010-2017). Monthly historical most probable forecasts were also available for this period, allowing for the analysis of scenarios using imperfect forecasts. First, daily averages for both pool elevations and river flows are discussed, followed by analysis of scenario behavior during exceptionally dry years and during exceptionally wet years.

Elevated End of May Target Scenario

Scenario Description

The first scenario, based on recommendations by Mr. Loren Smith of the Wyoming State Engineer's Office (Smith, 2018), adjusts the **2010 operating criteria** rule curves to ensure that the reservoir elevation is at or above 3,620 ft. by May 31st and fills gradually to the top of joint use by July 31st. At a reservoir elevation below or equal to 3,617 ft., the marina at Horseshoe Bend becomes unusable for boaters (Bureau of Reclamation, 2012c). The goal of this scenario is to ensure lake recreational access by Memorial Day weekend. This scenario will be hereafter referred to as the **elevated end of May target**. Figure 42 shows modified rule curves defining this scenario.

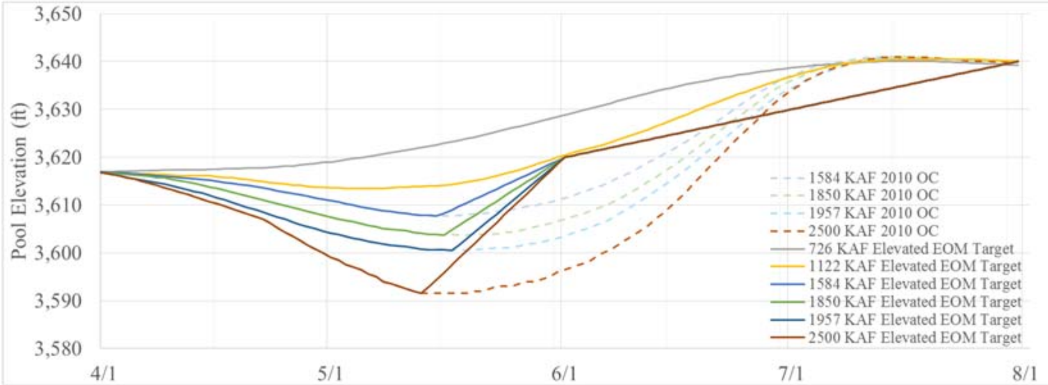

Figure 42: Adjusted rule curves for the elevated end of May scenario. Solid lines indicate the operating criteria adjusted for a pool elevation of 3,620 ft. by May 31st. Dashed lines show the current 2010 operating criteria rule curves.

Scenario Results

The **elevated end of May target** scenario begins filling earlier than the other cases. As expected, this provides earlier access to lake recreationists in years with higher inflows. It also results, on average, in lower summer pool elevations due to the mismatch between inflow timing and filling. This scenario fills too early and requires high releases in response to peak inflows (Figure 43). Downward ramping rate restrictions then result in greater releases following the peak inflow, and the reservoir is drawn down before releases can be reduced to an appropriate post-peak rate. Figure 43 shows the **elevated end of May target** scenario results in much higher peak release rates.

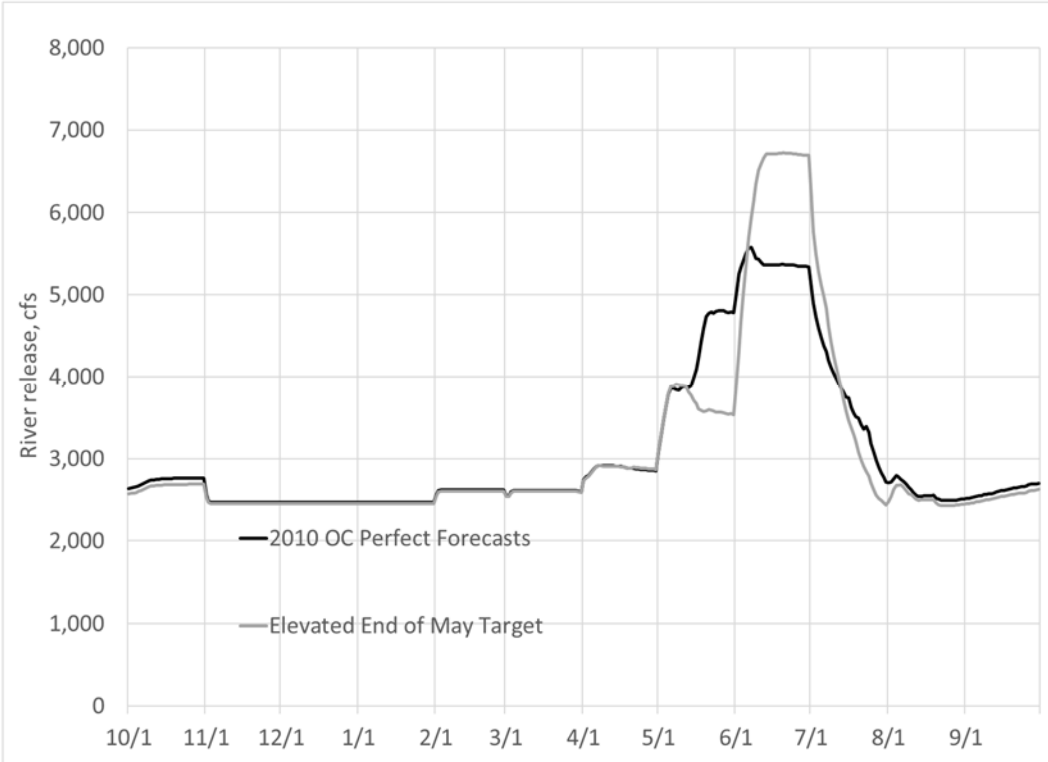

Figure 43: Mean daily river release for baseline and elevated end of May scenario.

The higher releases and subsequent lower pool elevations when starting a dry period ultimately can result in lower summer pool elevations, as shown in the period from 2009 through 2010. There is longer Horseshoe Bend Marina accessibility under the **elevated end of May target** scenario than the **2010 operating criteria** but with much higher river releases. Likewise, should two drought years occur in sequence, the second year could observe reduced recreational access due to lower starting elevations.

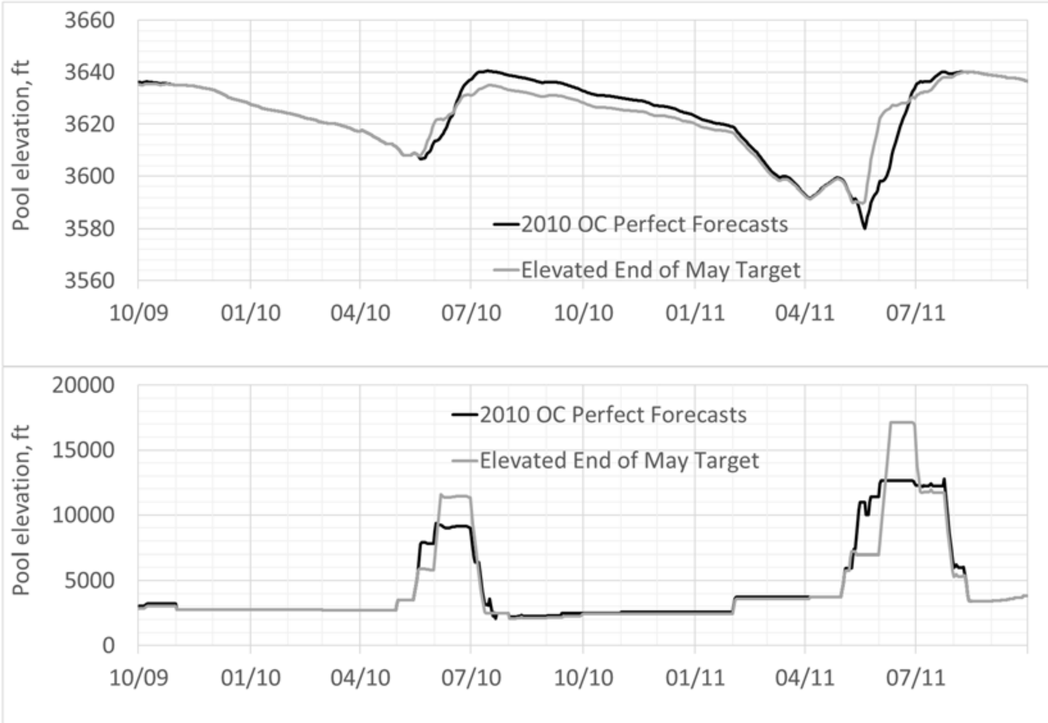

Figure 44: Pool elevations and river releases for the period water year 2010-2011 for 2010 operating criteria and elevated end of May target scenarios with perfect forecasts.

Lowered End of March Target Scenario

Scenario Description

The second scenario adjusts the March 31st target elevation used to set winter release rates from 3,617 ft. to 3,605 ft. The scenario will examine impacts of entering the April through July runoff period at a lower pool elevation. Rule curves are not modified in this scenario. Because releases are set to target the April 30 rule curve elevation beginning March 1 (or February 1 in high runoff volume years), the existing rule curves can be maintained without alteration. In essence, the first elevation of importance is the April 30 rule curve elevation and the April 1 rule curve elevation does not impact operations. This is further demonstrated in Appendix B.

Scenario Results

The mean daily **lowered end of March target** scenario pool elevation is lower than the **2010 operating criteria** scenario for all months of the year (Figure 45). The **lowered end of March target** scenario does not fill to the top of joint use pool on average, which could result in reduced river releases during dry periods. Periods of water shortage would likely hurt lake and river recreation as well as hydropower production.

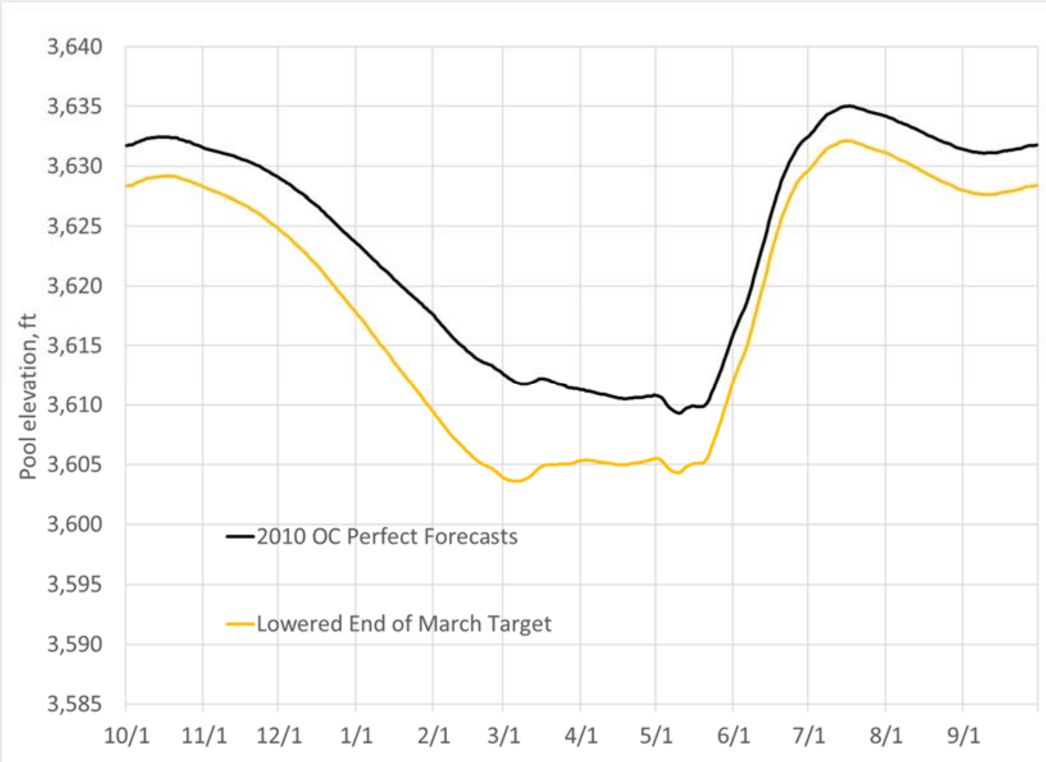

Figure 45: Mean daily pool elevations for baseline and lowered end of March scenario.

Interestingly, the **lowered end of March target** scenario does not result in lower peak releases when compared to the **2010 operating criteria** when modeled with perfect forecasts, as shown in Figure 46. The 2010 operating criteria starts at a higher elevation, but there is adequate time from March 1 through the peak runoff to draw the reservoir down in anticipation of higher flows.

Figure 46: River release for lowered end of March target and 2010 operating criteria for the period 2010-2017.

While the **lowered end of March target** scenario might perform better when analyzed with the historically under-forecast most probable plans (not shown), the reduced pool elevations would appear to have significant impact to lake recreation and hydropower head.

Increased Drawdown Scenario

Scenario Description

The third scenario examines the impact of increasing the minimum drawdown during the April through July runoff period. This scenario was developed based on recommendations by Ms. Anne Marie Emery (Emery, 2018) of the Bighorn River Alliance, changes the rule curves for the five highest April through July forecast volumes to allow for greater drawdown in the spring in anticipation of snowmelt runoff. Minimum drawdown under the current maximum rule curve, corresponding to 2,500 KAF April through July runoff, was reduced from elevation 3,591.5 ft. to elevation 3,580 ft. The scenario also adds a rule curve for a forecast inflow of 3,000 KAF. The 3,000 KAF rule curve reduces the minimum flood control drawdown from 3,591.5 ft. to 3,574.5 ft. Scenario rule curves appear in Figure 47.

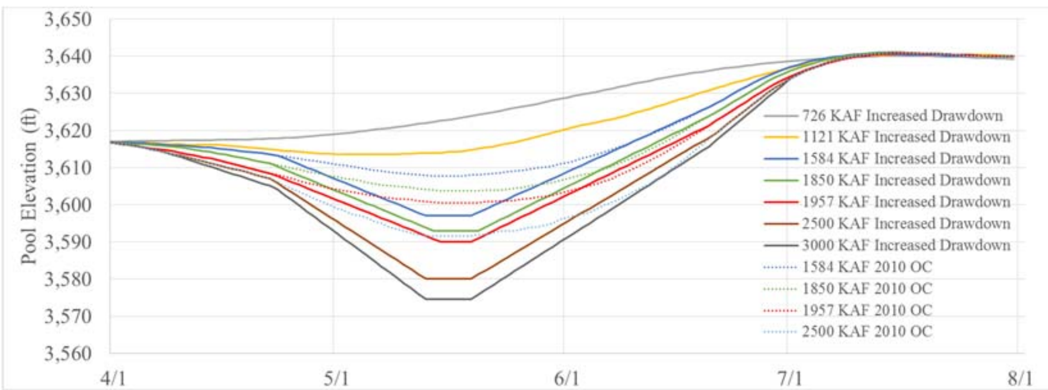

Figure 47: Solid lines indicate the rule curves for the Increased Drawdown scenario. Dashed lines show the current 2010 operating criteria rule curves. A 3,000 KAF case was created and added to the operating criteria.

Whereas existing rule curves were developed through an extensive process, the curves represented in this scenario were arbitrarily selected to represent a much greater drawdown for reconnaissance investigation of the impacts on lake levels and river releases. The Increased Drawdown rule curves are linear rather than the curved 2010 operating criteria rule curves due to the model’s frequency of targeting the rule curves. Because the model targets the end of month rule curve elevations and minimum and maximum rule curves, intermediate values do not impact operations. This is shown in Appendix B.

Scenario Results

The increased drawdown scenario was designed to reduce peak releases in high water years. Water year 2017 was the record April through July inflow volume and serves a good example year to test the effectiveness of this rule.

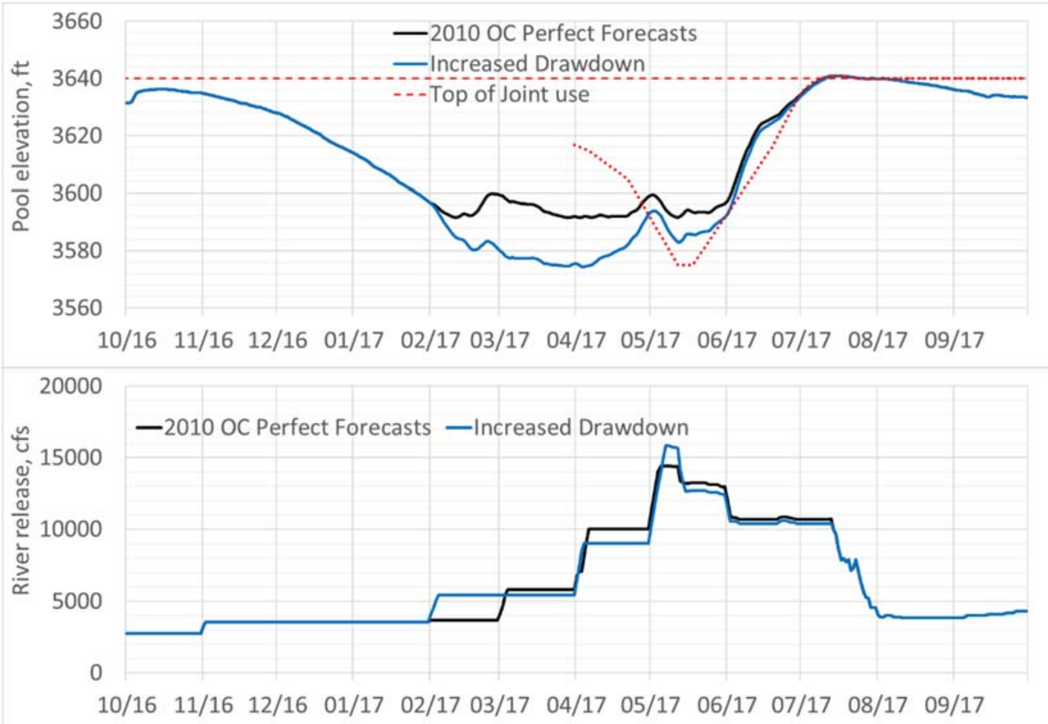

Figure 48: Water year 2017 modeled operations with 2010 operating criteria and increased drawdown scenarios.

Figure 48 shows operations for the **2010 operating criteria** and **increased drawdown** scenarios. **Increased drawdown** modeled operations have much greater releases in February targeting a lower end of April pool elevation than the **2010 operating criteria**. The April 30 target, however, results in lower April releases for the **increased drawdown** scenario. The **increased drawdown** scenario subsequently is limited by physical outlet capacity. The model attempts to meet the lower drawdown elevation in mid-May, but the calculated release to meet this target, while less than safe channel capacity, is greater than the dam's ability to convey the water due to low pool elevations. The peak release rate is also greater than that of the **2010 operating criteria**. This could potentially be mitigated by not targeting the end-of-April drawdown. However, the shape of the rule curve is intended to draw down the reservoir in April. By releasing a much higher volume in February, as in the **increased drawdown** scenario, operators would risk long-lasting impacts to water supply should conditions turn dry and the forecast was greater than the ultimate runoff.

Raise Top of Joint Use Pool Five Feet Scenario

Scenario Description

This scenario would serve to reallocate the bottom five feet (elevation 3,640-3,645 ft.) from exclusive flood control to the joint use pool. Reallocation would allow these five feet to be used for both conservation and flood control, rather than exclusively for flood control. USACE, which has sole responsibility over the exclusive flood control pool, examined this concept in the Yellowtail Dam Reallocation Study ((U.S. Army Corps of Engineers, 2010). The study investigated impacts to flood control due to reallocation but provided no recommendations. The study noted the following potential concerns:

> *The event based simulations were evaluated only by studying the reservoir elevation and outflow data. There were several issues that will need to be reviewed in relation to operations as a result of the reallocation. These items are listed here:*
>
> *1. For the inflow design flood, the reallocated condition reaches a peak pool elevation that is only 1.1 ft from the top of Yellowtail Dam.*
>
> *2. For the project design flood, the reservoir outflow is 1,150 cfs over the capacity of the Yellowtail Afterbay dam.*
>
> *3. For the 1923 event, the reservoir outflow is 8,050 cfs over the capacity of the Yellowtail Afterbay dam.*

It should be noted that under its Congressional authorization, Reclamation does not have the ability to reallocate exclusive flood control space to joint use space. It would require Congressional authorization to modify the flood control storage allocation which is explicitly defined in the 1962 Definite Plan Report revised in 1965 (Bureau of Reclamation, 1965).

This scenario was represented by shifting the rule curves uniformly up by five feet, raising the top of joint use pool by five feet, and increasing the end of October target elevation from 3,635 to 3,640 ft. The minimum flood control drawdown elevation was raised by five feet to 3,596.5 ft.

Scenario Results

Using perfect forecasts, modeled river releases while **raising the top of joint use pool** result in desirable impacts for both lake recreation (higher mean pools, not shown), lower peak releases on average, and higher releases in late summer and early fall.

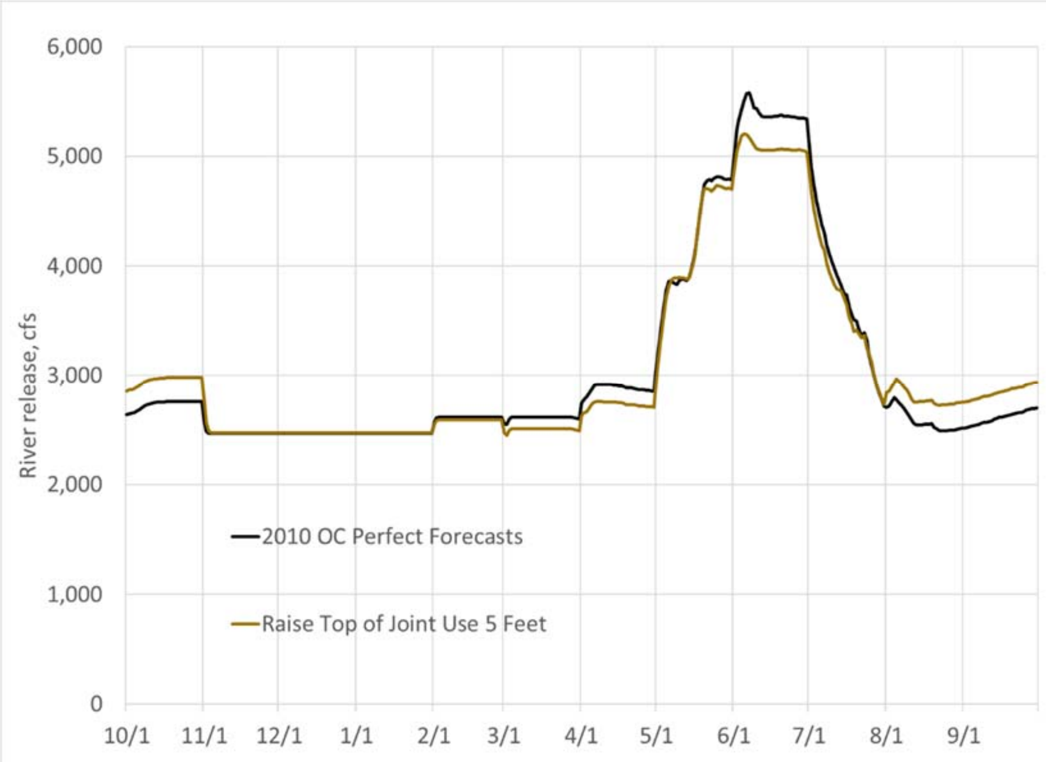

Figure 49: Mean daily river releases for baseline and increased top of joint use scenarios.

Increased pool elevations are a direct result of raising the rule curves by five feet, whereas the increased late summer releases are due to maintaining the existing end of October target. On average, this water comes from lower releases in April due to higher end of April targets, and lower releases in May and June.

The enhanced performance under the **raised top of joint use pool** scenario comes at a price that due to under-forecasting of inflows. This can be best represented by operations in 2015 when both Reclamation and NRCS forecasts were low by more than 900 KAF as late as May 1 (Table 14). As discussed previously, the modeled pool elevations using most probable forecasts reached elevation 3,656.2 ft., just below the top of exclusive flood pool and river releases reached the local flood control safe channel capacity. Reducing storage available for flood control could potentially have damaging effects. In this case, **raising the top of joint use pool** extended the period during which the river releases were held at safe channel capacity. Considering the frequency of June precipitation events, it is not inconceivable that **raising the top of joint use pool** could result in releases greater than the safe channel capacity. Also, the model does not represent system flood control. Because the modeled operations resulted in peak releases at the local flood control safe channel capacity, no system flood control targets could have been considered during this period.

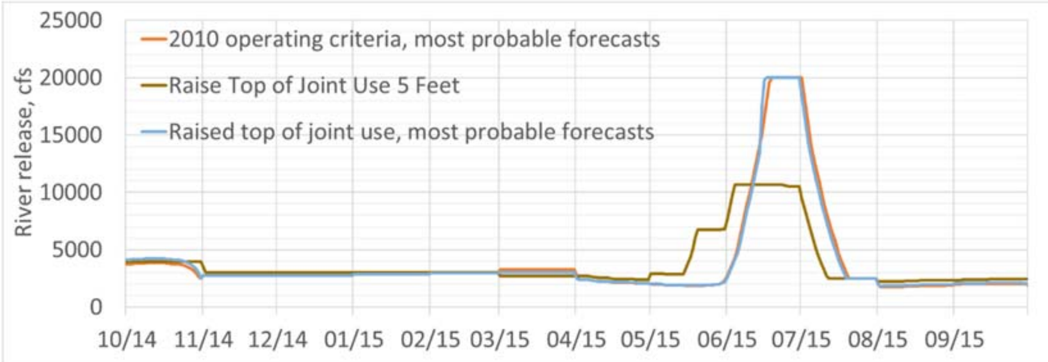

Figure 50: 2010 operating criteria and raised top of joint use pool scenarios with most probable forecasts during water year 2015.

Finally, the National Park Service has boat-in campgrounds at pool elevations between 3,640 and 3,645 ft., meaning this scenario would result in campground flooding.

Lower Top of Joint Use Pool Five Feet Scenario

Scenario Description

This scenario lowers the top of joint use pool by five feet. The goal of lowering the top of joint use pool is to add additional space for flood control storage, potentially reducing the magnitude of downstream river releases.

This scenario was represented by shifting the rule curves uniformly down by five feet and lowering the top of joint use pool by five feet. The end of October target elevation remained at 3,635 ft., the end of March target remained at 3,617 ft. and the minimum flood control drawdown elevation was reduced to 3,586.5 ft.

Scenario Results

Average pool elevations (Figure 51) are lower for the **lowered top of joint use pool** scenario when compared to the **2010 operating criteria**, as would be expected.

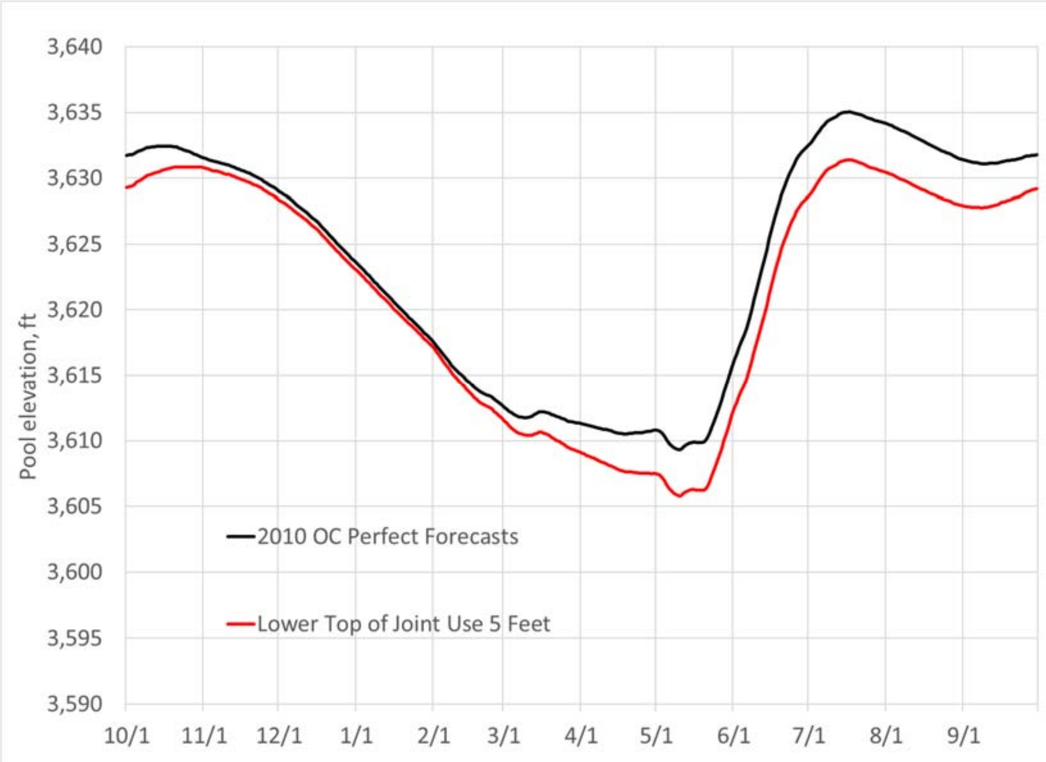

Figure 51: Mean daily pool elevations for the 2010 operating criteria and the lowered top of joint use scenarios for the period 1990-2017.

Contrary to the goals of the scenario, mean daily peak river releases shown in Figure 52 are higher and winter releases are lower due to the smaller difference between end of October pool elevations and the end of March target of 3,617 ft. This is likely due to the lowered elevation of the top of joint use pool, which would require more frequent higher releases to avoid entering the exclusive flood control pool.

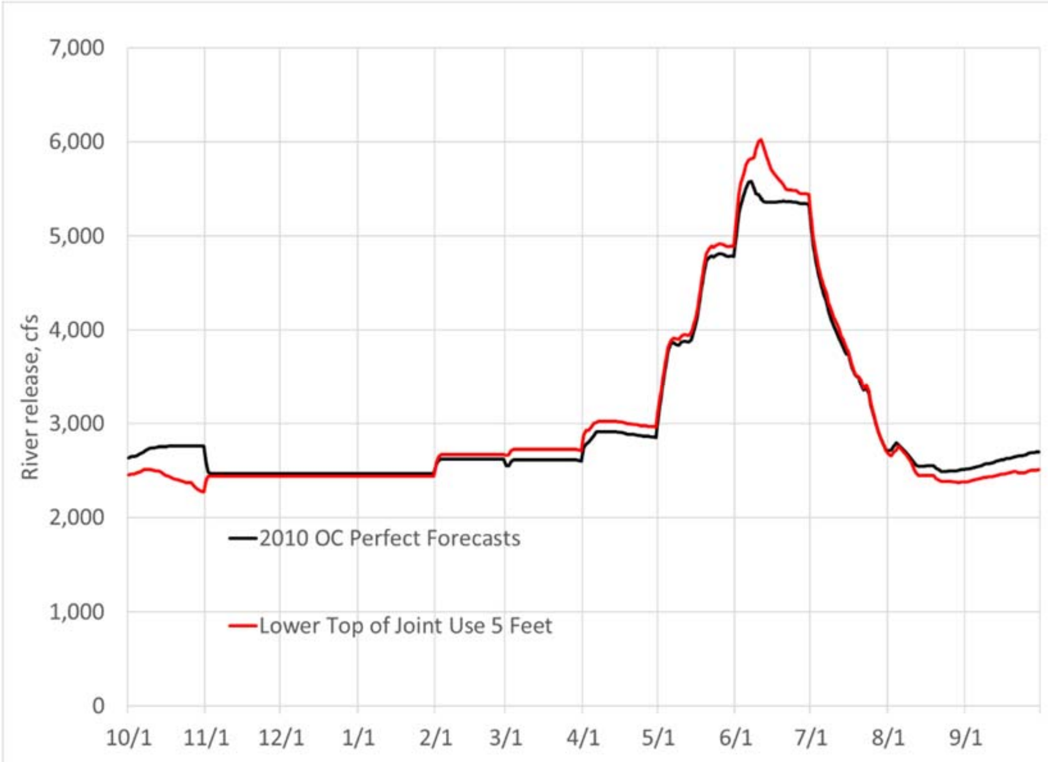

Figure 52: Mean daily river releases for the 2010 operating criteria and the lowered top of joint use scenarios for the period 1990-2017.

MELS Scenario

Scenario Description

The **MELS** Scenario was developed by two members of the Technical Working Group: Mr. Mark Elison, of the Montana Department of Natural Resources and Conservation, and Mr. Loren Smith of the Wyoming State Engineer's Office. The acronym refers to the first letter of each first and last name. According to their description (Elison & Smith, 2018):

> *The reasoning behind this draft concept is that there exists limited need for an October target elevation, there exists a desire to provide/maintain adequate river flows for the fall brown trout spawn as well as a consistent means to set outflows without introducing human emotions. Aiming for an arbitrary target in March limits the flexibility of operations and leaves too short of a timeframe to react to changing forecast volumes. This concept would satisfy those points while still making it possible to reach a late May lake level that will allow flat water recreation on [the] southern end of reservoir.*

Table 19 shows the release logic for the **MELS** scenario. The releases are selected based on the April through July forecast in comparison to the median April through July inflow. For example, if the April through July forecast is below 75 percent of the median, the very low forecast column is selected. After the runoff season is complete, inflows are released.

Table 19: MELS Scenario release logic.

	<75% of average	75%-95% of average	95%-105% of average	105%-150% of average	>150% of average
	Very Low Forecast	**Low Forecast**	**Average Forecast**	**High Forecast**	**Very High Forecast**
Month	**cfs**	**cfs**	**cfs**	**cfs**	**cfs**
Dec	1500	2000	3000	3500	3500
Jan	1500	2000	3000	3500	4000
Feb	1500	2000	3000	3500	4000
Mar	1500	2000	3000	4000	5000
Apr	1500	2000	3000	5000	6000
May	1500	2000	4000	6000	6000
Jun	1500	2000	5000	7000	6000
Jul	1500	2000	4000	4000	5000
Aug-Nov	Outflows=Inflows				

Scenario Results

The fixed river releases not based on pool elevation targets of the **MELS scenario** result in extreme drawdowns of Bighorn Lake, drafting it as much as 300 ft. (Figure 53). This would result in elevations below the minimum hydropower elevation by almost 150 ft. Interestingly, the scenario maintained pool elevations in the exclusive flood pool for much of the extreme drought in the early 2000s.

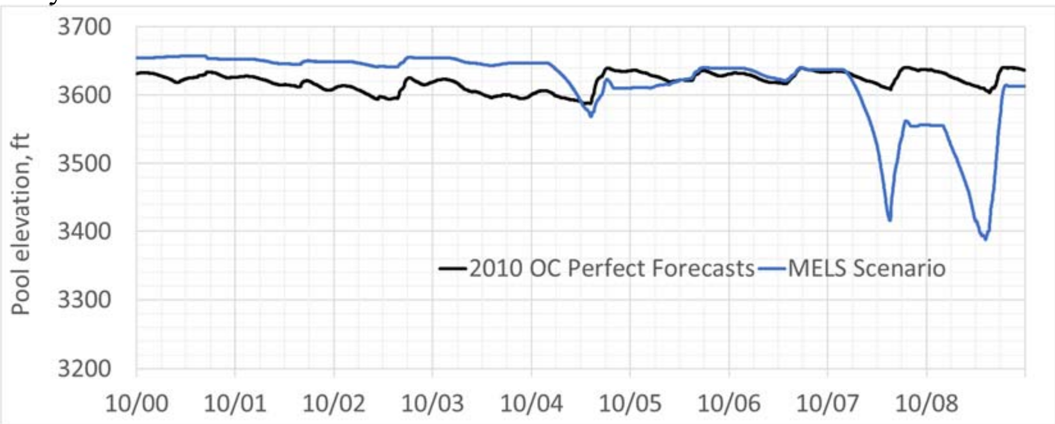

Figure 53: Pool elevations for MELS and 2010 operating criteria scenarios with perfect forecasts for the period WY 2000-2005.

Figure 54 shows river releases for the drought period. The additional drawdown does not result in favorable releases for fisheries due to summer and fall releases tracking inflows. Numerous periods result in river releases of about 500 cfs.

Figure 55 shows greatly reduced mean hydropower generation due to pool elevations below the minimum hydropower generation elevation.

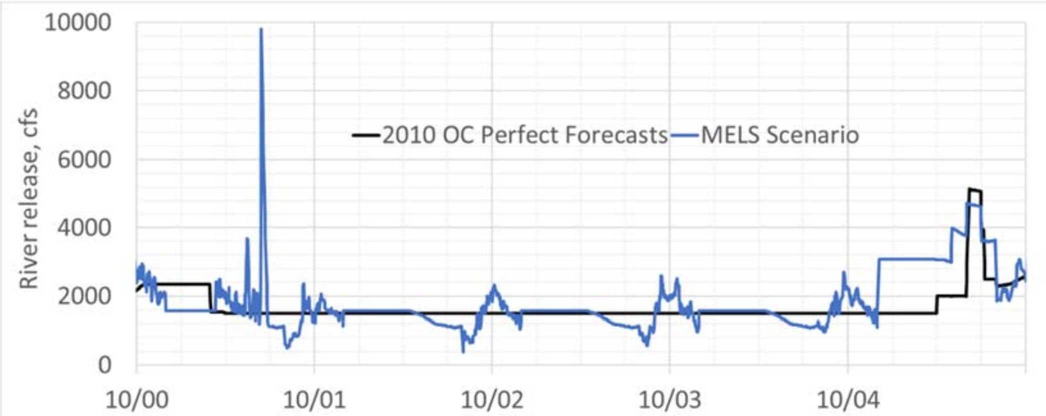

Figure 54: River releases for MELS and 2010 operating criteria scenarios with perfect forecasts for the period WY 2000-2005.

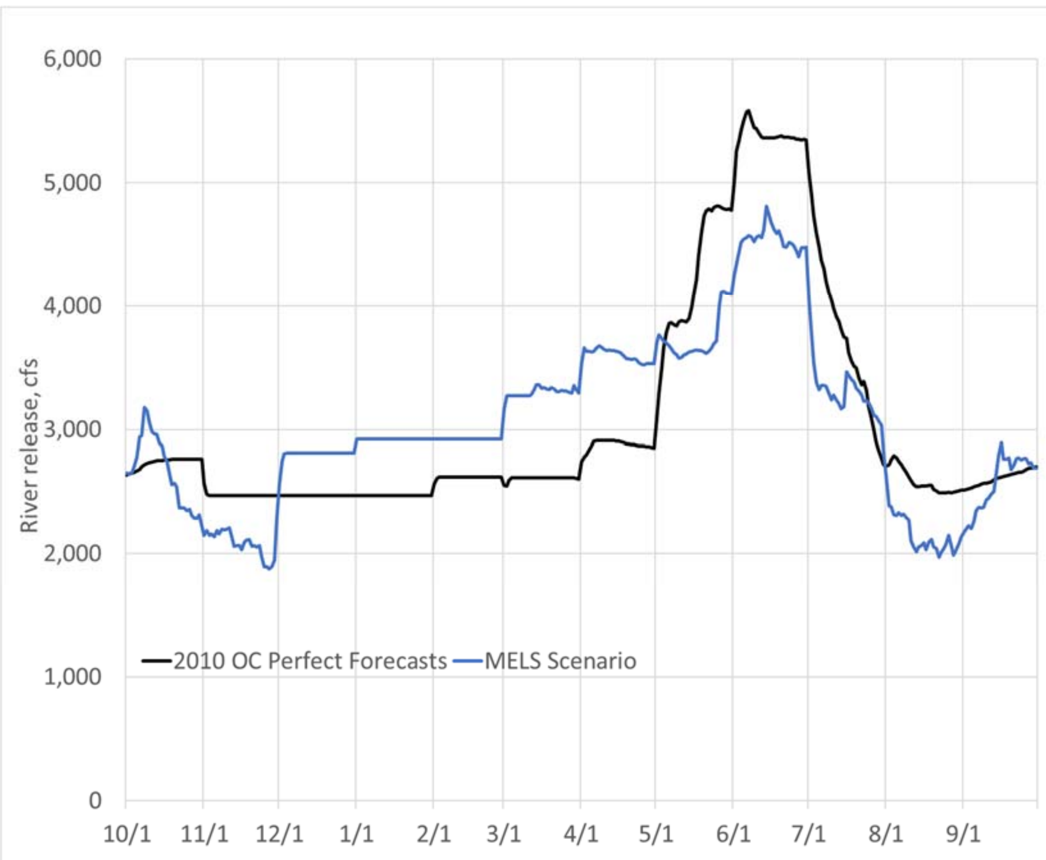

Figure 55: Mean daily hydropower generation for MELS and 2010 operating criteria scenarios with perfect forecasts for the period WY 1990-2017.

Fixed Winter Release Scenario

Scenario Description

The **fixed winter release** scenario sets a winter release rate regardless of forecasted runoff or current reservoir conditions. For the scenario shown here, the fixed release was 3,500 cfs. The remaining model logic remains the same.

Scenario Results

The **fixed winter release** scenario shows the same problems as the **MELS scenario.** Releases without consideration to current reservoir conditions, or in this case, inflows, result in dramatic drawdowns during the extended drought of the early 2000s (Figure 56).

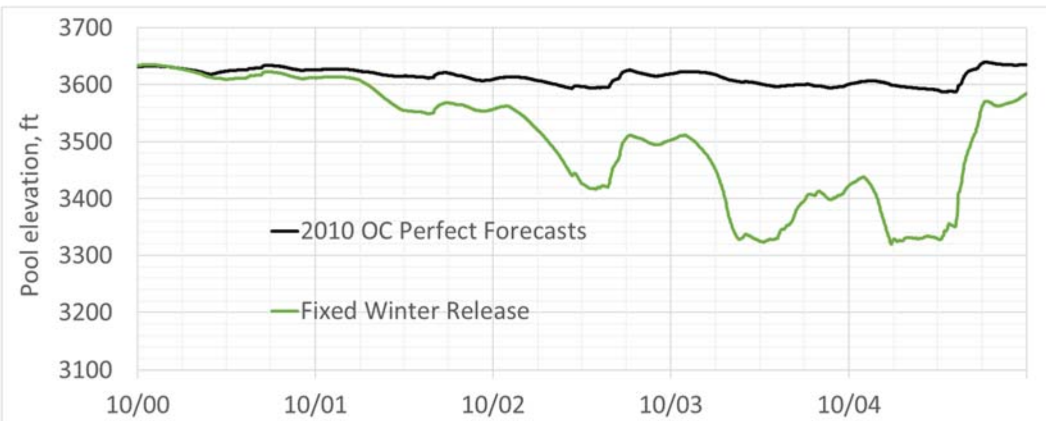

Figure 56: Pool elevations for fixed winter release and 2010 operating criteria scenarios with perfect forecasts for the period WY 2000-2005.

As with the **MELS** scenario, the **fixed winter release scenario** results in the desired higher winter releases (Figure 57), but releases in summer drop to 1,000 cfs on numerous occasions while drawing the reservoir below the minimum power generation elevation.

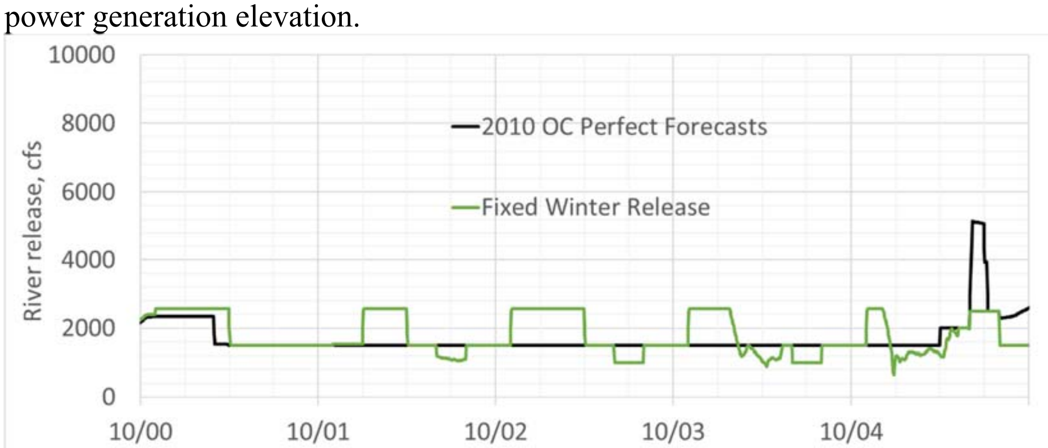

Figure 57: River releases for fixed winter release and 2010 operating criteria scenarios with perfect forecasts for the period WY 2000-2005.

RiverWISE Scenario Manager

The sample model applications were made available to the Technical Working Group through CADSWES' RiverWISE software. According to CADSWES (Center for Advanced Decision Support for Water and Environmental Systems, 2018):

> *RiverWISE (RiverWare Interactive Scenario Explorer) is a standalone application for viewing and exploring alternatives of certain specially configured models generated in the RiverWare software. RiverWISE is freely available and easy to use; it does not require the RiverWare software or training.*

The RiverWISE software allows stakeholders to develop alternative operating scenarios and share them with the model developer. No new alternative scenarios were submitted to Reclamation for further examination.

Conclusions

Impact of Hydrology

Hydrology was a key driver of the magnitude and duration of river releases. The period 2010-2018 saw the top three recorded April through July runoff years as well as two consecutive dry years. While forecasting, operating criteria, and Bighorn Lake operators may have had some impact on pool elevations and river releases, the sheer magnitude of inflow in relation to the flood control space available largely determined river releases in high inflow years such as 2011 and 2017.

Outside of extremely high inflow years, runoff timing also seems to have a large impact. Comparing inflow hydrographs from 2014 and 2015 shows the impact of the inflow hydrograph. The inflow hydrograph in 2014 was broad, with a relatively low peak, whereas 2015 saw a steep inflow hydrograph with high peak inflows. Total April through July inflow volume was greater in 2014 than 2015, yet peak releases were greater in the lower runoff year.

While inflow volume is driven by basin precipitation and upstream depletions, upstream operations are a significant component driving inflow timing. This provides an opportunity for flood control drawdown to be adjusted when upstream operators indicate releases will not correspond with the assumed inflow hydrograph.

Impact of Forecasting

As described above, hydrology was the key driver in the high inflow years of 2011 and 2017. Forecasting had a significant impact in average to below average inflow years, where smaller deviations in river releases may have greater impacts on recreation.

Forecasts tended to underestimate April through July inflow as well as winter inflow. This resulted in higher pool elevations than anticipated by the 2010 operating criteria. An example of this is 2015, where forecasts as late as May 1 were 900 KAF below observed inflow resulting in pool elevations higher than called for by operating criteria coming into the runoff season.

Several years (2010, 2012, 2015, and 2016) saw dry conditions in late winter and early spring, resulting in low forecasts. These were followed by wet late spring/early summer conditions, with runoff far exceeding forecasts. Because forecasts were below the minimum fill threshold of 727 KAF, operators were allowed discretion as to release rates and chose to reduce releases in anticipation of drought conditions. Later higher runoff in conjunction with high pool elevations tended to result in high river releases.

Impact of Operating Criteria

Operating criteria were developed based upon an assumed inflow hydrograph for each runoff forecast volume. However, runoff did not always closely match the assumed inflow hydrograph. Considering operations in 2014 and 2015 shows the impact of the inflow hydrograph when combined with the **2010 operating criteria's** fixed inflow timing. High releases are likely compounded by the drawdown curve developed based on the assumed inflow hydrograph.

The magnitude of peak drawdown also impacted operations. Rule curves were only developed for historical inflow volumes. April through July inflows records were broken in 2011 and 2017, with no rule curve developed to mitigate high reservoir inflows.

Dry water year operations under the **2010 operating criteria** were also key to the observed operations throughout this period and are linked to both forecasting and the impact of operators. As described above, forecasts below the minimum fill threshold allow operators flexibility in setting releases. Operators tended to conserve water by reducing releases when forecasts were below the minimum fill volume, resulting in higher than anticipated pool elevations. Because forecasts tended to under-predict inflows, operators were frequently afforded this flexibility. Over-prediction did occur in water year 2012, a drought year. The forecast error did not appear to have as significant an impact on river releases as under-forecasting high inflow water years. The operating criteria does not make significant drawdowns to evacuate space until May, at which point forecasts were much closer to the actual inflow volume. Over-forecasting did result in lower summer pool elevations.

Finally, the minimum fill volume was calculated as the volume required to fill Bighorn Lake from a starting elevation of 3,617 ft. on March 31 while releasing the standard fishery flow of 2,000 cfs. However, pool elevations frequently deviated from this elevation at the end of March, meaning the minimum fill volume as defined by the **2010 operating criteria** was no longer the volume required to fill the reservoir. The minimum fill volume should be dynamic depending on the actual end of March pool elevation. If end of March elevation is higher than 3,617 ft., the minimum fill volume should be reduced, and if lower than 3,617 ft., it should be increased.

Impact of operators

The review of individual water year operations only revealed one instance where operators may have deviated from the operating criteria. Winter flows set in water year 2013 used an assumption that releases would increase in March, rather than the uniform winter release described within the operating criteria. This had the ultimate impact of reducing releases in the winter and increasing releases the following summer when compared to the modeled operations with most probable operations.

While there was little evidence of deviation from the operating criteria, the operating criteria frequently provided operators full judgment-based control on operations due to the lack of direction when forecasts are below the minimum fill volume. During these periods, operators tend to reduce releases to conserve water. This increases the risk of impacts due to high inflows, as pool elevations increase and less space is available for flood control. This is likely a key cause of observed pool elevations being higher than anticipated by the **2010 operating criteria**.

Sample alternative operations scenarios

Seven alternative operating scenarios were analyzed with both perfect and most probable historical forecasts. None of the cases examined eliminated the risk of high flows, low flows, or low lake elevations.

The **lowered end of March target** scenario resulted in greater drawdowns than the other cases. The **lowered end of March target** scenario had such large drawdowns that in an average year the reservoir failed to fill to the top of joint use. The drought from 2000-2004 showed that persistent dry conditions resulted in much lower pool elevations, negatively impacting river releases, pool elevations, and hydropower generation. In addition to having several consequences, the expected benefits of the lowered end of March target scenario were not realized. The intent of the scenario was to reduce peak flows during spring and early summer. Considering the relative benefits and negative impacts, the **lowered end of March target** scenario is not recommended for further study.

The **elevated end of May target** scenario had several positive and negative impacts. High flows occurred because of filling the reservoir to desired lake recreational levels earlier in the spring than the other cases. This scenario resulted in significantly higher peak releases than the other scenarios, including one period with flows at the channel capacity of 20,000 cfs. This is a result of using fixed timing for operations when considerable variability in inflow timing exists. There are several benefits of the **elevated end of May target** scenario. The **elevated**

end of May target scenario does provide earlier access to a usable boat ramp at Horseshoe Bend Marina compared to the other cases. However, due to the significantly higher peak releases and higher total release volumes due to ramping rate restrictions, the **elevated end of May target** scenario results in greater drawdowns in drought periods with poorer lake recreational access. Therefore, this scenario is not recommended for further investigation.

The **increased drawdown** scenario had primarily negative impacts. While the new rule curves allowed for large drawdowns in mid to late spring, this did not seem to have the desired impact of reducing river flows in late spring to early summer. In 2017, the target drawdown elevation for the modified rule curves was so low that high releases were needed to reach that drawdown level. These releases were higher than any other case during 2017. However, the changes to rule curves were arbitrary, and not developed with the same scrutiny as the original rule curves. It should be noted that the impacts of changing rule curves were significantly overshadowed by the impacts of forecasting error, as demonstrated by modeling the **increased drawdown** scenario using most probable forecasts.

Two scenarios examined raising and lowering the elevation of the top of joint pool by five feet. **Raising the top of joint use pool elevation** benefitted users through reduced peak streamflows and higher pool elevations for recreational access and hydropower head when examining perfect forecasts. Two issues make implementing this scenario undesirable. First, several years were significantly under-forecast by Reclamation since implementation of the 2010 operating criteria. Operating the reservoir five feet higher increases the risk of reaching the local safe channel capacity of 20,000 cfs, as shown by modeled operations in water year 2015. This also reduces Missouri River Basin system flood control.

Lowering the top of joint use pool elevation resulted in higher mean daily peak river releases and lower pool elevations, negatively impacting lake and river recreation, local flooding, and hydropower generation. Neither scenario is recommended for further study.

Two additional scenarios examined the feasibility of using releases based on the forecasted inflow volume only (**MELS** scenario) and a **fixed winter release rate**. Both scenarios performed poorly during the extended drought period of the early 2000's, drawing down the reservoir several hundred feet and below the minimum hydropower generation elevation. As such, these scenarios are not recommended for further examination.

General assessment of 2010 Operating Criteria

According to Reclamation (Bureau of Reclamation, 2012c), the goal of the **2010 operating criteria** was "improving overall project benefits and to provide a better balance between competing interests." Higher March 31 pool elevations were intended to increase the probability of refilling the reservoir; higher end of

October targets were likewise intended to increase carryover storage for the following year, both intended to improve lake recreation and water supply reliability. Hydropower generation was expected to increase due to higher head resulting from greater pool elevations. These benefits appear to have been realized since the new operating criteria was implemented in water year 2010.

Flood control was also expected to improve. Reclamation (Bureau of Reclamation, 2012c) stated that rule curves were “designed to better time the evacuation of storage to its low point such that it reaches this point just prior to high snowmelt runoff. In addition, the rule curves will also carefully control the fill rate such that the lake is more likely to fill to its normal full level after the peak flood runoff has started to recede.” Since the **2010 operating criteria** were implemented, several extremely wet years resulted in high river releases. This has, understandably, put recent emphasis on flood control efforts.

The efficacy of flood control changes is somewhat harder to evaluate. This study shows that flood control operations are highly impacted by forecasting and inflow hydrograph differences from the rule curve anticipated inflow hydrograph. It appears that Reclamation (Bureau of Reclamation, 2012c) did not examine the impacts of forecasting error on rule curve implementation, nor did Reclamation take into account the impacts of inflow timing changes, either from differing upstream operations or from hydrologic changes.

Modeled operations using perfect forecasts with the **2010 operating criteria** had higher average pool elevations and higher peak releases than operations under the **2000 SOPs.** The higher peak releases are at least partially attributable to differences between the assumed runoff timing of the rule curves and actual inflow hydrology. Because **2000 SOP operations** provide only qualitative guidance on drawdown after the March 31 target, the model can minimize peak releases using actual inflow hydrology. Runoff timing is unknown, and operators cannot make the perfect decisions made by a model with exact advance information regarding inflow timing and volume. Representing **2000 SOPs** also required incorporating numerous assumptions to represent releases during dry years. This results in further uncertainty regarding comparisons between **2010 operating criteria** and **2000 SOP operations**. Even with beneficial dry year assumptions in **2000 SOP operations** representations, river releases were lower in dry years when compared to **2010 operating criteria**.

Ultimately, rule curves provide a heuristic technique providing adequate guidance for operations in the face of uncertain inflow volume and timing. Rule curves also provide transparency to operations and a well-defined balance between competing interests. The **2000 SOPs** provide none of this transparency. They also do not provide guidance for operators. The **2000 SOP operations** also showed worse performance in dry years. For these reasons, we do not consider the **2000 SOPs** preferable to the **2010 operating criteria**.

Based on the results of the statistical review and this modeling study, several potential improvements to the **2010 operating criteria** have become apparent. Forecasting appears to have significant impact on operations, particularly in drier years. Issues with rule curves include fixed assumed inflow timing and encroachment into the exclusive flood pool, and lack of guidance for forecasted inflows greater than observed in the historical record. Specific water years show the impacts of operator decisions, and transparency can also be improved.

It should be noted that possibly the largest cause of undesirable operations is hydrologic variability. The period following **2010 operating criteria** implementation contained the top three recorded highest inflow years. The impetus for implementing revised operating criteria in 2010 was severe drought conditions from 2000 through 2007 (Bureau of Reclamation, 2012c), and drought will return to the Bighorn River.

Recommendations

Recommendations address both the **2010 operating criteria** and Yellowtail operations as a whole. The **2010 operating criteria** is an important subset of Yellowtail operations but does not completely determine how Bighorn Lake and River are or should be operated.

Modeling scenarios representing modifications to the operating criteria show operations with the **2010 operating criteria** using perfect forecasts are relatively balanced between competing uses. The pool elevation targets for winter flows and rule curves do not appear to favor one party over another. However, the operating criteria lacks critical guidance on operations in several areas, including generating forecasts, operations during periods of low runoff forecasts, and adjusting operations when forecasts are in error.

Reclamation and stakeholders endured a long development process resulting in the **2010 operating criteria**. Potential improvements should not attempt to mitigate the high flows observed over the last nine years at the expense of operations for water supply during dry years and should maintain the agreed-upon balance between interests. It is important to incorporate only those improvements that benefit all parties, rather than improvements coming at the expense of a competing interest. Several potential improvements to the operating criteria exist which do not benefit one stakeholder group at the expense of another.

The following section describes several potential improvements to the **2010 operating criteria**. These improvements range from quickly implemented to an implementation time up to five years, and small impact to moderate impact. Some of these potential improvements are already under way.

The report describes Reclamation's Great Plains Regional Office's review of the **2010 operating criteria** and provides recommendations for improvement to MTAO. MTAO has responsibility for operations and therefore must determine which recommendations are implemented. It is likely that MTAO will need to prioritize these enhancements based on available staff labor and funding.

Forecasting

As described in the Statistical Analysis draft report (Bureau of Reclamation, 2018b) and previous sections, Reclamation's forecasts over the last decade have been biased toward under-forecasting reservoir inflows. The retrospective analysis of forecast error also shows errors greater than expected by the reported forecast uncertainty.

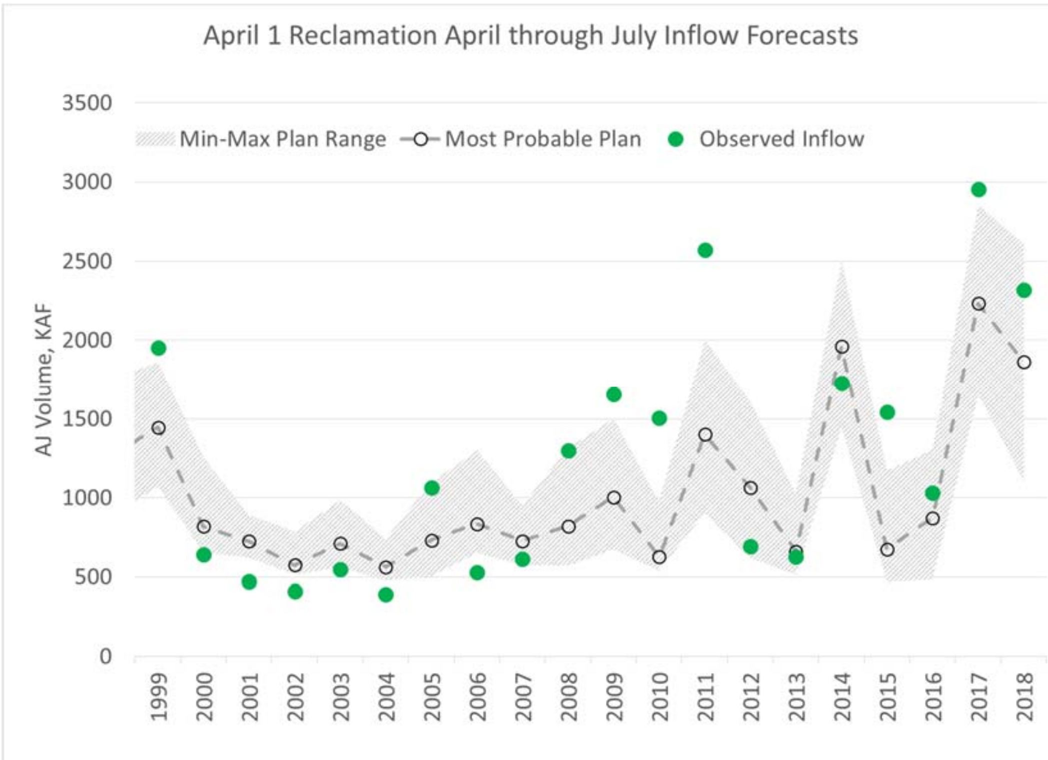

Figure 58: April 1 Reclamation forecast minimum-maximum plan range and observed inflow.

Minimum and maximum plans are developed at the 10 percent and 90 percent exceedance levels, meaning about 80 percent of forecasts should be within these bounds. Examining Figure 58 shows 12 of the last 20 years, or 60 percent outside the minimum-maximum plan bounds. Clearly the minimum-maximum plan range does not adequately describe the uncertainty contained within Reclamation's inflow forecasts. While a broader range of minimum-maximum plan range may not change operational plans, it is important to use accurate statistics of uncertainty for operations.

It should be noted that a certain level of forecast uncertainty is inherent, particularly due to future precipitation. The Bighorn Basin receives much of its precipitation from spring Front Range upslope events, as shown in Figure 59.

These events are difficult to forecast and may be a factor causing the large under-forecasts in the most recent decade, which tended to occur when wet late spring/early summer conditions followed dry winters. The unpredictability of upslope events also likely limits the potential for increased skill of forecasts.

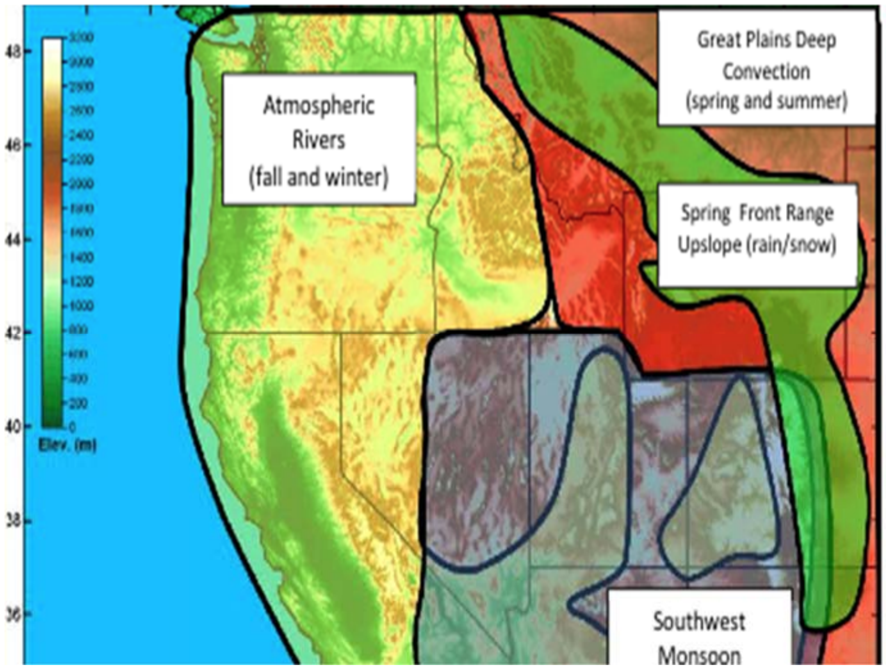

Figure 59: Summary of regional primary weather phenomena leading to extreme precipitation in the Western U.S. From (Ralph et al., 2014)

The following recommendations may aid in improving forecast skill, but also aim to improve quantification of forecast uncertainty. Operators can make better-informed decisions with an enhanced understanding of forecast uncertainty, as they will better understand the potential range of future inflow volume and timing.

Examine skill of forecast components

The statistical analysis report only examined the skill of forecasted inflow into Bighorn Lake. However, inflow forecasts are derived from three sources: Forecasted Boysen Reservoir release; Forecasted Buffalo Bill Reservoir release; and local gains and losses between the upstream reservoirs and Bighorn Lake. Examining the skill of each forecast source would direct future efforts for maximum forecast improvement.

Evaluate improvements to statistical forecasts

Forecasts are currently generated through operator selection of predictor variables. Operators only explore a limited number of potential forecast equations through experimentation. This potentially limits the skill of the resultant forecast equation.

The Great Plains Regional Office (GPRO) and its area offices, including Montana Area Office (MTAO), are currently testing a forecasting program which searches for the best equation from many potential forecasting equations using current statistical techniques. This software uses the methods described in (Natural Resources Conservation Service, 2011) and allows for more robust forecast generation. The software downloads snow, streamflow and climatic data from web sources. It then searches for the best permutations of available predictor variables and sorts forecast equations by metrics of forecast skill. The software then generates forecasts from the equations, allowing operators to examine a greater number of potential forecasts for each month.

The software was recently peer-reviewed and is currently undergoing beta testing in several Reclamation offices, including MTAO. Future efforts include hindcasting using the software and parallel testing with current methods. We expect the software to be available for operational implementation in January 2021.

Several potential improvements to statistical forecasts exist which can be further examined using this software, and are described in further detail below.

Incorporate climate indices El Niño Southern Oscillation (ENSO)

Certain climate indices such as the indicators of the ENSO have shown value in forecasting in the Western United States (Natural Resources Conservation Service, 2011). ENSO has been shown to impact winter precipitation and air temperature, with general patterns shown in Figure 60 below. Typically, La Niña years result in colder, wetter winters for Montana and Wyoming, and El Niño years result in warmer, drier winters in the Bighorn Basin.

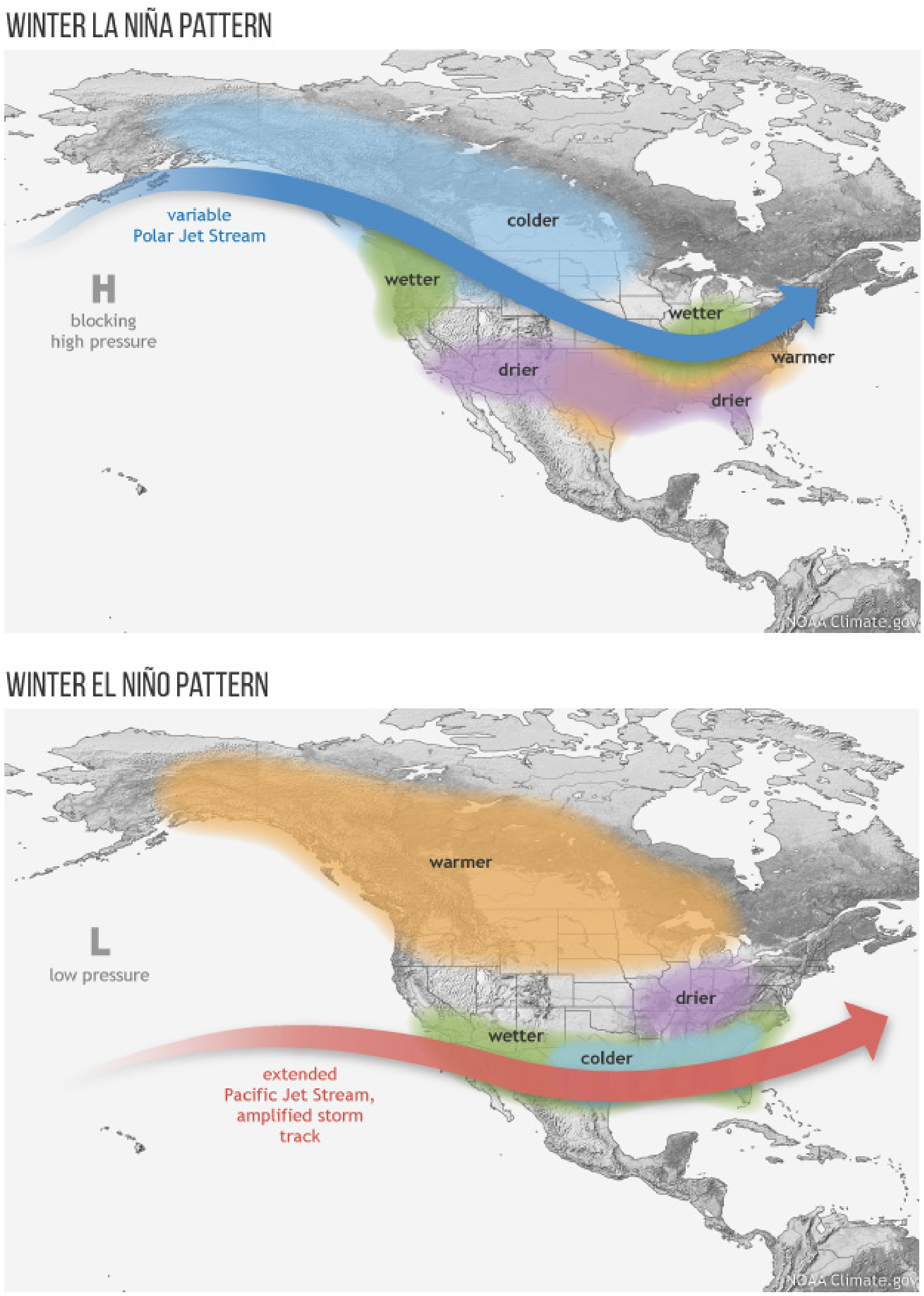

Figure 60: ENSO impacts on the United States. From NOAA, 2017.

Remove future precipitation as a potential predictor variable

Yellowtail Dam Standard Operating Procedures (Bureau of Reclamation, 2012b) states that "…*forecasts are based primarily on snow water content in the mountain snowpack, **expected precipitation during the runoff season** and forecasted river releases from Boysen and Buffalo Bill dams [Emphasis added].*"

Forecasts are generated using multiple linear regression, a process where two or more explanatory variables are used to predict a response variable. For forecasting streamflows, models typically incorporate snow water equivalent, past precipitation, and past streamflow as predictors of future seasonal reservoir inflow. Forecasts are generated monthly and, in some locations, bimonthly. Forecasts on January 1 through April 1 typically predict the total reservoir inflow volume for the period April 1 through July 31. Forecasters test various combinations of prediction variables to determine an equation with the best skill. Uncertainty in these forecasts is described by how well the equation predicts values in the historical dataset. Equations with poorer performance using historical data will result in greater uncertainty when forecasting future inflow.

On the forecast date, predictors such as snow water equivalent and streamflow are measured and used in the forecast equation to predict future streamflow. Forecasts for Bighorn Lake include an expected (future) precipitation term. When the multiple linear regression model is developed, historical precipitation is used to represent the future precipitation term. For example, a forecast generated on April 1 will use April through July precipitation as a predictor. However, forecasters have no advance knowledge of future precipitation. Typically, forecasters substitute the long-term average for the precipitation term when forecasting. As described in (Garen, 1992),

> *…the use of future variables and the substitution of averages can degrade forecast accuracy. An equation calibrated with all input data known is optimal only when all of those data are known; it is no longer an optimal forecaster when some of the input data are unknown. Improvements in forecast accuracy by not including future variables can be substantial, especially early in the forecasting season.*

Because the forecast equation is developed using historical precipitation, and precipitation is correlated with reservoir inflow, forecast equations can appear quite skillful. However, forecasters apply the forecast equation to predict future inflow without actual knowledge of precipitation. Therefore, the uncertainty bounds predicted by the multiple linear regression will be much smaller than the actual uncertainty of the forecast when considering the lack of advance precipitation knowledge. This may be a cause of the large number of historical forecasts falling outside the uncertainty bounds. The future precipitation term should be removed from consideration when generating forecast equations. As described above, certain climatic indices may have predictive value for future precipitation. These indices should be evaluated for inclusion rather than the future precipitation terms.

Examine statistical forecast uncertainty distributions

Traditional statistical forecast methods use a Student's t distribution for forecast error (Natural Resources Conservation Service, 2011) which is evenly distributed about the mean. However, inflow distributions may not be evenly distributed about the mean; for example, forecasts in dry years can result in negative forecasts on the lower end of the forecast distribution. Negative forecasts are not possible for many locations and the forecast distribution should be skewed (skew measures asymmetry in probability distributions). Understanding skew of forecast uncertainty may enhance operational decisions in very dry and very wet years and assist in the development of more appropriate forecasts for these extremes.

Operations should be based on the forecast uncertainty distribution rather than modifying the most probable forecast to determine desired operations. Several forecast products available are calculated and then modified through professional judgment. For example, NRCS may alter its forecasts (Natural Resources Conservation Service, 2011):

> *[Forecast] preparation includes ensuring that all required data are available and of reasonable quality, executing the statistical forecasting models, reviewing the results, and making adjustments if necessary. During the review and adjustment process, the hydrologist may rely on various sources and displays of relevant information, such as tables or maps of snow water equivalent, precipitation, and streamflow data, as well as long-range weather outlooks. Advice and guidance from State Program personnel can also be helpful.*

Rather than modifying forecasts, operators should consider the range of uncertainty contained within the forecast to make decisions. Operators should consider the potential adverse impacts due to inflows throughout the forecast range and develop operational decisions mitigating these potential impacts.

Evaluate Skill of NWS and other ensembles

The National Weather Service's (NWS) Missouri Basin River Forecast Center (MBRFC) generates ensemble forecasts using its River Forecast System. NWS generates ensembles through a hydrologic model which is "spun up" or initialized to current hydrologic conditions (streamflows, snowpack, soil moisture, etc.) The model is then driven with projections of future climate or historical observations of climate to generate unique hydrographs, each representing a potential future streamflow.

The first five days of the forecast period use NWS' forecasted air temperature and precipitation to drive the hydrology model. The remainder of the forecast period uses historical air temperature and precipitation to drive the hydrology model.

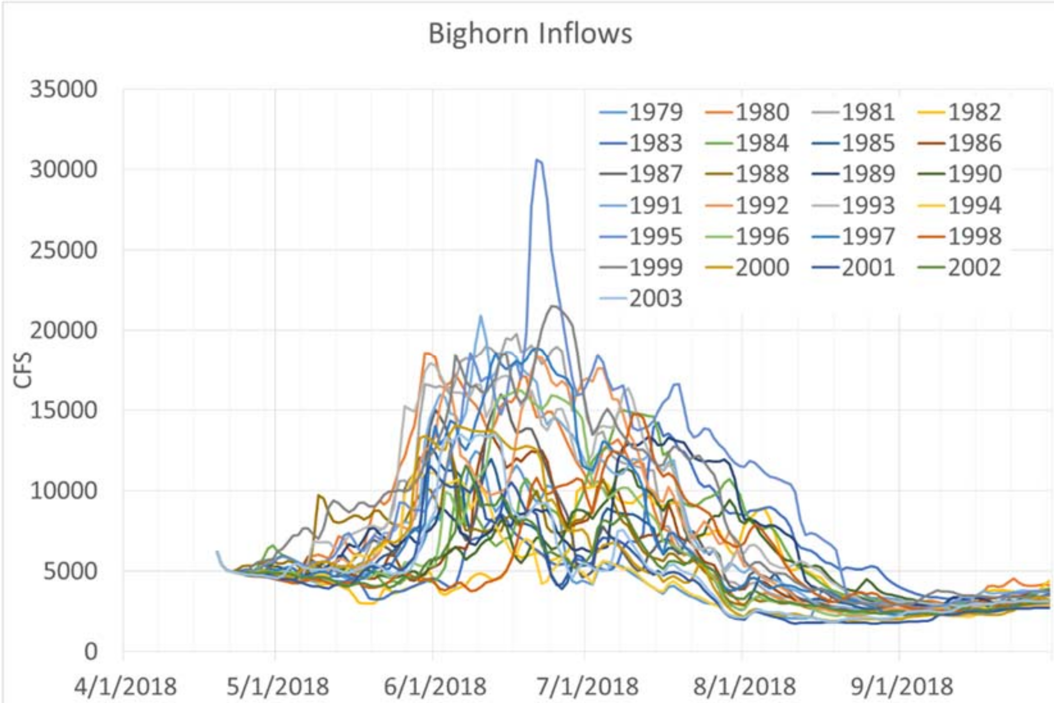

Figure 61: Example of a Bighorn Lake inflow ensemble.

The resultant ensemble comprises 25 potential future hydrographs. The range in timing and volume of these hydrographs can be used to inform reservoir operators regarding future uncertainty in streamflow, like the uncertainty bounds of a statistical forecast. These ensembles are also useful for running through a daily RiverWare operations model.

To properly utilize these ensembles, however, operators must understand the skill of the ensemble forecasts. This is done through a process called “hindcasting,” in which the hydrologic model is spun up to conditions at a point in the past and forced with the same 25 climate traces as the current forecasts are. The hindcast ensembles are then compared to the observed inflow traces to determine whether the forecasts adequately describe uncertainty and are not biased.

To date, NWS has not evaluated its ensembles through hindcasting. Reclamation has requested NWS prioritize hindcasting the Wind/Bighorn basin. We recommend that MTAO evaluate implementation of NWS ensembles after hindcasting is complete.

Study enhanced low-elevation snowmelt runoff forecasting techniques

Another uncertain component of November through March inflow is low-elevation snowmelt runoff. It is not uncommon for the Bighorn Valley, both above and below Bighorn Lake, to develop snowpack which melts in late winter or early spring. Current statistical forecasting techniques, which are dependent on mountain snowpack, do not describe this runoff component well. Reclamation's Science and Technology program has funded a study of low-elevation snowmelt runoff being performed by the Technical Service Center and National Center for Atmospheric Research (NCAR). This study uses the Wind/Bighorn basin as a test-case and is scheduled to be complete in 2021.

Operating Criteria and Rule Curves

Model and evaluate explicit low-flow rules

According to the Final Operating Criteria Assessment Report (Bureau of Reclamation, 2012c)

> *For years with forecasted April-July Inflow falling below a 26 percentile year (April-July inflow less than 727,000 acre-feet) rule curves were not developed, as it was found that these are years when the lake will need to be managed to provide a careful balance between the need for a minimum river release for the river fishery flows (2,000 cfs or less) and sufficient storage to provide adequate longer term water supply for all users… Decisions to reduce releases below 2,000 cfs and especially 1,500 cfs are not decisions that can or should be spelled out in this report. Flexibility should be left to Reclamation to address the needs of each of the interests in Bighorn Lake in determining a properly balanced operation between the lake and the river under these situations.*

However, examination of water years 2010, and 2013, and 2015 show that Reclamation used flexibility to reduce releases below 2,000 cfs. This resulted in greater than anticipated pool elevations and subsequent higher releases than the perfect forecast scenario. To improve transparency of operations and avoid reacting to short-term conditions, explicit rules for operations below the minimum fill volume should be evaluated for inclusion in the operating criteria. This should include examining a dynamic minimum fill threshold based on actual pool elevations rather than elevation 3,617 ft. If previous forecasts have resulted in higher or lower pool elevations than anticipated by the operating criteria, the minimum fill threshold should be adjusted according to current reservoir storage rather than the storage assumed by the operating criteria.

Operating criteria updates

Remove planned encroachment into the exclusive flood pool

According to the Standard Operating Procedures (Bureau of Reclamation, 2012b), "[t]he COE is responsible for the operations when the reservoir is in the exclusive flood pool (between elevations 3,640.0-3,657.0 ft.). Between elevations 3,614.0-3,640.0 ft. (joint-use storage zone), Reclamation and the COE are jointly responsible. Reclamation has full responsibility of this zone when the space is not required for seasonal flood control purposes." All rule curves greater than the median inflow forecast contained within the **2010 operating criteria** plan to enter exclusive flood pool by as much as one foot.

Reclamation should reformulate rule curves to remove any planned encroachment on the exclusive flood pool. This may require lowering minimum drawdown elevations to provide the same level of flood control as contained within the current rule curves.

Update rule curves to anticipate inflow volumes outside the historical record

Inflows exceeded the previous April through July record during two of the nine water years since implementation of the 2010 operating criteria. Reclamation updated its maximum rule curve to the 2011 April through July inflow volume after water year 2011 and has not updated rule curves following the record 2017 runoff. Reclamation should update rule curves in anticipation of not only the new historical record April through July runoff, but also greater inflow volumes. This would not change the rule curves for forecast volumes already in the historical runoff record. It would simply develop additional rule curves for forecasted volumes greater than historically observed. Rule curves should be proactive rather than reactive to new conditions.

Likely, a study developing additional rule curves would scale historical inflow hydrographs for an array of potential higher April through July volumes and examine scaled rule curves for the best performance under higher inflow conditions.

Explicitly define relationship between flood pool and releases

According to the Operating Criteria Final Assessment Report (Bureau of Reclamation, 2012c) "Concern was expressed with the need to have the lake evacuated a sufficient amount in the spring to effectively manage high spring snowmelt and rain induced flood flows. Input from interests along the river indicated that a flow above 10,000 cfs results in some overbank flow and minor flooding. This is much lower than the channel capacity of 20,000 cfs identified by the COE at the time the Yellowtail Unit was constructed."

Operators consider the maximum desirable release without using flood control space to be 15,000 cfs. This allows for a 5,000 cfs "buffer" on releases which can be used in conjunction with flood control space to mitigate potential flooding from unforeseen spring and summer precipitation events (Micek, 2018). If an event with significant precipitation downstream of Yellowtail Dam occurs while releasing a high flow rate for snowmelt runoff, as did in 2011, operators still have room to mitigate high flows downstream on the Bighorn and Yellowstone Rivers with both safe channel capacity and exclusive flood storage in Bighorn Lake. This is a reasonable approach but has not been defined within operating criteria or standard operating procedures and should be clarified. Because USACE has exclusive control over the exclusive flood control space and joint control with Reclamation over the joint use pool, Reclamation should coordinate with USACE when describing this procedure in standard operating procedures.

Explicit guidance on rule curve tracking

According to the 2010 Operating Criteria Final Report (Reclamation, 2012):

> *Some flexibility and judgment should be exercised in determining how close the actual operations follow the rule curves as making operations strictly follow the rule curve could result in a number of significant and frequent release adjustments. Normally, adjustments to the lake releases should be based on looking several days or a week ahead to allow time for the lake level to come back on track with the rule curve.*

It is not clear how frequency of adjustments to rule curves impact operations. MTAO should examine the impacts of different frequencies of targeting the rule curves. Similarly, guidance should be developed on how large of deviations can be allowed before changing river releases to track back to both rule curves and targets used to set winter flows.

Examine variable drawdown timing

The rule curves were constructed using assumed, average inflow timing. Changes in hydrology, irrigation practices upstream of Bighorn Lake, and management of Boysen and Buffalo Bill Reservoirs all impact inflow timing. As shown by operations under the perfect forecast scenario in 2016, Bighorn Lake was unable to fill due to the assumed inflow timing contained by the rule curves. Reclamation's coordination between MTAO and WYAO operators allows them to obtain better information regarding inflow timing than the assumed inflow hydrograph used to develop rule curves. Likewise, if ensemble forecasts indicate an increased likelihood of earlier/later runoff timing due to inclusion of temperature forecasts, reservoir drawdown should be shifted to maximize the efficiency of operations.

MTAO should conduct a study or review of similar studies examining the potential for prediction of peak inflow timing and variable rule curve timing. Should skill exist in predictions of inflow timing, it would potentially be feasible to change the peak drawdown date of rule curves to reduce the magnitude and duration of peak river releases.

General Operations

Avoid hedging operations with the uniform release factor

The Bighorn Lake ROMS model utilizes a monthly factor described as a "uniform release factor." (Bureau of Reclamation, 2009) The model calculates required mean release in excess of demands to a certain storage target and multiplies the mean release by the uniform release factor. This allows operators to distribute the excess volume amongst the months before the required target storage. For example, if the rule curves target an April 30 pool elevation of 3,610 ft., and the forecast date is January 1, the operator has four months to distribute the excess volume releases. The uniform release factor can be implemented to weight certain months higher than others. An example of this operation is setting winter flows during water year 2013, as described above.

Applying a uniform release factor may result in higher or lower releases, and therefore pool elevations, for certain months. The operator can use this to hedge operations toward either ensuring filling or greater drawdown in anticipation of flood control. The study defining the **2010 operating criteria** did not consider the use of a uniform release factor for hedging, and it is possible that implementing uniform release factors can result in inequitable operations preferring either lake recreation or river recreation. Absent reasons to hedge operations toward filling or drawdown (such as skewed forecast error distributions), operators should maintain releases as directed by the operating criteria. It should be noted that the uniform release factor is useful when developing minimum and maximum plans, where the current month release is typically set by the most probable plan. This should result in plans showing release changes after the current month.

Daily operations modeling

Currently, MTAO operators create monthly plans using a monthly timestep operations model. Short-term operations are use a daily timestep spreadsheet model. Operations using daily inflows and monthly average inflows result in significant differences for calculated releases. Monthly modeling obscures the impacts of inter-monthly variability, and typically will result in lower calculated peak releases than daily modeling.

The model used for this study can be run in a forward-looking operational mode. This model is currently being tested in parallel with current operating tools with the goal of replacement of both monthly Reservoir Operations Modeling System (ROMS) models and daily spreadsheet models. Moving to a RiverWare model for operations will also result in labor efficiency improvements for MTAO operators.

Implement basin-wide operations model

As described previously, forecasts used for setting winter flows were updated under the (Bureau of Reclamation, 2012c) through a linear regression between August through October local gains and November through March local gains. This effort assumed that a downward trend in gains indicated increasing depletions above Bighorn Reservoir.

November 1 forecasts for the post-2012 period showed a significant bias toward underestimating November through March inflows. Because it is undesirable to change flows during the winter period, forecast errors have resulted in large deviations from the anticipated pool elevations.

One approach that may provide better forecasts of winter gains is to explicitly model the diversions, depletions, return flows, and local gains above Bighorn Lake. The post-November gains and losses above Bighorn Lake are impacted by these numerous factors. For example, return flows from irrigation result in streamflow gains. These return flows are dependent on irrigation practices during the summer months and lag by several months of the actual diversions.

GPRO has begun development a daily RiverWare model of the Bighorn and Shoshone Rivers between Boysen and Buffalo Bill Reservoirs and Bighorn Lake. This model represents all significant diversions and inflow points and distributes return flows both spatially and temporally. MTAO should further evaluate this model for implementation and incorporate the model into a more robust approach at forecasting the November through March gains. Because mountain snowmelt is not a significant component of November through March runoff, forecasts generated through hydrologic modeling are more appropriate for forecasting than statistically based forecast models.

Modeling the entire Wind/Bighorn Basin is a logical extension of modeling gains and losses above Bighorn Lake and would aid operators in understanding variability in inflow timing and volume. Boysen and Buffalo Bill Reservoir operations impact inflow timing. Implementing a basin-wide operations model in conjunction with inflow ensembles or other forecast sources would allow operators to quickly examine a much fuller range of inflow scenarios.

Creating a combined operations model would require close consultation and coordination between MTAO and WYAO while developing this model, as well as during operations. A similar example exists within Reclamation's management of the Colorado River Basin. Reclamation splits management of the Colorado River Basin between its Upper Colorado and Lower Colorado Regional Offices. The two offices use a common RiverWare model which is jointly maintained by staff in both offices. The Upper Colorado Region, which manages upstream reservoirs, completes its reservoir operations plans with the RiverWare model and loads model data to a Hydrologic Database (HDB). The Lower Colorado Region then retrieves the model data and completes its reservoir operations plans.

While the basin-wide model will represent WYAO-managed reservoir operations, models rarely completely contemplate all potential operations situations. Modeling assumptions, such as local gains and return flows, will also result in deviations from current conditions. This makes operator adjustments necessary to upstream conditions prior to conveying inflow scenarios to MTAO for operational decisions.

Incorporate ensemble inflow forecasts

Incorporating the ensembles described above will allow operators to quickly evaluate a large number of potential future inflow conditions. Operators currently evaluate "what if?" scenarios while making daily operational decisions during the spring and early summer. For example, operators might generate a median forecast and evaluate the impacts of scaling the volume by a certain percentage or alter the peak inflow timing by several days. This allows the operators to determine potential risks from runoff volume and timing uncertainty, and make decisions mitigating these potential risks. Incorporating automated ensembles from sources such as the NWS will allow operators to dramatically reduce time spent generating potential future inflow scenarios while also increasing the number of scenarios evaluated.

Incorporating these ensemble forecasts is dependent on hindcasting the ensembles, as described above, and implementation of a basin-wide RiverWare model. The basin-wide model would represent basin depletions between the headwaters where most of the flow comes from. Precipitation-runoff models better represent these headwaters basins, whereas operations models better represent the depletions and diversions between basin inflow points and Bighorn Lake.

Implementation

The recommendations described above are extensive and implementing all the recommendations would be time-consuming and costly. MTAO and GPRO considered available resources, implementation time, and impact to operations when developing the following preliminary implementation plan, shown in Table 20.

Table 20: Recommendations and implementation effort and impact to operations.

	#				
Previously initiated	1		**Avoid hedging operations using uniform release factor**	Completed	MTAO
	2		**Implement daily time-step operations model**	Model 100% complete Parallel testing Started Jan 1, 2019	GPRO & MTAO
	3		**Evaluate improvements to statistical forecasts**	Started - 30% complete	MTAO, GPRO and WYAO
	4		**Study enhanced resolution snowmelt runoff modeling**	Started - 5% complete	TSC/NCAR/GPRO
Priority Recommendations	5		**Model and evaluate explicit low-flow rules**	Not Started (1)	GPRO
	6		**Examine frequency of elevation targeting**	Not Started (2)	MTAO
	7		**Remove Encroachment into Flood Pool**	Not Started (3)	MTAO
			Update rule curves to anticipate higher inflow volumes	Not Started (3)	MTAO
			Explicitly define relationship between flood pool and releases	Not Started (3)	MTAO or GPRO
	8		**Examine skill of forecast components**	Not Started (4)	GPRO, MTAO, & WYAO
	9		**Implement basin-wide operations model**	Not Started (5)	MTAO, GPRO & WYAO
	10		**Evaluate skill of NWS and other forecast ensembles**	Not Started (6)	GPRO, NWS
Dependent Recommendations	11		**Incorporate ensemble inflow forecasts**	TBD	TBD
	12		**Examine variable drawdown timing**	TBD	TBD

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