Low-Flow Operations Study at Bighorn Lake

Missouri Basin Regional Office

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Cover Photo: Light shining through over Yellowtail Dam and Reservoir

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Introduction and Objectives

Reclamation implemented changes to the Bighorn Lake Operating Criteria in October 2009. These operating criteria specify how to operate the reservoir to balance water supply, instream flow, flood control space, and hydropower needs. Reservoir operational decisions are based on a variety of factors and depend on the time of year. This Low-Flow Operations study primarily focuses on reservoir operations during the runoff season, which is typically between March and July. Reservoir operations rely on rule curves or low-flow thresholds to set reservoir releases during runoff season. Reservoir operators use rule-curves to set releases when the forecasted inflows meet the minimum fill volume threshold. The minimum fill volume threshold is met when the reservoir is forecasted to fill to an elevation of 3,640 ft by the end of July while maintaining instream flows downstream of at least 2,000 cfs. If the inflow forecasts do not meet the minimum fill volume threshold requirements, then reservoir operators follow low-flow operating criteria.

The final draft report regarding the Yellowtail Unit operating criteria evaluation conducted from 2007 through 2010 did not specify how to set releases in low-flow conditions (Reclamation, 2012a). The report did provide guidance that releases should be set to 2,000 cfs if current reservoir conditions and forecasts predict that a release near 2,000 cfs will allow the lake to meet the target elevation of 3,617 ft on the following March 31 (Reclamation, 2012a). If meeting the following March 31 target is not likely to be met with a minimum 2,000 cfs release, the report left decisions up to operator discretion. The Yellowtail Unit operating criteria evaluation uses a minimum fill volume threshold to determine if the reservoir is in rule-curve or low-flow operations by comparing the forecasted inflow volume with a volume calculated to fill the reservoir. The volume calculated to fill the reservoir in the Yellowtail Unit operating criteria evaluation is a static inflow forecast volume of 726,768 AF that assumes a pool elevation of 3,617 ft is achieved on March 31. However, the pool elevation on March 31 of any given year could be a range of pool elevation values. The policies included in the Yellowtail Unit operating criteria evaluation (Reclamation, 2012a) are the policies examined in the 2019 Bighorn Lake Operating Criteria Review (Reclamation, 2019). Therefore, this study uses the operating criteria evaluation from 2012 (Reclamation, 2012a) as a baseline for model development and testing.

The 2019 Bighorn Lake Operating Criteria Review highlighted the ambiguity in low-flow operational guidance as an area for improvement. The Operating Criteria Review recommended modeling and evaluating explicit low-flow conditions. Additionally, the Operating Criteria Review recommended a minimum fill volume threshold that considers current reservoir conditions, rather than the static minimum fill volume threshold in the Bighorn Operating Criteria. This study aims to fulfill this recommendation by developing a minimum fill volume threshold that considers current reservoir conditions and by developing and evaluating specific low-flow operating criteria.

One objective of the study is developing a minimum fill volume threshold that uses a dynamic inflow volume based on pool elevations to determine if the reservoir should follow rule-curve or low-flow operations. The second objective of this study is developing and evaluating low-flow operating criteria for Bighorn Lake. Using the analysis of the existing low-flow operations in the model, this study determines several areas for improvement and develops, tests, and analyzes multiple new low-flow operational policies. While analyzing low-flow operational policies, the study identified the need for more in-depth forecasting analysis for long-range forecasts.

Methods

The water resources model used for this study is based on the Bighorn RiverWare model developed in the Bighorn Lake Operating Criteria Review (Reclamation, 2019). The RiverWare model is able to test the performance of multiple policy scenarios under various hydrologic and forecast conditions. Only one policy scenario is run at a time to isolate the impact of each policy change. This study examines the time period between 1990 and 2018 because this range includes record drought conditions, record high inflow conditions, and a diverse range of inflows between the extremes.

One objective of the study is developing a minimum fill volume threshold that uses a dynamic inflow volume based on pool elevations to determine if the reservoir should follow rule-curve or low-flow operations. The current operating criteria uses a static inflow volume of 726,768 AF to differentiate between rule-curve and low-flow operations. A static inflow volume of 726,768 AF is the minimum calculated inflow volume required to fill the reservoir by the end of July with a 2,000 cfs release, assuming a pool elevation of 3,617 ft on March 31. A dynamic inflow volume is tested in this study that uses a mass balance computation to determine the inflow volume required to fill the reservoir based on current pool elevations and outflows needed to maintain 2,000 cfs instream river flows. This study summarizes an evaluation of several model scenarios that test the impacts of the dynamic minimum fill volume threshold on operations.

In the process of completing the second objective of this study, developing and evaluating low-flow operating criteria for Bighorn Lake, this study analyzes the existing low-flow operations in the Bighorn RiverWare model. The existing low-flow operations in the Bighorn RiverWare model originate from the 2019 model described in the Bighorn Lake Operating Criteria Review (Reclamation, 2019). Additionally, a number of new low-flow operational policies are tested and developed as a part of this study.

While analyzing the new low-flow operational policies, the study identified the need for more in-depth forecasting analysis for long-range forecasts. Many of the tested low-flow operational policies rely on long-range forecast accuracy to guide operations. Therefore, understanding the accuracy of long-range forecasts and the impact inaccurate forecasts have on low-flow operations became necessary for the completeness of this study. Inflow forecasts at Bighorn Lake represent a total volume of forecasted inflows to the reservoir over a specified time period. Inflow forecasts are made up of three components: Boysen Reservoir releases, Buffalo Bill Reservoir releases, and local gains. Forecasted releases from Boysen and Buffalo Bill Reservoirs are provided to Montana Area Office by the Wyoming Area Office. Montana Area Office forecasts gains. Gains represent the volume of water that is unaccounted for in Boysen and Buffalo Bill release volumes, which could include natural seepage, snow melt, flow from tributaries, etc. Gains are forecasted by Montana Area Office using the PyForecast software, which takes into account mountain snowpack, precipitation data, antecedent conditions and historic inflows (Reclamation, 2020a).

The forecast analysis completed for this study used historical observed inflows and the inflow forecasts made at the time of operations to test forecast error, goodness of fit, and forecast distributions. These computations were completed by comparing observed inflows with forecasted inflows using Python Pandas programming and Excel.

Monthly forecasts and period forecasts were the two main types of component forecasts analyzed. Historical forecasts are issued on the first of the month and consist of forecasted inflow volume for each of the next twelve months. Monthly component analysis looks at the skill of each month's forecasts for the next twelve months. For example, the monthly component analysis for January would look at the forecast made on January 1 for each month January-December. Period component analysis looks at the skill of each applicable month's April through July forecast (or forecast date through July forecast if forecast date is during this period), each month's forecast through the following March, and each applicable month's forecast for August through the following March, each applicable month's forecast for the fall months, and each applicable month's forecast for the winter months through March.

Results

The dynamic minimum fill volume threshold examined in this study showed differences from the existing Bighorn Operating Criteria in three of the twenty-eight years included in the study. The differences between the dynamic minimum fill volume threshold and the static minimum fill volume threshold found in the existing operating criteria are caused by low pool elevations. The dynamic minimum fill volume threshold considers pool elevations in the calculation process, while the existing Bighorn Operating Criteria do not. Extremely low pool elevations cause the reservoir to enter low-flow operations earlier in the season when using the dynamic minimum fill compared with using the static minimum fill. The impacts of the modeled dynamic minimum fill volume threshold to reservoir operations and to lake and river recreation are negligible. Therefore, the dynamic minimum fill volume threshold is recommended for implementation. The dynamic minimum fill volume threshold is used in the additional modeling analyses that are outlined below to evaluate several low-flow operating policies (Table 1).

In addition to analyzing a dynamic minimum fill volume threshold, this study developed and evaluated nine different low-flow operational policies. Montana Area Office operates the reservoir and can ultimately choose which of these policies to implement. However, this study does provide recommendations for each individual policy. Three of these policies are recommended for implementation, two policies are possible options for Montana Area Office (MTAO) to consider implementing, and four policies are not recommended for further consideration. Table 1 contains a list of low-flow operating policies considered in addition to a description of how the policy performed and the recommended next steps for each policy.

Table 1. Summary of low-flow operating policies examined in this study.

Low-Flow Operating Policy Name	Description of Policy	Description of Policy Performance	Recommendation?
Inactive Conservation Check	Allows releases to drop below 1,500 cfs only if pool elevations are forecasted to drop below the top of inactive conservation within the next month.	Decreases amount of time with pool elevations below 3,547 ft and stabilizes release patterns.	Recommended for implementation - clarifies operating criteria and fixes an error made in model development.
Removal of Summer Low-Flow Targets	Removes high pool fall targets from consideration during summer low-flow operations.	No impact to releases, pool elevations, or hydropower.	Recommended for implementation.
Intermediate Fall Target	Considers intermediate fall targets to guide spring and summer releases to target 3,617 ft in the following March.	Inconsistent release patterns through the spring, summer, and fall with detrimental impacts to pool elevations.	Not recommended for further consideration.
Dynamic Early Spring Target	Set March releases to target an end of March pool elevation calculated to fill the reservoir by the end of July given the current forecasts while maintaining 2,000 cfs instream flows.	Releases were almost always set to 1,500 cfs to hit a high end of March target.	Not recommended for further consideration. The purpose of the target was to fill the reservoir while maintaining 2,000 cfs, so releases of 1,500 cfs in most scenarios is not acceptable.
Balanced March Target	Balances releases between maintaining 2,000 cfs instream flows and conserving water for the following year by averaging the release to hit 3,617 ft the following March with 2,000 cfs during the spring and summer months.	Increases releases between 1,500 cfs and 2,000 cfs. Some impacts to pool elevations in single year drought events, major impacts to pool elevations in multi-year drought events.	Operating policy analysis provided for MTAO's consideration. Needs some additional checks and balances in multi-year events to avoid major detriments to pool elevations.
2020 Operating Criteria	Low-flow operating criteria described in 2020 Condensed Operating Criteria. Sets releases to target following March elevation of 3,617 ft as long as that release is between 1,500 cfs and 2,000 cfs.	This case limits releases to 2,000 cfs in all low-flow conditions which has some benefits to pool elevations and some detriments to releases.	Operating policy analysis provided for MTAO's consideration.

End of March Target	Set March releases to target the end of the month rather than target the following March 13 months into the future.	Stabilizes release patterns when using historical forecasts by avoiding April through July forecast errors but performs poorly when given advanced knowledge of inflow conditions.	Not recommended for further consideration.
Year Out Inactive Conservation Check	Performs the same calculation as the inactive conservation check but looks out a full year rather than one month into the future.	Similar impacts to the inactive conservation check, but the releases below 1,500 cfs are less extreme because there is more time for the operator/model to adjust.	Recommended for implementation – if this policy is implemented the Inactive Conservation Check is no longer necessary.
Low Pool Elevation Check	Caps releases at 1,500 cfs if the pool elevation is below the minimum drawdown elevation of 3,591.5 ft.	Avoids unrealistically high releases when pool elevations are extremely low.	Recommended for implementation.

Additionally, this study considers how these separate operating policies interact with one another by modeling various combinations of each policy. The two combined models analyzed in this study are the Combined Balanced March Target case and the Combined 2020 Operating Criteria case. The Combined Balanced March Target case combines the Balanced March Target case with the dynamic minimum fill volume threshold, the Year Out Inactive Conservation Check, the Low Pool Elevation Check, and the Removal of the Summer Low-Flow Targets. The Combined 2020 Operating Criteria case combines the 2020 Operating Criteria Target case with the dynamic minimum fill volume threshold, the Year Out Inactive Conservation Check, the Low Pool Elevation Check, and the Removal of the Summer Low-Flow Targets.

The two combined policies were first compared against one another using modeled data from individual years. However, looking at specific years may only represent the year in question and may not apply to future years or correctly identify patterns. Therefore, the study compared several cases and years against one another at once, with data compiled for different seasons and metrics. By comparing multiple years at once, identification of patterns in the data is more straight-forward.

Choosing the most appropriate operational policy for Bighorn Lake low-flow conditions will require careful consideration. The Combined 2020 Operating Criteria increases pool elevations in all scenarios compared with the Combined Balanced March case, but the impacts to releases are more complicated. Generally, the Combined 2020 Operating Criteria reduces the quantity of time with releases at or below 1,500 cfs, while the Combined Balanced March case increases the quantity of time with releases at or above 1,750 cfs. There are no major differences between either case in Yellowtail hydropower energy value.

Lastly, this study analyzes the performance of various components of historical forecasts when compared with the actual observed inflows. The results of the monthly forecast analysis varied depending on the season and the metric. Generally, forecast skill is reasonably high for forecasts looking ahead two months. For example, the forecasts made on March 1 have low error and high goodness of fit metrics for March and April. The March 1 forecast for May has a lower goodness of fit but similar error. The March 1 forecast for June and July has high error and low goodness of fit. The error is lower for August-February than the June and July forecasts, but a similarly low goodness of fit metric. There is some variation between months, but generally the two-month forecast window is skillful, with less skill as the months progress. Months with high variations in inflow volumes, such as June and July, have the least skillful forecasts.

The period forecast analysis showed two main patterns: the April through July forecasts increase in skill with each month and the other period forecasts show little variation between months. The forecasts made on January 1, February 1, March 1, and April 1 for April through July inflows have high errors and low goodness of fit metrics, with skill improving with each month. The long-range forecasts periods (current month through following March, August through following March, August-October, and November-March) all show less variation in skill than the April through July forecasts. The long-range forecasts made on March 1 and April 1, regardless of the period examined, have the least amount of skill.

Recommendations

The recommended low-flow operating criteria implements a combination of the following policies:

- Dynamic minimum fill volume threshold
- Year Out Inactive Conservation Check
- Low Pool Elevation Check
- Removal of the Summer Low-Flow Targets

In addition to the recommended low-flow operating criteria policies, two policies are recommended for MTAO's consideration:

- Balanced March Target
- 2020 Operating Criteria

Both the Balanced March Target and the 2020 Operating Criteria cases have positive and negative impacts to operations. The Balanced March Target balances storage with water use in the current year and increases the quantity of time with river releases above 1,750 cfs during the spring and summer months. The 2020 Operating Criteria prioritizes storage for the following year and therefore increases the quantity of time with lake recreation in the current year. Conversely, the

Balanced March Target has a risk of being too aggressive with releases, resulting in a storage deficit for the following year. The 2020 Operating Criteria has a risk of being too conservative with releases, which could cause large release events downstream if an unforecasted inflow event occurs. This study lays out the risks and advantages of each policy but leaves the final decision for policy implementation up to Montana Area Office.

Regardless of which policy or combination of policies is implemented, policies selected for implementation should be clearly defined in the Bighorn Operating Criteria. The previous renditions of operating criteria at Bighorn Lake have been inconsistent and unclear when defining low-flow operations. This study recommends defining low-flow operations to improve transparency and operational guidance in future versions of the Bighorn Operating Criteria.

Separate from the low-flow operational policy recommendations, there are two recommendations for improving forecasting methods during low-flow operations at Bighorn Lake. The first recommendation is to continue setting releases to target 3,617 ft at the end of March for January and February during periods of low-flow forecasts. Starting in March, the reservoir can either enter rule-curve operations or low-flow operations targeting the following March. The second recommendation is to modify the long-range forecast procedure. The main part of this recommendation is to avoid using forecasted April through October gains to forecast the November through March gains, which could compound the errors in a long-range forecast window. One possible solution is to use the median forecast for November through March gains. However, investigating this solution is dependent on the results of another Bighorn Recommendation that examines component forecasts.

This is a short summary of all the recommendations of this study:

- Implement the dynamic minimum fill volume threshold.
- Implement the Year Out Inactive Conservation Check.
- Implement the Low Pool Elevation Check.
- Implement the Removal of the Summer Low-Flow Targets.
- Consider implementing one of the following operational policies:
    - The Balanced March Target
    - 2020 Operating Criteria
- Define low-flow operations in the Bighorn Operating Criteria to improve transparency and operational guidance.
- Consider setting releases to target 3,617 ft at the end of March for January and February during periods of low-flow forecasts.
- Consider modifying the long-range forecast procedure.

Limitations

Lastly, there are a number of limitations of this study. Most of the limitations for the modeling analysis are model limitations and include model granularity, unrealistically high releases, and poor response times to unexpected inflow events. A major limitation of this study for both modeling and forecast analysis is that it uses past results to predict the future. Past hydrologic and forecast conditions are a useful tool, but do not represent the full range of possible hydrologic and forecast conditions. Additionally, there are only thirty years of historical data available for analysis, but only sixteen years of data with at least one low-flow forecast made and only ten years of actual low-flow inflow conditions. These sample sizes pose a limitation to the accuracy of the modeling and forecast analysis.

Introduction

Reclamation implemented changes to the Bighorn Lake Operating Criteria in October 2009. The operating criteria precipitated from a prolonged drought from 2000 to 2007 and were intended to improve water supply reliability, recreation, hydropower generation, and flood control. As part of the operating criteria development process, the Bighorn River Issues Group formed. The Bighorn River Issues Group is comprised of stakeholders from various groups and provides opportunities for input and direct communication between Reclamation and stakeholders. Reclamation and the Bighorn River Issues Group worked collaboratively to form the Bighorn Lake Operating Criteria in 2010, and later revised the operating criteria in 2011, 2012, and 2015. In 2020, Reclamation published a condensed summary of the Bighorn Operating Criteria (abbreviated 2020 Condensed Operating Criteria, Reclamation 2020).

The Bighorn Operating Criteria govern operations using reservoir elevation targets, instream flow targets, rule curves, inflow forecasts, and a minimum fill volume threshold. There are three reservoir elevation targets throughout the year that are used to balance instream flows with adequate storage space. August through February operations set releases to target reservoir elevations and to balance winter releases with carryover storage needs. March through July operations either use rule-curve operations or low-flow operations to balance spring and summer water needs with flood control and water supply storage needs. The reservoir follows rule-curve operations when the forecasted inflows meet the minimum fill volume threshold. The minimum fill volume threshold is met when the reservoir is forecasted to fill to an elevation of 3,640 ft by the end of July while maintaining instream flows of 2,000 cfs. If the inflow forecasts do not meet the minimum fill volume threshold requirements, then the reservoir follows low-flow operations.

In 2019, Reclamation completed the RiverWare Modeling Review of Bighorn Lake Operating Criteria (Reclamation, 2019). The goals of this report were to determine if differences existed between the expected and the realized benefits of the operating criteria created in 2010 and to identify potential causes of differences between these benefits. Additionally, the 2019 Operating Criteria Modeling Review provided several recommendations to potentially improve reservoir operations. One of the recommendations from the Operating Criteria Modeling Review was to create, model, and evaluate explicit low-flow rules. An additional component of the low-flow recommendation was to reconsider the minimum fill volume threshold.

This study examines several versions of low-flow operating criteria from 2010 through 2020. The low-flow operations examined in the 2019 RiverWare Modeling Review of Bighorn Lake Operating Criteria (abbreviated Operating Criteria Modeling Review) were not explicitly defined (Reclamation, 2019). The criteria provide some guidelines for operators to consider when setting releases in low-flow conditions, but ultimately leave operational decisions up to operator discretion. The low-flow operations from the 2020 Condensed Operating Criteria offer more guidance to operators, but these operations were not included in the Operating Criteria Modeling Review model. The 2020 Condensed Operating Criteria are examined as a low-flow operating criteria option.

Study Objectives

The RiverWare Modeling Review of Bighorn Lake Operating Criteria recommended developing a new minimum fill volume threshold methodology. The minimum fill volume threshold is used to determine when low-flow rules are applicable to operations. In the Bighorn Operating Criteria from 2012, the minimum fill volume threshold is a fixed inflow volume that will result in a reservoir elevation of 3,617 ft on March 31 (Reclamation, 2012a), assuming a 2,000 cfs constant release from the reservoir. Due to differences between forecasting and actual inflows, infrequent release changes during winter, and setting releases to target rule curves at some point during the early spring, the March 31 pool elevation is not always 3,617 ft. A dynamic value that considers the March 31 elevation could provide an accurate volume required to fill.

In addition to the minimum fill volume threshold, the Operating Criteria Modeling Review recommended modeling and evaluating explicit rules for periods with inflows forecasted below the minimum fill volume threshold. The low-flow operations reviewed in the Operating Criteria Modeling Review provided limited guidelines and left operational decisions to operator discretion. The Operating Criteria Modeling Review identified the lack of explicit low-flow rules as a potential area of improvement to operations. To complete this recommendation, both the low-flow operations within the Bighorn RiverWare Model and additional low-flow operational policies were evaluated to determine whether improvements, such as efficient water supply use for hydropower and fishery use or efficient water supply storage for lake recreation and water conservation, could be made to operations at Bighorn Lake.

This report is split into two main sections. The Dynamic Minimum Fill Threshold section discusses the minimum fill volume threshold scenario. The Low-Flow Operating Criteria section discusses the low-flow operating criteria scenarios. The dynamic minimum fill volume threshold was developed and tested prior to the low-flow operating criteria because the dynamic minimum fill volume threshold determines when low-flow operating criteria is in effect. Therefore, changes to the minimum fill volume threshold could have major impacts on low-flow operations. After the minimum fill changes were tested, all low-flow operating criteria scenarios were based on the recommended minimum fill changes.

Model Background and Methodology

The model used for this study is based on the Bighorn RiverWare Model from the Operating Criteria Modeling Review (Reclamation, 2019). RiverWare is a river system modeling software developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES). The Bighorn Model uses RiverWare to represent physical attributes and operational policies of the Bighorn Basin. Modeling the Bighorn Basin provides the opportunity to test impacts of model and policy changes on operations under various hydrologic and forecasting scenarios. This study considers water years 1990 through 2018. This period includes both the most extreme drought conditions and highest inflows on record, as well as a diverse range of inflows between the extremes.

Operating Criteria Background

Between 2010 and 2020, Reclamation published four different versions of the Bighorn Operating Criteria in 2010, 2011, 2012, and 2020. The report entitled "Changes for the 2012 Water Year" was published in 2011 and outlined several changes from the 2010 Yellowtail Unit Operating Criteria Evaluation Study and Report. The Yellowtail Unit Operating Criteria Evaluation, published in 2012, formally reviewed the 2010 Operating Criteria and provided several revisions based on this analysis. Despite the difference in publishing dates, the Changes for the 2012 Water Year report is the more recent document in terms of operational policies. The operating criteria changes in 2015 were minor and were not accompanied with a report or formal documentation. These changes were first formally documented in the 2020 Condensed Operating Criteria. The 2020 Condensed Operating Criteria provides an overview of the operating criteria currently in use at Bighorn Lake. See Table 2 for an explanation of each operating criteria and the naming convention used in this report.

Table 2. Summary of Bighorn Lake operating criteria versions. If Bighorn Operating Criteria is referenced with no date, the study is referring to the operating criteria generally rather than an individual year.

Formal Report Name	Year Published	Description	Name Used in this Report
Draft Bighorn Lake Operating Criteria Evaluation Study and Report – 2010 (Reclamation, 2010)	2010	Original document	2010 Bighorn Operating Criteria
Draft Bighorn Lake Operating Criteria Changes for the 2012 Water Year (Reclamation, 2011)	2011	Some changes from the 2012 Bighorn Operating Criteria, more recent than 2012 Bighorn Operating Criteria despite earlier publishing date	2011 Bighorn Operating Criteria
Final Draft Bighorn Lake Operating Criteria Evaluation Study and Report – 2011 (Reclamation, 2012a)	2012	Changes from 2010 Bighorn Operating Criteria. 2019 Modeling Review used the low-flow operations from this version	2012 Bighorn Operating Criteria OR operating criteria used in 2019 Modeling Review

No formal documentation	2015	Minor changes to the Draft Bighorn Lake Operating Criteria Changes for the 2012 Water Year	N/A
Condensed Yellowtail Dam Operating Criteria (Reclamation, 2020a)	2020	No changes made from 2015 operating criteria version	2020 Bighorn Operating Criteria

The 2019 Operating Criteria Modeling Review studied the operational impacts of implementing the Bighorn Operating Criteria and provided a number of recommendations for further study. Due to unclear documentation and confusion around the published dates of the existing documentation, the low-flow operations represented in the 2019 Operating Criteria Modeling Review only include operational changes made in the 2012 Bighorn Operating Criteria and changes made in 2015. The low-flow operations represented in the 2019 Operating Criteria Modeling Review do not include operational changes from the 2011 Operating Criteria.

This study uses the 2019 Operating Criteria Modeling Review model, and therefore uses the low-flow operating criteria presented in the 2012 Bighorn Operating Criteria instead of the most up-to-date 2011 or 2020 Bighorn Operating Criteria, to represent a base case for low-flow operations. There are several reasons for basing the analysis on low-flow operations from the 2011 Bighorn Operating Criteria instead of the 2011 or 2020 Bighorn Operating Criteria. The low-flow operations from the 2012 Bighorn Operating Criteria have undergone review and analysis through the 2019 Operating Criteria Modeling Review. Testing the low-flow operations from 2011 and 2020 Bighorn Operating Criteria requires a base case model to isolate what modeled results are caused by differences in operational policies and what modeled results are due to the limitations in modeled operations. This study models the low-flow operations from the 2011 and 2020 Bighorn Operating Criteria against both the low-flow operations from the 2012 Bighorn Operating Criteria and against other scenarios considered throughout this study. Therefore, all operating criteria versions are thoroughly reviewed in this study.

2012 Low-Flow Operating Criteria

The 2012 Bighorn Operating Criteria provides low-flow operational guidance. In the 2012 Bighorn Operating Criteria, low-flow conditions exist when the April through July forecasted inflows are less than the minimum fill volume threshold. The 2012 Bighorn Operating Criteria does not specify how to set releases in low-flow conditions and instead provides the following guidelines and leaves operational decisions up to the operator's discretion:

> *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****. (Reclamation, 2012a)*

2011 and 2020 Low-Flow Operating Criteria

The low-flow operating criteria is the same in both the 2011 and 2020 Bighorn Operating Criteria documents. There is more operational guidance provided in the 2011 and 2020 Bighorn Operating Criteria than in the 2012 Operating Criteria. The 2011 and 2020 Bighorn Operating Criteria specify that releases during low-flow operations should be between 1,500 cfs and 2,000 cfs while targeting 3,617 ft in the following March:

> *It may be necessary to reduce the river release to 2,000 cfs or less to adequately conserve storage for long term operations in years with forecasted runoff of less than 727,000 acre-feet. The primary goal in low water years is to conserve storage to provide a stable river release rate of between 1,500 cfs to 2,000 cfs while allowing storage to stay near the desired elevation of 3617 feet by March 31 of the following year. (Reclamation, 2020a)*

River Releases and Pool Elevation Background

Understanding the context for the river release rates and pool elevation targets discussed in this study requires some background information on Bighorn Lake. River release targets used in the Bighorn Model and Bighorn Operating Criteria originate from the Streamflow and Lake Level Management Plan, Bighorn River and Bighorn Lake, which is connected with the Crow Tribe water rights settlement (State of Montana, Crow Tribe, Department of the Interior, 2000). The Management Plan defines releases as follows, as measured at the USGS 0627000 Bighorn River near St. Xavier river gaging station and in accordance with water supply availability:

- *Optimum Instream Flow: A minimum flow target of 2,500 cubic feet per second. Under current conditions, this flow level provides good spawning, rearing and cover conditions for fish in all major side channels. Optimum Instream Flow shall be provided as consistently as possible as determined by the monthly plans.*
- *Standard Instream Flow: A minimum flow target of 2,000 cubic feet per second. Under current conditions, this flow level provides adequate spawning and rearing conditions for fish in most side channels but cover for adult fish is limited. Standard Instream Flow shall*

be provided when water is not available to meet Optimum Instream Flow as determined by the monthly plans.

- *Minimum Instream Flow: During low flow periods, the minimum flow target of 1,500 cubic feet per second. Under current conditions, this flow level protects main channel habitat for fish but not important side channels. Fish populations will decline at this flow level. Minimum Instream Flow shall be provided when water is not available to meet Optimum Instream Flow or Standard Instream Flow as determined by the monthly plans. In the event of emergency, dam safety inspection, or when the forecasted water supply indicates that maintaining the Minimum Instream Flow presents a serious risk of fully depleting available storage, Releases may be reduced below 1,500 cubic feet per second (State of Montana, Crow Tribe, Department of the Interior, 2000).*

Additionally, there is a maximum safe channel capacity at St. Xavier of 20,000 cfs (United States Army Corps of Engineers, 1971).

Pool elevation targets seen in Table 3 used in the Bighorn Model originate from the 2020 Bighorn Operating Criteria (Reclamation, 2020a).

Table 3. Seasonal Bighorn Lake elevation targets based on the Bighorn Operating Criteria.

Date	Pool Elevation Target (ft)
October 31	3,635-3,640
March 31	3,617 (for establishing winter release)
July 31	3,640

For additional context, the Bighorn Lake allocation diagram defines storage allocation pools as described in Table 4 (Reclamation, 2020b).

Table 4. Bighorn Lake storage allocations, as defined by the Bighorn Lake allocation diagram.

Top of Storage Allocation Pool	Pool Elevation (ft)
Maximum Water Surface	3,660.0
Top of Exclusive Flood Pool	3,657.0
Top of Joint Use Pool	3,640.0
Top of Active Conservation Pool	3,614.0
Top of Inactive Conservation Pool	3,547.0
Top of Dead Pool	3,296.5
Streambed	3,166.0

In 2021, the National Park Service published a press release recommending a minimum boat launch lake elevation of 3,620 ft at Horseshoe Bend (National Park Service, 2021). Large boats are only recommended to launch from Horseshoe Bend at lake levels of at least 3,625 ft. Previously, the recommended minimum launch level was 3,617 ft at Horseshoe Bend.

Bighorn Modeling Review Low-Flow Modeled Operations

The Bighorn RiverWare Model represents the low-flow operations from the 2012 Bighorn Operating Criteria. Limitations in the RiverWare model software and lack of clarity in the operating criteria limits the model's ability to precisely replicate the operating criteria. Factors in the model that limit model accuracy in representing real-world conditions include timestep granularity, unrealistically high releases, and poor response times to unexpected inflow events. See the "Limitations" section for further information on model limitations. Lack of clarity in the Bighorn Operating Criteria necessitates interpreting operating criteria language into clearly defined logic that the model can use to make decisions.

The first task of this study is examining and analyzing the existing low-flow operations in the model. This section describes the existing operations represented in the Bighorn RiverWare Model, called the base case model. The modeled low-flow operations are split into several sections including the minimum fill volume threshold, as well as seasonal operations in Early Spring, Spring, and Summer seasons as defined in Table 5.

Bighorn Lake modeled operations are set up on a seasonal basis. The model seasons are defined in Table 5.

Table 5. Definitions of seasons used in the Bighorn RiverWare model.

Season	Start Date	End Date
Early Spring	January 1	March 31
Spring	April 1	May 31
Summer	June 1	July 31
Fall	August 1	October 31
Winter	November 1	December 31

Minimum Fill Volume Threshold

The minimum fill volume threshold in the Bighorn Operating Criteria is the minimum April through July inflow volume required to fill the reservoir by July 31 while maintaining a Bighorn River release of 2,000 cfs. This threshold is the divider between rule-curve operations and low-flow operations. The static minimum fill volume threshold also assumes that the reservoir elevation is 3,617 ft on March 31 of that year. With this pool elevation assumption, the static minimum fill volume threshold April through July inflow volume is 726,768 acre-feet, which is based on 26th percentile of inflow. The model compares the forecasted April through July inflow volume to the minimum fill volume threshold. If the forecasted inflow volume is less than the minimum fill volume threshold, the reservoir is not expected to fill by July 31 with 2,000 cfs releases and the model enters low-flow operations. If the forecasted inflow volume is greater than or equal to 727,768 acre-feet, thereby allowing the reservoir to fill by July 31 with 2,000 cfs releases, the model enters rule-curve operations. All Bighorn Operating Criteria versions from 2010 to 2020 include the static minimum fill volume threshold.

Although the static minimum fill volume threshold assumes the reservoir will reach an elevation of 3,617 ft on March 31, the actual observed elevation can be several feet lower or higher than 3,617 ft on March 31. This discrepancy is because the March 31 target of 3,617 ft is used to set winter releases (November 1 – December 31) and is not used to set releases during the month of March. Because the March 31 target is used for winter release calculations only and because releases can switch to targeting rule curves instead of the March 31 target in Early Spring, there can be a discrepancy between observed and expected elevations on March 31.

There are several reasons to consider adding a minimum fill volume threshold that considers current pool elevations to the Bighorn Operating Criteria. The minimum fill volume threshold is intended to inform whether the reservoir can fill during the current runoff season (Reclamation, 2012a) while maintaining the standard instream flow target. However, setting a target pool elevation of 3,617 ft on March 31 limits the ability of the reservoir to fill by July 31. This limitation seems to be counter to the intent of the minimum fill volume threshold and appears to be an oversight in the Bighorn Operating Criteria. By considering the current and forecasted pool elevations in a minimum fill calculation, the actual needed inflow volume to fill the reservoir could be more accurately quantified. A more accurate estimate of minimum fill volume threshold would better represent the intent of the operating policy. In this study, a dynamic minimum fill volume threshold calculation is described that incorporates current and future pool elevations. Use of a dynamic minimum fill volume threshold will be described later.

Early Spring Modeled Operations

Early Spring operations (January 1 through March 31) rely on one of two calculations. If the forecasted inflow volume for April 1 – July 31 is less than the upper quartile forecast threshold, which is calculated as 1,584,000 acre-feet, and the model timestep is in either January or February, the model sets releases to meet the 3,617 ft pool elevation target on March 31. If this calculated release is less than 1,500 cfs, the model sets the release to 1,500 cfs.

In March, the model checks the minimum fill volume threshold and determines if reservoir should enter rule-curve operations or low-flow operations. If the model enters low-flow operations, it sets releases to reach the targeted March 31 pool elevation in the following year. This means that operations are setting releases while targeting a pool elevation 13 months away from March 1 of the current year. If this release is less than 1,500 cfs, the model sets the release to 1,500 cfs. See Figure 1 for a flowchart further describing the model logic.

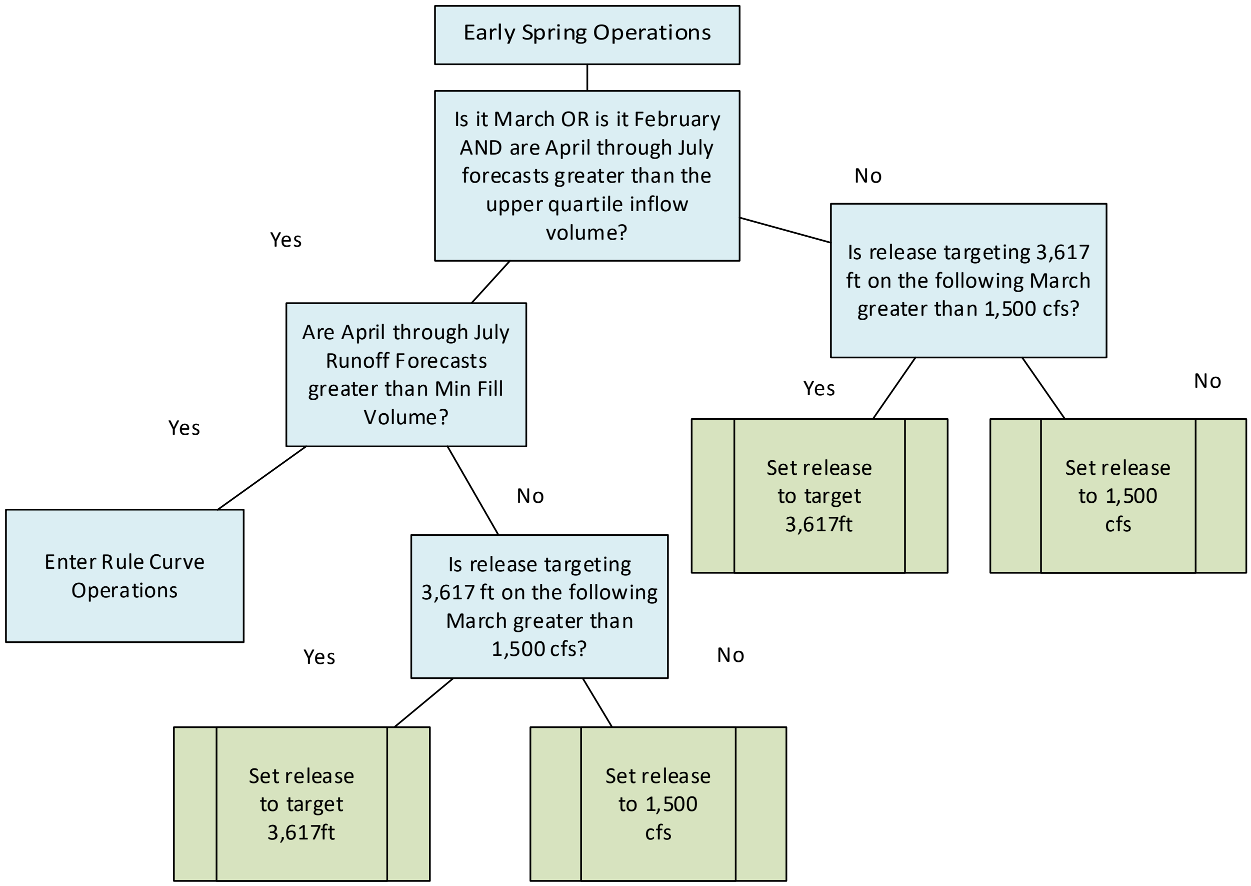


Figure 1. Flowchart with early spring low-flow operations in the existing model. Early spring operations are in effect from January 1 through March 31 of each year.

Spring Modeled Operations

In Spring operations, the model checks the minimum fill volume threshold to determine if the reservoir should follow rule-curve operations or low-flow operations. Spring operations are in effect from April 1 through May 31 of each year. If conditions trigger low-flow operations, the model sets releases based on the March 31 pool elevation target or at 1,500 cfs, whichever is greater. See Figure 2 for a flowchart further describing the model logic.

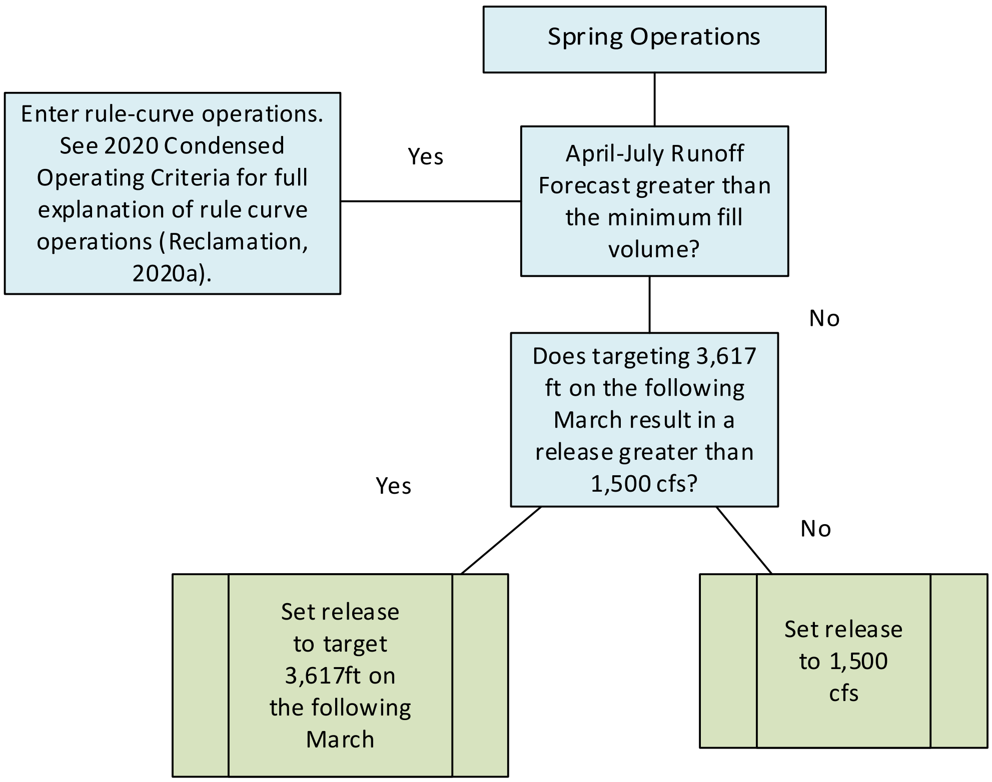


Figure 2. Flowchart with spring low-flow operations in the existing model. Spring operations are in effect from April 1 through May 31 of each year.

Summer Modeled Operations

In Summer operations, the model checks the minimum fill volume threshold to determine if the reservoir should follow rule-curve operations or low-flow operations. Summer operations are in effect from June 1 through July 31 of each year. If conditions trigger low-flow operations, there are several targets and releases the model considers. Depending on how the releases compare to each other, the model could set releases to 1,000 cfs, 1,500 cfs, 2,500 cfs, or set releases to maintain the top of inactive conservation (3,547 ft) pool elevation target on the following March 31, the following March 31 target pool elevation (3,617 ft), the maximum fall target (3,640 ft), or the minimum fall pool elevation target on October 31 (3,635 ft). For a complete description of how the summer release is calculated see the flowchart in Figure 3.

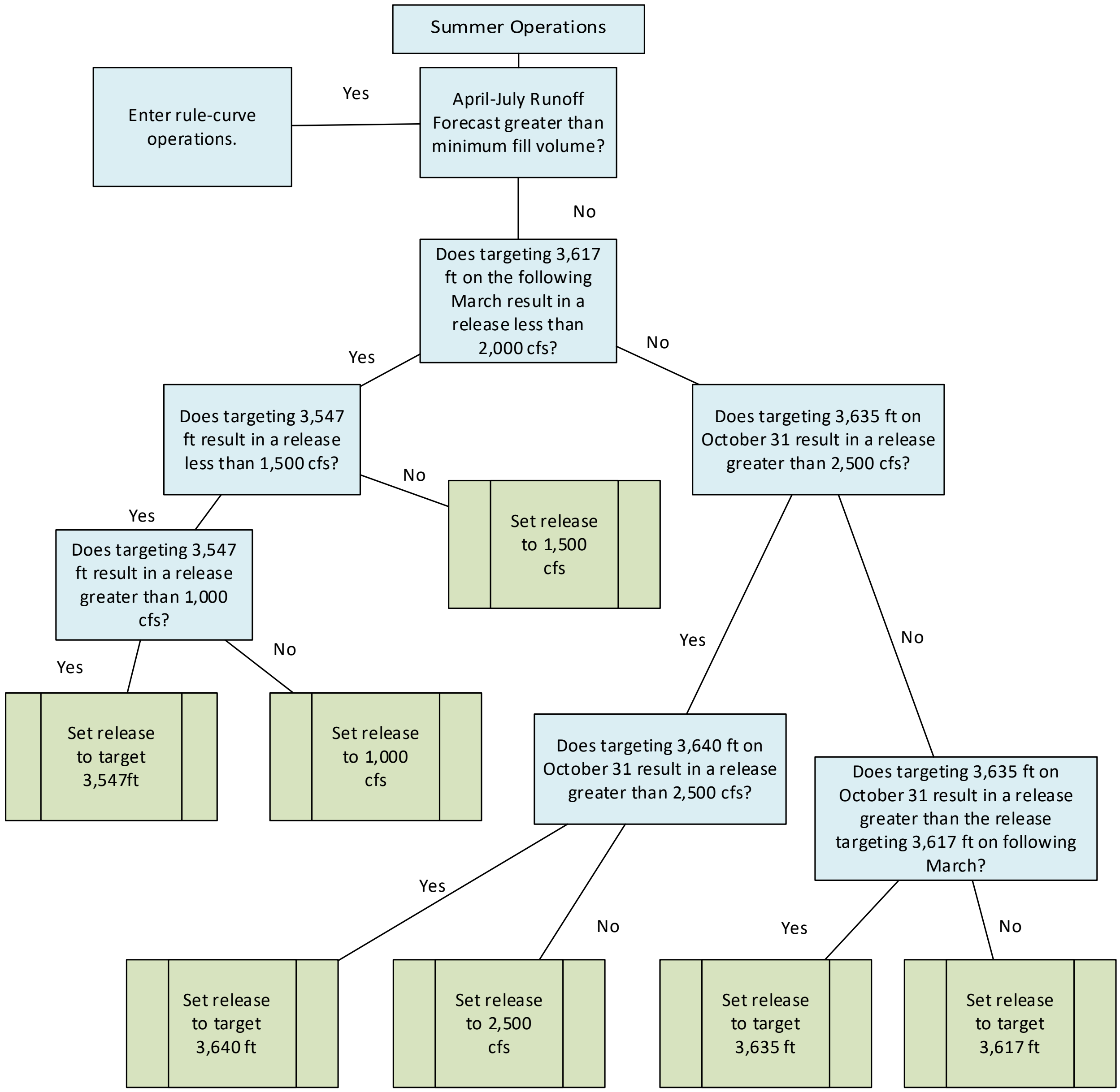


Figure 3. Flowchart with summer low-flow operations in the existing model. Summer operations are in effect from June 1 through July 31 of each year.

Bighorn Lake Inflow Forecasts

Inflow forecasts at Bighorn Lake represent a total volume of forecasted inflows to the reservoir over a specified time period. Inflow forecasts are made up of three components: Boysen Reservoir releases, Buffalo Bill Reservoir releases, and local gains. Forecasted releases from Boysen and Buffalo Bill Reservoirs are provided to Montana Area Office by the Wyoming Area Office. Montana Area Office forecasts gains. Gains represent the volume of water that is unaccounted for in Boysen and Buffalo Bill release volumes, which could include natural seepage, snow melt, flow from tributaries, etc. Gains are forecasted by Montana Area Office using the PyForecast software, which takes into account mountain snowpack, precipitation data, antecedent conditions and historic inflows (Reclamation, 2020a).

The three types of Bighorn inflow forecasts focused on in this study include the most probable forecasts, minimum probable forecasts, and maximum probable forecasts. The most probable forecast inflow volume represents the median inflow volume of all the forecasts made. The minimum probable forecast inflow represents the 10^{th} percentile inflow volume of all the forecasts made. The maximum probable forecast inflow represents the 90^{th} percentile inflow volume of all the forecasts made.

Bighorn RiverWare Model Forecast Type

Within the Bighorn RiverWare model, there are two types of reservoir inflow forecasting methods used: perfect forecasts and most probable forecasts. A model run using perfect forecasts makes operational decisions with perfect advanced knowledge of future monthly inflows. A model run using most probable forecasts makes operational decisions using median historical forecasts made at the time of operations, obtained from monthly plans (Reclamation, 2016). Therefore, the model does not have perfect advanced knowledge of future inflows and instead estimates future inflows based on the historical forecasts.

Perfect forecast model runs have no forecast uncertainty (with the exception of some intramonth timing issues) and isolate the impact of operational changes. Perfect forecasts are used to test hypothetical performance unimpacted by forecast uncertainty. Most probable forecasts allow forecast inflow volume and forecast inflow timing uncertainty to impact model run results. Using both forecast types in model runs allows for scenario testing under both hypothetical and realistic forecast conditions.

Methodology for RiverWare Simulations

In order to assess the impacts of each operations scenario on reservoir operations, only one operational change was made at a time in the Bighorn Model. The results from each change were then compared with the base case model (described above). In the "Dynamic Minimum Fill Threshold Results and Conclusions" section of the report, the base case model is the official Bighorn Lake model described in the Operating Criteria Review. In the "Low-Flow Operating Criteria Scenarios and Results" section below, the Dynamic Minimum Fill model (as described in the "Dynamic Minimum Fill Threshold Results and Conclusions") is used as the base case model. There are some scenarios where a different base case model may be used. The relevant base case model will be defined throughout the report.

Dynamic Minimum Fill Volume Threshold Methods

The process of developing and testing a dynamic minimum fill volume threshold required comparing two different operating policies. One policy, the Static Minimum Fill Case, uses the Bighorn Model described in the 2019 Model Review, which is based on the 2012 Bighorn Operating Criteria. The second policy, the Dynamic Minimum Fill Case, tests a new dynamic minimum fill volume threshold. The Static Minimum Fill Case uses the static minimum fill threshold of 726,768 acre-feet. The Dynamic Minimum Fill Case calculates a dynamic minimum fill volume instead of using the static minimum fill volume of 726,768 acre-feet.

In both cases, the model checks the minimum fill volume threshold when making decisions on April 1, May 1, and June 1 of each year. The April 1 minimum fill volume threshold check uses the entire April through July inflow forecast. The May and June minimum fill volume threshold checks use the volume from the forecast date through the end of July.

The dynamic minimum fill volume threshold uses a mass balance equation to calculate the minimum April (or forecast date, if later) through July inflow volume required to fill the reservoir while maintaining 2,000 cfs releases. Instead of assuming a reservoir elevation of 3,617 ft on March 31, the model uses the current timestep's reservoir storage to determine if the model can fill using the following mass balance calculation at each timestep in the model:

$$Inflow\ Required\ to\ Fill = (S_e - S_s) + O$$

In the equation above, S_e is the desired storage for July 31. This storage is 1,011,052 acre-feet, which corresponds to the top of the joint use pool, or 3,640 ft in elevation. S_s is the reservoir storage corresponding to the current model timestep. O represents outflow, but it is the total volume of water required to maintain a 2,000 cfs river release from April 1 (or the current timestep, if later) to July 31. The outflow volume factors in canal diversions and an estimated natural seepage. The inflow required to fill the reservoir is the dynamic minimum fill volume threshold in acre-feet.

After the dynamic minimum fill volume threshold is calculated, the value is compared to the season's forecasted inflows into Bighorn Lake from April 1 (or the current timestep, if later) to July 31. If the forecasted inflow volume is less than the minimum fill volume threshold, then the reservoir is not expected to fill by July 31 while maintaining a river release of 2,000 cfs. Therefore, the reservoir enters low-flow operating conditions in the model rather than rule-curve operating conditions.

Low-Flow Operating Criteria Methods

This study examines several potential low-flow operating policies. Each policy was tested individually against a base case, and some policies were tested in various combinations. The first low-flow operating policies examined were operating criteria interpretations made during the 2019 Bighorn Model development. The metrics used in this study to compare results are described in the Metrics section.

Several additional policies were tested after testing of the first round of policy changes was completed. This second set of policies consider several ideas for reservoir operations during low-flow conditions. Some of these ideas came from Montana Area Office staff, other ideas came from Missouri Basin Regional Office staff, and additional ideas were collaboratively developed as the study progressed.

Finally, several combinations of individual policies were tested. Individual policies could have unexpected impacts or advantages when combined with other policies, so several combinations were considered. Some of the policies had impacts as standalone policies that could be mitigated when combined with other policies. See the "Summary of Low-Flow Operating Criteria Scenarios" section for a brief summary of the policies considered in this study.

Metrics

Three metrics were used to compare results and to provide understanding of the impacts of different model runs on operations, recreation, and power generation. These metrics allow for quantitative comparisons of alternative operating scenarios to the base case, or current operating criteria. With this information, the study team can determine whether proposed alternatives improve operations.

Low Summer Pool Elevations

Low pool elevations generally refer to pool elevations below 3,620 ft throughout this report. A pool elevation of 3,620 ft is the National Park Service's minimum recommended launch elevation at Horseshoe Bend (National Park Service, 2021). Summer pool elevations are of particular importance. For the purposes of the metric, summer days are defined as days between the Friday before Memorial Day and Labor Day. Typically, this is 102 days. This metric is used to objectively compare the impacts of various model scenarios on lake recreation.

Low River Releases

Low river releases generally refer to river releases below 2,000 cfs throughout this report. A 2,000 cfs river release is classified as the Standard Instream Flow and provides "spawning and rearing conditions for fish in most side channels but cover for adult fish is limited" (State of Montana, Crow Tribe, Department of the Interior, 2000). This metric is used to objectively compare the impacts of various model scenarios on the fisheries and river recreation.

Yellowtail Energy Value

The Yellowtail Energy Value metric calculates the monetary value of energy generated at the Yellowtail Powerplant. Western Area Power Administration (WAPA) has a monthly marketing plan. This marketing plan is the energy that WAPA has agreed to generate each month. If WAPA falls short of this agreement, the administration has to purchase energy on the open market to make up the power deficit.

WAPA provided their average monthly purchase prices for both on-peak and off-peak power from 2008 to 2020 (Western Area Power Administration, 2020). To determine an average monthly price for the model to use, monthly prices for on-peak and off-peak prices were averaged for each month from October 2009 to September 2020. Then, an average monthly price from water year 2010 to water year 2020 was calculated. As an example, all the average October monthly prices were averaged from October 2009 to October 2019 to determine an average monthly price for October.

The following calculation was used to determine the monthly Yellowtail Energy Value:

$$Energy\ Value = (Energy\ generated\ for\ the\ month) * (Average\ monthly\ price) - MAXIMUM(Marketing\ Plan\ monthly\ energy\ requirement - Energy\ generated\ for\ the\ month, 0) * (Average\ monthly\ price)$$

Additionally, energy values were adjusted for inflation into May of 2021-dollar amounts. The monthly Yellowtail Energy Value was used to objectively compare the impacts of various model scenarios on energy production at the Yellowtail Powerplant.

Forecast Analysis

While analyzing the low-flow operational policies, the study identified the need for more in-depth forecasting analysis for long-range forecasts. The forecast analysis used historical observed inflows and the inflow forecasts made at the time of operations to test forecast error, goodness of fit, and forecast distributions.

The error metric used in this study is Normalized Root Mean Square Error (NRMSE). NRMSE is the Root Mean Square Error (RMSE) normalized to a forecast mean. RMSE is the standard deviation of the error between forecasted and observed values (Statistics How To, 2021). It finds the error between forecasted (y_i) and observed inflow values ($\hat{y}_i$), squares this error, then sums the squares. The sum of the squares is then divided by the number of measurements (n). RMSE is the square root of this final value. See equation below:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

Because RMSE uses the sum of the squares of error, larger forecast errors are weighted heavier than smaller errors. RMSE outputs a value in the units of the forecasted and the observed values, in this case the storage volume unit of acre-feet. This study compares forecast error for different periods, such as April-July forecasts or August-March forecasts, which have different expected total inflow volumes based on hydrologic patterns. Therefore, the error volume associated with April-July is not directly comparable with an error volume associated with August-March. The RMSE was normalized to a mean of forecast volumes for the forecast period so that different forecast periods could be directly compared. The NRMSE is in units of percent.

$$NRMSE = \frac{RMSE}{Mean\ of\ forecasted\ inflows}$$

A low NRMSE percentage indicates less forecast error than a higher NRMSE percentage.

The goodness of fit metric used in this study is the coefficient of determination, or R-Squared. The R-Squared value measures how well actual inflow volumes are estimated by forecasted inflow volumes. R-Squared values are represented in decimals or percentages. A higher R-Squared value indicates better goodness of fit than a lower R-Squared value. An R-Squared of 1 or 100% would mean that 100% of the actual inflow volumes were estimated by forecasted inflow volumes, or that every forecast was perfect.

The forecasted inflow volume used to calculate both the NRMSE and R-Squared metrics is the most probable forecast inflow volume. The most probable forecast inflow volume represents the median inflow volume of all the forecasts. See the "Bighorn Lake Inflow Forecasts" section for more information on how forecasts are developed.

Lastly, this study examined forecast distributions as a part of the forecast analysis. Forecast distributions use the minimum probable forecasts and maximum probable forecasts as the lower and upper limits of a distribution. The minimum probable forecast is roughly equivalent to a 10th percentile forecast. The maximum probable forecast is roughly equivalent to a 90th percentile forecast. Given this distribution, it is expected that 10% of observed inflows would fall below the minimum probable forecast, 10% of observed inflows would fall above the maximum probable forecast, and 80% of the values would fall between the minimum and maximum probable forecasts. If the quantity of observed inflows outside these boundaries is greatly different from the expected distribution, this means that the minimum and maximum forecasts are poorly capturing the range of possible values.

Monthly forecasts and period forecasts are the two main types of component forecasts analyzed. Historical forecasts are issued on the first of the month and forecast inflow for each of the next twelve months. Monthly component analysis looks at the skill of each month's forecasts for the next twelve months. For example, the monthly component analysis for January would look at the forecast made on January 1 for each month January-December.

Period component analysis compiles monthly forecasts into seasonal or long-range periods. Period component analysis looks at the skill of each applicable month's April through July forecast, each month's forecast through the following March, and each applicable month's forecast for August through the following March.

These computations were completed by comparing observed inflows with forecasted inflows using Python Pandas programming and Excel.

Dynamic Minimum Fill Volume Threshold Results and Conclusions

Results

Perfect Forecasts

With perfect forecasts the model has advance knowledge of inflow conditions, which allows the model to match the inflows to the correct rule curve or operating policy throughout the entire season. Without a discrepancy in forecasted inflows and actual inflows, the model will target a reasonable pool elevation for future inflow conditions. The Dynamic Minimum Fill Case was only expected to produce different results from the Static Minimum Fill Case when the actual inflows are different from forecasted inflows and pool elevations are too low or too high for the actual inflow volumes. Therefore, the Dynamic Minimum Fill Case was not expected to affect operational results under perfect forecast conditions. As expected, the results did not show any differences between the two cases.

Most Probable Forecasts

There are several differences in operational results between the Static Minimum Fill Case and the Dynamic Minimum Fill Case using most probable forecasts. In most probable forecast scenarios, the model does not have advanced knowledge of future inflows and instead relies upon historical most probable inflow forecasts. The lack of advance knowledge in inflows highlights the impact of forecast error, which could result in the model targeting a rule curve that is too low or too high for the actual inflow conditions. By targeting an inappropriate rule curve early in the season due to forecast error, the model provides an opportunity to use the dynamic minimum fill volume threshold. There were three years between 1990 and 2018 that used the dynamic minimum fill volume threshold as expected: 2003, 2005, and 2006.

2003 Results

The 2000s drought was a period of record drought from 2000 through 2005. By runoff season of 2003, Bighorn Lake pool elevations were significantly lower than normal in both modeled and historical operations due to the extended drought conditions. In all model runs including 2003, the dynamic minimum fill volume threshold considers low pool elevations when deciding if low-flow operations are appropriate, while the static minimum fill volume threshold does not. On May 1, 2003, the forecasted inflows from May to July total 626,000 acre-feet. The static minimum fill volume threshold for May through July inflow is 598,540 acre-feet. Since the forecasted inflow volume is larger than the minimum fill volume threshold, the Static Minimum Fill Case enters rule-curve operations. Rule-curve operations set river releases to 2,000 cfs. However, the pool elevation on April 30, 2003 was 3,546 ft. The April 30 target under rule-curve operations with the same forecast volume would be 3,618 ft. Please refer to the 2020 Condensed Operating Criteria for a full explanation of how rule-curve operations work (Reclamation, 2020a). This is a shortage of 72 ft or

340,000 acre-feet. The static minimum fill volume threshold does not take current pool elevation into account and the Static Minimum Fill Case therefore enters rule-curve operations even though pool elevations are 72 ft below the rule-curve target.

The Dynamic Minimum Fill Case takes current pool elevation into consideration and calculates that the reservoir will need a May through July inflow volume of 950,800 acre-feet to fill the reservoir, rather than 598,540 acre-feet, as associated with the Static Minimum Fill Case May through July inflow volume. The Dynamic Minimum Fill Case compares 950,800 acre-feet to the forecasted inflows from May through July of 626,000 acre-feet. Since the forecasted inflows are less than the minimum fill volume threshold, the model enters low-flow operations and sets releases to 1,500 cfs.

The results for both cases for 2003 can be found in Figure 4 and Figure 5.

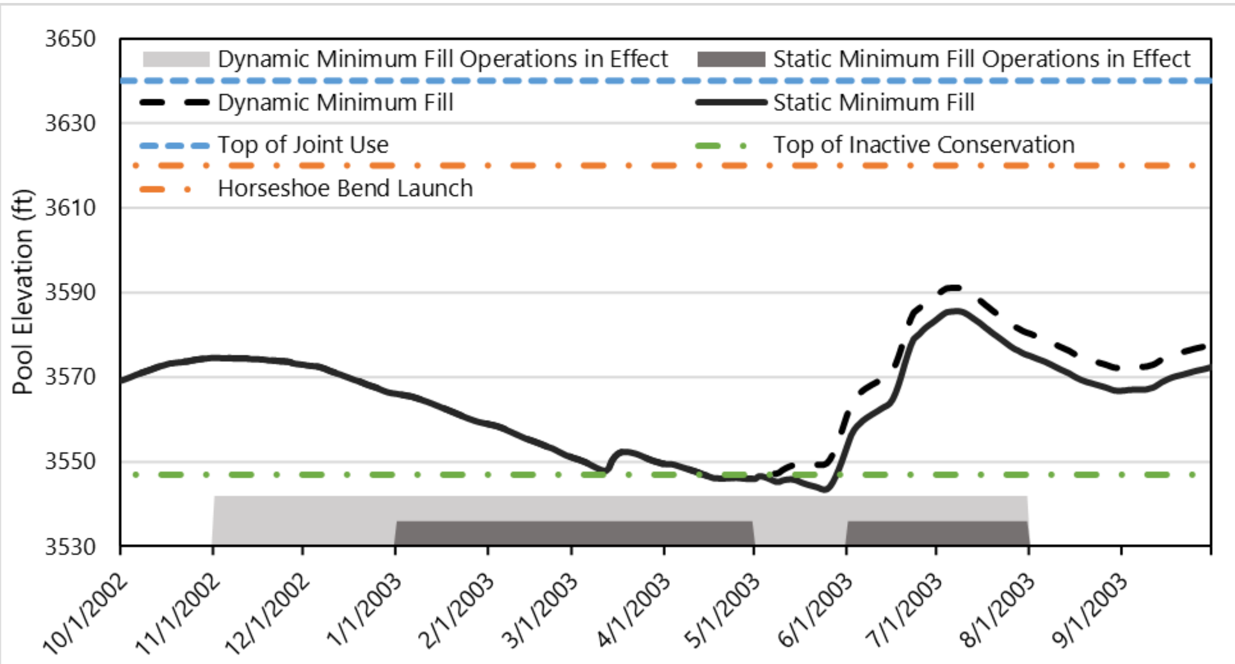


Figure 4. Modeled pool elevation data for 2003 using most probable forecasts and dynamic and static minimum fill volume thresholds.

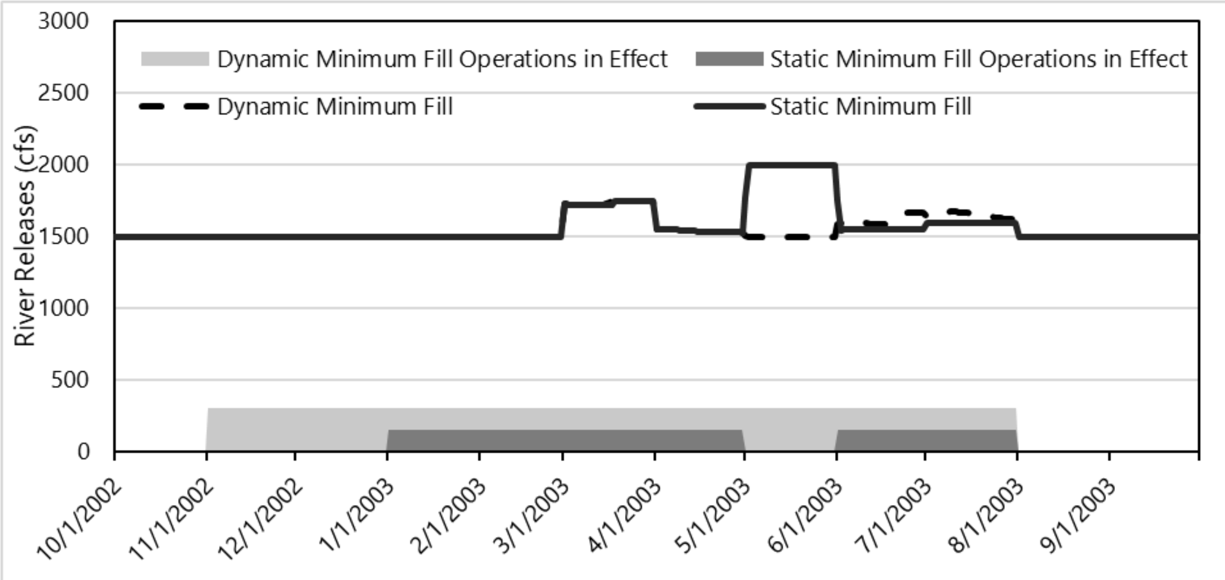


Figure 5. Modeled river release data for 2003 using most probable forecasts and dynamic and static minimum fill volume thresholds.

Interestingly, the release difference in 2003 has sustained impacts to pool elevations from 2003 through 2005, as seen in Figure 6. The Dynamic Minimum Fill Case maintains higher pool elevations than the Static Minimum Fill Case for the whole period. Releases for this period can be seen in Figure 7. The major differences in releases are in 2003 and 2005.

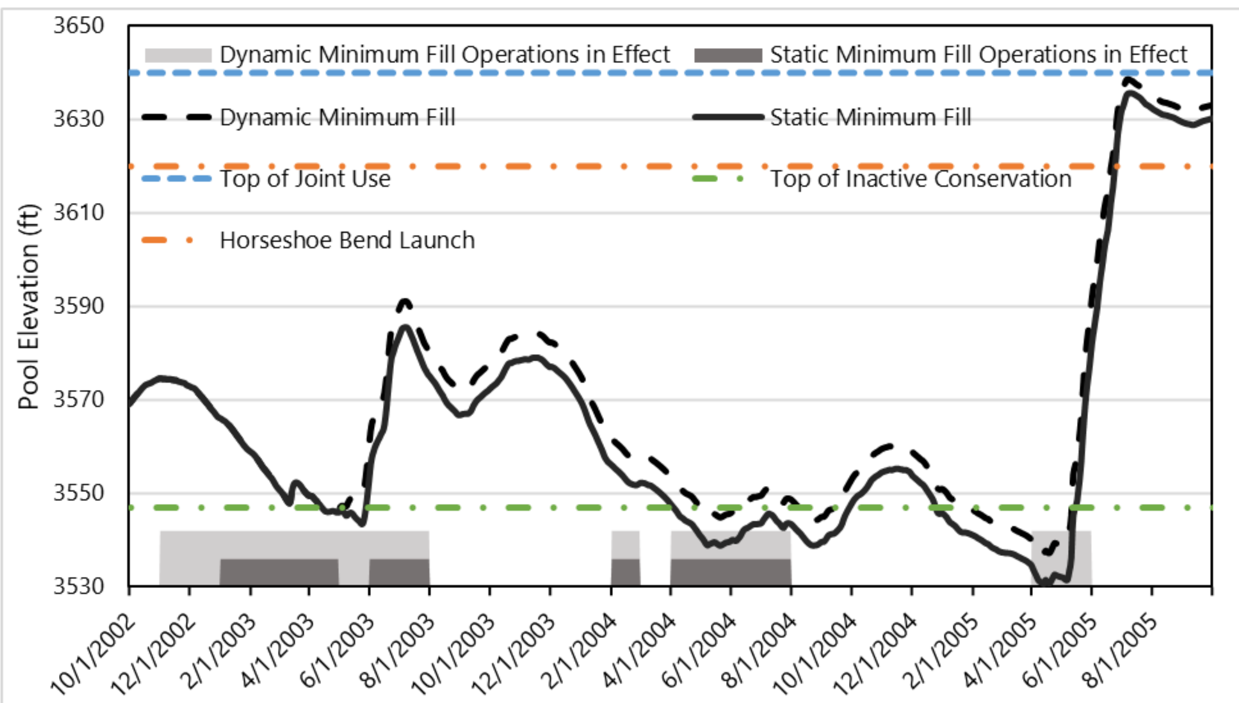


Figure 6. Modeled pool elevation data for 2003 to 2005 using most probable forecasts and dynamic and static minimum fill volume thresholds.

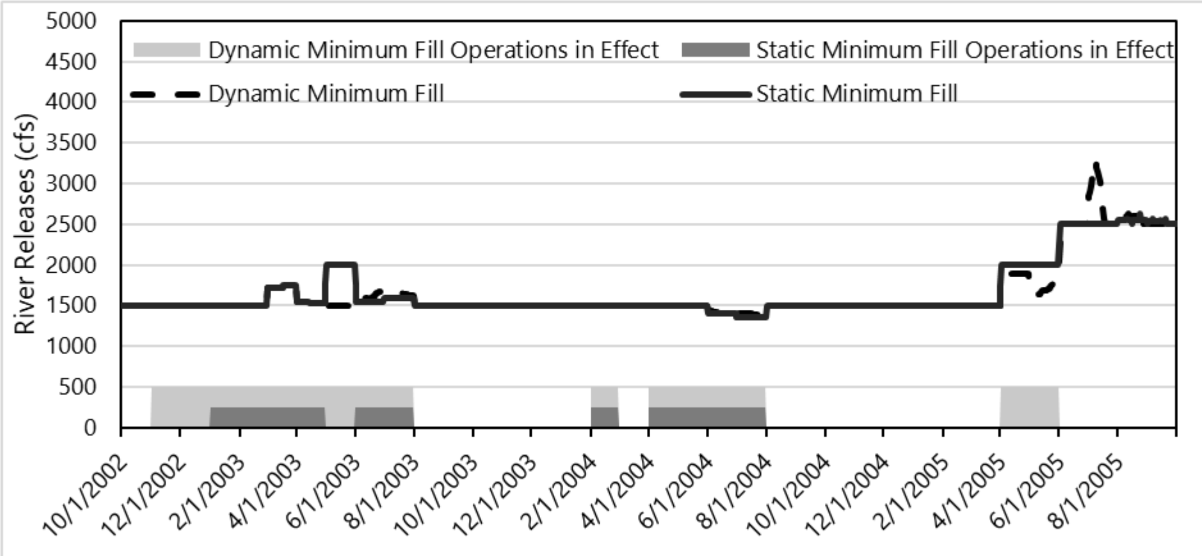


Figure 7. Modeled river release data for 2003 to 2005 using most probable forecasts and dynamic and static minimum fill volume thresholds.

The Dynamic Minimum Fill Case and the Static Minimum Fill Case both show too low of pool elevations to be advantageous to lake recreation. The Static Minimum Fill Case has higher river releases during May for fishery and river recreation, but 2,000 cfs releases and entering rule-curve operations are clearly inappropriate when pool elevations are at the bottom of the active conservation pool.

The Dynamic Minimum Fill Case yields slightly higher energy value from to powerplant operations compared to the Static Minimum Fill Case. The powerplant energy value was calculated using the Yellowtail Energy Value metric methodology. In August and September of water year 2003, the Dynamic Minimum Fill Case yields a slightly higher monthly energy value than the Static Minimum Fill Case. For both months this higher monthly energy value is about a 1.5 percent increase from the Static Minimum Fill Case to the Dynamic Minimum Fill Case. See Table 6 for results. Prior to August in water year 2003, the two cases produced the same energy value in water year 2003. October of water year 2004 saw a small improvement from the Dynamic Minimum Fill Case as well. After October, the two cases produced the same energy value for the remainder of water year 2004.

Table 6. Energy value from Yellowtail Powerplant in water years 2003 and 2004, adjusted for inflation.

	Bighorn Energy Value for Static Probable (2021 $)	Bighorn Energy Value for Dynamic Probable (2021 $)	Difference (Dynamic - Static) (2021 $)	Dynamic as a Percent of Static (%)
8/2003	$1,504,661	$1,527,567	$22,907	101.52%
9/2003	$1,082,417	$1,099,505	$17,088	101.58%
10/2003	$974,208	$982,586	$8,378	100.86%

2005 Results

The Dynamic Minimum Fill Case yields similar results in 2005 as in 2003. On May 1, 2005, the forecasted inflows from May to July are 625,900 acre-feet. The static minimum fill volume threshold for May through July inflow is 598,540 acre-feet. Since the forecasted inflow is larger than the minimum fill volume threshold, the Static Minimum Fill Case enters rule-curve operations. Rule-curve operations set river releases to 2,000 cfs. Refer to Figure 8 and Figure 9 for illustration of 2005 simulation year results.

With the observed low pool elevation on April 30, 2005 of 3,539 ft, the Dynamic Minimum Fill Case calculates that the reservoir will need a May through July inflow volume of 963,800 acre-feet to fill the reservoir. Since the forecasted inflows are less than the minimum fill volume threshold, the model enters low-flow operations and sets releases to a minimum of 1,500 cfs.

The spike in releases in July of 2005 (Figure 9) is due to a strict interpretation of the Bighorn Operating Criteria. The Dynamic Minimum Fill Case has slightly higher pool elevations than the Static Minimum Fill Case throughout 2005 and the model predicts that the Dynamic Minimum Fill Case will enter the flood pool. When the model was developed, Reclamation and the Bighorn Issues Group decided on a strict following of safe channel capacity, 20,000 cfs, and rule-curve timing. This means that the model cannot plan to enter the flood control pool unless releases would exceed 20,000 cfs. Therefore, the model quickly ramps up releases to avoid entering the flood pool. See Figure 8 and Figure 9 for pool elevations and river releases for both cases.

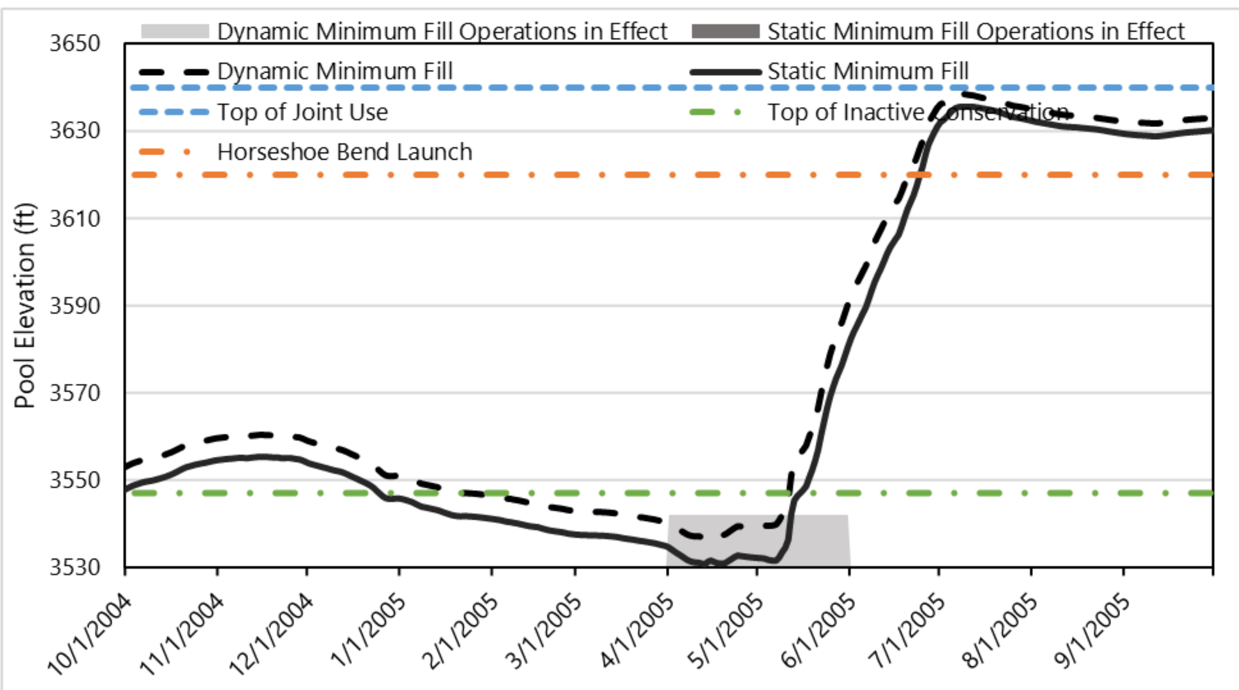


Figure 8. Modeled pool elevation data for 2005 using most probable forecasts and dynamic and static minimum fill volume thresholds.

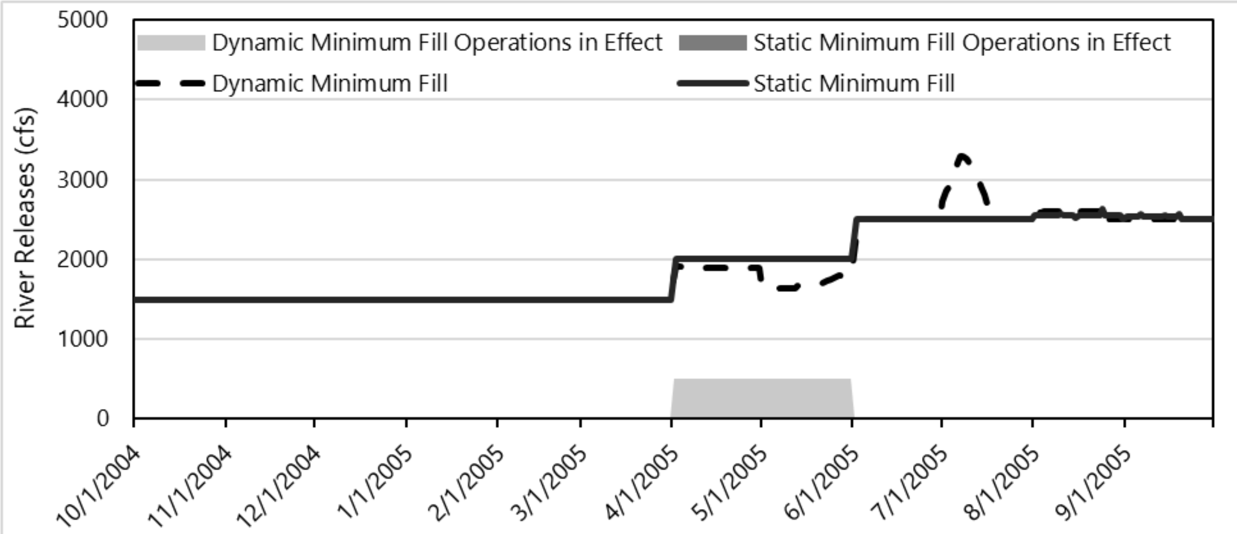


Figure 9. Modeled river release data for 2005 using most probable forecasts and dynamic and static minimum fill volume thresholds.

Both cases provide full access to lake recreation. The Dynamic Minimum Fill Case yields slightly higher energy value from powerplant operations compared to the Static Minimum Fill Case. June and August of water year 2005 saw about a 1.5 percent increase in energy value from the Static Minimum Fill Case to the Dynamic Minimum Fill Case. July 2005 saw a larger energy value increase of 9.5 percent. This was caused by the spike in releases seen in July 2005. September saw a 0.5 percent decrease in energy value from the Static Minimum Fill Case to the Dynamic Minimum Fill Case. Despite the September values, the Dynamic Minimum Fill Case has higher energy values than the Static Minimum Fill Case overall. Prior to June 2005, the two cases produced the same energy value in water year 2005. See Table 7 for a summary of energy value in 2005.

Table 7. Energy value from Yellowtail Powerplant in water year 2005, adjusted for inflation.

	Bighorn Energy Value for Static Probable (2021 $)	**Bighorn Energy Value for Dynamic Probable (2021 $)**	**Difference (Dynamic - Static) (2021 $)**	**Dynamic as a Percent of Static (%)**
6/2005	$1,657,408	$1,685,663	$28,255	101.70%
7/2005	$2,495,100	$2,733,591	$238,491	109.56%
8/2005	$2,736,264	$2,770,518	$34,254	101.25%
9/2005	$2,007,623	$1,996,916	-$10,706	99.47%

2006 Results

The Dynamic Minimum Fill Case in May of 2006 enters low-flow operations while the Static Minimum Fill Case enters rule-curve operations. The May 1 through July 31 inflow forecast is 629,000 acre-feet. The dynamic minimum fill volume threshold is 682,000 acre-feet on May 1, while the static volume threshold is 598,500 acre-feet on May 1. Due to low inflow forecasts and a low pool elevation of 3,608 ft on May 1, the Dynamic Minimum Fill Case enters low-flow operations.

The dynamic minimum fill volume threshold is working as expected in this scenario, but the results are unexpected. The Dynamic Minimum Fill Case enters low-flow operations in May of 2006. The expected result was that releases during low-flow operations would be lower than releases during rule-curve operations. However, the low-flow operations set higher releases than rule-curve operations in May of 2006. See Figure 10 for river releases and Figure 11 for pool elevations in 2006. In low-flow operations, the model is setting releases to target the following March 31 target of 3,617 ft. This is a release of 2,300 cfs. This release is higher than expected because of forecast error in the May 1 through the following March 31 forecast. The May 1 through the following March 31 forecasts are about 40 percent higher than the actual inflows during the same period. The forecasts made on June 1, 2006 are substantially more accurate, with the June 1 through March 31 forecasts only about 4 percent higher than the actual inflows. The inaccurate May forecasts cause the higher than expected releases when targeting the following March.

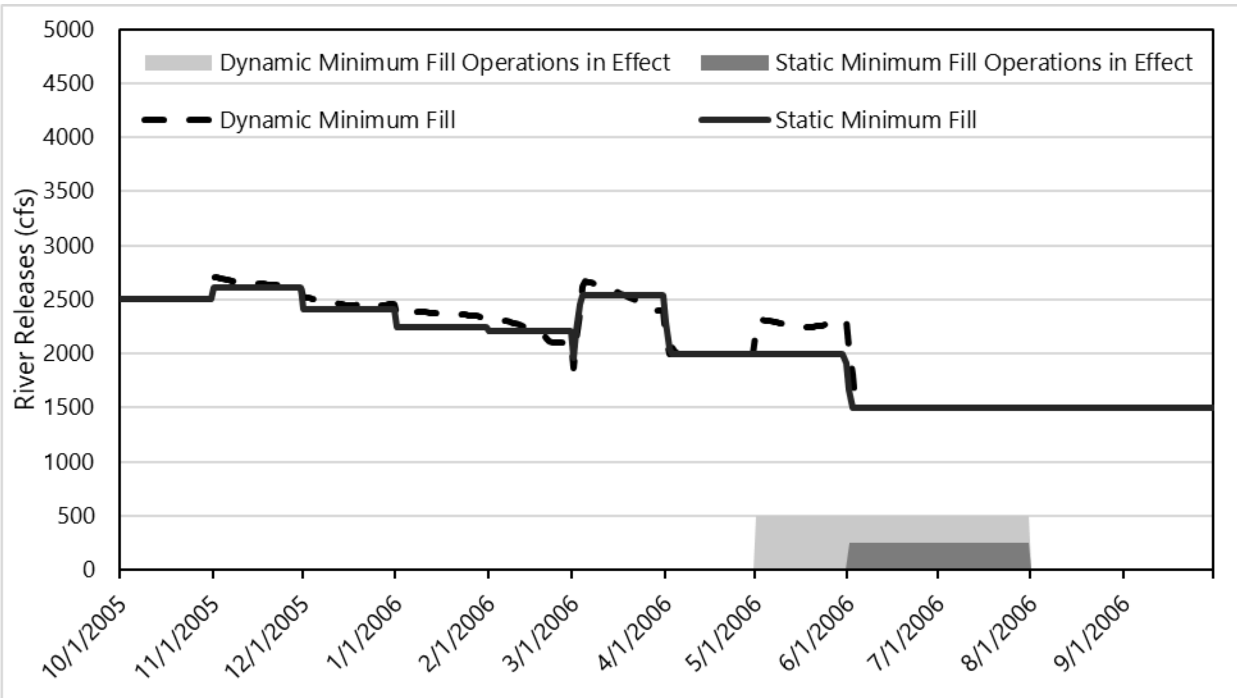


Figure 10. Modeled river release data for 2006 using most probable forecasts and dynamic and static minimum fill volume thresholds.

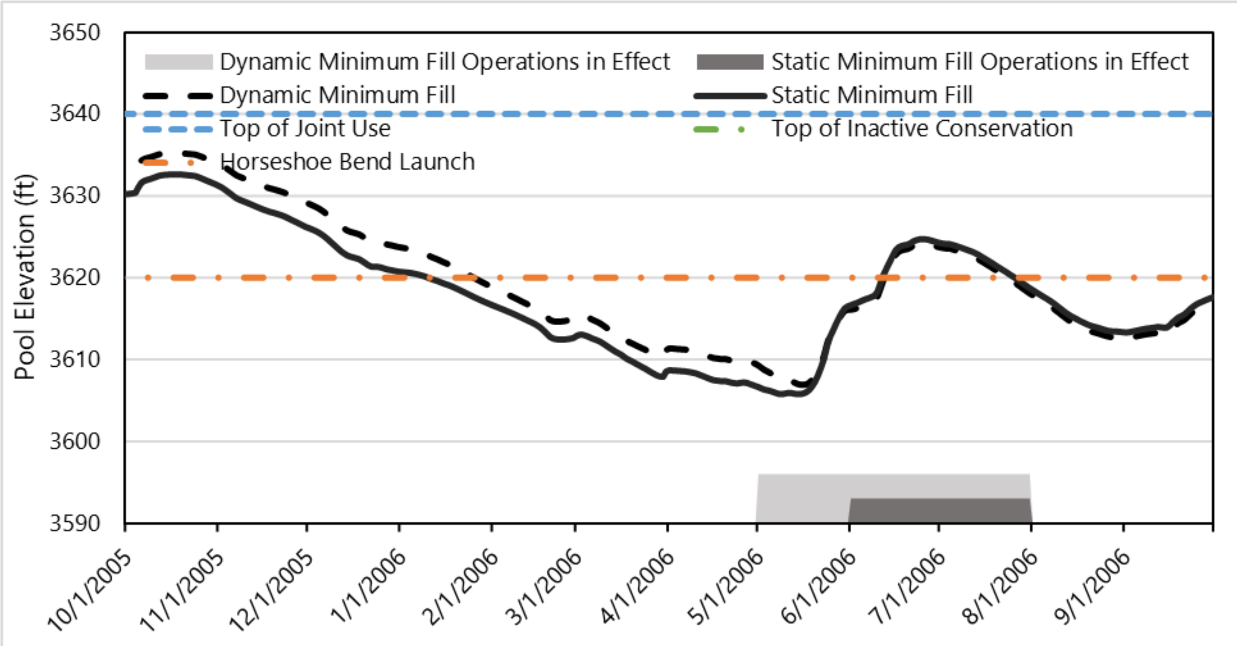


Figure 11. Modeled pool elevation data for 2006 using most probable forecasts and dynamic and static minimum fill volume thresholds.

On May 1, the Static Minimum Fill Case is setting releases to meet the end of month rule-curve target elevation of 3,627 ft. Because pool elevations are low on May 1, about 3,608 ft, the release to maintain 3,627 ft on May 31 is 1,040 cfs. During spring rule-curve operations, the model does not allow releases to drop below 2,000 cfs, so releases in May of 2006 are set to 2,000 cfs. The discrepancy between the rule-curve releases and low-flow operations releases is not ideal, but the primary issue in 2006 is poor forecasting and not operational policies. The difference in releases in May of 2006 does have some impact to pool elevations, but the pool elevations only decrease enough to match the Static Minimum Fill Case pool elevations in May.

Table 8. Energy value from Yellowtail Powerplant in water year 2005, adjusted for inflation.

	Bighorn Energy Value for Static Probable (2021 $)	Bighorn Energy Value for Dynamic Probable (2021 $)	Difference (Dynamic - Static) (2021 $)	Dynamic as a Percent of Static (%)
1/2006	$1,422,297	$1,495,106	$72,809	105.12%
2/2006	$1,222,863	$1,282,847	$59,985	104.91%
3/2006	$1,314,522	$1,346,100	$31,578	102.40%
4/2006	$910,686	$913,391	$2,704	100.30%
5/2006	$963,364	$1,100,566	$137,202	114.24%
6/2006	$1,719,737	$1,705,167	-$14,570	99.15%
7/2006	$1,488,000	$1,488,000	$0	100.00%
8/2006	$1,453,157	$1,444,844	-$8,313	99.43%
9/2006	$1,016,171	$1,010,506	-$5,665	99.44%

Overall, the Dynamic Minimum Fill Case yields higher energy values than the Static Minimum Fill Case in 2006. However, the higher energy values for the Dynamic Minimum Fill Case occur between January and Mary, while the Static Minimum Fill Case has higher energy values between June and September. See Table 8 for results.

Experiment to Further Test Minimum Fill

While the period of 1990 to 2018 includes a diverse range of inflow conditions, there were only three years where the dynamic minimum fill volume threshold impacted operations in model runs with historical conditions. Due to the limited impacts of the policy on historical conditions, experiments were set up to evaluate the impact of the dynamic minimum fill volume threshold on a range of inflow, forecast, and pool elevation conditions more representative of the full range of variability.

Experiment Setup

The experiments had three variables to consider: forecasted volumes, inflow volumes, and starting pool elevations. All experiments were run from April 1 to September 30 of each year considered. Forecasted volumes are important to test to account for the impact of forecast error on model results. Both over-forecasting and under-forecasting conditions were considered. Over-forecasting means that the forecasted inflows were greater than the historical inflows for the same period. Under-forecasting means that the forecasted inflows were less than the historical inflows for the same period.

Additionally, high and low inflow volumes from April through July were considered. Inflow volume refers to the historical inflow volume per day throughout the model run. To test combinations of forecast errors and inflow conditions, past years were selected that had the desired set of conditions. These desired conditions included over-forecasting of inflow volume, under-forecasting of inflow volume, as well as observed low inflow volume, and observed high inflow volume. As an example, 2006 had low inflow conditions and over-forecasted inflows during the run-off season. Table 9 shows the combinations of inflow and forecast conditions considered and the water year selected to represent those conditions.

Table 9. Combinations of inflow and forecast conditions considered and year selected to represent those conditions.

	Under-Forecasting	**Over-Forecasting**
Low Inflows	1993	2006
High Inflows	2009	2014

To further test the dynamic minimum fill volume threshold on various hydrologic and forecast conditions, pool elevations on March 31 were artificially edited to test various starting conditions. Pool elevations were set to low, middle, or high starting conditions: 3,610 ft, 3,617 ft, and 3,625 ft respectively. All of these starting conditions are possible starting pool elevation conditions and have been met in historical operations. Each year selected in Table 9 was run twelve times. Table 10 shows all the model runs completed for each year to complete the experiment.

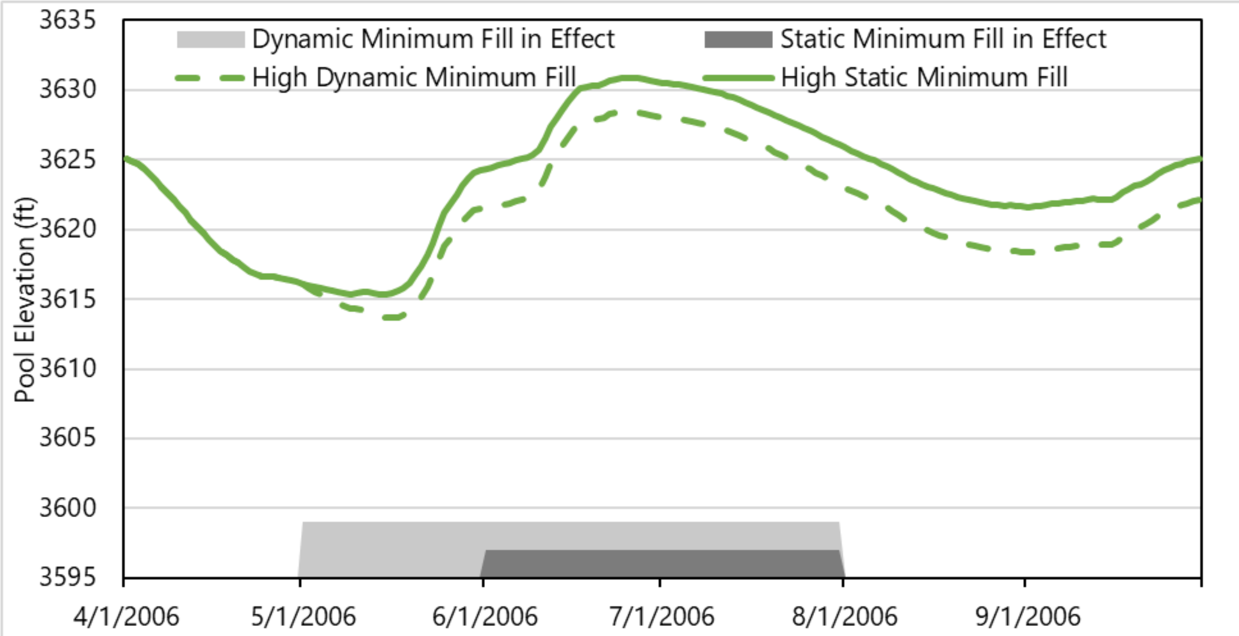
Table 10. Model runs completed for each year analyzed.

Model Run	Pool Elevation Starting Condition	Forecast Type	Dynamic or Static Minimum Fill Threshold
1	Low (3,610 ft)	Perfect Forecast	Dynamic Minimum Fill
2	Middle (3,617 ft)	Perfect Forecast	Dynamic Minimum Fill
3	High (3,625 ft)	Perfect Forecast	Dynamic Minimum Fill
4	Low (3,610 ft)	Most Probable	Dynamic Minimum Fill
5	Middle (3,617 ft)	Most Probable	Dynamic Minimum Fill
6	High (3,625 ft)	Most Probable	Dynamic Minimum Fill
7	Low (3,610 ft)	Perfect Forecast	Static Minimum Fill
8	Middle (3,617 ft)	Perfect Forecast	Static Minimum Fill
9	High (3,625 ft)	Perfect Forecast	Static Minimum Fill
10	Low (3,610 ft)	Most Probable	Static Minimum Fill
11	Middle (3,617 ft)	Most Probable	Static Minimum Fill
12	High (3,625 ft)	Most Probable	Static Minimum Fill

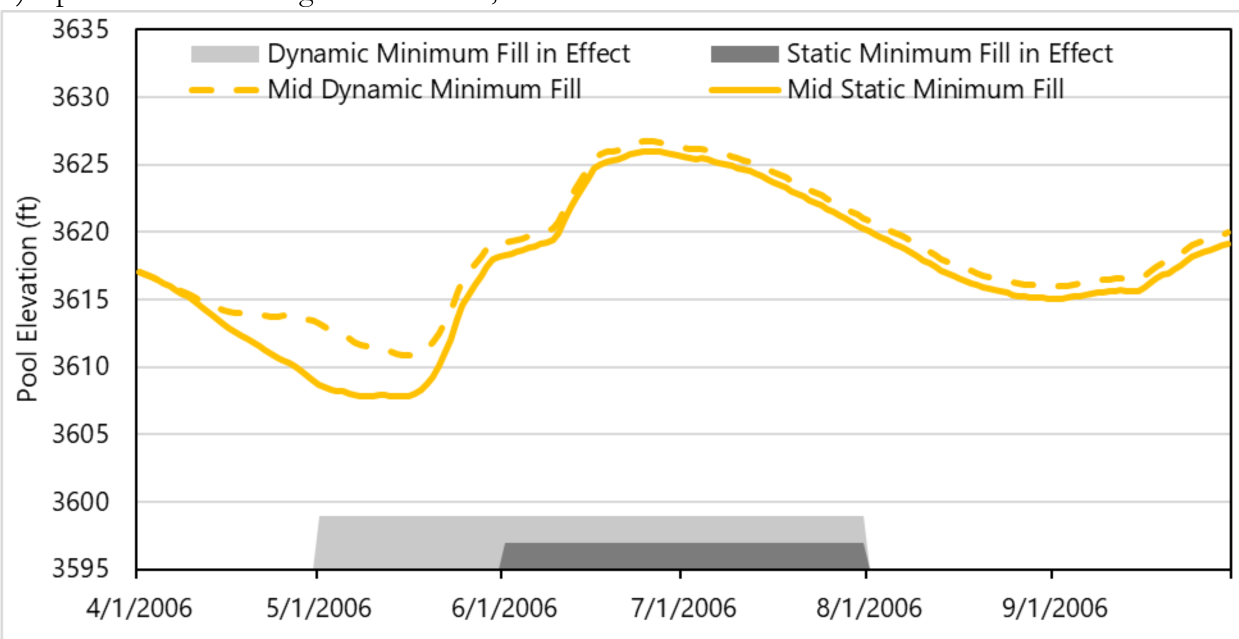
Results

Despite all the model runs and variables considered, the experimental data and minimum fill volume threshold methodology did not cause different results than the modeled historical data in the four years considered. The only year examined that showed different results with most probable forecasts between the Dynamic Minimum Fill Case and Static Minimum Fill Case was 2006, but these differences were similar to those discussed in the 2006 Results section. See Figure 12 and Figure 13 for modeled pool elevations and releases in 2006.

a) April 1 high starting elevation of 3,625 ft.



b) April 1 middle starting elevation of 3,617 ft.



c) April 1 low starting elevation of 3,610 ft.

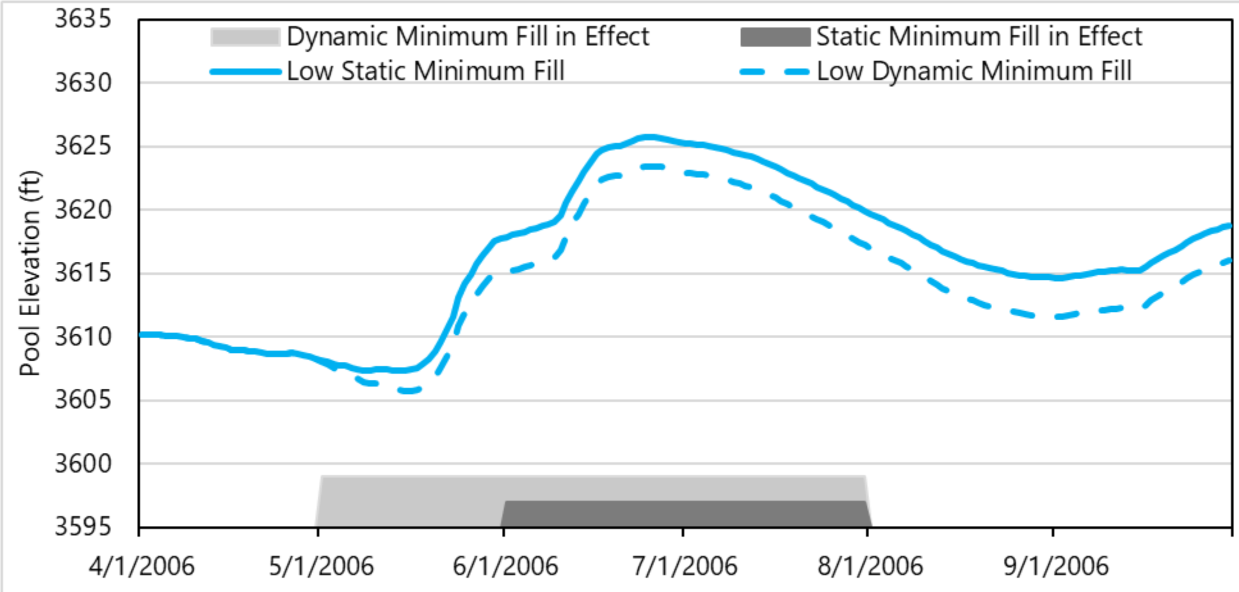
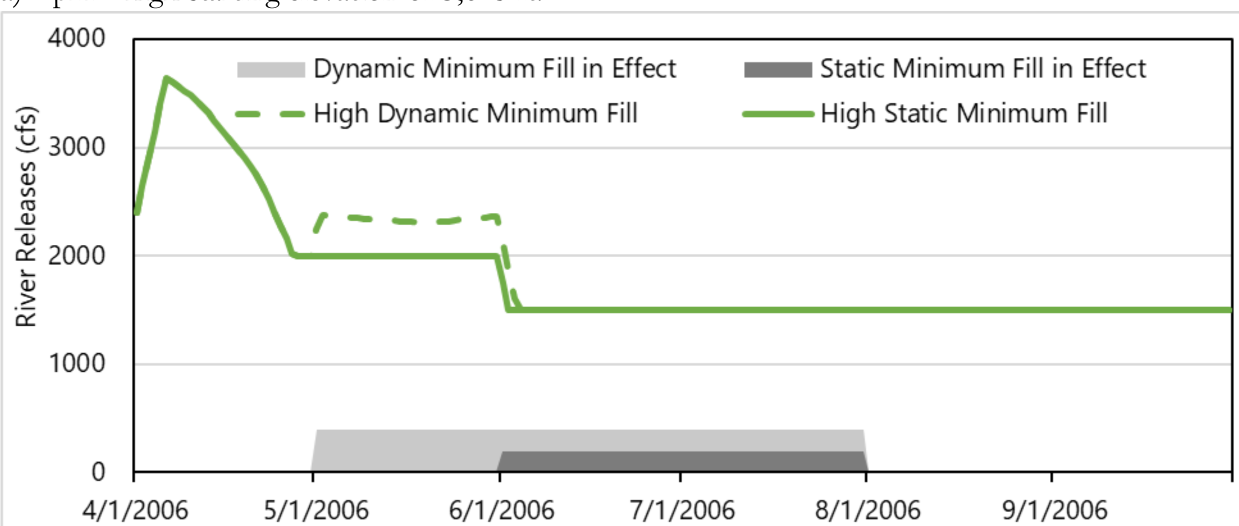
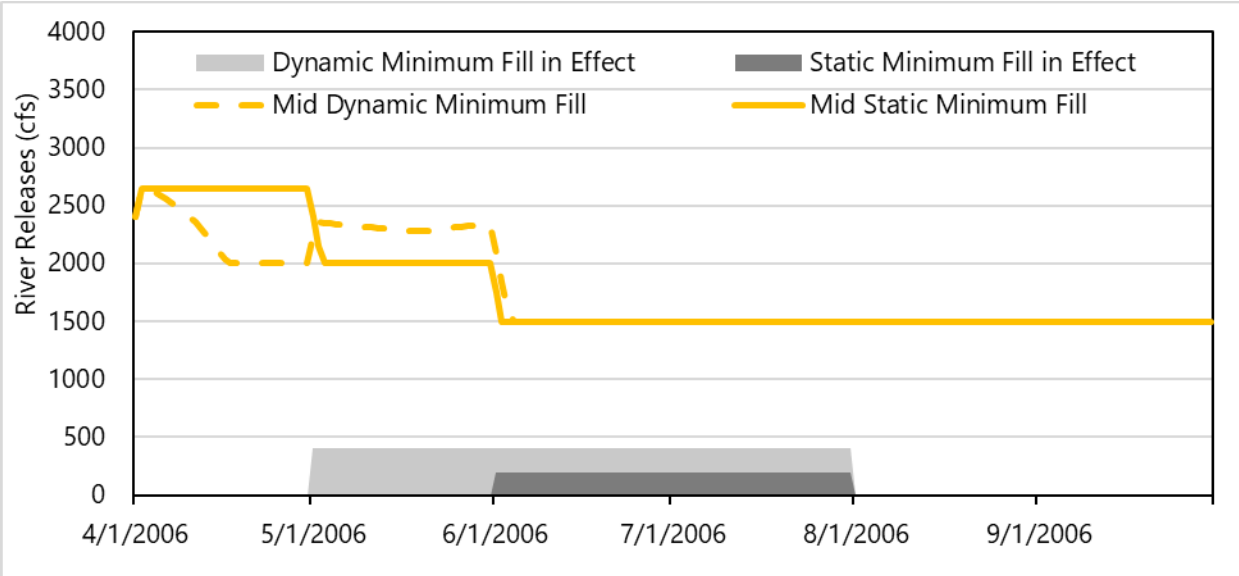


Figure 12. Modeled pool elevation data for 2006 using most probable forecasts, different minimum fill volume thresholds, and different starting pool elevations. Different starting pool elevations are shown on different panels.

a) April 1 high starting elevation of 3,625 ft.



b) April 1 middle starting elevation of 3,617 ft.



c) April 1 low starting elevation of 3,610 ft.

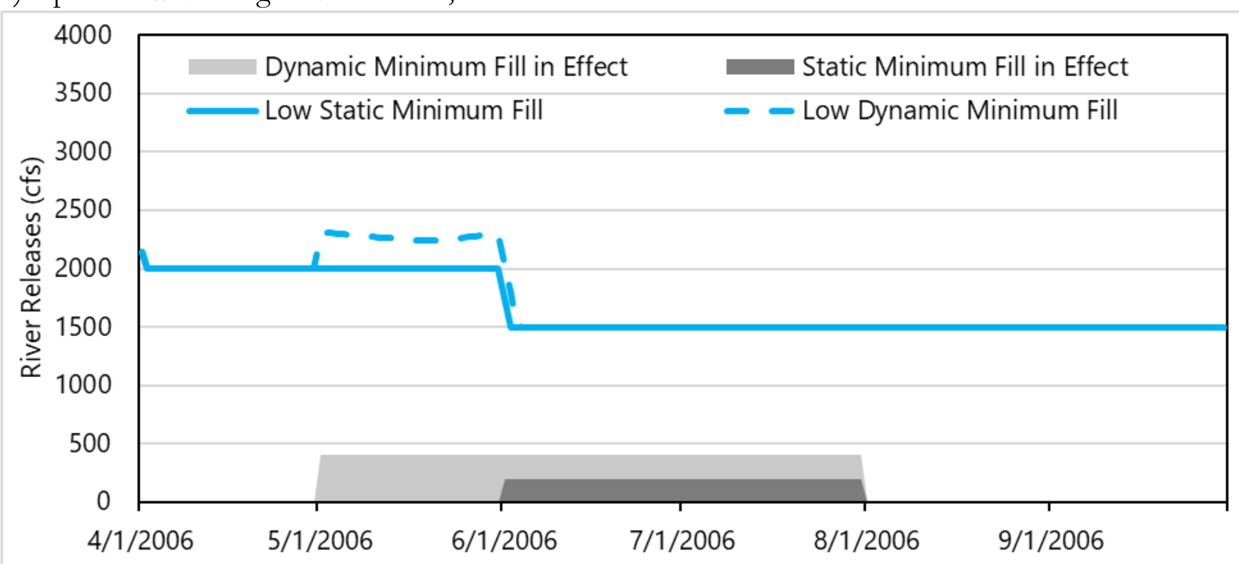


Figure 13. Modeled river release data for 2006 using most probable forecasts, different minimum fill volume thresholds, and different starting pool elevations. Different starting pool elevations are shown on different panels.

For pool elevations on April 1, 2006, all low-pool cases start at 3,610 ft, all mid-pool cases start at 3,617 ft, and all high-pool cases start at 3,625 ft as expected. For river releases on April 1, 2006, each model run is targeting the rule curves and therefore sets a different release depending on what starting elevation each model run uses. All model runs are following rule-curve operating criteria in April.

On May 1, 2006, the model runs set identical river releases to the 2006 Results section which used modeled data with historical starting conditions from 1989 to 2018. This means that the artificially edited April starting elevations did not impact May releases. There are some differences in pool elevations between the starting elevation conditions. This is not caused by low-flow operations or by the dynamic minimum fill volume threshold, but only a result of starting the model at different pool elevations.

Conclusions

Implementing a dynamic minimum fill volume threshold into Bighorn Lake operations has little impact on modeled historical inflow conditions. As expected, under perfect forecast conditions the dynamic minimum volume threshold has no impact on the results. Under most probable forecast conditions, the dynamic minimum fill volume threshold impacts results in 2003, 2005, and 2006.

Results from the model experiments did not show major benefits or drawbacks of implementing the dynamic minimum fill volume threshold. Even by creating artificial scenarios to highlight differences between the static and dynamic minimum fill volume thresholds, only one year, 2006, showed differences in operations between the two minimum fill volume thresholds. The differences in experimental results in 2006 were similar to the differences seen in the modeled historical results and showed minor impacts.

From analyzing both historical and experimental results, the only situation that the dynamic minimum fill volume threshold impacts operations is during periods with large forecast error, namely 2006, and during extremely low pool elevation conditions, namely 2003 and 2005. Entering rule-curve operations during periods of extremely low pool elevation conditions is not desirable. Implementing the dynamic minimum fill volume threshold limits rule-curve operations during low pool elevation conditions and, therefore, makes modeled operations and the Bighorn Operating Criteria more realistic to how an operator might manage Bighorn Lake. Additionally, given the narrow range of conditions in which the dynamic minimum fill volume threshold impacts results and the slightly higher energy value generated from hydropower from using the dynamic minimum fill volume threshold, it is recommended to implement the dynamic minimum fill volume threshold.

The remainder of low-flow operating criteria changes, for which results are summarized in the following section, used the dynamic minimum fill volume threshold in all modeling analysis.

Low-Flow Operating Criteria Scenarios and Results

Analysis of Existing Model Operations

The existing low-flow operations in the Bighorn Model need to be examined and tested prior to the development of new low-flow operating policies. This section identifies areas for improvement within the existing Bighorn Model low-flow operations.

The modeled Early Spring and Spring low-flow operations match the 2012 Bighorn Operating Criteria. The releases are either targeting pool elevation at the end of the following March or are setting releases to 1,500 cfs. The low-flow Summer operations add complexity by considering two additional pool elevation targets, the top of the inactive conservation pool and the end of fall target elevation, in addition to the end of March target. Full descriptions of seasonal operations in the Bighorn Model can be found in the Bighorn Modeling Review, Low-Flow Modeled Operations section.

The top of inactive conservation pool target was intended to maintain releases between 1,000 cfs and 1,500 cfs and only affect the model releases if the reservoir is approaching the full depletion of the active conservation pool. The source of this calculation is from the 2012 Bighorn Operating Criteria: "Reducing the river release below 1,500 cfs should only be considered when needed to prevent full depletion of the active conservation pool" (Reclamation, 2012a). However, under the 2019 Bighorn Lake Operating Criteria Review model policy, the model was frequently targeting 3,547 ft (top of inactive conservation pool) in low-flow operations even when pool elevations were not approaching 3,547 ft. This was a mistake in the model development. As written, the model did not match the Bighorn Operating Criteria when considering the top of the inactive conservation pool. Because this was a mistake in the model, one of the first changes as a part of this study was re-writing the model logic as described in the "Inactive Conservation Check" section.

Setting releases so the reservoir can achieve the end of fall targets is not explicitly stated in the 2012 Bighorn Operating Criteria for low-flow operations. However, the 2012 Bighorn Operating Criteria specifies that low-flow operations are typically between 1,500 cfs and 2,000 cfs and also specifies that low-flow operations are up to Reclamation discretion. The purpose of fall targets during summer operations was to guide operations into the following March and to achieve releases greater than 2,000 cfs. There is no specific guidance for a release greater than 2,000 cfs in the 2012 Bighorn Operating Criteria, so there is flexibility for these releases. Setting releases to test the fall targets is tested for efficacy and appropriateness at Bighorn Lake in the "Removal of Summer Low-Flow Targets" section.

Summary of Low-Flow Operating Criteria Scenarios

This study develops and evaluates nine different low-flow operational policy scenarios. Two of these operational scenarios are discussed in the Initial Model Changes section and address the areas for improvement identified in the Analysis of Existing Model Operations section below. Seven of the operational scenarios are experimental low-flow policies and are discussed in the New Low-Flow Operating Criteria Model Testing section below. A few policies are combined with one another to test how interactions between policies impact operations. Lastly, the Comparison of Policies section below provides summary statistics to further compare combinations of low-flow operating criteria options.

Table 11 contains a list of low-flow operating policies considered in addition to a description of how the policy performed and the recommended next steps for each policy.

Table 11. Summary of low-flow operating policies examined in this study.

Low-Flow Operating Policy Name	Description of Policy	Description of Policy Performance	Recommendation?
Inactive Conservation Check	Allows releases to drop below 1,500 cfs only if pool elevations are forecasted to drop below the top of inactive conservation within the next month.	Decreases amount of time with pool elevations below 3,547 ft and stabilizes release patterns.	Recommended for implementation - clarifies operating criteria and fixes an error made in model development.
Removal of Summer Low-Flow Targets	Removes high pool fall targets from consideration during summer low-flow operations.	No impact to releases, pool elevations, or hydropower.	Recommended for implementation.
Intermediate Fall Target	Considers intermediate fall targets to guide spring and summer releases to target 3,617 ft in the following March.	Inconsistent release patterns through the spring, summer, and fall with detrimental impacts to pool elevations.	Not recommended for further consideration.
Dynamic Early Spring Target	Set March releases to target an end of March pool elevation calculated to fill the reservoir by the end of July given the current forecasts while maintaining 2,000 cfs instream flows.	Releases were almost always set to 1,500 cfs to hit a high end of March target.	Not recommended for further consideration. The purpose of the target was filling the reservoir while maintaining 2,000 cfs, so releases of 1,500 cfs in most scenarios is not an acceptable result.
Balanced March Target	Balances releases between maintaining 2,000 cfs instream flows and conserving water for the following year by averaging the release to hit 3,617 ft the following March with 2,000 cfs during the spring and summer months.	Increases releases between 1,500 cfs and 2,000 cfs. Some impacts to pool elevations in single year drought events, major impacts to pool elevations in multi-year drought events.	Operating policy analysis provided for MTAO's consideration. Needs some additional checks and balances in multi-year events to avoid major detriments to pool elevations.

2020 Operating Criteria	Low-flow operating criteria described in 2020 Condensed Operating Criteria. Sets releases to target following March elevation of 3,617 ft as long as that release is between 1,500 cfs and 2,000 cfs.	This case limits releases to 2,000 cfs in all low-flow conditions which has some benefits to pool elevations and some detriments to releases.	Operating policy analysis provided for MTAO's consideration.
End of March Target	Set March releases to target the end of the month rather than target the following March 13 months into the future.	Stabilizes release patterns when using historical forecasts by avoiding April through July forecast errors but performs poorly when given advanced knowledge of inflow conditions.	Not recommended for further consideration.
Year Out Inactive Conservation Check	Performs the same calculation as the inactive conservation check but looks out a full year rather than one month into the future.	Similar impacts to the inactive conservation check, but the releases below 1,500 cfs are less extreme because there is more time for the operator/model to adjust.	Recommended for implementation – replace the Inactive Conservation Check.
Low Pool Elevation Check	Caps releases at 1,500 cfs if the pool elevation is below the minimum drawdown elevation of 3,591.5 ft.	Avoids unrealistically high releases when pool elevations are extremely low.	Recommended for implementation.

Initial Model Changes

The first set of model changes and tests examine modeled low-flow operational guidance already in the base case model. There are two existing model logic components that were identified as needing additional testing: the top of inactive conservation check and the summer operations to achieve fall targets. The base case model used in this section of the report is the Bighorn Model with the dynamic minimum fill volume threshold.

Inactive Conservation Check

The Bighorn Operating Criteria states that releases below 1,500 cfs should only be considered if they are needed to prevent the full depletion of the active conservation pool. The bottom of the active conservation pool and the top of the inactive conservation pool are 3,547 ft. In the existing model operations, summer operations set releases to target 3,547 ft pool elevation in certain conditions and set releases below 1,500 cfs if the target 3,547 ft could not be met. This was an error in the model development and needed to be reconsidered.

To create a model policy that better aligns with the Bighorn Operating Criteria language, a daily pool elevation forecast check was created. This pool elevation check operates at the end of the release calculations for all seasons and for every timestep. The check takes the current release setting and performs a mass balance calculation to determine the minimum forecasted pool elevation over the next month. The mass balance calculation uses inflow forecasts, the starting pool elevation, and assumes that releases will stay at the current release over the next month to calculate the minimum pool elevation. If the mass balance computation yields a minimum pool elevation below 3,547 ft, or the top of the inactive pool elevation, then the model reduces releases to reach 3,547 ft by the forecasted minimum pool elevation date. If this computed release is less than 1,000 cfs, the model will only reduce releases to a minimum of 1,000 cfs. If this release is greater than 1,500 cfs, the model will cap releases at 1,500 cfs. The model will continue this release pattern until the forecasted minimum pool elevation is greater than 3,547 ft. See Figure 14 for a flowchart depicting the inactive conservation pool elevation check.

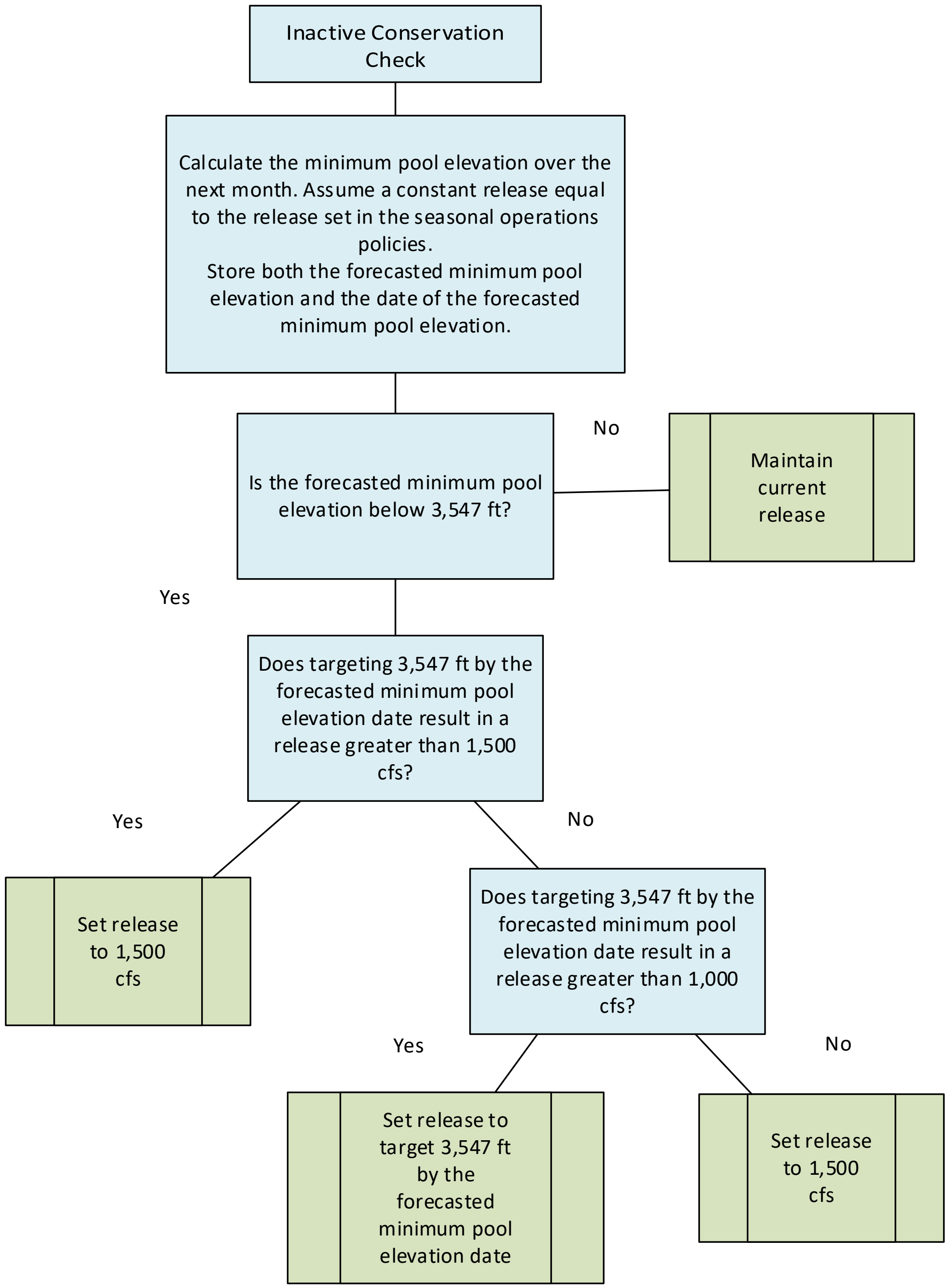


Figure 14. Flowchart depicting the inactive conservation pool elevation check. This pool elevation check operates at the end of the release calculations for all seasons and for every timestep.

In addition to the pool elevation forecast check, the model's summer operations logic removed targeting the top of the inactive conservation pool from the operations. The changed summer operations model logic is in Figure 15.

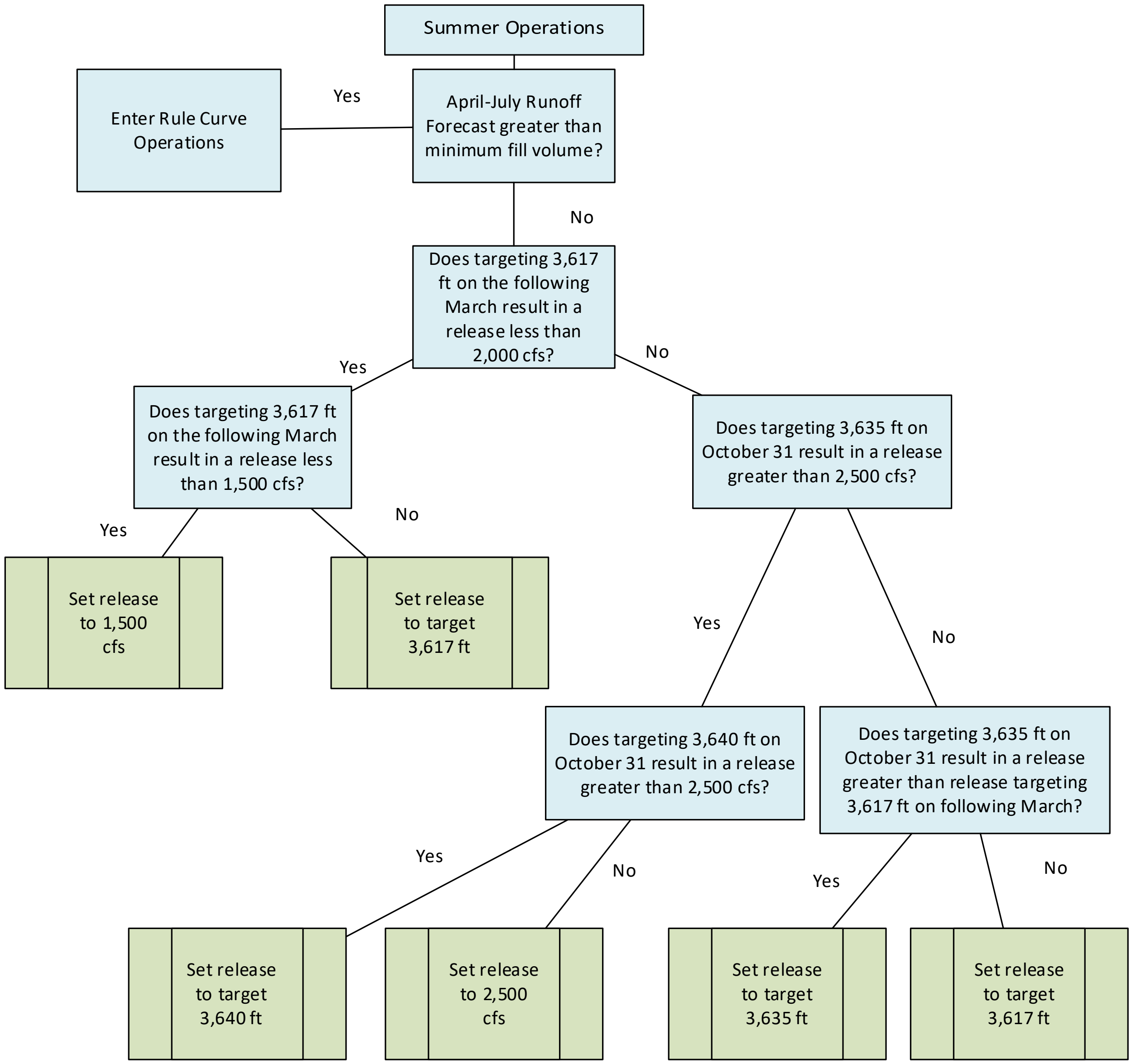


Figure 15. Flowchart with summer low-flow operations after implementing inactive conservation changes. Summer operations are in effect from June 1 through July 31.

One impact of the model change was a decreased amount of time with pool elevations below 3,547 ft. The only period with pool elevations low enough for the check to impact operations was the 2000s drought. The one-month forecasted pool elevation check prevented the model from dropping below 3,547 ft in 2003 and 2004 when compared with the base case. See Figure 16 for pool elevations during the 2000s drought. There is room for further improvement during the 2000s drought, but this policy does improve 2000s drought operations by reducing the time and volume below inactive conservation pool elevation.

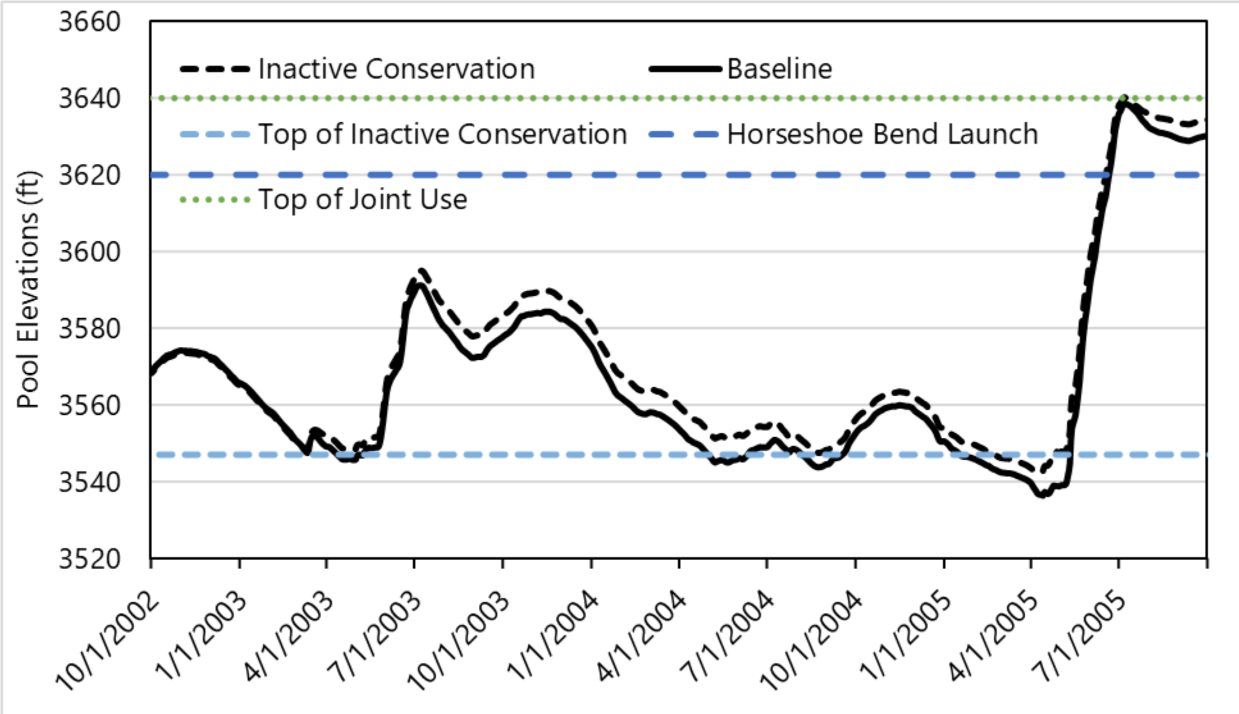


Figure 16. Modeled pool elevations during the 2000s drought showing the impacts of the inactive conservation changes.

The second impact of this model change was more consistent release patterns during low-flow year summer operations due to the removal of the inactive conservation pool target. Spring operations in low-flow years consider a target the following March. By removing the top of inactive conservation pool target, the summer operations also set releases by looking out to the following March in most low-flow scenarios and therefore sets a similar release to the spring release. Figure 17 shows modeled results for water years 2012 and 2013. June and July of both 2012 and 2013 show improved release consistency over the base case. The increased releases do lower pool elevations in the summer of water year 2012 and through the fall and winter of water year 2013 in comparison to the base case. However, the pool elevations do not drop below 3,620 ft between Memorial Day and Labor Day.

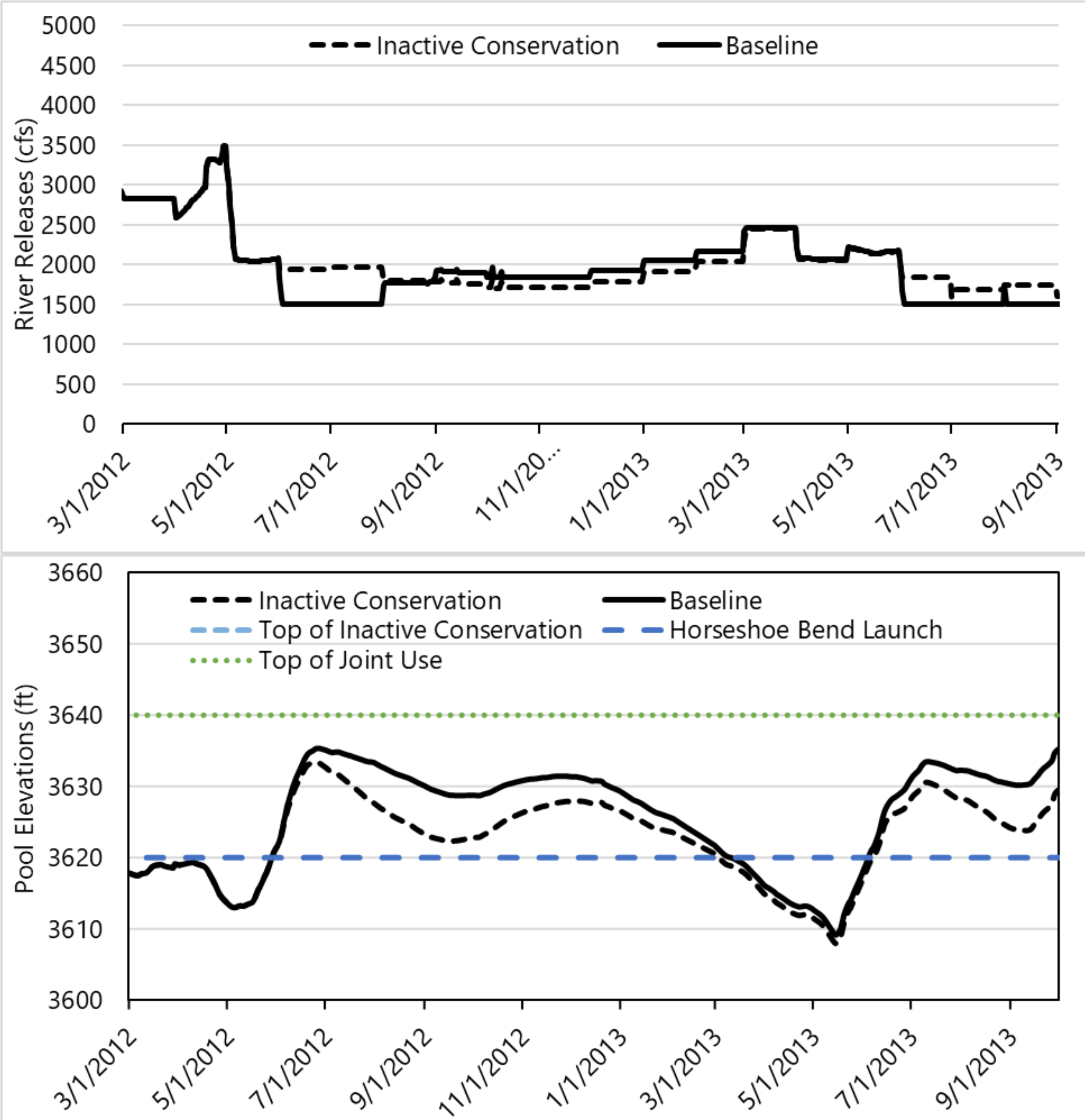


Figure 17. Modeled river releases and pool elevations during 2012 and 2013 showing the impacts of the inactive conservation changes.

This model change fixes an error that was made in model development and more closely aligns the model to the 2012 Bighorn Operating Criteria. The results of this model change primarily provide more stability in release patterns. This model change also causes some decreased pool elevations in summer and fall, but the percentage of days with pool elevations below 3620 ft between the Friday before Memorial Day and the Labor Day from 1990 to 2018 went from 25 percent of summer days for the base case to 26 percent of summer days for the modeled case. Given the minimal impact of the change and given that this change is fixing an error in the model development, this model change is recommended for implementation into the official Bighorn Model. All model testing described in the following sections uses this model as the base case.

Removal of Summer Low-Flow Targets

The end of October targets in summer operations also required testing. The base case model used to test the impact of fall targets on summer operations used the inactive conservation changes described in the previous section and the dynamic minimum fill volume threshold. The flowchart showing summer operations in the base case model can be found in Figure 15. The test model is the exact same as the base case model except that the test model removes the end of October targets from summer operations. A flowchart showing summer operations in the test model can be found in Figure 18.

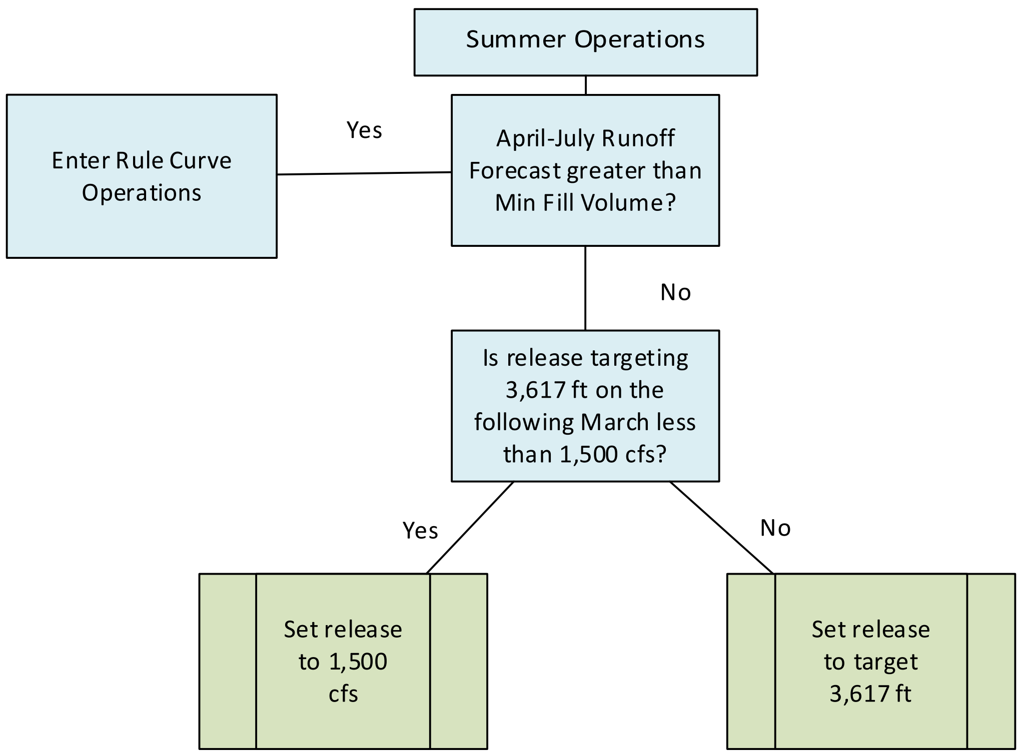


Figure 18. Flowchart with summer low-flow operations after implementing fall target changes. Summer operations are in effect from June 1 through July 31.

The test model results showed that removing the end of October targets from summer operations had no impact on river releases, pool elevations, or hydropower energy production value. This means that the base case model was only considering the following March pool elevation target or 1,500 cfs in all historical low-flow conditions and never set releases to reach either the end of October target or 2,500 cfs releases. These results indicate that between 1990 and 2018 hydrology conditions never resulted in low-flow operations that could maintain a release to allow the reservoir to achieve the end of October target or maintain 2,500 cfs releases. Therefore, it is recommended to remove end of October targets from summer operations in future model runs and to use this model as the base case model moving forward.

Fall operations, which begin August 1, still allow the model to consider setting releases to achieve the end of October targets. This recommendation does not remove the end of October targets entirely from modeled operations, only from modeled summer operations.

New Low-Flow Operating Criteria Model Testing

The next batch of model changes and tests examine new modeled low-flow operational guidance. There could be operational improvements at Bighorn Lake with new low-flow policies. This study analyzed and tested seven new operational policies that feature a variety of different rules, targets, and goals.

Intermediate Fall Target

In low-flow years, most hydrologic conditions and forecasts result in releases that aim to achieve a pool elevation of 3,617 ft in the following March or set the release at 1,500 cfs. One concern with setting releases to meet a pool elevation the following March is that the suitability of these target releases depends on accurate long-range forecasts. As an example, in several low-flow years, releases are set to achieve the following March target from March 1 of the current year. This is a 13-month forecast window. Forecasts outside the snowmelt runoff period tend to have low skill.

An intermediate fall target could be used to shorten the forecast window. The purpose of an intermediate fall target would be guiding releases to achieve a pool elevation of 3,617 ft in the following March. The intermediate fall target would only be used to set releases in spring and summer seasons. It would not be used during fall operations when forecasts based on climatology have some skill predicting the following spring, so fall operations would not attempt to reach the intermediate fall target at the end of October. By reducing the forecast range, from March 1 of the current year to March 31 of the following year, to a forecast range from March 1 to October 31, the model removes five months of uncertain long-range forecasts to consider while setting releases. This could potentially improve accuracy of target release calculations.

There were two intermediate fall targets considered for this study, as well as several implementation strategies. The two targets were considered independently in two separate model runs. The first intermediate fall target was 3,632 ft on October 31. This target assumes a lower quartile inflow from November through March. It also assumes a release of 2,000 cfs from November 1 to March 31 is used to reach 3,617 ft on March 31. The second intermediate fall target was 3,623 ft on October 31 which assumes a lower quartile inflow like the first intermediate fall target, but assumes that the November 1 to March 31 release is 1,750 cfs, not 2,000 cfs, to reach 3,617 ft on March 31.

Adding an intermediate fall target did not improve operations. The model targeting the higher elevation at the end of October generally decreased releases in spring and summer only to have releases increase in the fall, while the lower fall target model generally increased releases to an unsustainable level in the spring and summer, causing low releases throughout the fall and winter. Pool elevations were lower in most cases. Overall, the intermediate fall target caused inconsistent and unsustainable release patterns and had detrimental impacts to pool elevations. The intermediate fall target is not recommended for further consideration.

Dynamic Early Spring Target

In low-flow years, the March release is set to either achieve 3,617 ft on the following March 31 or 1,500 cfs, whichever is larger. The following March target uses a 13-month forecast window to set releases. One way to shorten this forecast window is to set March releases to meet the current year March 31 target of 3,617 ft instead of next year's March 31 target. In April, releases would resume targeting the following March if forecast conditions remain in low-flow operations.

Additionally, in some years the existing end of March 3,617 ft target may be too low to be able to fill the reservoir by July 31 while maintaining 2,000 cfs releases. Instead of using a static end of March target of 3,617 ft, a dynamic end of March target was tested that calculates the March 31 pool elevation need to fill the reservoir by July 31 while also maintaining 2,000 cfs releases. Unfortunately, in extremely low-flow years, filling the reservoir by July 31 with 2,000 cfs releases is not possible. For example, in 2004, the inflow conditions are so low that a March 31 pool elevation of 3,645.8 ft would be needed for a pool elevation of 3,640 ft on July 31 while maintaining 2,000 cfs releases. Therefore, an early spring target cap of 3,625 ft was implemented. The model will either try to achieve the dynamic March target calculated with a mass balance calculation, or 3,625 ft, whichever is smaller.

The dynamic early spring target did not provide the expected benefits. The expected benefit was a range of possible end of March targets and releases generally in the 1,750 cfs to 2,000 cfs range. However, in almost all scenarios that the dynamic early spring target impacted release patterns, the model was trying to achieve the March 31 target pool elevation of 3,625 ft. Additionally, the release needed to let the pool elevation reach 3,625 ft by March 31 was much less than 1,500 cfs, so the March release was almost always set to 1,500 cfs in low-flow conditions. The purpose of the early spring target is to fill the reservoir while also maintaining 2,000 cfs releases, so having the release drop to 1,500 cfs in most low-flow March operations is not an acceptable result. The dynamic early spring target is not recommended for further consideration.

Balanced March Target

The primary goal of including a target for the following March is to conserve storage during a low-flow year with the hope that the following year will return to normal operations. The March target of 3,617 ft is a balanced elevation condition that can react to low or high inflow conditions. By targeting this elevation one year out, low-flow operations are attempting to return the reservoir to normal operations the following year. However, this is pushing the use of stored water for hydropower and fisheries to the following year. It is assuming that the current year's hydropower and fishery operations will suffer in low-flow conditions, but hopes that next year will return to normal as a result of conserving and storing water. There is a chance that the next year will result in higher spring and summer runoff as a result of conserving water in the current year, thus negatively impact hydropower and fishery operations for both years. There is also a risk of higher than expected inflows, resulting in a full recovery of rule-curve operations sooner than expected. Recovering rule-curve operations and unexpectedly high inflows could cause high releases, especially after cutting releases to conserve storage earlier in the run-off season.

Between 1962 and 2020, there was a 47 percent chance of a low-flow year followed by a second low-flow year and a 53 percent chance of a low-flow year followed by a normal or high inflow year.

These probabilities were calculated using a transition matrix. In an effort to better balance the potential of recovering operations within the next year and the need to conserve storage, a "Balanced March Target" case was considered.

The Balanced March Target averages the release targeting the following March and a 2,000 cfs release in spring and summer low-flow operations. There are a few other checks performed when setting releases, which can be seen in Figure 19. The general goal of this release pattern is to balance the using water in a low-flow year for hydropower and fishery flows with the need to store water for the following year.

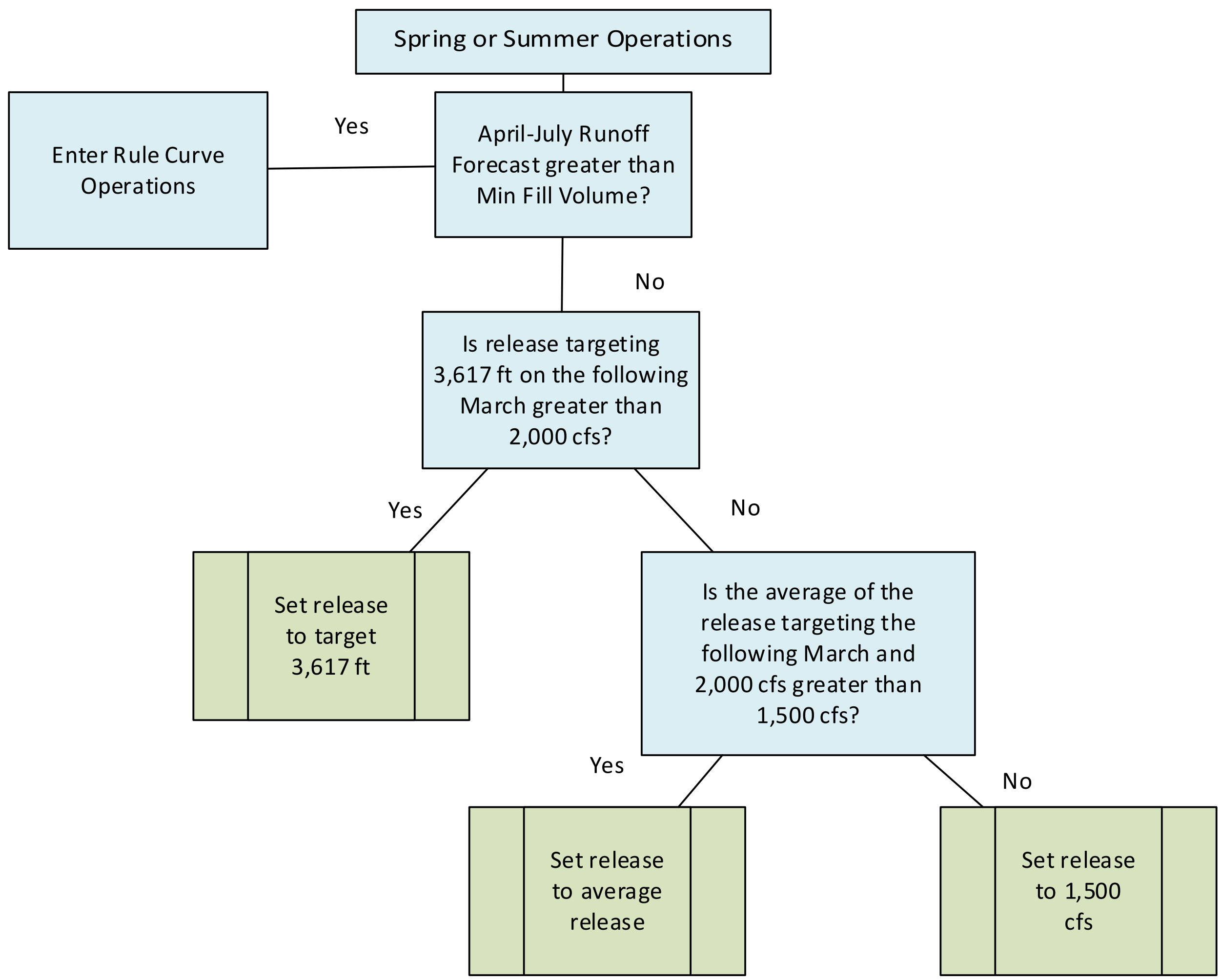


Figure 19. Flowchart with spring and summer low-flow operations after implementing Balanced March changes. Spring operations are in effect from April 1 through May 31 and summer operations are in effect from June 1 through July 31.

Water year 1994 is an example of this policy working as expected and working well. Water year 1994 was a low-flow year followed by a wet year in 1995. There were some poor forecasts in April and May of 1994 which cause high releases, but in June the model enters low-flow conditions. June and July show the releases splitting the difference between maintaining 2,000 cfs and targeting the following March. There is some increased pool drawdown in summer and fall of 1994, including six additional days of summer pool elevations below 3,620 ft (minimum recommended boat launch elevation), but the pool elevations recover during the spring of 1995. See Figure 20 for modeled results. When a dry year is followed by a wet year, the results are sufficiently balanced between storage conservation and releases.

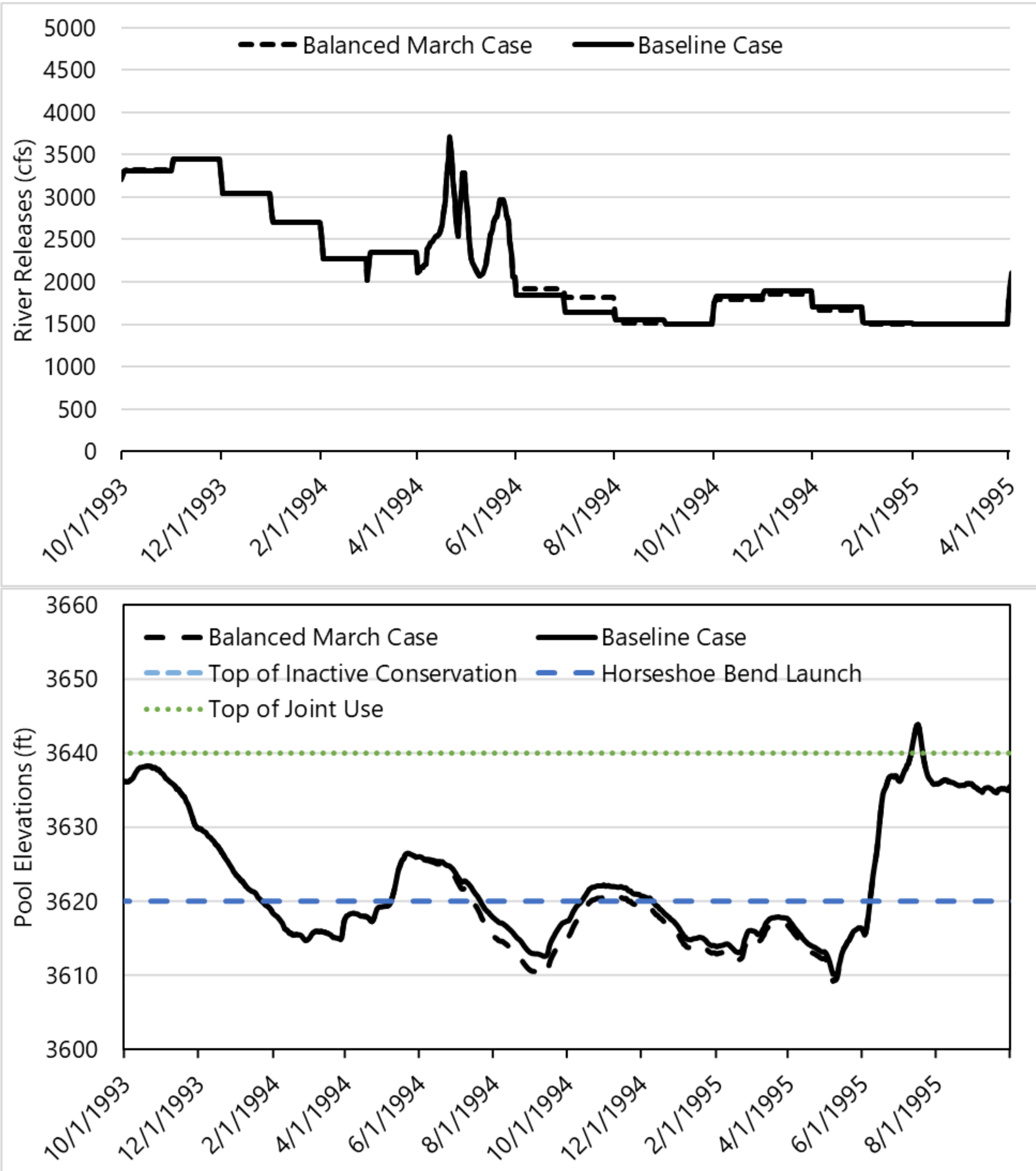
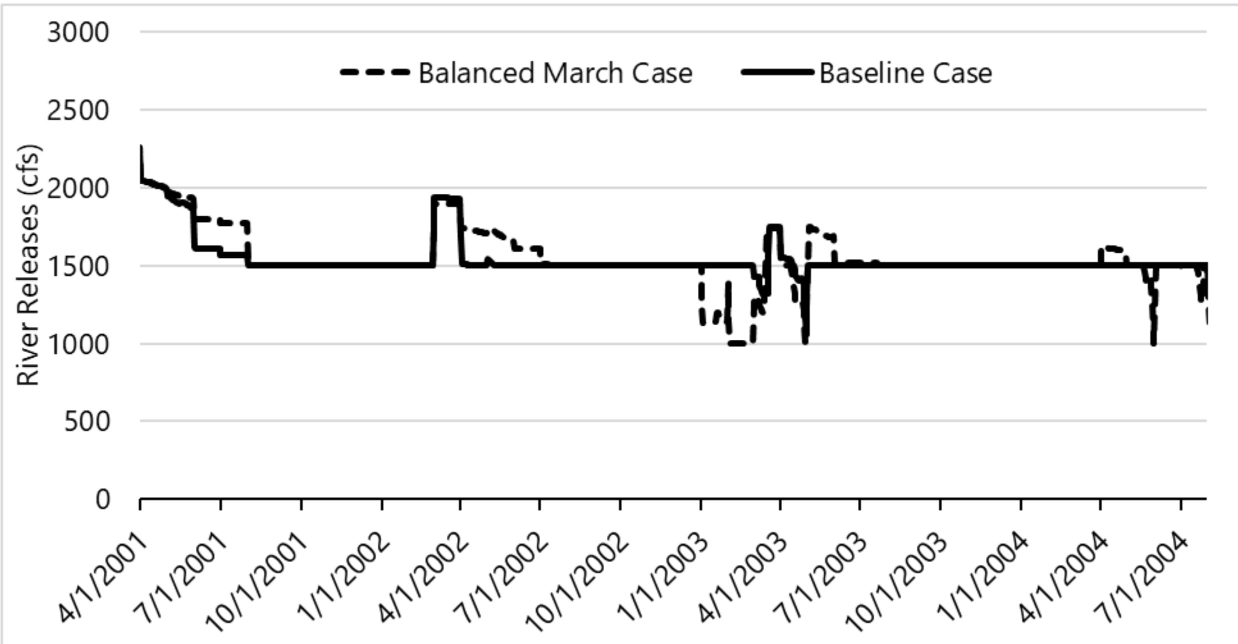


Figure 20. Modeled river releases and pool elevations during 1994 showing the impacts of the Balanced March changes.

The 2000s drought is an example of this policy working as expected but working poorly. Most releases higher than 1,500 cfs draw the reservoir past the point of reaching the following March target for most of the 2000s drought. The higher releases in 2001 and 2002 due to the Balanced March Target reduce reservoir pool elevation by an additional ten feet in 2002, which results in pool elevations hovering around 3,547 ft for several months in 2003 and 2004. This causes releases to drop below 1,500 cfs for several months which negates any releases above 1,500 cfs in 2001 and 2002 for releases. Pool elevations and power generation are negatively impacted as well. See Figure 21 for model results.



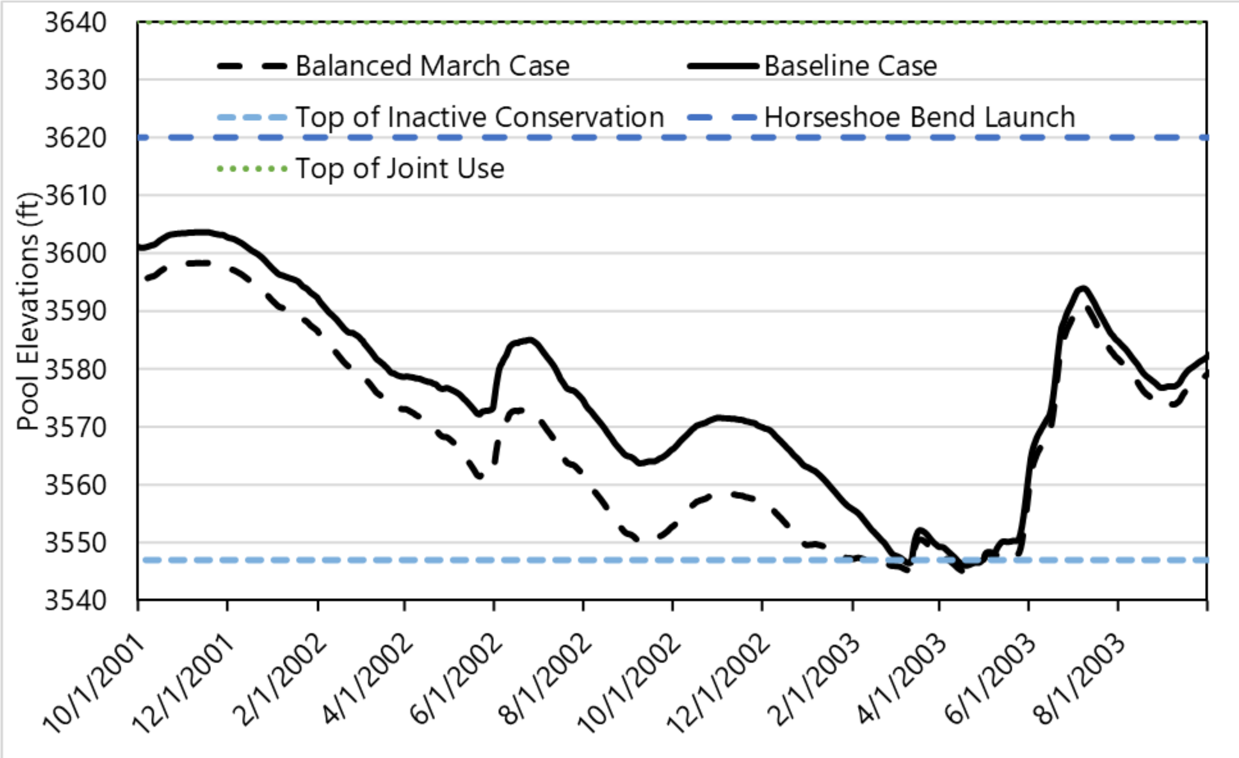


Figure 21. Modeled river releases and pool elevations during the 2000s drought showing the impacts of the Balanced March changes.

The Balanced March Target low-flow policy may be feasible if there are additional checks and balances in place to balance pool elevations and releases. In single year droughts, the Balanced March Target policy provides balance between conserving water for storage the following year and using water for river users. However, in multi-year droughts, the Balanced March Target policy sets too high of releases and poorly balances water conservation with water use. Maximizing releases in 2001 and 2002 results in releases below 1,500 cfs in 2003 and 2004 because the model forecasts that pool elevations are expected to drop below the top of the inactive conservation pool. Additionally, pool elevations in 2001 and 2002 are low enough that returning to a normal operational year the following year is implausible. Reservoir operations should focus on water conservation from 2001 through 2004 due to these low pool elevations and not on maximizing releases. On its own, the Balanced March Target is overly aggressive in setting releases, with too many negative consequences for pool elevations to justify the benefits. However, with additional checks and balances limiting aggressive releases in the multi-year droughts, the Balanced March Target could be considered in combination with some of the other recommended policies. Because potential future multi-year droughts are highly uncertain, consideration to incorporate flexibility in operations could be beneficial. This policy is recommended for MTAO's consideration when used in combination with other policies, as discussed in the Combinations of Policies section.

2020 Operating Criteria

The low-flow operating criteria described in the 2020 Condensed Operating Criteria (Reclamation, 2020a) is the same as the low-flow operating criteria described in the 2011 Operating Criteria (which comprises the base case model in this study). Although the 2020 Operating Criteria case is presented in this section as a model alternative, the 2020 Condensed Operating Criteria is what governs operational decisions at the time of this report publication. This study encompasses modeling of the 2020 Condensed Operating Criteria to isolate the impact of the operating criteria on modeled operations and to directly compare these results with other scenarios examined in this report.

The 2020 Condensed Operating Criteria describes low-flow operations in the following paragraph:

> *It may be necessary to reduce the river release to 2,000 cfs or less to adequately conserve storage for long term operations in years with forecasted runoff of less than 727,000 acre-feet. The primary goal in low water years is to conserve storage to provide a stable river release rate of between 1,500 cfs to 2,000 cfs while allowing storage to stay near the desired elevation of 3617 feet by March 31 of the following year. (Reclamation, 2020a)*

Translating the 2020 Operating Criteria language into model logic, the initial release aims to achieve a target elevation of 3,617 ft the following March. If the calculated March target release is higher than 2,000 cfs, the model sets releases to 2,000 cfs. If the calculated March target release is lower than 1,500 cfs, the model sets releases to 1,500 cfs. See Figure 22 for a flowchart of release decisions.

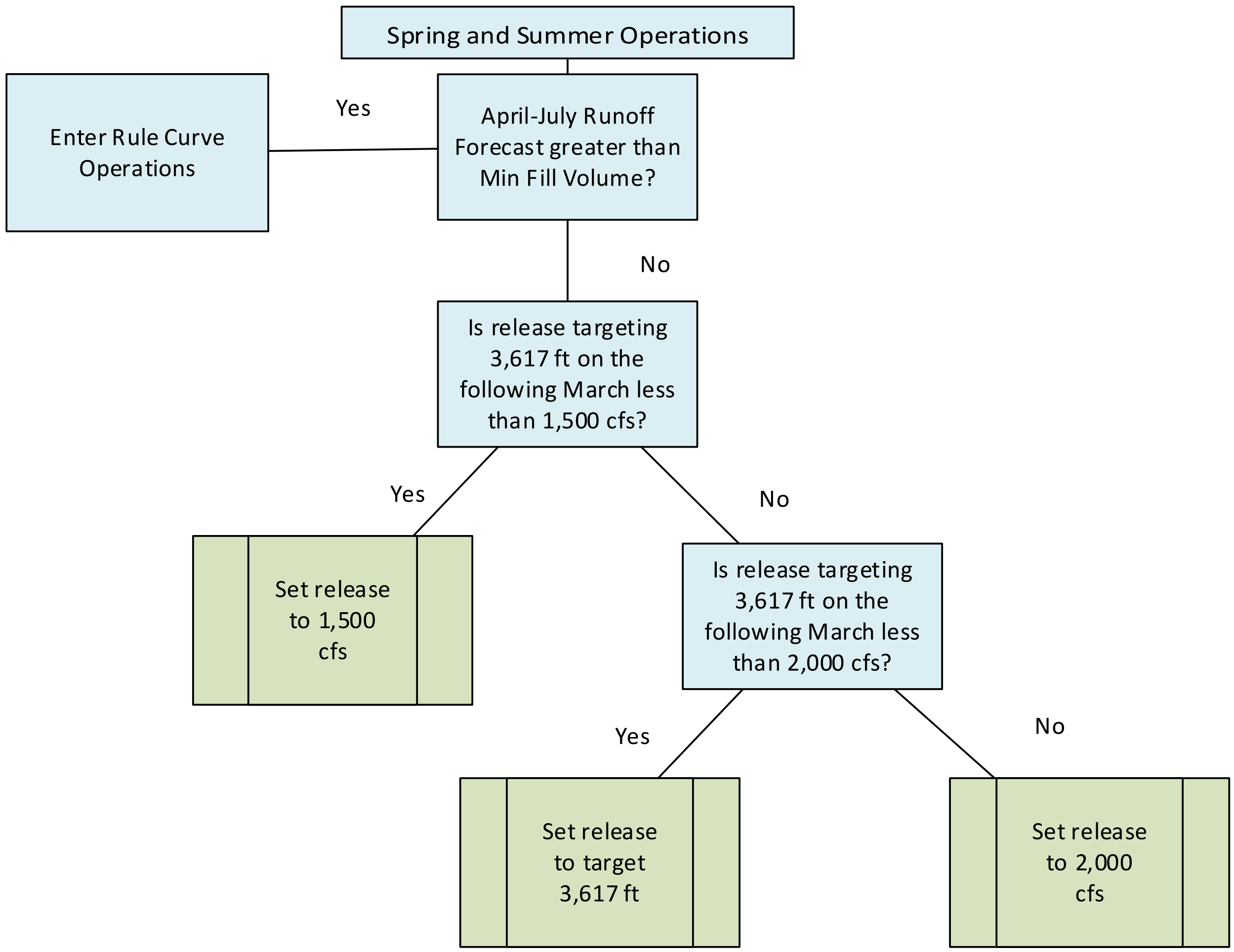


Figure 22. Flowchart with spring and summer low-flow operations after adding the 2020 Operating Criteria to the RiverWare model. Spring operations are in effect from April 1 through May 31 and summer operations are in effect from June 1 through July 31.

All of the differences in results between the 2020 Operating Criteria and the base case (2011 Operating Criteria) are a result of the 2,000 cfs release cap. The 2020 Operating Criteria does not allow releases higher than 2,000 cfs if the reservoir is in low-flow operations. Alternatively, the base case operating criteria allows releases higher than 2,000 cfs if the release targeting the following March is higher than 2,000 cfs based on water supply conditions and forecasts.

The release cap in the 2020 Operating Criteria case does increase pool elevations in some conditions. Water year 2006 provides an example of this scenario's increased pool elevations. The pool elevation increases are not substantial in terms of feet of pool elevation improvements, but the capped releases do yield an extra 11 summer days of lake elevations above 3,620 ft (minimum recommended boat launch elevation. The 2020 Operating Criteria reduces releases, but the spring months have fewer release changes which may provide some benefit to trout spawning because trout spawn periods benefit from stable, consistent flow rates. Figure 23 shows pool elevations and releases for 2006.

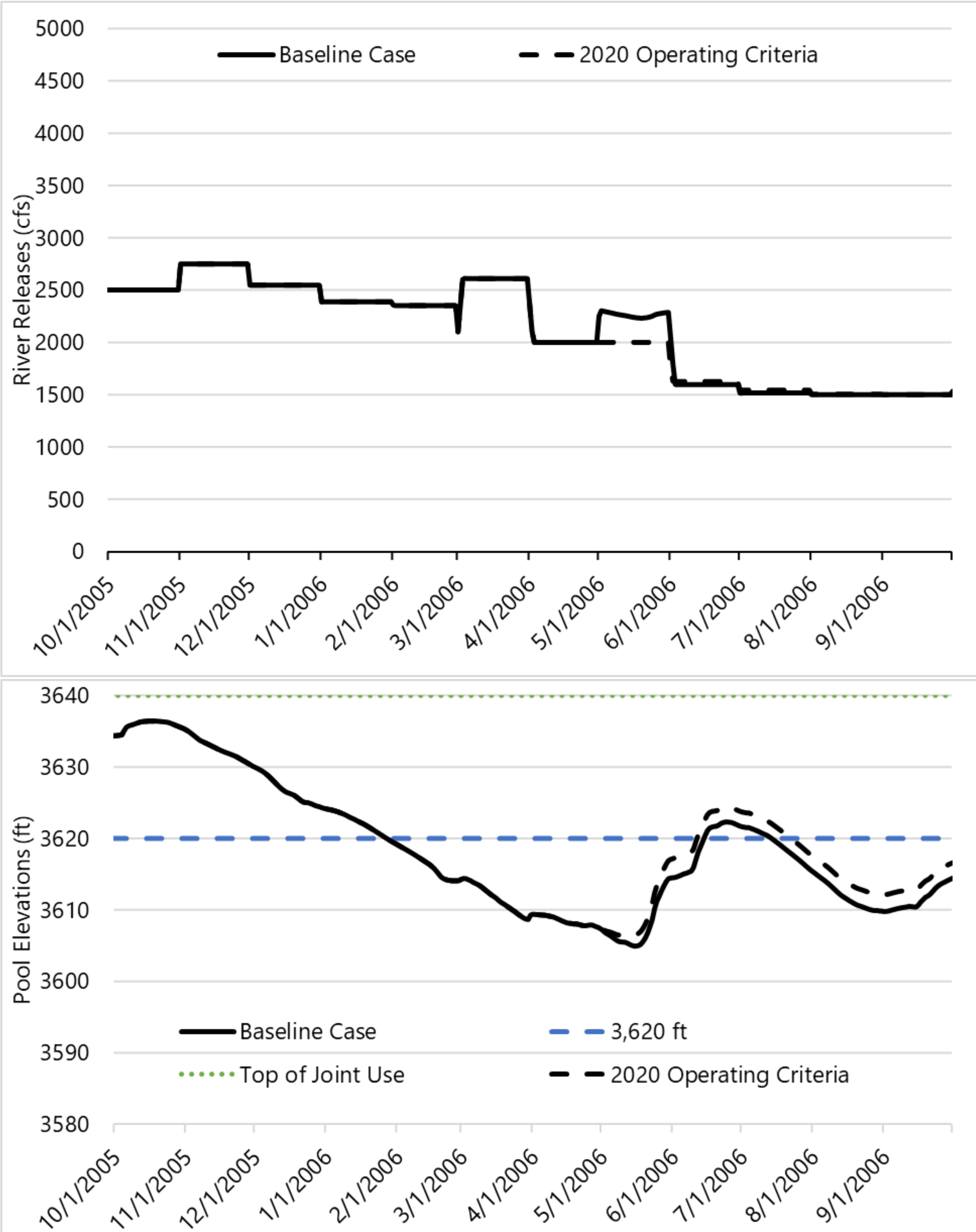
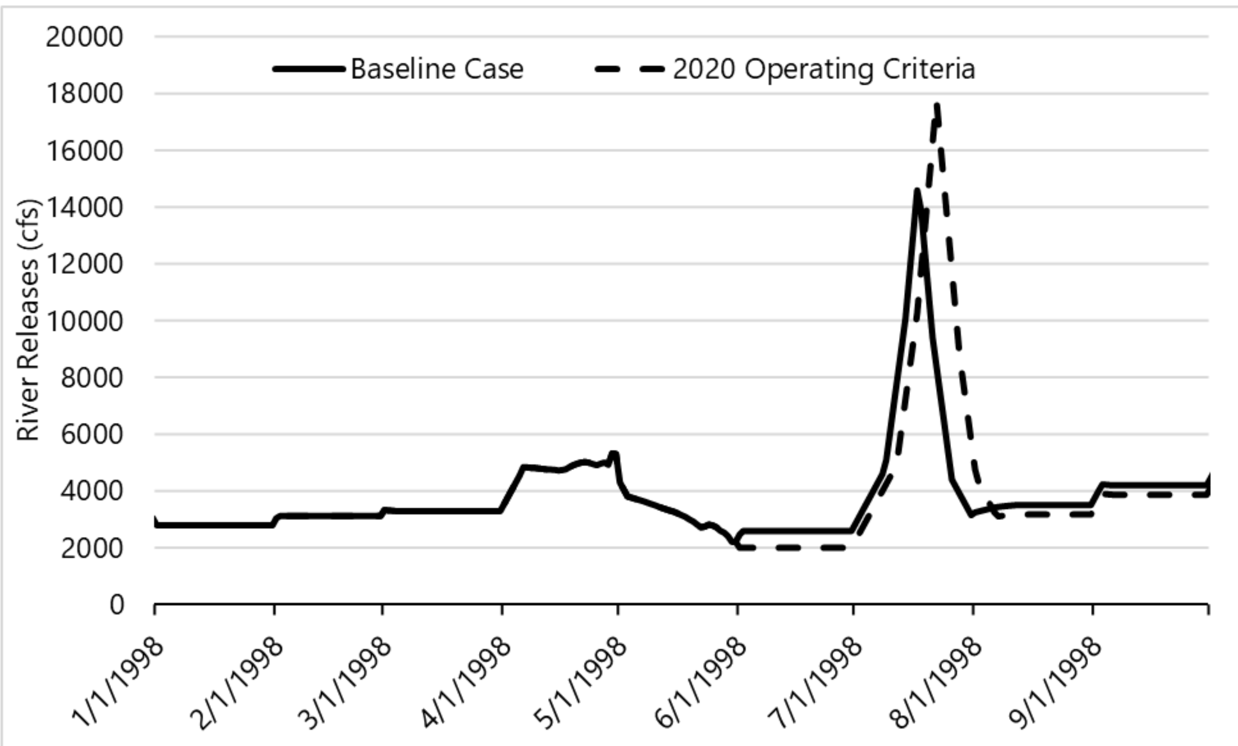


Figure 23. Modeled river releases and pool elevations during 2006 showing the impacts of the 2020 Operating Criteria changes.

There are risks and undesirable consequences of this policy. The 2,000 cfs release cap could result in overly conservative releases if water supply conditions and forecasts indicate a higher release is possible. The risk of having large release events later by capping releases in low-flow conditions regardless of inflow forecasts is highlighted in 1998. June forecasts in 1998 indicated a low-flow inflow year but an unexpected high inflow volume occurred in early July. See Figure 24 for releases and pool elevations in 1998. The base case sets June releases to 2,590 cfs while the 2020 Operating Criteria case caps releases at 2,000 cfs. The impact of capping releases for the month of June is substantially higher peak flows and a peak flood control pool elevation of 3,648 ft. However, the model does not realistically handle unexpected inflow volumes. This is a limitation of the model. Looking at historical inflows, the 1998 inflow event starts on July 1 and ends on July 21. In historical operations, the July 1 pool elevation is 3,632 ft. In the modeled results, the base case has a July 1 pool elevation of 3,632.7 ft and the 2020 Operating Criteria case has a pool elevation of 3,636 ft. While it is difficult to predict how high releases would peak in more realistic operations, the capped releases result in a higher pool elevation on the date of the inflow event which would likely cause higher peak releases than the base case due to limited storage.



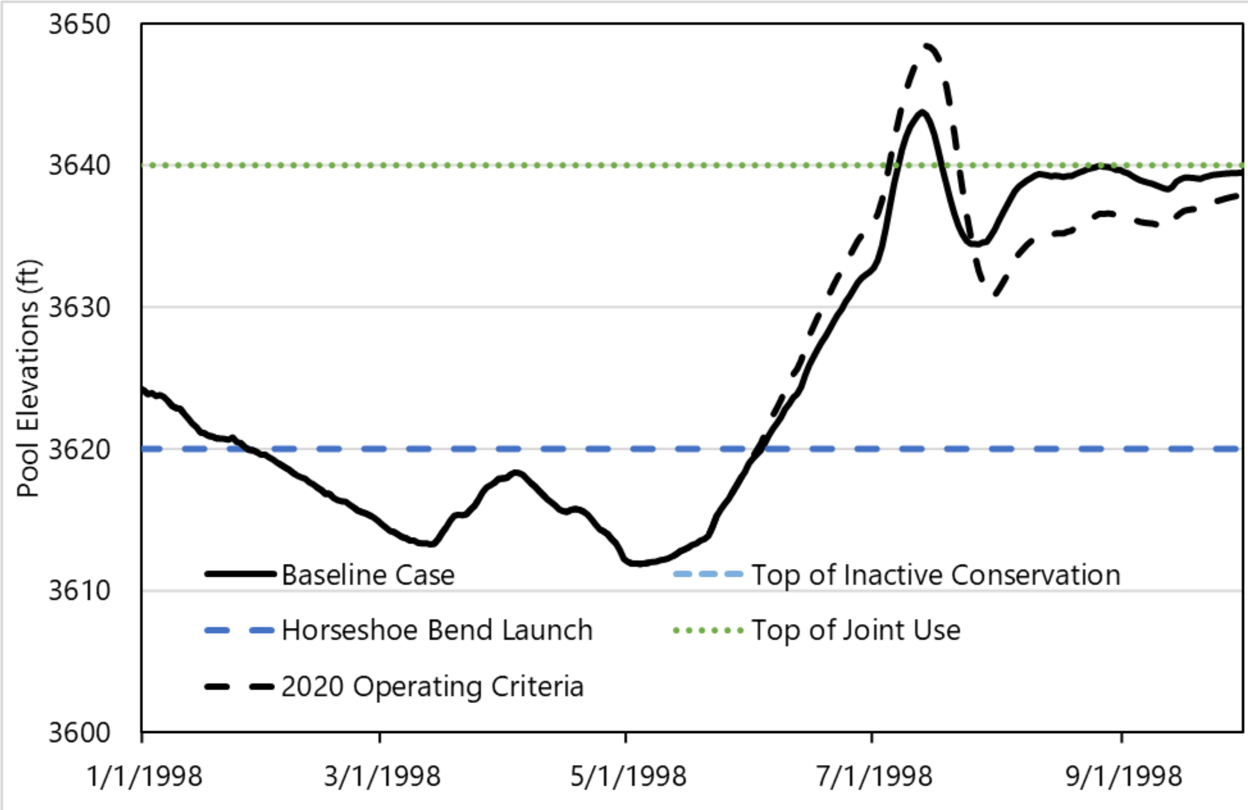


Figure 24. Modeled river releases and pool elevations during 1998 showing the impacts of the 2020 Operating Criteria changes.

The 2,000 cfs release cap stabilizes spring release patterns and increases pool elevations in some instances. Inaccurate forecasts pose a risk to the 2,000 cfs release cap, which could result in large release events. This policy is recommended for MTAO's consideration when used in combination with other policies, as discussed in the Combinations of Policies section.

End of March Target Change

This scenario is similar to the Dynamic Early Spring Target scenario. In low-flow years, the March release is set to target either 3,617 ft on the following March 31 or 1,500 cfs, whichever is larger. This is a 13-month forecast window to decide how to set target releases. The End of March Target Change scenario shortens the forecast window by setting March releases to meet the current year March 31 target of 3,617 ft instead of next year's March 31 target. On April 1, the operator has one extra month of available forecasts which shortens the 13-month forecast window to 12 months, plus it provides an additional month of information on if the current runoff season is expected to be low-flow or if inflow conditions and forecasts have improved.

When run with most-probable forecasts, this scenario improves operations in all modeled water years in which the scenario had an impact. The base case shows high releases in March in several water years followed by significant cuts on April 1 when new long-range forecasts are made. This occurs when March long-range forecasts overestimate long-range inflows. March long-range forecasts that underestimate long-range inflows result in low releases in March followed by significant increases to releases later in the spring and summer. By targeting the end of the current

March instead of the following March under most-probable forecast conditions, the End of March Target Change scenario mitigates some of the impacts of poor-quality long-range March forecasts reflected in the base case, with benefits to both river releases and pool elevations.

However, the End of March Target case performs poorly under perfect forecast conditions. When the model has perfect advanced knowledge of reservoir inflow conditions, the End of March Target case draws the reservoir down to achieve 3,617 ft at the end of the month by maintaining winter releases. The winter release rate is often higher than the release rate targeting the following March, so releases are reduced on April 1 in many years and the lower release is maintained for the remainder of the spring and summer. Large reductions in releases in spring and early summer could negatively impact the trout spawning season. Additionally, pool elevations are negatively impacted by the increased drawdown.

The End of March Target case is attempting to resolve issues caused by forecasting error with a policy change. The poor results under perfect forecast conditions coupled with improvements to results under most-probable conditions highlights that the issue should be mitigated with forecast improvements instead of low-flow operational policy changes.

The End of March Target case is not recommended for low-flow operational policy implementation. However, this policy did expose the need for an improved long-range forecast methodology and precipitated the Forecast Analysis section of this study.

Year Out Inactive Conservation Check

While the inactive conservation check that forecasts one-month into the future for pool elevations below 3,547 ft (top of inactive conservation pool) is a beneficial policy, a possible improvement could be forecasting pool elevations from the current timestep to the following March. This would give the model and the operator more time to adjust releases, potentially avoiding approaching pool elevations of 3,547 ft in any scenario.

As expected, this policy change only impacts results under the 2000s drought. The model reduces releases once it forecasts that pool elevations could drop below 3,547 ft by the following March. The reductions in releases below 1,500 cfs are less extreme in the long-range scenario than in the one-month scenario. This could be caused by the increased amount of time the model has to avoid dropping pool elevations below 3,547 ft. Increases to reservoir storage were less than expected, but there was still some improvement. See Figure 25 for releases and pool elevations.

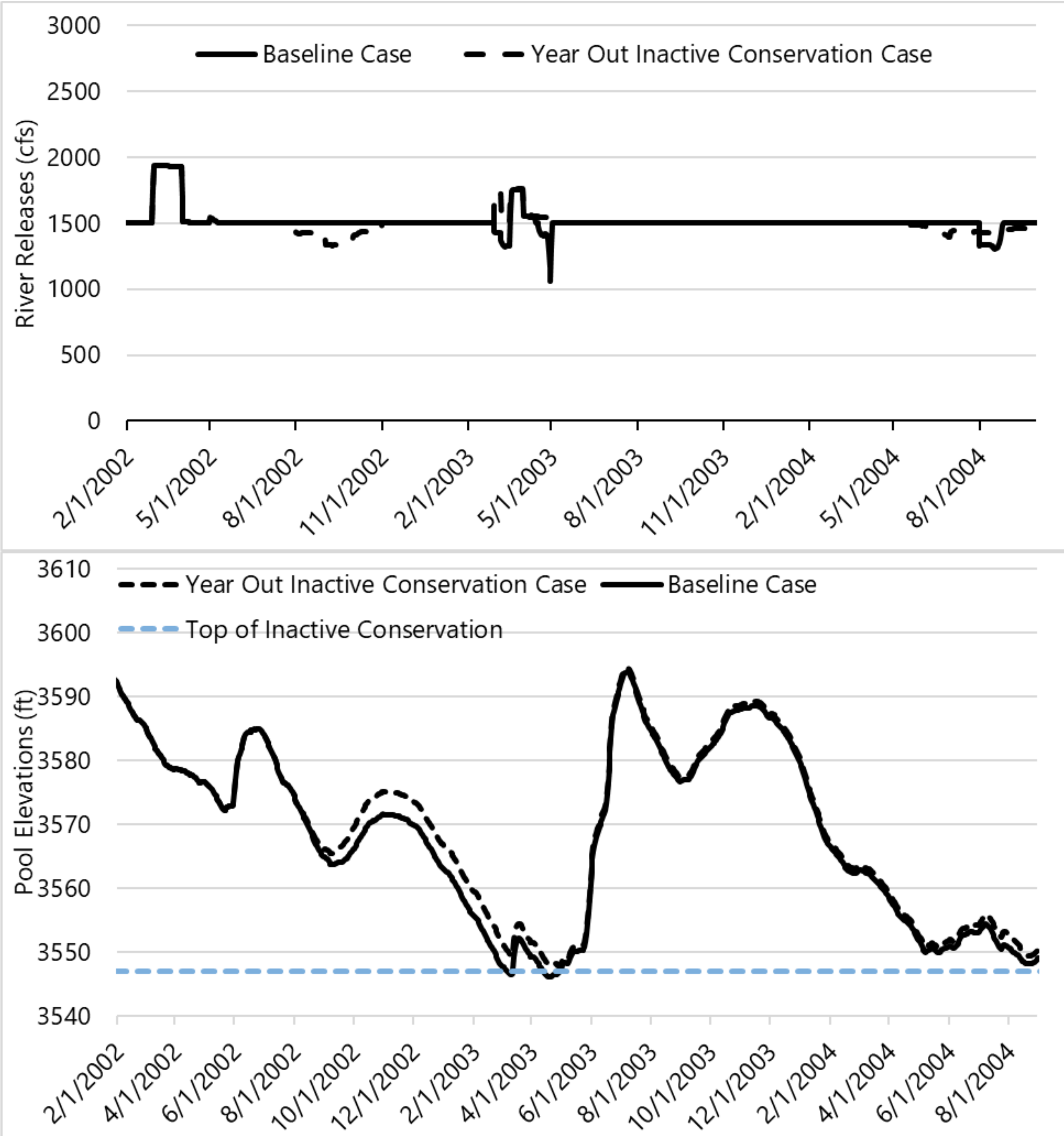


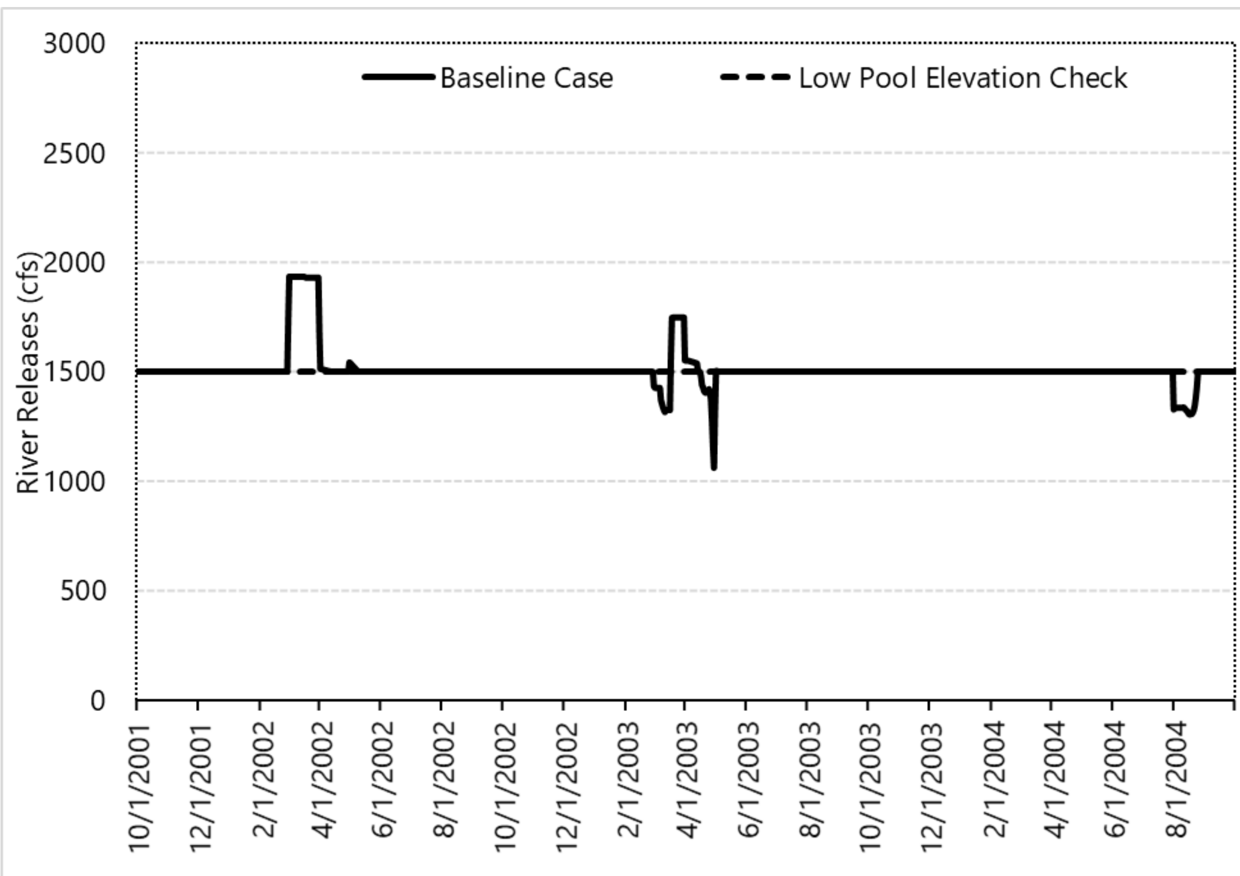
Figure 25. Modeled river releases and pool elevations during the 2000s drought showing the impacts of the Inactive Year Out changes.

This policy is recommended for implementation, either as a standalone policy or in combination with other policies. Increases in pool elevations were less than expected, but the policy is still giving the model and the operator more time to adjust releases to avoid dropping pool elevations below 3,547 ft.

Low Pool Elevation Check

None of the operating criteria policies examined thus far in the study prevent unrealistic releases higher than 1,500 cfs in extremely low pool elevation conditions. One way to prevent these releases is to add a check to the model to prevent releases greater than 1,500 cfs when pool elevations are extremely low. For the check in the model, an extremely low pool elevation is less than 3,591.5 ft. While this is an arbitrary cutoff, it is unlikely that an operator would choose to release more than 1,500 cfs with a low-flow forecast if pool elevations are below 3,591.5 ft. The intent of the Low Pool Elevation Check is to fix unrealistically high release settings in the model and is not intended to govern operational policy.

The Low Pool Elevation Check only impacts results in the 2000s drought. This was the expected result, because this is the only time period that modeled pool elevations drop below 3,591.5 ft in low-flow conditions. River releases between 2001 and 2004 do not exceed 1,500 cfs and pool elevations improve between 2001 and 2004. In the spring of 2003, pool elevations with the Low Pool Elevation Check are seven and a half feet higher than the base case. Pool elevations also never drop below 3,547 ft with the Low Pool Elevation Check The improvements in pool elevations prevent the need for releases to drop below 1,500 cfs. See Figure 26 for results.



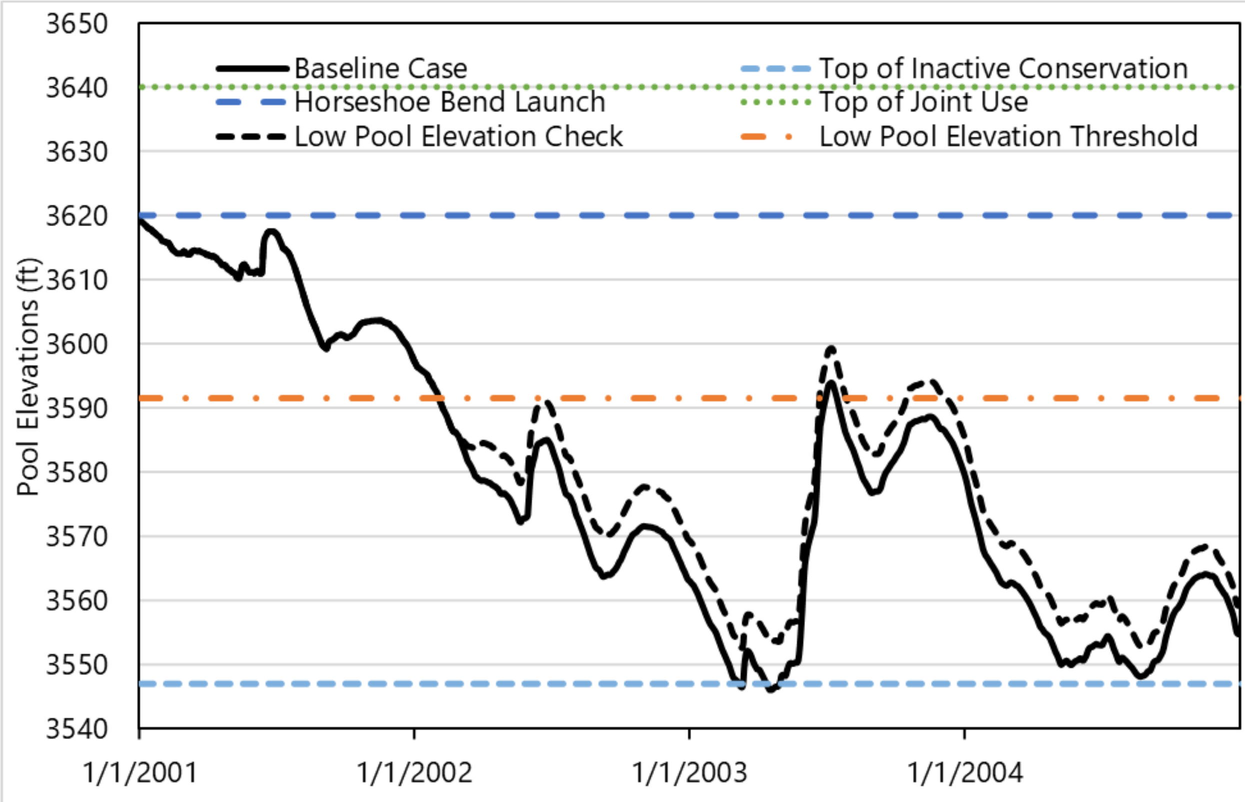


Figure 26. Modeled river releases and pool elevations during the 2000s drought showing the impacts of the Low Pool Elevation Check.

This policy is recommended for implementation, either as a standalone policy or in combination with other policies. Pool elevations are increased in some years over the base case model, including the prevention of pool elevations below 3,547 ft. The Low Pool Elevation Check benefits river releases because releases never drop below 1,500 cfs.

Combinations of Policies

After completing the analysis of individual policies, this study examined the impact of combining multiple individual policies into one model run. There were two combined policies examined:

1. A combined model with the Year Out Inactive Conservation Check, the Low Pool Elevation Check, the removal of the Summer Low-Flow Targets, and the Balanced March Target.
2. A combined model with the Year Out Inactive Conservation Check, the Low Pool Elevation Check, the removal of the Summer Low-Flow Targets, and the 2020 Operating Criteria.

The difference between the two combinations is inclusion of the Balanced March Target or 2020 Operating Criteria. When compared with the individual Balanced March Target and 2020 Operating Criteria cases, the only impact of the combined policy models occurred during the 2000s drought. Both of these combined policies have the same general impacts, but with slightly different magnitudes of impact. Both combined policies improve pool elevations from 2001 to 2005.

Additionally, both policies prevent releases above 1,500 cfs in several situations and cause releases to drop below 1,500 cfs in 2002. Both policies prevent releases below 1,500 cfs from 2003 through 2005. See Figure 27 for Combined Balanced March Target river releases and pool elevations and see Figure 28 for Combined 2020 Operating Criteria river releases and pool elevations. The figures show the difference in impact magnitudes, as well as the general impacts described above.

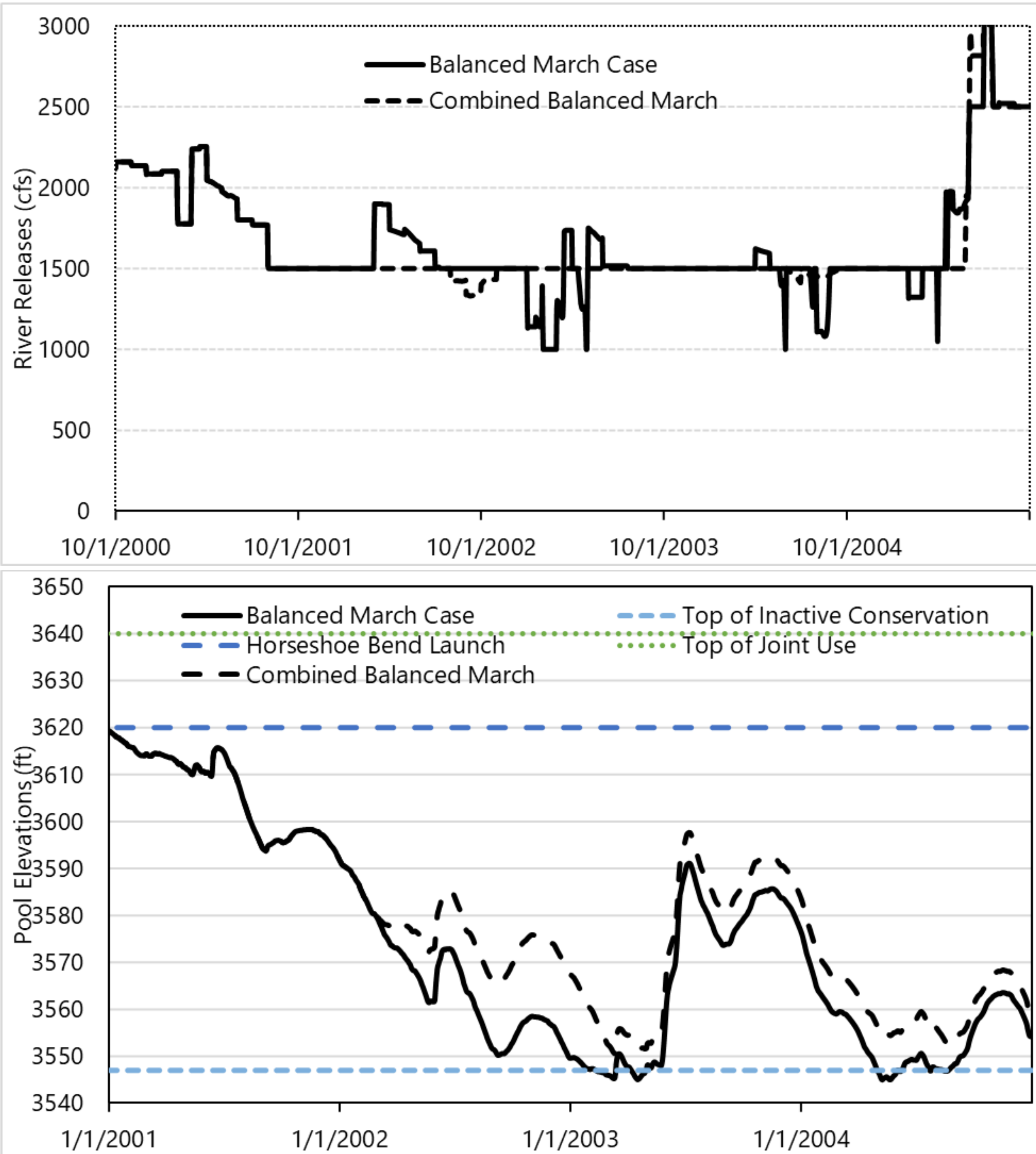
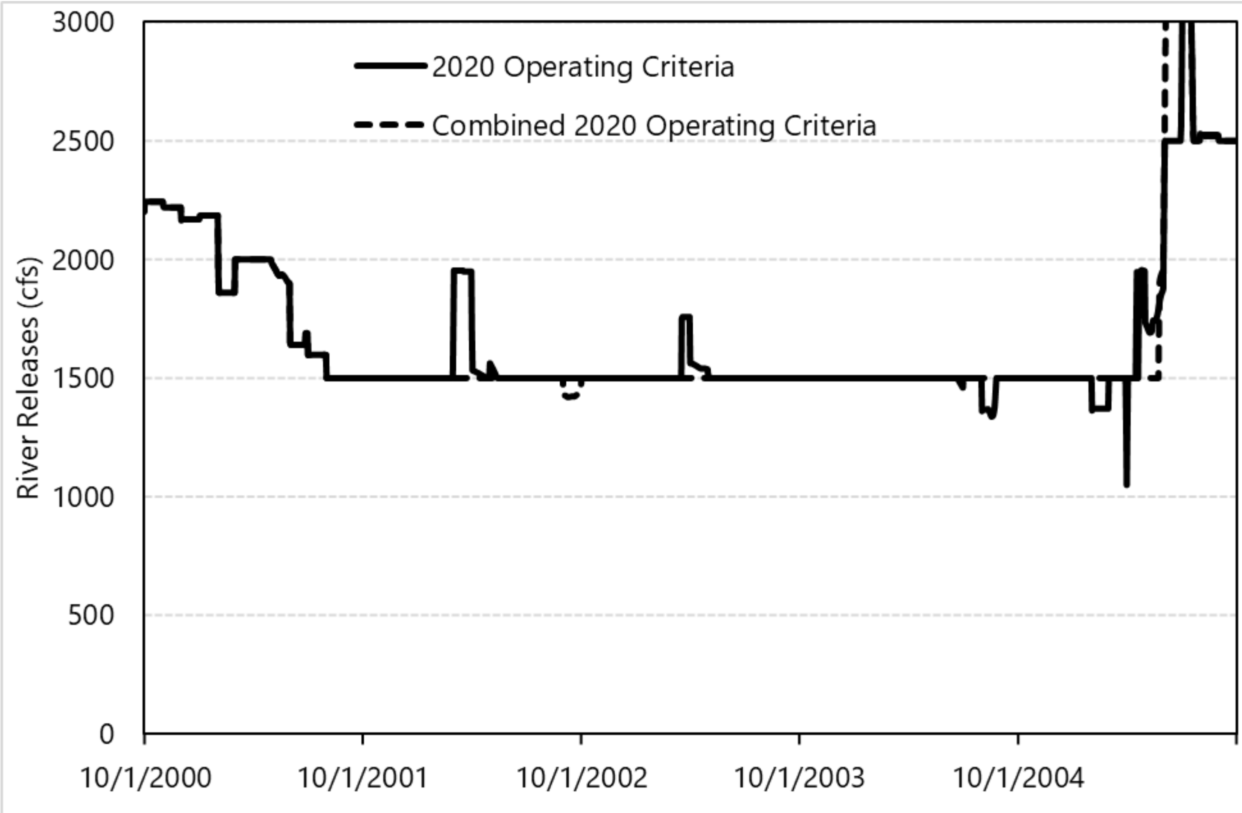


Figure 27. Modeled river releases and pool elevations during the 2000s drought showing the impacts of adding the Combined Balanced March Target changes to the Balanced March Target case.


2020 Operating Criteria
Combined 2020 Operating Criteria
River Releases (cfs)
3000
2500
2000
1500
1000
500
0
10/1/2000
10/1/2001
10/1/2002
10/1/2003
10/1/2004

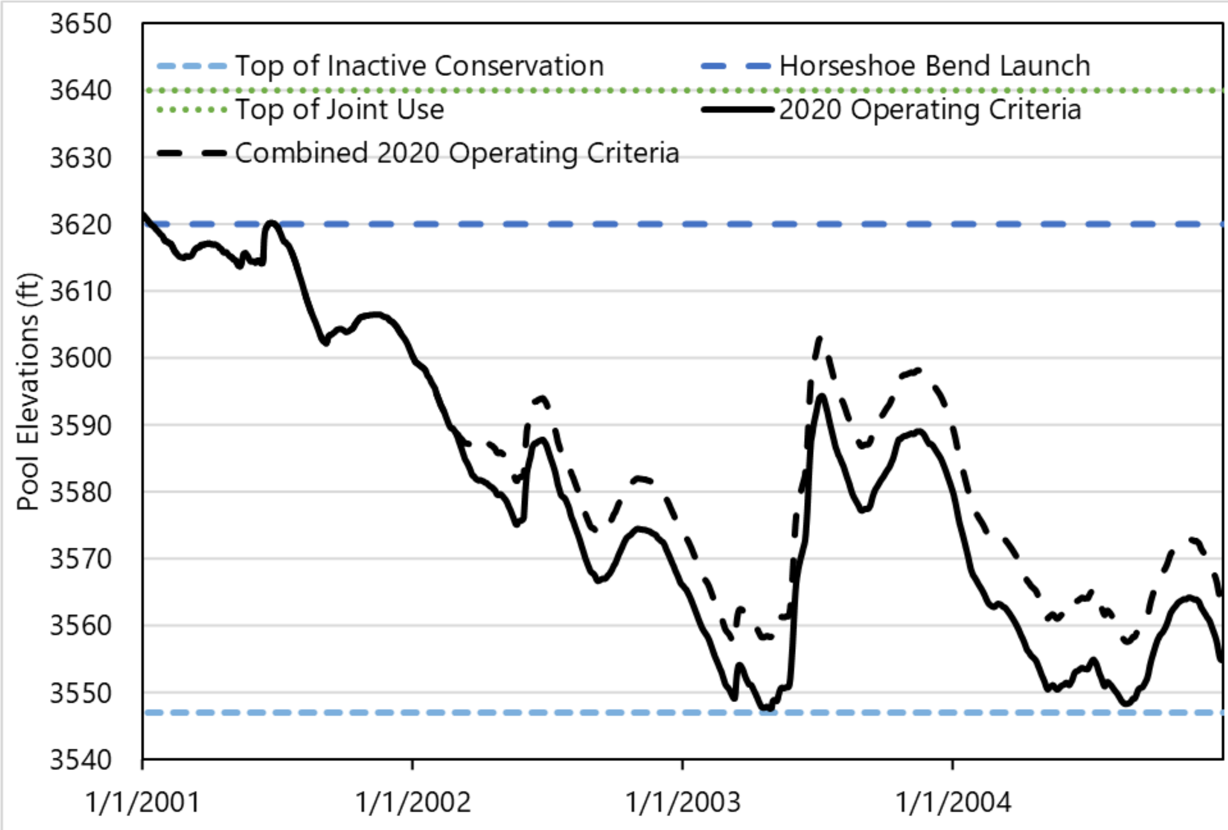


Figure 28. Modeled river releases and pool elevations during the 2000s drought showing the impacts of adding the Combined 2020 Operating Criteria changes to the 2020 Operating Criteria case.

Both combined policies benefit operations in comparison with their respective individual policies. Both policies are recommended as possible options for MTAO's consideration. This section only represents the impact of adding the additional policies to both the Balanced March Target and the 2020 Operating Criteria cases. The differences between the Combined Balanced March Target and the Combined 2020 Operating Criteria are fully described in the Comparison of Policies section.

Comparison of Policies

The low-flow modeling analysis presented thus far has compared the modeled data for each individual case to a modeled base case (2012 Bighorn Operating Policy). This section compares individual cases against one another and the base case. There are two different types of comparisons completed in this section: Combined Model Comparisons and Composite Comparisons. The Combined Model Comparisons compare the Combined Balanced March Target and the Combined 2020 Operating Criteria against one another. The Composite Comparisons compare several cases and several years against one another at once, with data compiled for different seasons and metrics.

Combined Model Comparisons

All of the observable differences between the Combined 2020 Operating Criteria and the Combined Balanced March Operating Criteria can be found in Appendix A. Most of the differences between the two combined cases are due to the 2,000 cfs release cap in the Combined 2020 Operating Criteria. There are some differences in releases between 1,000 cfs and 2,000 cfs that are caused by the Balanced March Target spring and summer release methodology.

Table 12 shows a simplified summary of the main advantages and risks of each operational policy compared in Appendix A. Each impacted year is a bit different in terms of advantages and risks, so the information in Table 12 only describes major patterns. See Appendix A for all data.

Table 12. Summary of risks and advantages to operations of the Combined 2020 Operating Criteria and the Combined Balanced March Target.

Policy	Advantages	Risks
Combined 2020 Operating Criteria	2,000 cfs release cap conserves water in years like 2013, improving pool elevation conditions	2,000 cfs release cap can cause risk of higher flow events in years that were initially forecasted as low-flow years, but later recorded high inflow events
Combined Balanced March Target	Small improvements to spring and summer releases between 1,500 cfs and 2,000 cfs	Risk of depleting water storage and low pool elevations

Composite Comparisons

Examining modeled data in individual years displays possible operational conditions using historical inflow data. However, looking at specific years may not be representative of general policy implications and may not apply to future years or correctly identify patterns. The composite comparisons include data from all years with at least one forecasted low-flow month. By comparing multiple years at once, identification of patterns in the data is more straight-forward.

Methods

The composite comparisons only include a select number of years from the 28-year study period. Years included in the analysis contained at least one forecasted low-flow month. The analysis included years with at least one low-flow forecast but actual inflows were higher than forecasted, such as 2015. The analysis also included years that were forecast as low-flow and actually had low inflow volumes. The analysis avoided years that were forecasted as rule-curve operations for the entire year to avoid skewing data with rule-curve operations unrelated to low-flow operations. This analysis used calendar years instead of water years. Years included in this analysis are the following: 1992, 1993, 1994, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2010, 2012, 2013, 2015, and 2016.

For river release composite comparisons, there were a number of bins developed to compare the percentage of time that operations set releases to a quantity inside of each bin. These percentages allow for a quick comparison between different cases of the percentage of time operations spent with releases at, below, or above certain levels. Here are the river release bin definitions:

- River release below 1,500 cfs
- River release at 1,500 cfs
- River release greater than 1,500 cfs and less than 1,750 cfs
- River release greater than or equal to 1,750 cfs and less than 2,000 cfs
- River release at 2,000 cfs
- River release greater than 2,000 cfs and less than 2,500 cfs
- River release greater than or equal to 2,500 cfs and less than 6,000 cfs
- River release greater than or equal to 6,000 cfs and less than 8,000 cfs*
- River release greater than or equal to 8,000 cfs*

* In seasons without releases over 6,000 cfs, only release bins up to 6,000 cfs are displayed.

Pool elevation composite comparisons also use bins to compare the percentage of time pool elevations are in each bin for different cases. Here are the pool elevation bin definitions:

- Pool elevations under 3,547 ft
- Pool elevations greater than or equal to 3,547 ft and less than 3,580 ft
- Pool elevations greater than or equal to 3,580 ft and less than 3,620 ft
- Pool elevations greater than or equal to 3,620 ft and less than 3,630 ft
- Pool elevations greater than or equal to 3,630 ft and less than 3,640 ft
- Pool elevations greater than or equal to 3,640 ft

To compare Yellowtail monthly energy values between each case, this analysis calculated total monetary value of energy generated at Yellowtail Powerplant for each case.

The composite comparisons calculated the percentage of time spent with various river release and pool elevation amounts, as well as the totals for Yellowtail energy values, for several seasons and for each calendar year included in the analysis. The results were isolated by season to better understand how releases, elevations, and energy varies with seasonal operations. Seasonal operations include Early Spring, Spring, Summer, Fall, Winter, and Full Year. See Table 5 for season definitions. The Full Year analysis provides a simplified comparison between the cases. For pool elevations, another season, Cultural Summer, was examined that includes dates from the Friday before Memorial Day to Labor Day each year.

After all the data was compiled through a Python program, figures summarizing the composite calculations for each season were created and analyzed in each of the results sections below.

Early Spring Results

Early Spring results show minor increases to pool elevations with the Combined 2020 Operating Criteria case. Additionally, the Combined 2020 Operating Criteria case shows minor improvement to releases between 1,500 cfs and 1,750 cfs in Early Spring. Early Spring includes January, February, and March. The Combined Balanced March case yields an additional energy value of approximately $188,000 over the Combined 2020 Operating Criteria (Combined Balanced March yields $4,021,000 compared with $3,833,000 for the Combined 2020 Operating Criteria).

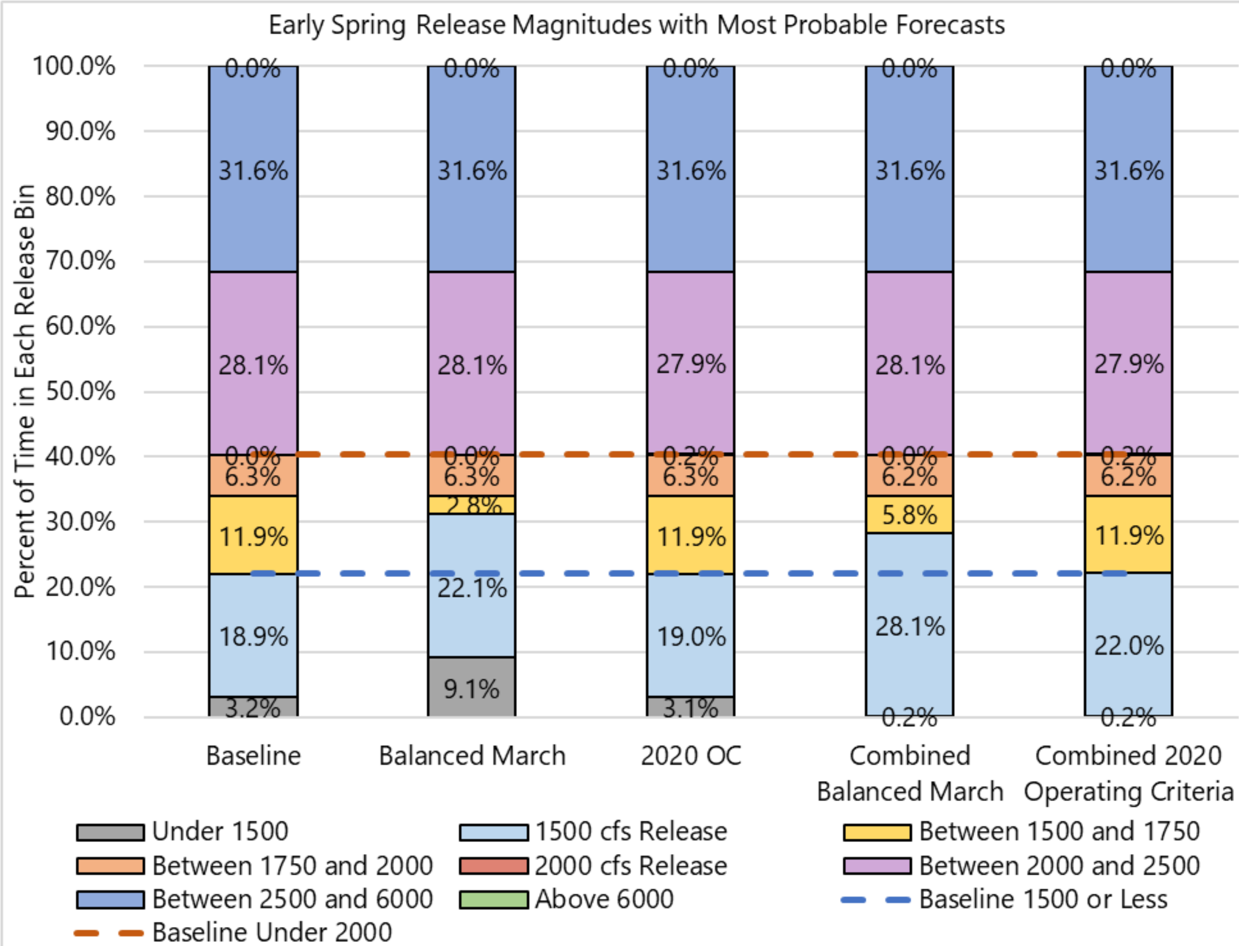


Figure 29. Composite comparisons for river releases in Early Spring. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with releases in between certain values.

For releases, seen in Figure 29, both of the combined cases almost eliminate releases below 1,500 cfs when compared with the non-combined cases. The only major difference between the two combined cases is that the Combined 2020 Operating Criteria has more time with releases between 1,500 cfs and below 1,750 cfs and fewer time with releases at 1,500 cfs when compared with the Combined Balanced March case. Therefore, the Combined 2020 Operating Criteria case has a slight benefit to releases.

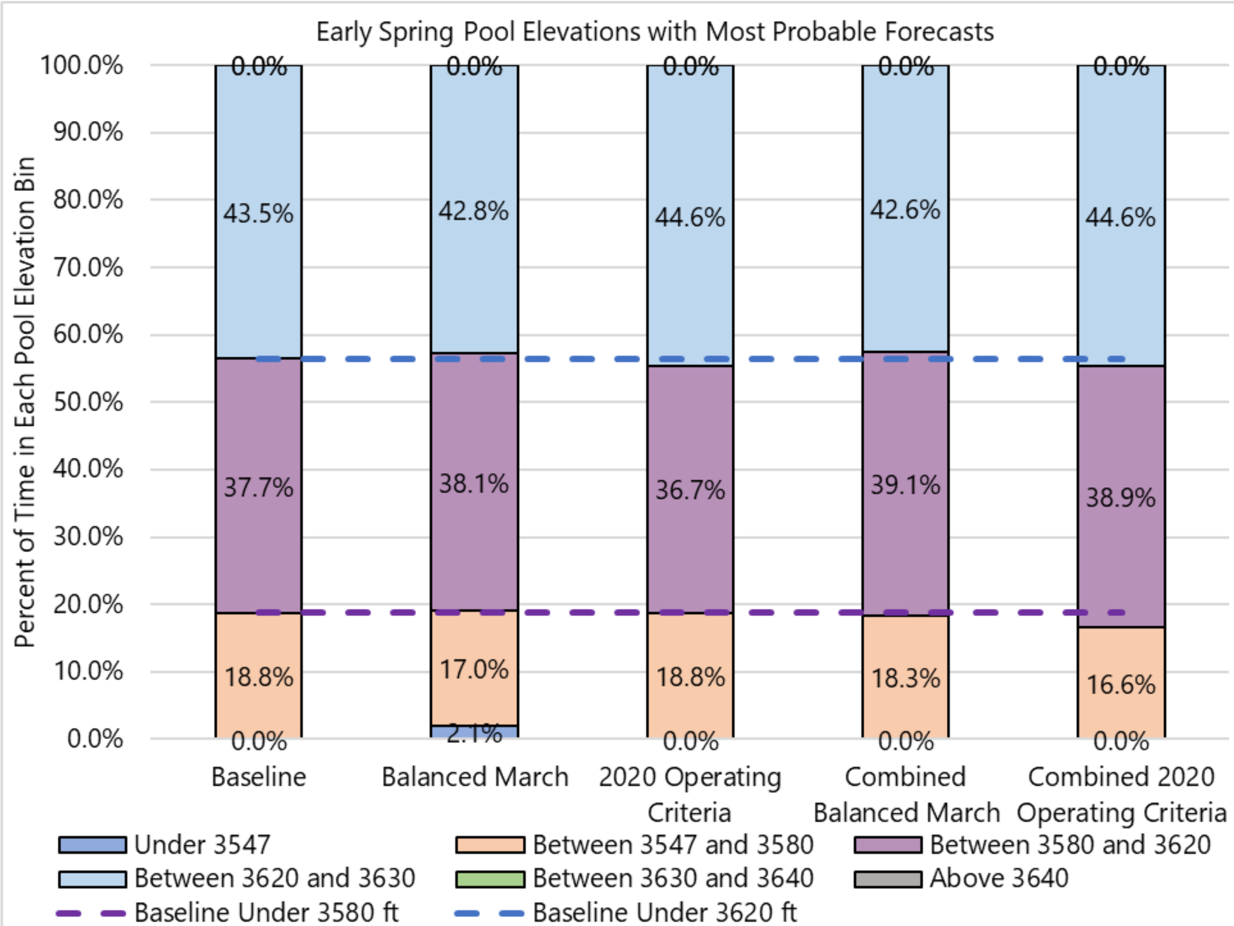


Figure 30. Composite comparisons for pool elevations in Early Spring. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with pool elevations in between certain values.

For pool elevations, seen in Figure 30, the Combined 2020 Operating Criteria case has a slight advantage over the Combined Balanced March case because it reduces the amount of time pool elevations are below both 3,620 ft and 3,580 ft.

Spring Results

Spring results show increased pool elevations with the Combined 2020 Operating Criteria case, but the Combined Balanced March case increases the quantity of time with river releases at or above 2,000 cfs. Spring includes April and May. The Combined 2020 Operating Criteria case yields an additional energy value of $147,000 over the Combined Balanced March case. The Combined 2020 Operating Criteria had an energy value of $3,242,000 while the Combined Balanced March Case had an energy value of $3,389,000.

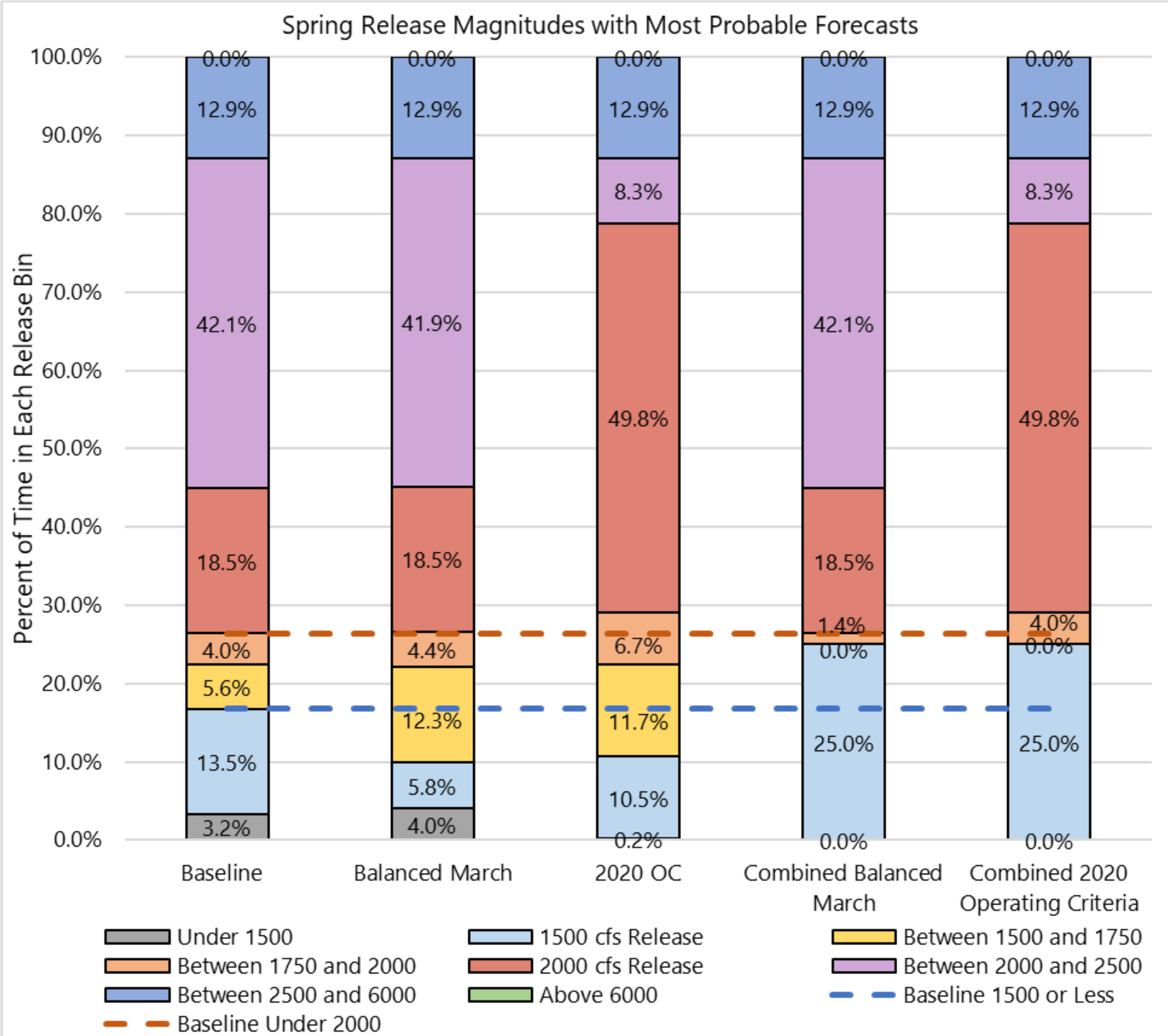


Figure 31. Composite comparisons for river releases in Spring. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with releases in between certain values.

See Figure 31 for Spring river release results. Both of the combined cases avoid releases below 1,500 cfs. The Combined 2020 Operating Criteria case has more time with releases below 2,000 cfs compared with the Combined Balanced March case, as well as having almost 50% of spring releases set to 2,000 cfs compared with the Combined Balanced March case's 18.5%. Therefore, the Combined Balanced March case increases the quantity of time with river releases at or above 1,750 cfs.

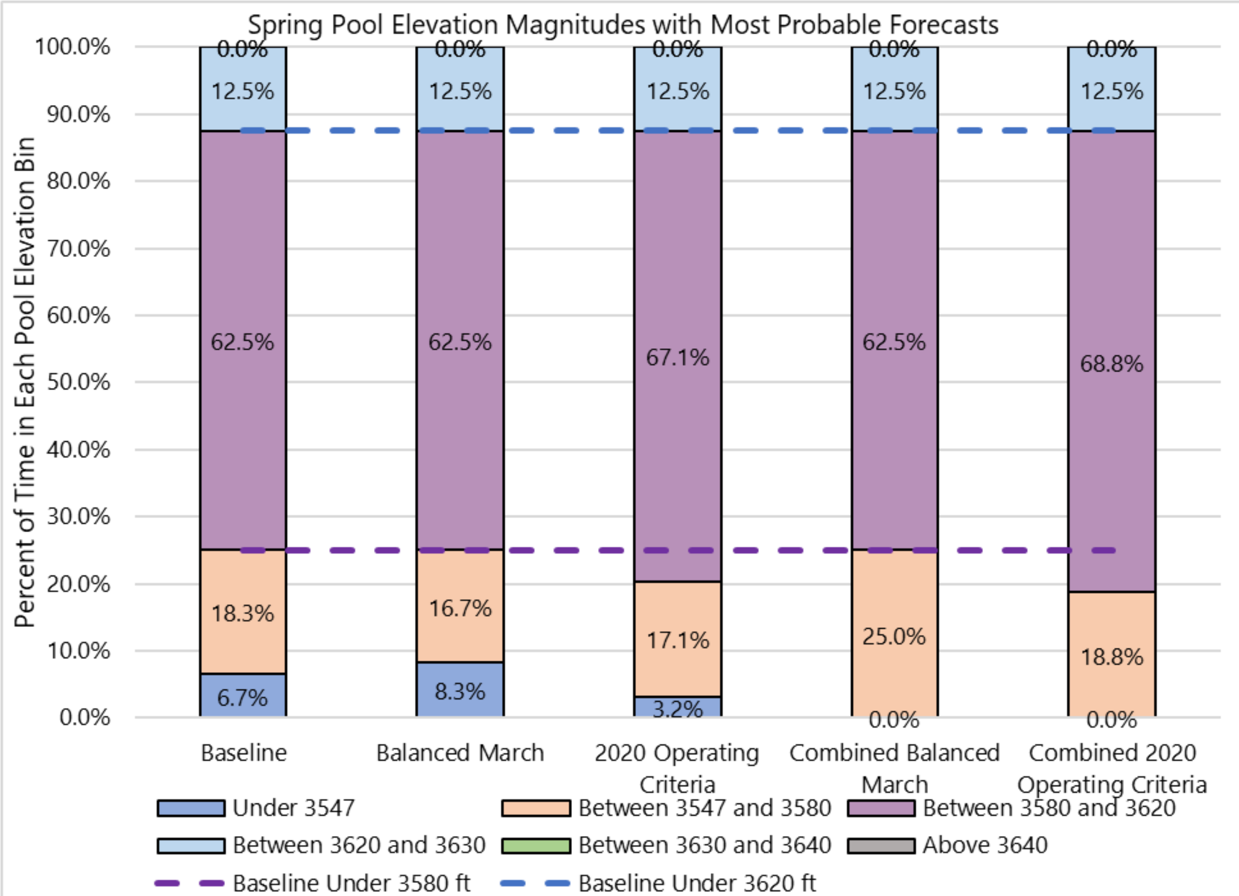


Figure 32. Composite comparisons for pool elevations in Spring. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with pool elevations in between certain values.

See Figure 32 for Spring pool elevation results. There is a slight advantage to the Combined 2020 Operating Criteria case for pool elevations during spring. The Combined 2020 Operating Criteria case has less time with pool elevations below 3,580 ft (which is the elevation required to launch boats from Barry's Landing) over the Combined Balanced March case.

Summer Results

For Summer results, the Combined 2020 Operating Criteria case increases pool elevations. Summer includes June and July. The river release results are complicated, with no clear advantage to any case. There are no major differences to hydropower energy value between any of the cases.

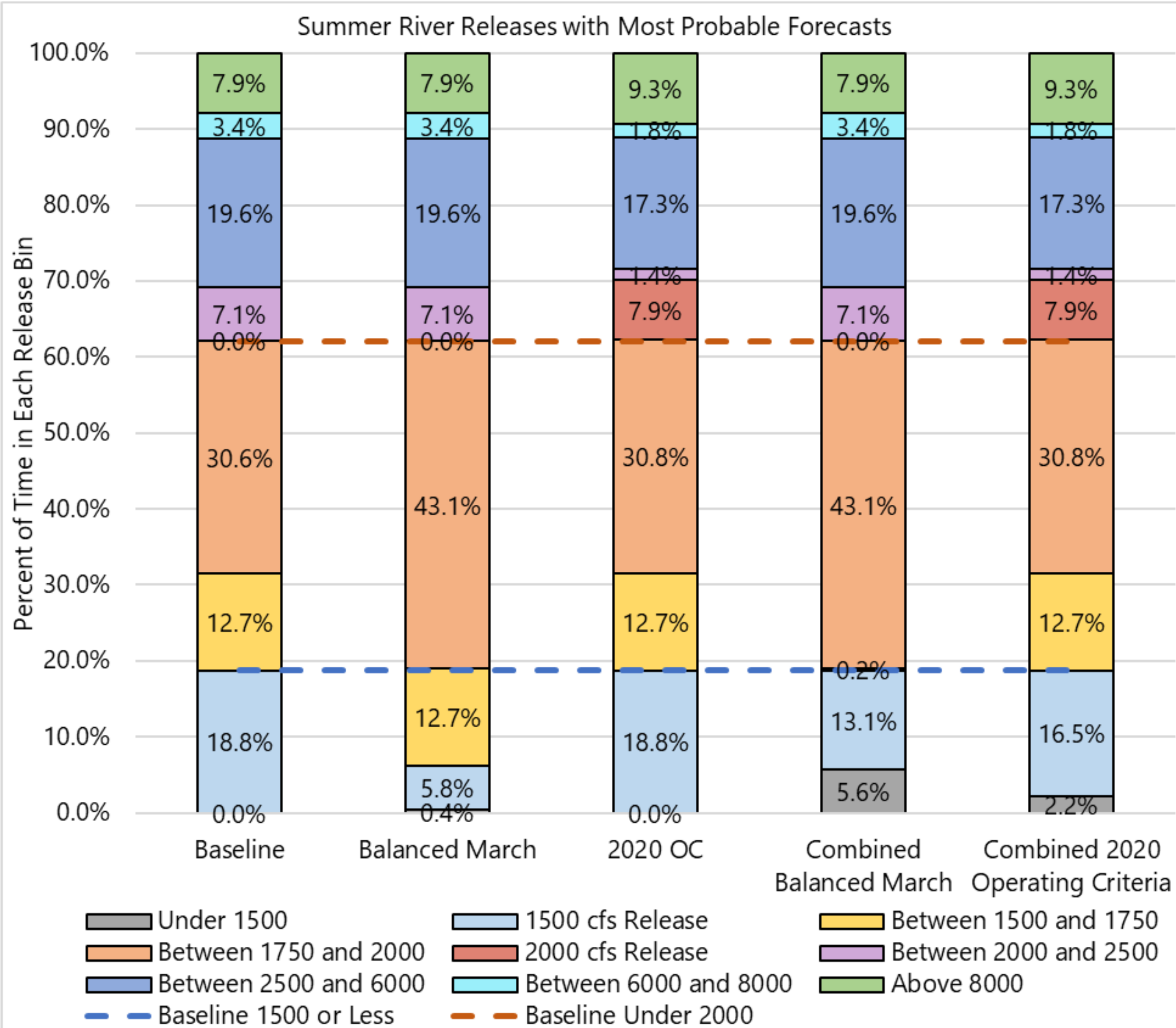


Figure 33. Composite comparisons for river releases in Summer. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with releases in between certain values.

The summer river release results are complicated. See Figure 33 for results. The Combined 2020 Operating Criteria has less time with releases below 1,500 cfs than the Combined Balanced March case. The Combined Balanced March case has more time between 1,750 cfs and 2,000 cfs due to the Balanced March logic, which benefits releases. Additionally, the Combined Balanced March case has more time with releases above 2,000 cfs, but less than 6,000 cfs, than the Combined 2020 Operating Criteria case. This is due to the 2,000 cfs release cap, and therefore the Combined Balanced March case benefits releases in these release bins. The Combined 2020 Operating Criteria case has less time with releases between 6,000 cfs and 8,000 cfs than the Combined Balanced March case. However, the Combined Balanced March case has less time with releases above 8,000 cfs compared with the Combined 2020 Operating Criteria. Both cases have roughly the same amount of time with releases over 6,000 cfs, but the distribution of these releases differs. The Combined Balanced March case limits the releases above 8,000 cfs, but consequently has more time with releases between 6,000 cfs and 8,000 cfs than the Combined 2020 Operating Criteria case.

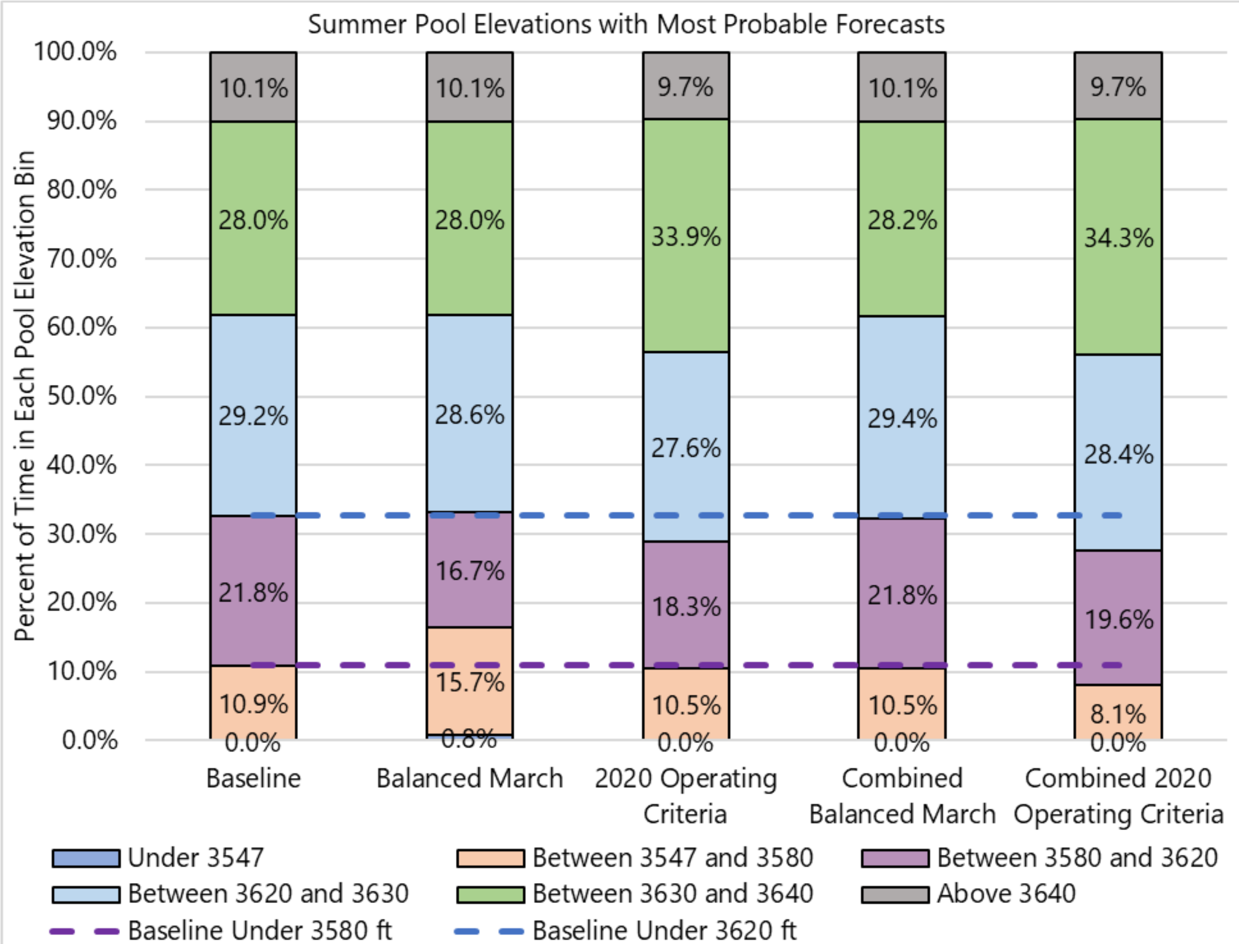


Figure 34. Composite comparisons for pool elevations in Summer. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with pool elevations in between certain values.

The Combined 2020 Operating Criteria benefits pool elevations over all other cases both by increasing percent of time with elevations over 3,620 ft and by increasing percent of time with elevations over 3,580 ft. See Figure 34 for results.

Cultural Summer Results

The Cultural Summer results were only calculated for pool elevations, due to the focus on access to boat ramps for recreation, and show similar results to the Summer results. Cultural Summer starts on the Friday before Memorial Day and ends on Labor Day. This range of dates is the most important time period for lake recreation. The Combined 2020 Operating Criteria benefits pool elevations over all other cases both by increasing elevations over 3,620 ft and by increasing elevations over 3,580 ft. See Figure 35 for results.

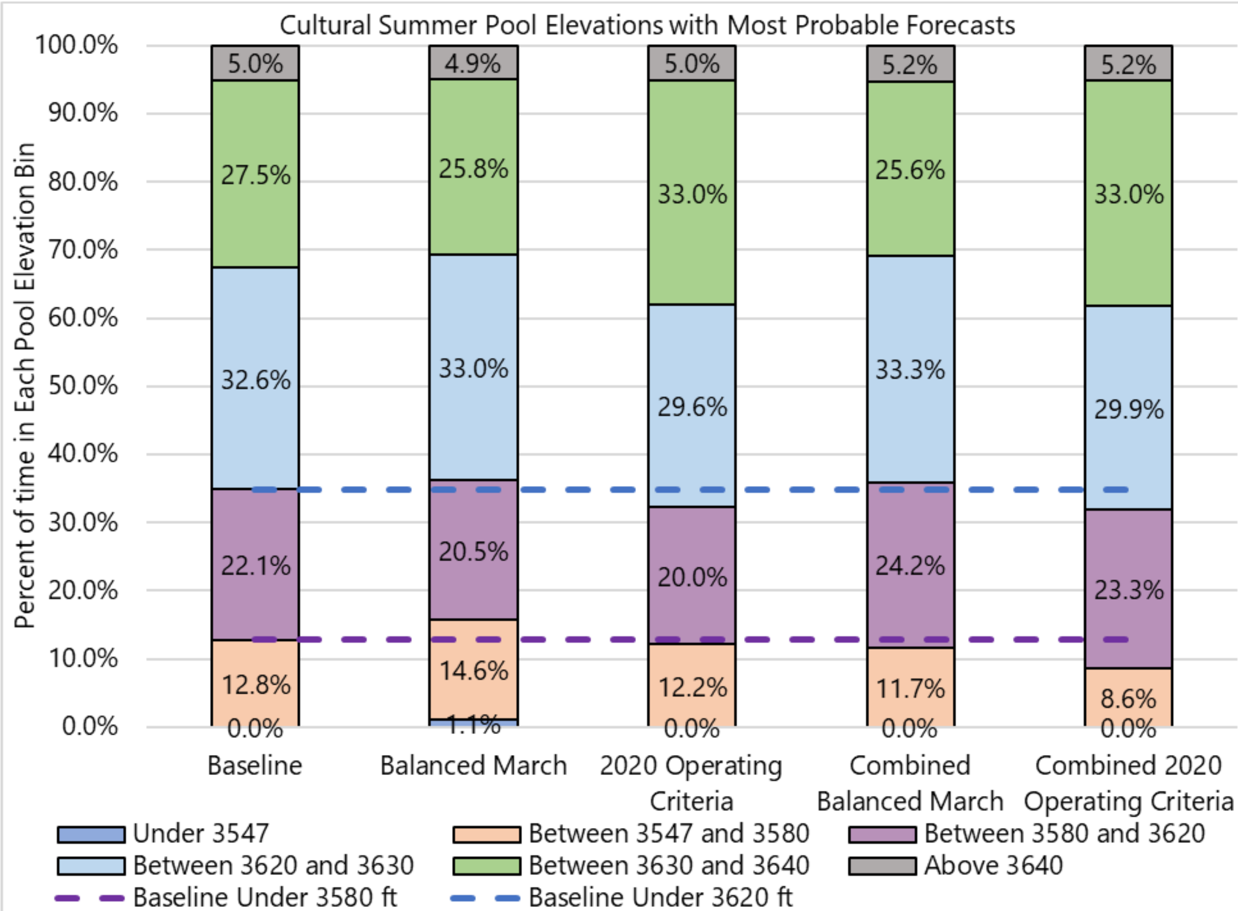


Figure 35. Composite comparisons for pool elevations in Cultural Summer. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with pool elevations in between certain values.

Fall and Winter Results

The Fall and Winter results are quite similar. Fall includes August, September, and October, while Winter includes November and December. The Combined 2020 Operating Criteria increases pool elevations and decreases the quantity of time river releases are at 1,500 cfs in Fall and Winter. There is no difference between any of the cases for hydropower energy value.

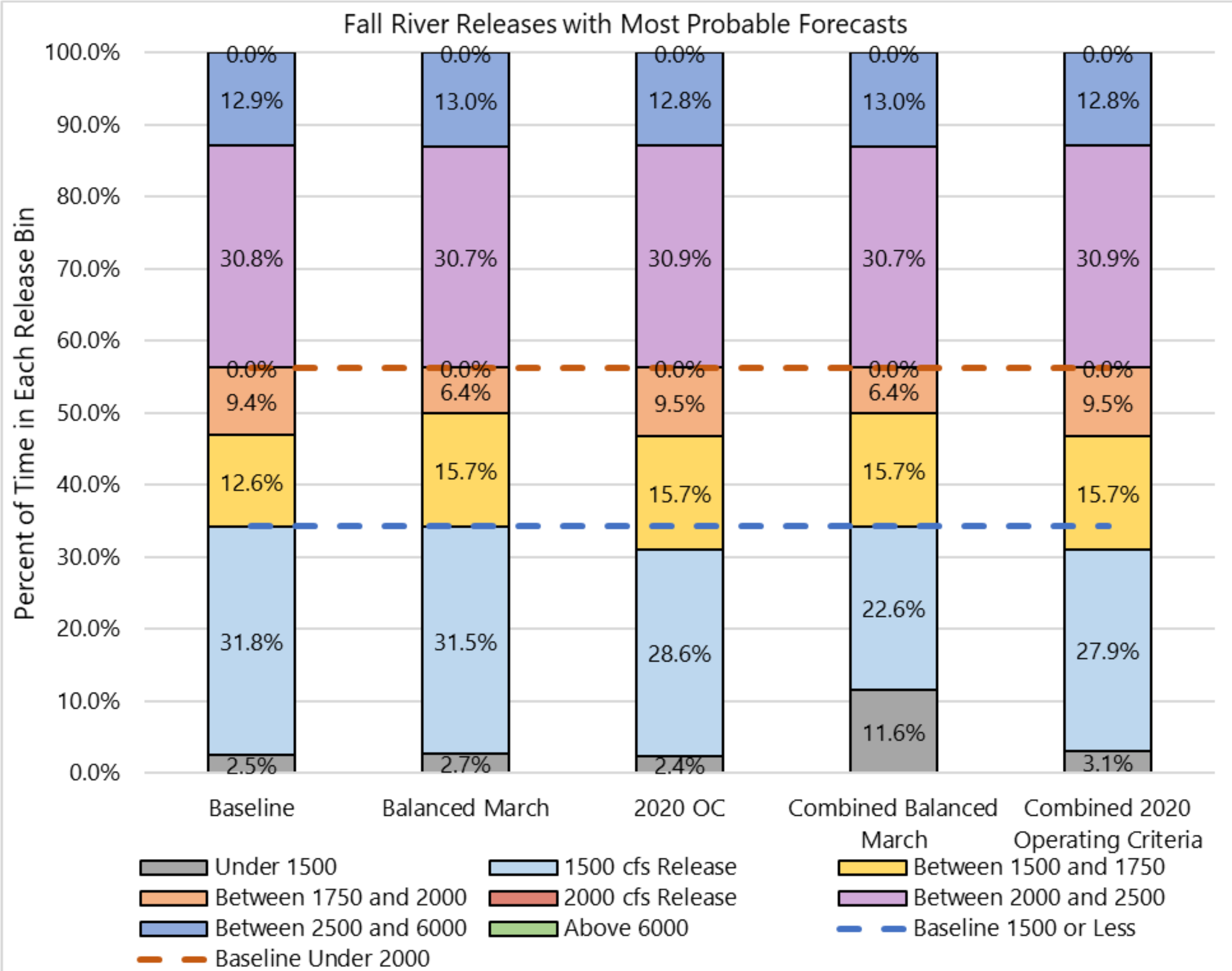


Figure 36. Composite comparisons for river releases in Fall. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with releases in between certain values.

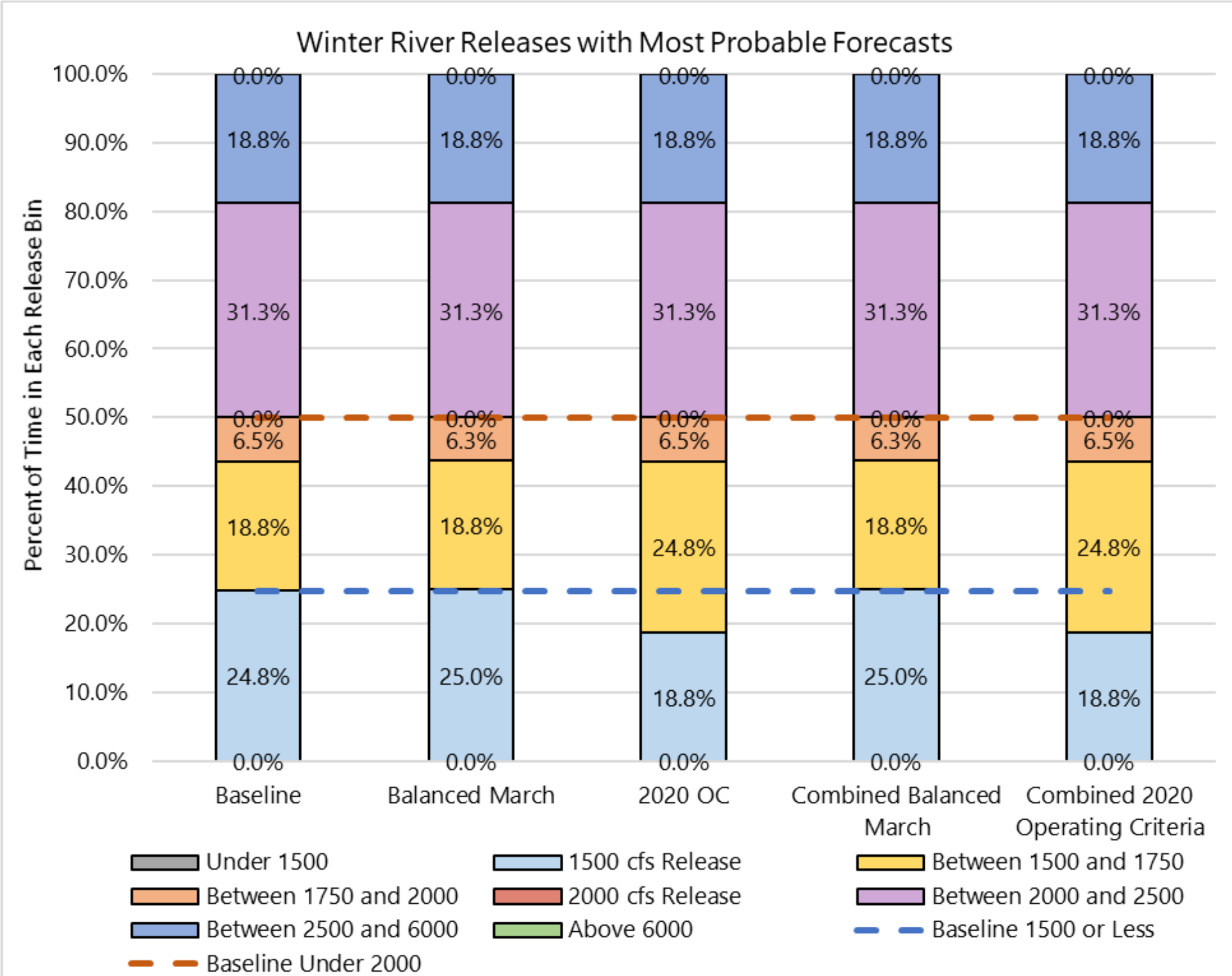


Figure 37. Composite comparisons for river releases in Winter. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with releases in between certain values.

The Combined 2020 Operating Criteria case has less time with releases below 1,500 cfs and more time with releases between 1,750 and 2,000 cfs compared with the Combined Balanced March case. Therefore, the Combined 2020 Operating Criteria has modest benefits to releases in Fall and Winter. See Figures 36 and 37 for results.

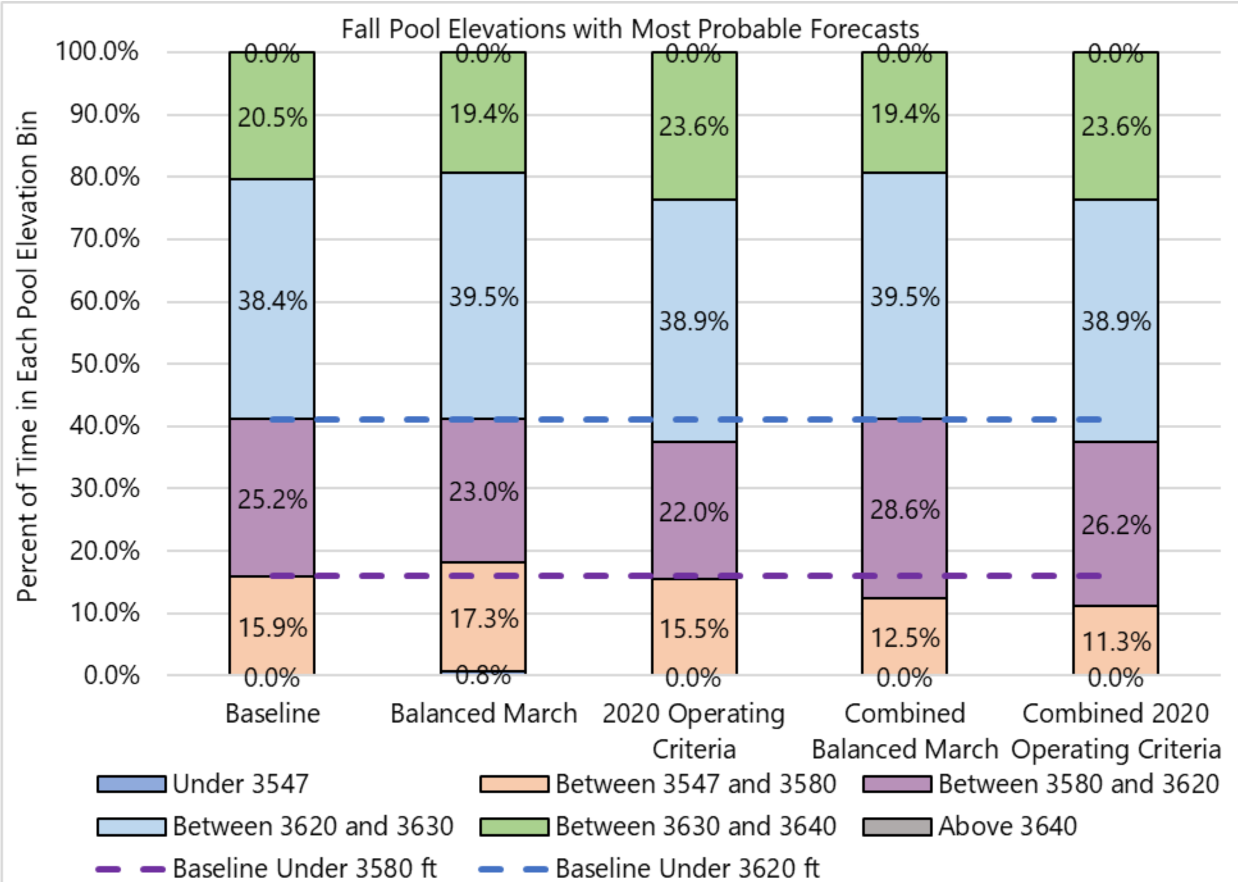


Figure 38. Composite comparisons for pool elevations in Fall. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with pool elevations in between certain values.

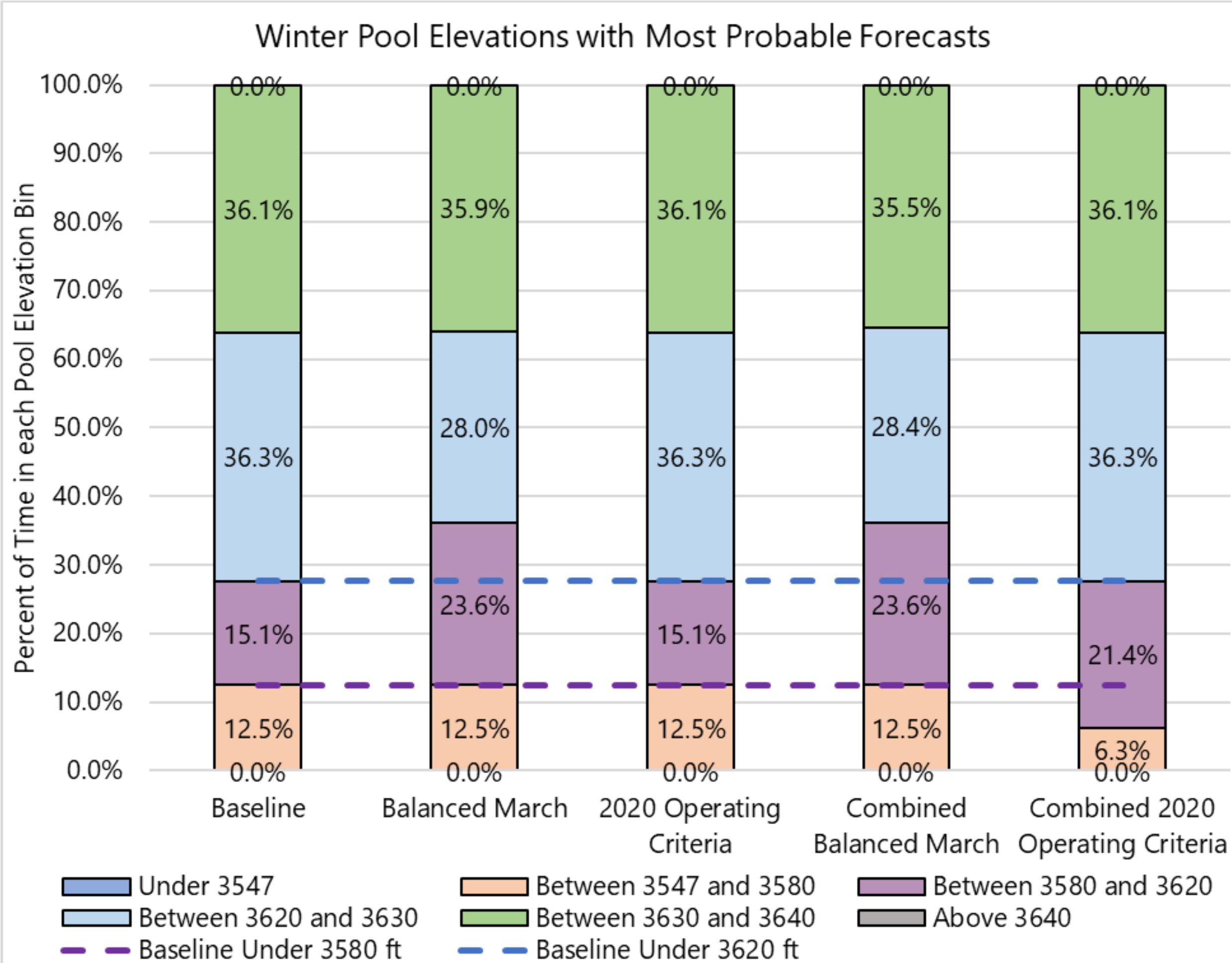


Figure 39. Composite comparisons for pool elevations in Winter. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with pool elevations in between certain values.

The Combined 2020 Operating Criteria has a small advantage over the Combined Balanced March due to less time with pool elevations below 3,620 ft. See Figures 38 and 39 for results in Fall and Winter.

Full Year Results

In addition to seasonal analysis, this study analyzes the release and pool elevation breakdown for the full calendar year including all the of the years in the Composite Comparison analysis. The Combined 2020 Operating Criteria increases pool elevations in the full year analysis. The Combined Balanced March case generally has more frequent river releases above 1,750 cfs, but the Combined 2020 Operating Criteria case provides has fewer releases at or below 1,500 cfs. There are not major differences between any of the cases for hydropower energy value.

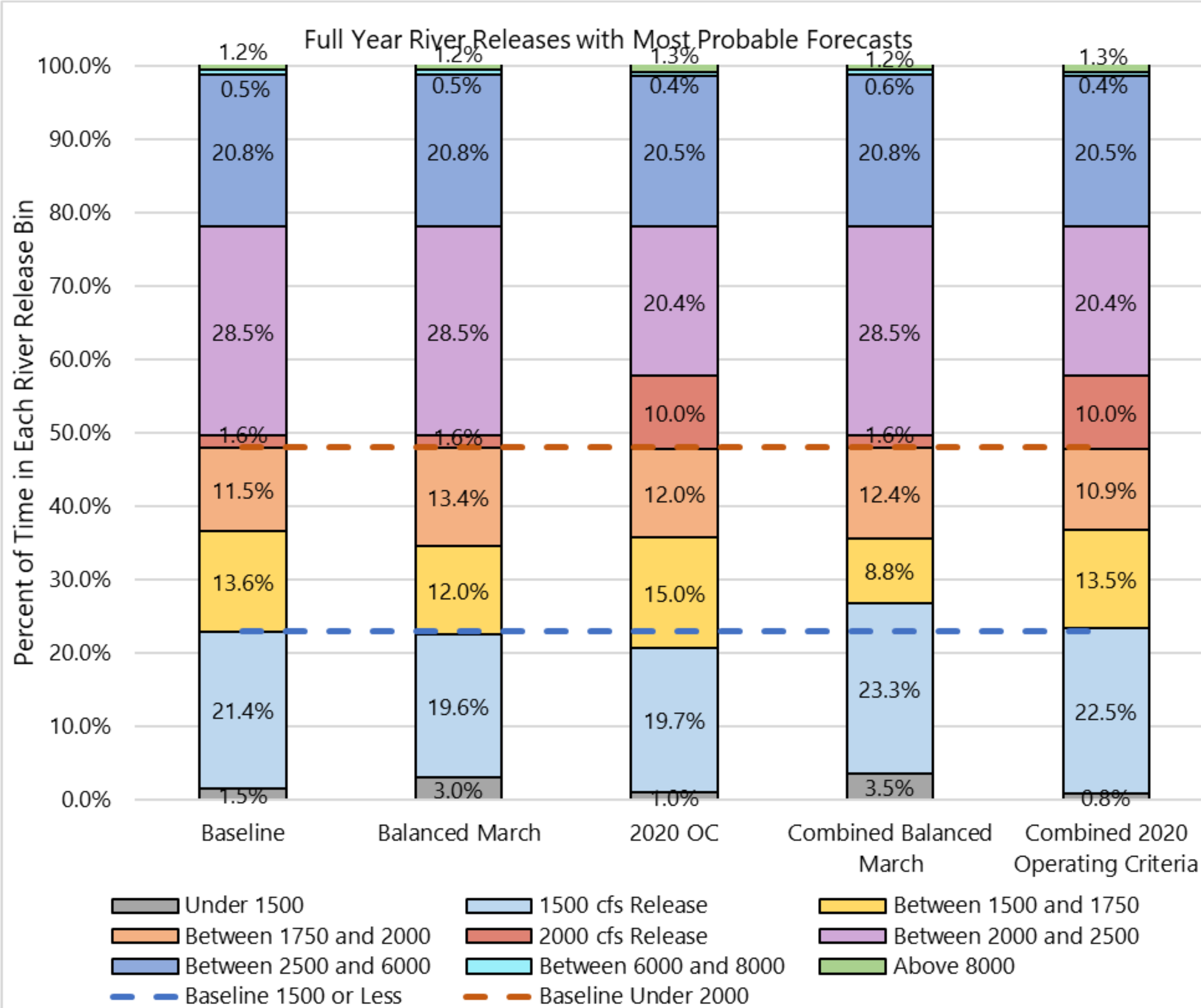


Figure 40. Composite comparisons for river releases for the full calendar year. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with releases in between certain values.

The Combined 2020 Operating Criteria case has less time with releases at or below 1,500 cfs than the Combined Balanced March case. Additionally, the Combined 2020 Operating Criteria has more time with releases between 1,500 cfs and 1,750 cfs compared with the Combined Balanced March case. Both of these results show that the Combined 2020 Operating Criteria case has higher river release rates during low-flow conditions.

However, the Combined Balanced March case has more time with releases between 1,750 cfs and 2,000 cfs, less time with releases at 2,000 cfs, and more time with releases greater than 2,000 cfs than the Combined 2020 Operating Criteria. These results show that the Combined Balanced March case higher river release rates greater than 1,750cfs. See Figure 40 for results.

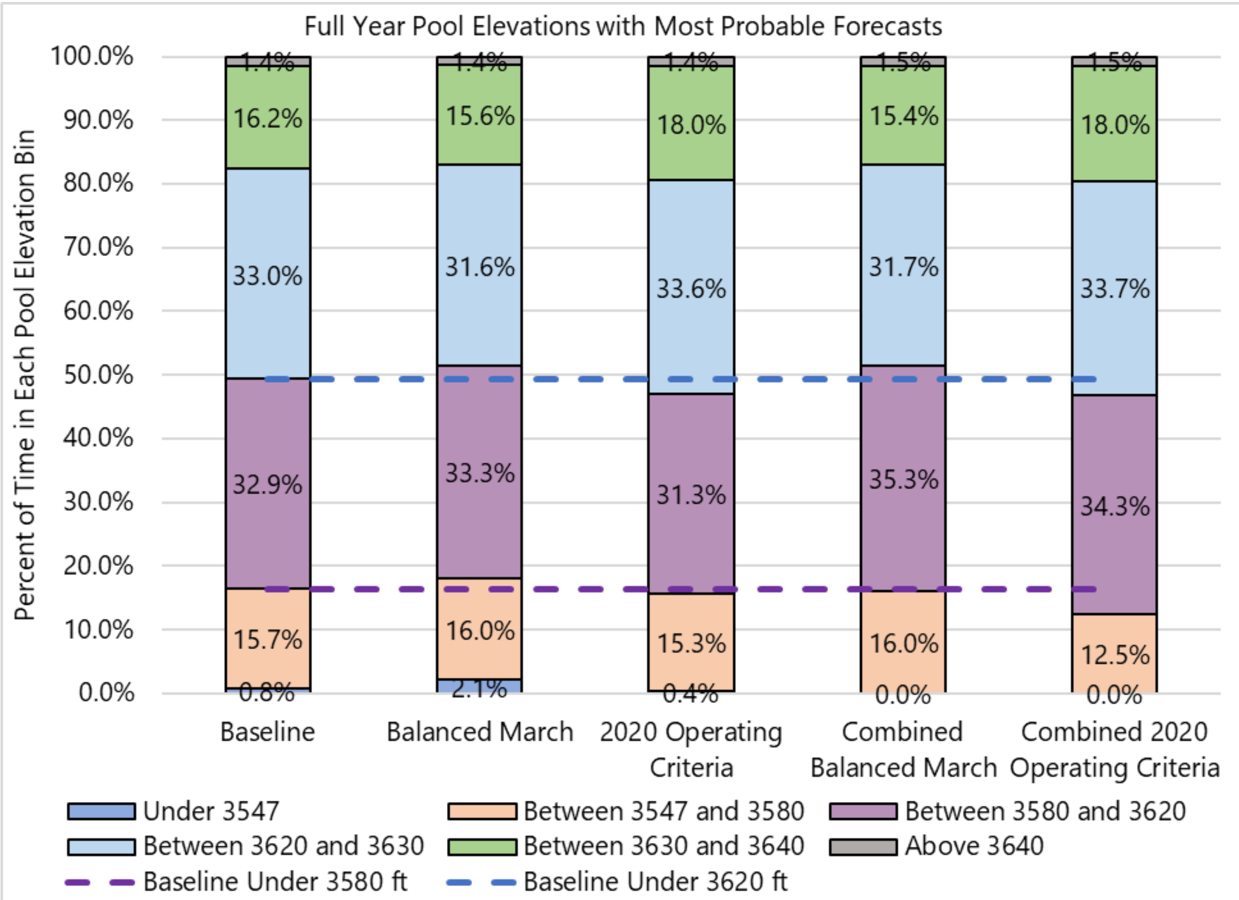


Figure 41. Composite comparisons for pool elevations for the full calendar year. Each stacked column represents a different case and each bin within each column represents the percent of time each case spends with pool elevations in between certain values.

The Combined 2020 Operating Criteria increases pool elevations over all other cases both for increasing percent of time with elevations over 3,620 ft and increasing percent of time with elevations over 3,580 ft. See Figure 41 for results.

Summary of Results

For river releases, the Combined 2020 Operating Criteria case has higher river release rates for composite comparisons in Fall, Winter, and Early Spring Operations. The Combined Balanced March case has higher river release rates for composite comparisons in Spring Operations. The river release composite results for Summer and Full Year seasons are complicated by the interplay of releases at or below 1,500 cfs and releases at or above 2,000 cfs, as well as high releases above 6,000 and 8,000 cfs.

Generally, the Combined Balanced March case has more frequent river releases above 1,750 cfs. This is likely due to the impacts of the 2,000 cfs release cap present in the Combined 2020 Operating Criteria case and the Balanced March logic. The Combined 2020 Operating Criteria case generally has fewer releases at or below 1,500 cfs. This is likely due to higher pool elevations for the Combined 2020 Operating Criteria case, which limits the need for 1,500 cfs releases or below, compared with the Combined Balanced March case.

For pool elevations, the Combined 2020 Operating Criteria results in higher pool elevations in all seasonal operations compared with the Combined Balanced March case.

For hydropower energy value, the Combined Balanced March case has greater hydropower generation in Early Spring, while the Combined 2020 Operating Criteria case has greater hydropower generation in Spring. When examined over the course of a full year, the differences in hydropower generation between the two cases and two seasons cancel one another out and neither case provides more hydropower energy value over another.

The complexity of these results highlights the need for metrics and priorities when deciding which policy is more advantageous at Bighorn Lake. This study presents two valid policy options for MTAO's consideration: the Combined 2020 Operating Criteria and the Combined Balanced March cases. Both options have advantages and detriments in terms of operations and will require careful consideration to decide the best policy for operating Bighorn Lake. Table 13 shows several comparisons, metrics, and priorities MTAO could consider when deciding which policy is the most appropriate.

Table 13. Summary of possible policy considerations for MTAO.

Question	Combined 2020 Operating Criteria Advantages	Combined Balanced March Advantages
Are certain seasons more operationally important in terms of releases?	Combined 2020 Operating Criteria increases August-March releases.	Combined Balanced March increases April-July releases.
What are balanced operations between releases and pool elevations?	See Balanced Operations section for more information. Generally, Combined 2020 Operating Criteria increases the quantity of time with releases under 1,500 cfs. The Combined 2020 Operating Criteria increases pool elevations in all seasons.	See Balanced Operations section for more information. Generally, Combined Balanced March increases the quantity of time with releases over 1,750 cfs.
Is avoiding releases below 1,500 cfs more important than maximizing releases above 1,750 cfs?	Combined 2020 Operating Criteria sets conservative releases and conserve storage, so releases under 1,500 cfs are less likely.	Combined Balanced March sets aggressive releases which increases the quantity of time with releases greater than 1,750 cfs, but does draw the reservoir down making releases under 1,500 cfs more likely.
Is avoiding releases above 8,000 cfs more important than conserving storage?	Combined 2020 Operating Criteria sets conservative releases and conserves storage, which can cause higher peak releases in the event of unforecasted inflow events.	Combined Balanced March sets aggressive releases and draws down the reservoir, this can reduce the peak releases in the event of unforecasted inflow events.

Balanced Operations

A potential topic for MTAO's consideration is defining balanced operations. This section does not attempt to define balanced operations, nor does it equate certain pool elevations with certain releases. Instead, this section aims to provide some supplemental information for MTAO's consideration of Balanced Operations.

Table 14 compares percentages of time that releases or pool elevations are below certain metrics. Low percentages are beneficial in this table. River release percentages are averaged for spring and summer operations, while pool elevation percentages reflect Cultural Sumer operations (period from Friday before Memorial Day to Labor Day). Combined Balanced March has less time with releases below 2,000 cfs and more time with releases below 1,500 cfs than the Combined 2020 Operating Criteria. Combined Balanced March has more time with pool elevations below 3,620 ft and below 3,580 ft than the Combined 2020 Operating Criteria.

When comparing the gap between time with releases below 2,000 cfs and time with pool elevations below 3,620 ft, both cases show less time with pool elevations below 3,620 ft than time with releases below 2,000 cfs. The Combined Balanced March case has a smaller gap between the two metrics than the Combined 2020 Operating Criteria.

When comparing the gap between time with releases below 1,500 cfs and time with pool elevations below 3,580 ft, both cases show more time with pool elevations below 3,580 ft than time with releases below 1,500 cfs. The Combined 2020 Operating Criteria case has a smaller gap between the two metrics than the Combined Balanced March case.

Table 14. Policy comparisons showing percentages of time that releases or pool elevations are below certain critical metrics. Low percentages are beneficial in this table.

	Percent of Time with Release below 2,000 cfs Spring and Summer*	Percent of Time with Pool Elevations below 3,620 ft for Cultural Summer	Percent of Time with Release below 1,500 cfs Spring and Summer	Percent of Time with Pool Elevations below 3,580 ft for Cultural Summer
Combined Balanced March	44.25%	35.91%	2.80%	11.66%
Combined 2020 Operating Criteria	45.65%	31.90%	1.10%	8.57%

*Does not include releases equal to 2,000 cfs

Table 15 shows percentages of time that releases or pool elevations are above certain critical metrics. High percentages are beneficial in this table. The Combined Balanced March case has major benefits over the Combined 2020 Operating Criteria with this release metric, especially compared to the Combined Balanced March case's detriment to pool elevations. Both cases have sizable gaps between the release metric and the pool elevation metric, with the Combined 2020 Operating Criteria has a much larger gap between the two operations metrics.

Table 15. Policy comparisons showing percentages of time that releases or pool elevations are above certain critical metrics. High percentages are beneficial in this table.

	Percent of Time with Release above 2,000 cfs Spring and Summer*	Percent of Time with Pool Elevations above 3,620 ft for Cultural Summer
Combined Balanced March	46.25%	64.09%
Combined 2020 Operating Criteria	25.5%	68.1%

*Does not include releases equal to 2,000 cfs

Conclusions

In summary, choosing the most appropriate operational policy for Bighorn Lake low-flow conditions will require careful consideration. The Combined 2020 Operating Criteria increases pool elevations in all seasons, but the impacts to releases are more complicated. Generally, the Combined 2020 Operating Criteria reduces the frequency of releases at or below 1,500 cfs, while the Combined Balanced March case increases the frequency of releases at or above 1,750 cfs. There are no major differences between either case in Yellowtail hydropower energy value.

Forecast Analysis

The End of March case analysis identified the need for an improved long range forecast methodology. Long range forecasts influence all the low-flow operational policies examined in this study, so the skill of these forecasts is vital for effective low-flow operational decisions. Only forecasts that are used to make low-flow operational decisions are examined in this analysis. See the Forecast Analysis subsection of the Methods section for more information on metrics and methods used to complete this analysis.

Period Analysis

Period component analysis looks at the skill of each applicable month's April through July forecast, each month's forecast through the following March, and each applicable month's forecast for August through the following March. All of these periods are used for low-flow operational decisions.

Figure 42 looks at the skill of April through July forecasts made on the first of each month from January through July. For May, June, and July forecasts, these forecast periods are for May through July, June through July, and July respectively. The forecast skill increases with each month. R-Squared values increase from January through July while NRMSE values decrease from January through July. The distribution of min and max forecasts also increases in skill from April through July. January and February April through July forecasts are particularly poor, with modest improvements to skill in March and April.

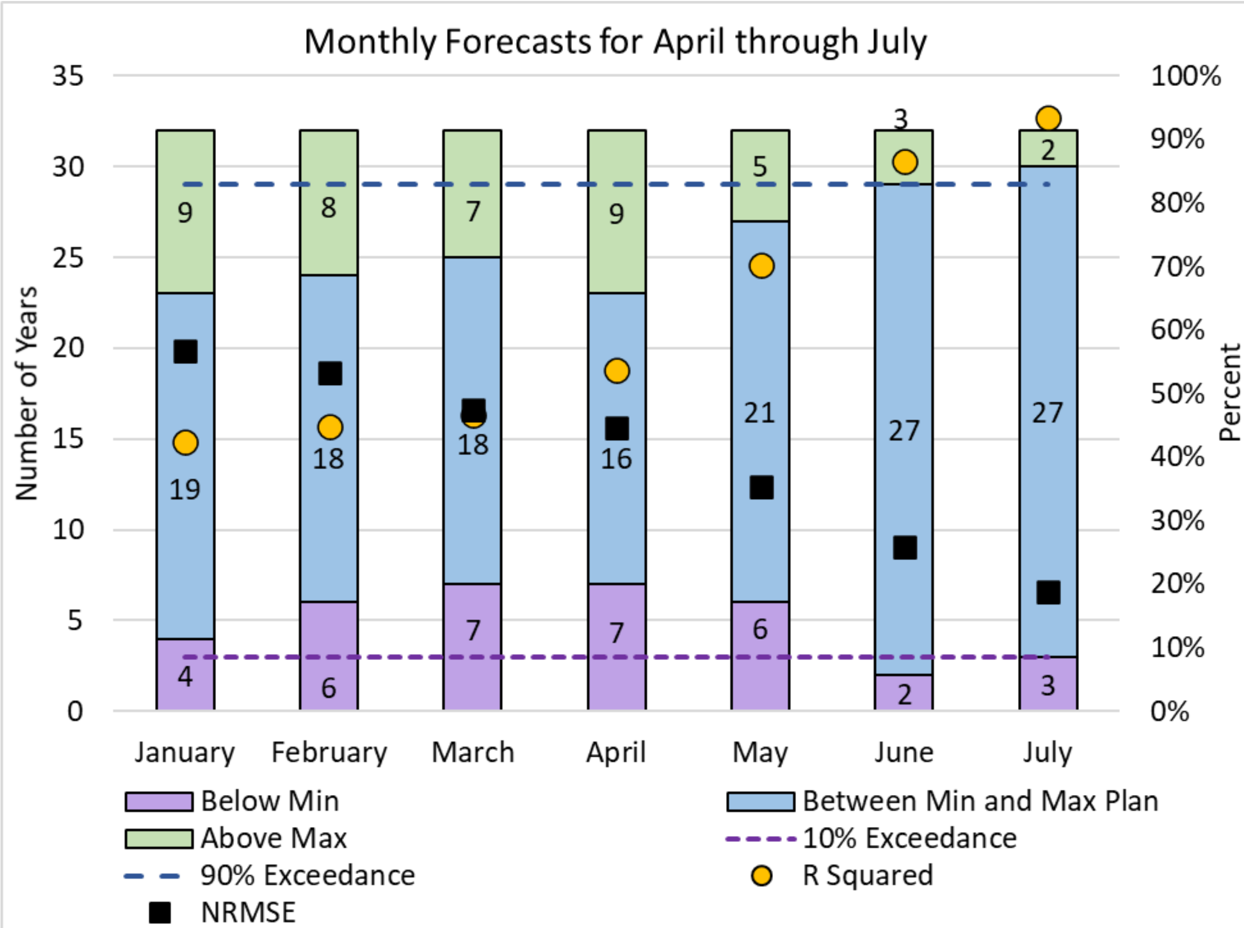


Figure 42. The skill of April through July forecasts made on the first of each month from January through July. Skill metrics include R-Squared, NRMSE, and forecast distribution.

Figure 43 shows the current month through following March forecast period for forecasts made on the first of the month from March 1 through February 1. As an example, the May 1 forecast for May through the following March represents the total volume of water forecasted from May 1 through March 31 in the following year (11-month window). The January and February forecasts only include January 1 through March 31 forecasts (3-month window) and February 1 through March 31 forecasts (2-month window).

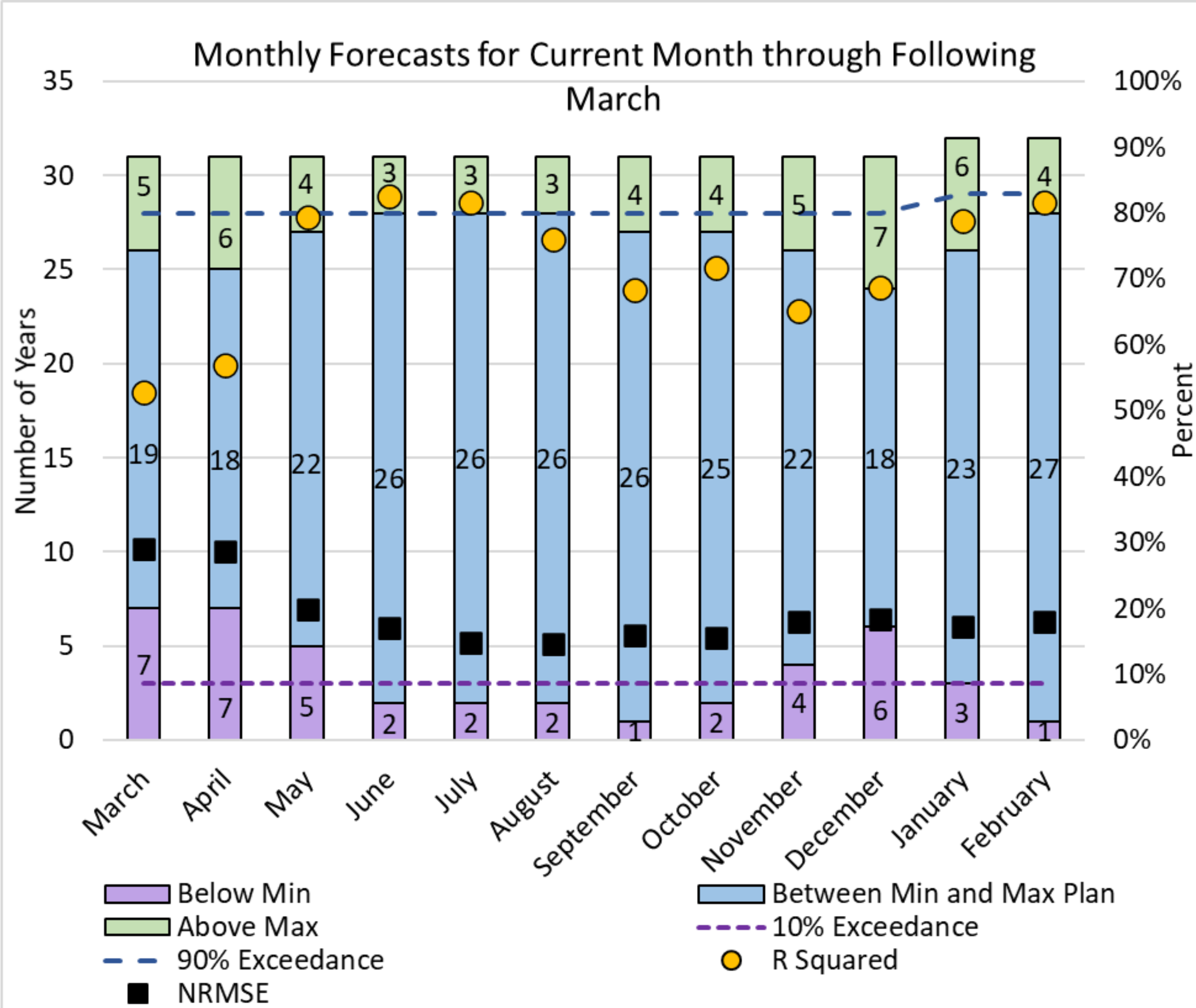


Figure 43. The skill of current month through the following March forecasts made on the first of each month from March through February. Skill metrics include R-Squared, NRMSE, and forecast distribution.

Figure 44 shows August through following March forecast period for forecasts made on the first of the month from March through August. As an example, the May 1 forecast for August through the following March represents the total volume of water forecasted from August 1 through March 31 in the following year (8-month window).

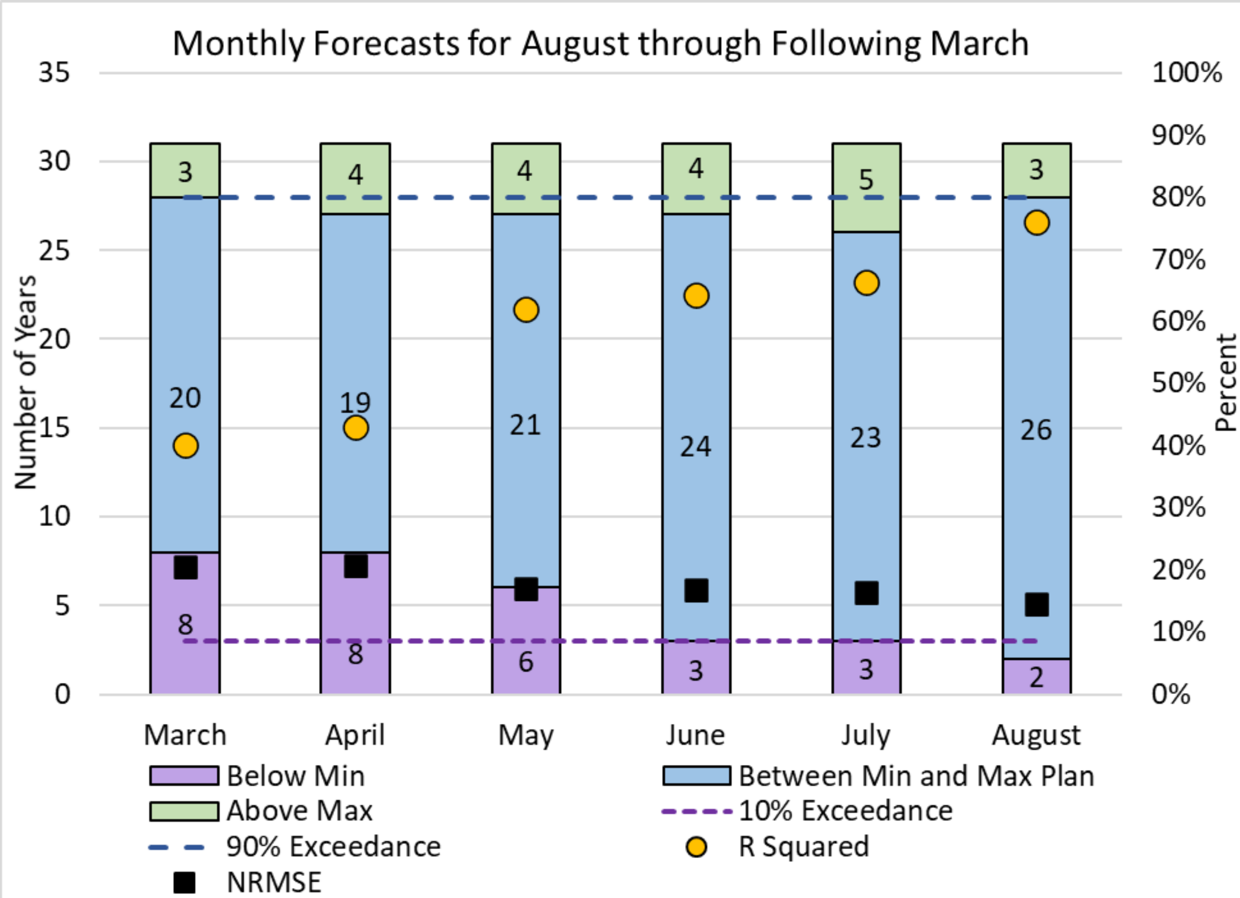


Figure 44. The skill of August through the following March forecasts made on the first of each month from March through August. Skill metrics include R-Squared, NRMSE, and forecast distribution.

Both long-range forecast periods, Figures 43 and 44, show less variation in skill compared with the April through July forecasts, Figure 42. This may be due to long-range forecasts averaging out some of the error occurring from month to month. Generally, March and April long-range forecasts have the lowest skill, with skill metrics stabilizing for subsequent months.

Monthly Analysis

Historical forecasts are issued on the first of the month and forecast inflow volumes for each of the next twelve months. Monthly component analysis looks at the skill of each month's forecasts for the next twelve months. For example, the monthly component analysis for January would look at the forecast made on January 1 for each month January-December. All months were examined as a part of this study, but only January 1 through April 1 monthly forecasts are included in this report. The results for January through April are the most interesting and most applicable to low-flow operations.

Figures 45 through 48 show monthly forecasts made on January 1, February 1, March 1, and April 1.

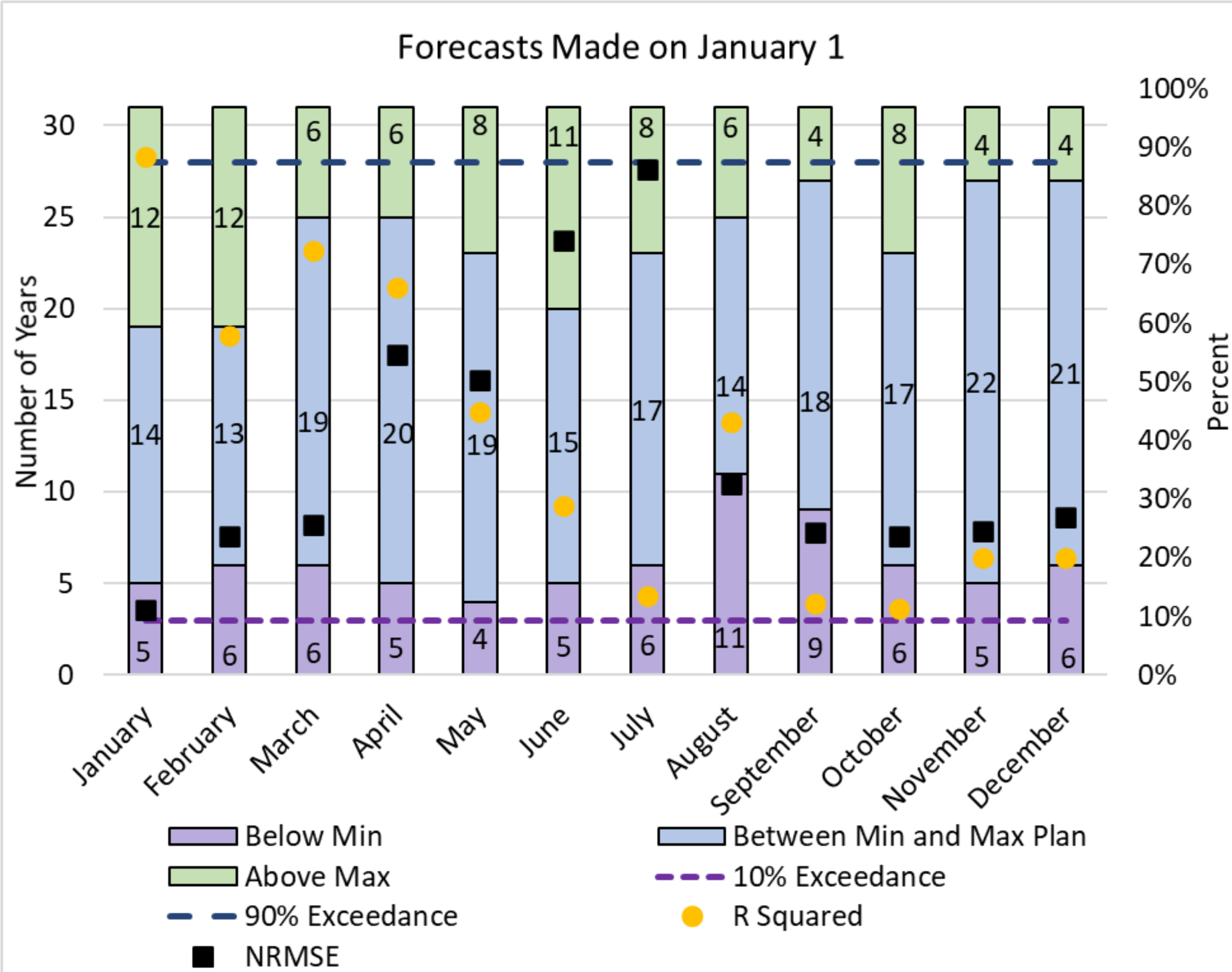


Figure 45. The skill of each individual monthly forecast from January through December. All forecasts are made on January 1. Skill metrics include R-Squared, NRMSE, and forecast distribution.

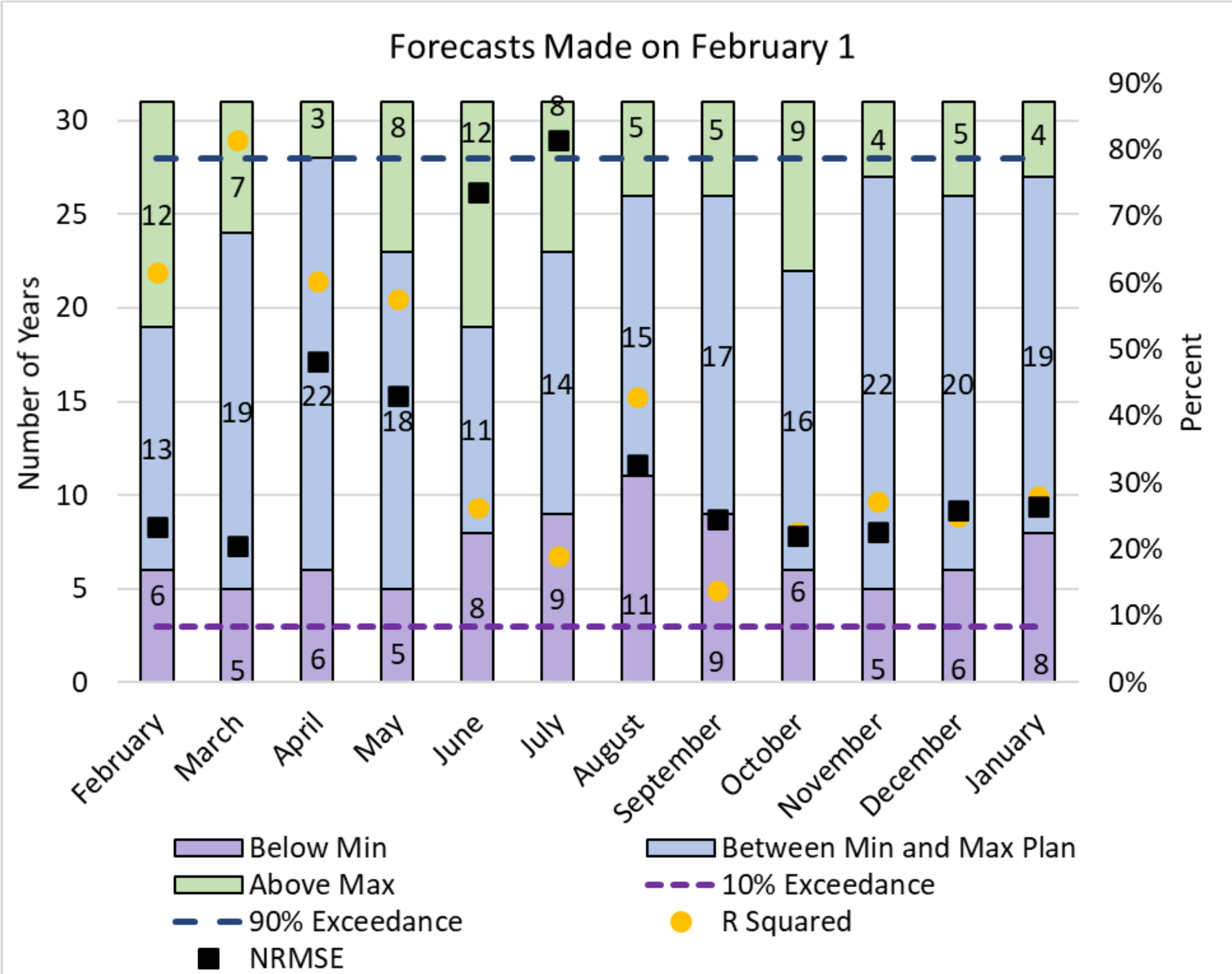


Figure 46. The skill of each individual monthly forecast from February through January. All forecasts are made on February 1. Skill metrics include R-Squared, NRMSE, and forecast distribution.

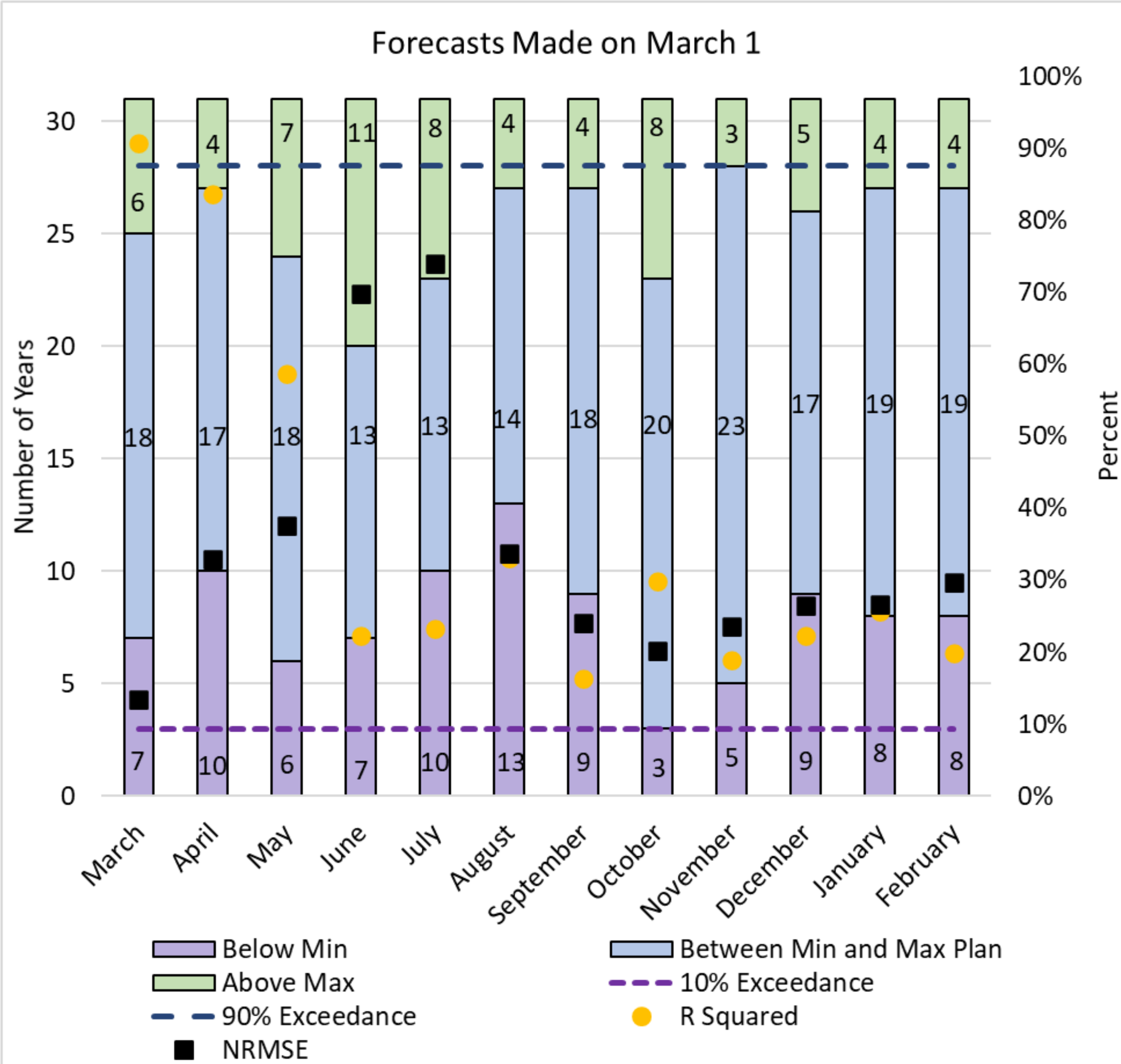


Figure 47. The skill of each individual monthly forecast from March through February. All forecasts are made on March 1. Skill metrics include R-Squared, NRMSE, and forecast distribution.

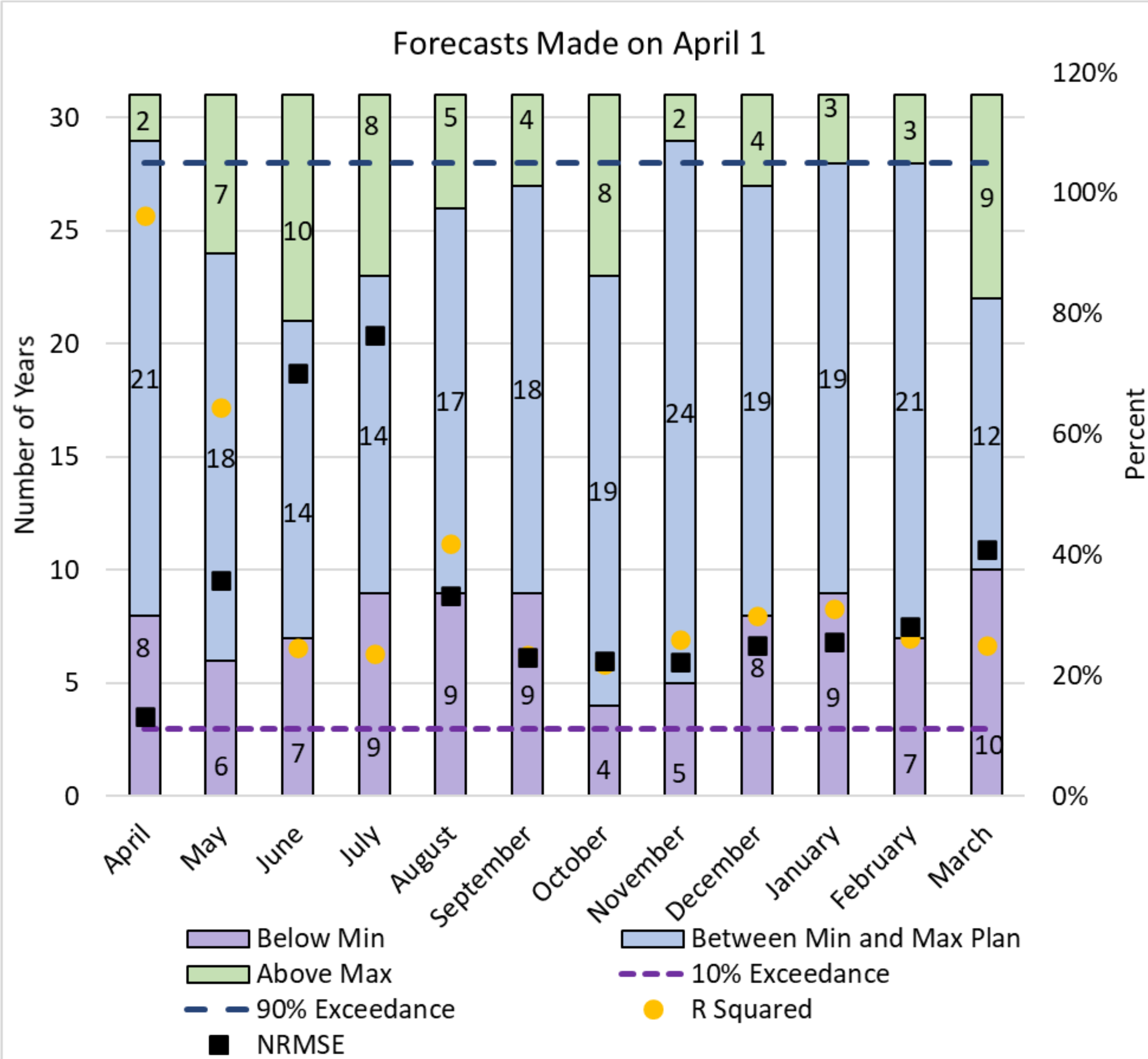


Figure 48. The skill of each individual monthly forecast from April through March. All forecasts are made on April 1. Skill metrics include R-Squared, NRMSE, and forecast distribution.

There are several observable patterns in monthly forecasts in Figures 45 through 48. Regardless of the month, forecasts are reasonably skillful for a two-month window. For example, the January 1 forecast for January and February inflow volumes has the highest skill in terms of R-Squared and NRMSE values. Inflow forecasts for June and July have poor skill, regardless of the month these forecasts are made (i.e. lead time). Lastly, NRMSE values are relatively low for August-Early Spring forecasts, but the R-Squared value is also low. This indicated that the correlation between forecasts and inflows is poor during these months, but that the error is relatively small. This could be due to the smaller inflow volume range typically observed from August through the following spring, compared with April through July forecast inflow volumes.

January and February Forecasts

The April through July forecasts made in January and February have poor skill. The NRMSE value for the January 1 April through July forecast is 56% while the R-Squared value is 42%. The errors in these forecasts could negatively impact low-flow operations if these forecasts are used to set releases. The January through March forecasts made in January and the February through March forecasts made in February, referred to as "short-range forecasts" from here on, have comparatively higher skill than the April through July forecasts made in January and February. The January-March forecasts made on January 1 are reasonably skillful, with a NRMSE value of 17% and a R-Squared value of 79%. The February-March forecasts made on February 1 are similarly skillful, with a NRMSE value of 17% and a R-Squared value of 82%.

While not yet discussed in this study, operators can use professional judgement to decide if the April through July forecasts are low enough to justify reducing releases in January or February to begin conserving storage for the current and following year. This decision requires the use of April through July forecasts made in January and February. Given the poor skill associated with the April through July forecasts made in January and February, it may be beneficial to avoid the use of these forecasts in low-flow operations entirely.

One way to limit the use of April through July forecasts for setting releases in January and February is to continue the winter release, which targets 3,617 ft at the end of March, throughout January and February. This is how the model operates. Targeting 3,617 ft at the end of March throughout January and February only relies on accuracy of the short-range forecasts to set releases, which are known to be more accurate than the April through July forecasts. This study recommends using January and February short-range forecasts to set January and February releases to target 3,617 ft at the end of March. This study recommends discontinuing the use of April through July forecasts to justify cutting releases in January and February.

While some additional testing and modeling analysis was completed to assess the impacts of this recommendation, it is difficult to say with certainty what the impact of this recommendation is to operations. Representing professional judgement in a model is extremely difficult and many assumptions and approximations were necessary to test the impacts of the recommendation. However, there are three clear conclusions from the modeling results:

1. The risk of maintaining winter releases in a low-flow year is conserving storage and having lower river releases later in the year.
2. The risk of reducing winter releases to conserve storage in a forecasted low-flow year that later has unexpected high inflow events is high later in the spring and summer.
3. The quality of January and February forecasts of April through July inflow volume are poor (56% NRMSE and 42% R-Squared), while the forecasts of January through March inflow volume made on January 1 and the forecasts of February through March inflow volume made on February 1 are reasonably skillful.

The recommendation is not for higher or lower winter releases, only for maintaining the storage target of 3,617 feet in low-flow years rather than switching to something more conservative, until the April-July forecasts are more accurate later in the spring. Additionally, the 3,617 ft March target is the agreed upon end of March target for balancing river releases and pool elevations for winter releases. The practice of veering from this target by reducing releases in January based on forecasts that are known to have low skill, even if this decision later proves advantageous to operations, should be reconsidered.

Long-Range Forecasts

The long-range forecasts discussed in the Period Analysis section showed that the March and April long-range forecasts have the least amount of skill when compared with long-range forecasts made in other months. After examining the monthly forecasts made on March 1 and April 1, the June and July forecasts seemed to have the largest impact on long-range forecast accuracy. The June and July forecasts made on March 1 and April 1 have particularly low skill, especially compared with the forecasts from August through March made on March 1 and April 1. Even for forecasts made on May 1 and June 1, most of the forecast error stems from June and July inflow forecasts. The high errors in June and July inflow forecasts indicate that minimizing the impact of April through July forecasts on long-range forecasts could improve operational decisions.

One way to minimize the impact of April through July forecasts on long-range forecasts is discontinuing the use of forecasted April through October gains to calculate November through March gains. Currently, November through March gains are calculated using a liner regression equation developed from historical data. One of the inputs into this linear regression equation is the April through October gains. When a forecast is made on April 1 for the inflow volume through the following March, the November through March gains are calculated using the forecasted April through October gains as an input. Generally, it is bad practice to use a forecasted value with high error to predict another value through linear regression. This can compound the error of the forecasts.

There are several possible options for estimating November through March gains without using forecasted April through October gains. One option is to use a median value for the November through March gains instead of attempting to forecast the gains. Unfortunately, at the time of this analysis, the forecast components needed to test this methodology were unavailable. Forecast components include river gains, inflows from Boysen Reservoir, and inflows from Buffalo Bill Reservoir. River gains are the unmetered gains between the measured outflows at Boysen Reservoir and Buffalo Bill Reservoir and the computed inflow at Bighorn Reservoir. Analyzing the skill of these forecast components is underway as part of a separate recommendation from the 2019 Bighorn Lake Operating Criteria Review at the time of this report publication. Without the results from this analysis, different possible options for estimating November through March gains without using forecasted April through October gains cannot be analyzed.

After the forecast component recommendation is completed, this study recommends investigating methods to discontinue the use of forecasted April through October gains to calculate the November through March gains.

Recommendations

Operating Criteria Recommendations

This study provides three operating criteria recommendations to improve low-flow operations at Bighorn Lake. Firstly, this study recommends implementing the following four individual policies as model improvements or improvements to the Bighorn Operating Criteria:

1. **Dynamic Minimum Fill Volume Threshold.** The dynamic minimum fill volume threshold should be adopted into both the Bighorn Operating Criteria and into the Bighorn Model. This calculation-based method to determine low-flow or rule-curve operations replaces the existing Static Minimum Fill Threshold in both the Bighorn Operating Criteria language and the Bighorn Model.
2. **Year Out Inactive Conservation Pool Elevation Check.** The Year Out Inactive Conservation Pool Elevation Check should be added into the Bighorn Model. This check decides when outflows should be set below 1,500 cfs. Additionally, the Bighorn Operating Criteria should include language for when to set releases below 1,500 cfs, which should outline how the Year Out Inactive Conservation Pool Elevation Check makes this decision.
3. **Removal of Summer Low-Flow Targets.** The Bighorn Model logic setting releases to meet the end of October 31 targets during summer low-flow operations should be removed. This recommendation does not impact the Bighorn Operating Criteria, it is only a model improvement.
4. **Low Pool Elevation Check.** The low pool elevation check limits releases to a maximum of 1,500 cfs if pool elevations are less than 3,591.5 ft. This elevation check is intended to be a model improvement recommendation, but it could be implemented into the Bighorn Operating Criteria at Montana Area Office's discretion.

Secondly, this study provides analysis of two different low-flow policies for Montana Area Office's (MTAO) consideration. These two policies are mutually exclusive, so only one policy will be selected. Both policies have advantages and disadvantages. MTAO will need to carefully consider the advantages and detriments of each policy prior to selecting one for the Bighorn Operating Criteria. This study does not make a final decision for policy implementation and instead leaves this decision up to MTAO's discretion.

One of the policies recommended for MTAO's consideration is the Combined Balanced March Target policy. This policy combined the Balanced March Target individual policy with all four recommended policies in the first study recommendation. If this policy is selected for implementation at Bighorn Lake, this policy should be implemented into the Bighorn Model and clearly documented in the Bighorn Operating Criteria.

The second policy recommended for MTAO's consideration is the Combined 2020 Operating Criteria policy. This policy combined the 2020 Operating Criteria individual policy with all four recommended policies in the first study recommendation. The 2020 Operating Criteria case is currently in use at Bighorn Lake and outlined in the 2020 Bighorn Operating Criteria. Therefore, if this policy is selected the Bighorn Model will need to be updated, but the only changes to the Bighorn Operating Criteria are outlined in the first study recommendation.

Thirdly, this study recommends clearly outlining low-flow operations in the Bighorn Operating Criteria. Regardless of the policies or recommendations implemented from this study, MTAO should provide clear and transparent language for low-flow operations at Bighorn Lake. It may be beneficial to provide supplemental documentation including the history of various Bighorn Operating Criteria, what official document is currently in use, and possible updates to the Yellowtail Dam Standard Operating Procedure, subject to MTAO's discretion.

Forecast Recommendations

In addition to the operating criteria recommendations, this study provides two forecast recommendations to improve low-flow operations at Bighorn Lake. The first recommendation is to set January and February releases to target 3,617 ft at the end of March during periods of low-flow forecasts. The purpose of this recommendation is to avoid the use of poor quality April through July forecasts in January and February, and instead use short-range January and February forecasts that have more accuracy, to make low-flow operational decisions during January and February.

The second forecast recommendation is to investigate the low-flow long-range forecast methodology. One possible improvement for the long-range forecasts is avoiding the use of forecasted April through October gains to forecast the November through March gains. Using forecasted values to predict another set of forecasted values through linear regression methods could compound forecast errors. In order to develop and analyze tests for new long-range forecast methodologies, MTAO will need data on Bighorn Lake's compound forecasts, which, at the time of this writing, is the subject of a separate study. Therefore, this study recommends investigating the low-flow long-range forecast methodology as a separate effort at a later date.

Limitations

There are a number of limitations associated with modeled data from the Bighorn RiverWare model. There are several conditions in which modeled data may not accurately represent real world conditions or future hydrology conditions. One limitation is that modeled operations are more granular than real world operations. The RiverWare model performs some calculations on a daily timestep, but some calculations are performed on a monthly timestep. In real-world operations, operators make decisions on hourly or daily timesteps and consider mid-month forecasts, short-range weather forecasts for precipitation events and temperature induced snowmelt and changing snowpack when making decisions. The hourly and daily timestep considerations in the real-world allow for more flexible and dynamic operations than the modeled operations.

Another limitation occurs during high inflow events, particularly when these inflow events are not forecasted or arrive at a different time than originally forecasted. These poorly forecasted inflow events can be caused by unexpected precipitation events or temperature induced snowmelt. The model cannot adjust quickly to these types of events because it cannot plan to enter the flood control pool, which limits the storage space the model can use, and because the model only considers monthly forecasts. Therefore, the model sets unrealistically high releases during most high inflow events, which makes it difficult to accurately assess how the recommended policy impacts years with high inflow events.

Additionally, this study uses past results to predict how the low-flow policy will perform in future hydrologic conditions. Monthly plan forecasts only exist from water year 1990 through the current year, so there is a limited number of years to use to predict future operations. Of the 28 years considered in this study, only 10 years were true low-flow years. Therefore, this study is using 10 years to predict future operations. This time range certainly does not represent the whole range of possible future hydrology conditions. The limited data used to analyze the recommended policy is a major limitation of this study.

Climate change is another source of uncertainty in using past data to predict future conditions. In 2017, a collaboration of researchers completed Montana Climate Change Assessment (Whitlock et al., 2017). This assessment describes potential impacts of climate change on water resources within Montana. While the study does not cover the Bighorn Basin, the study does examine the Powder River and Upper Yellowstone Basins which are geographically close to the Bighorn Basin. In both the Powder River and Upper Yellowstone Basins, temperatures are expected to rise over the next century which will likely reduce snowpack at mid and low elevations (Whitlock et al., 2017). Multi-year droughts are thought to be a natural component of Montana's climate, but "rising temperatures will exacerbate drought when and where it occurs, leading to more rapid onset of drought and increased intensity" (Whitlock et al., 2017). These climate change projections underscore the importance of studying drought condition reservoir operations, but the projections also increase the uncertainty of using past conditions to predict the future as global and regional climates continue to change.

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Appendix A: Combined Model Comparisons

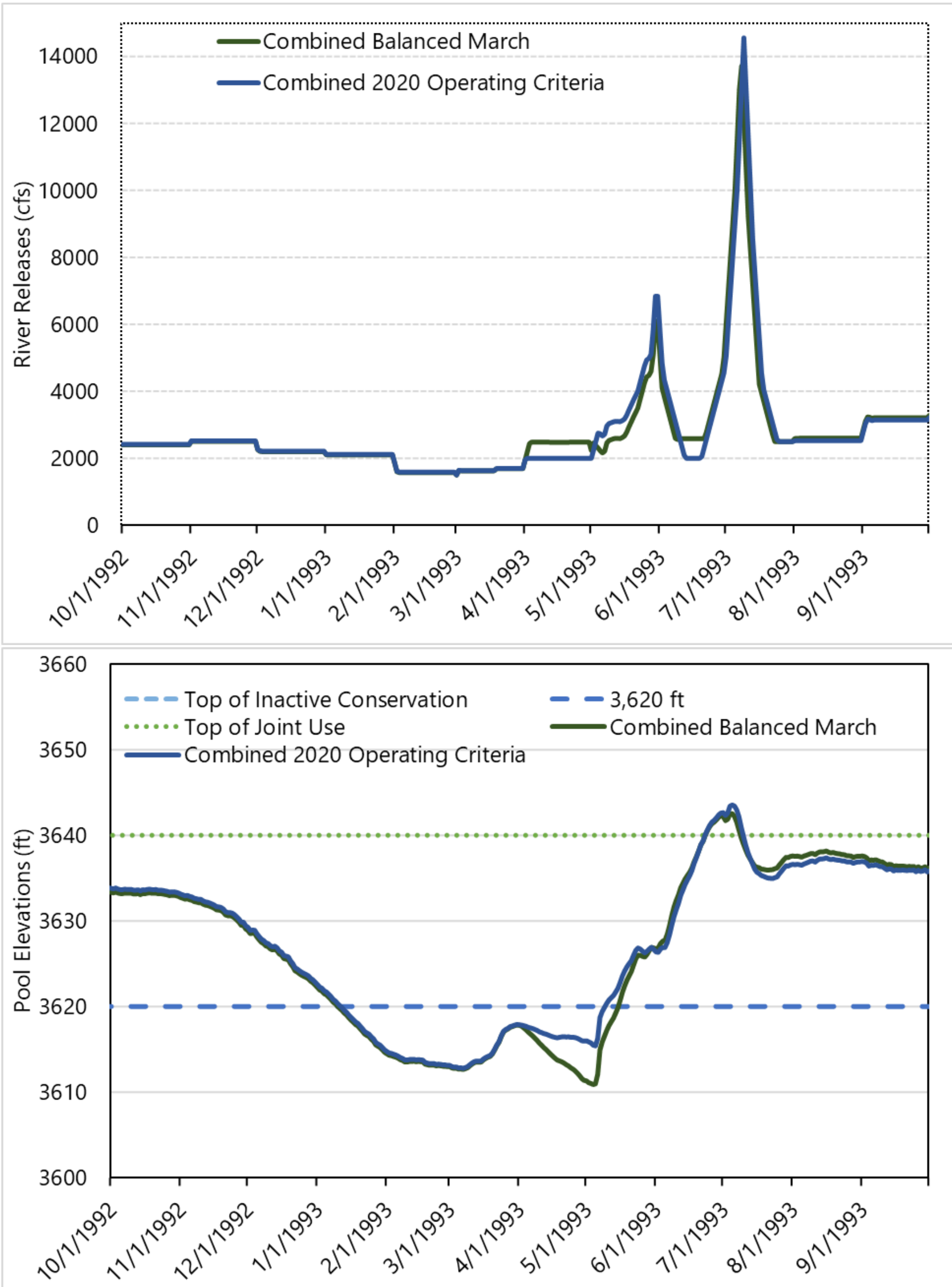


Figure 49. River releases and pool elevations for Water Year 1993. Differences between two cases caused by 2,000 cfs release cap.

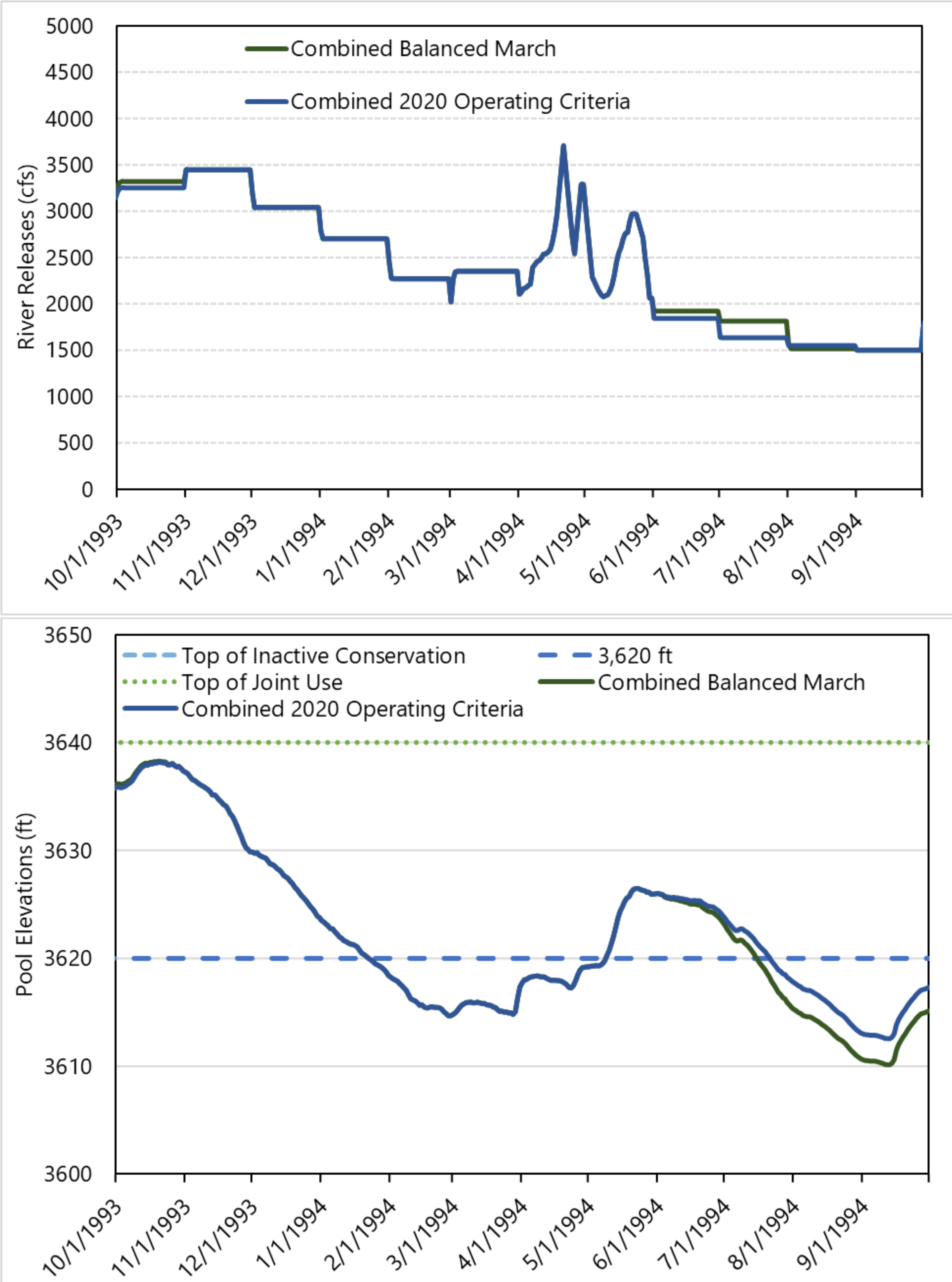
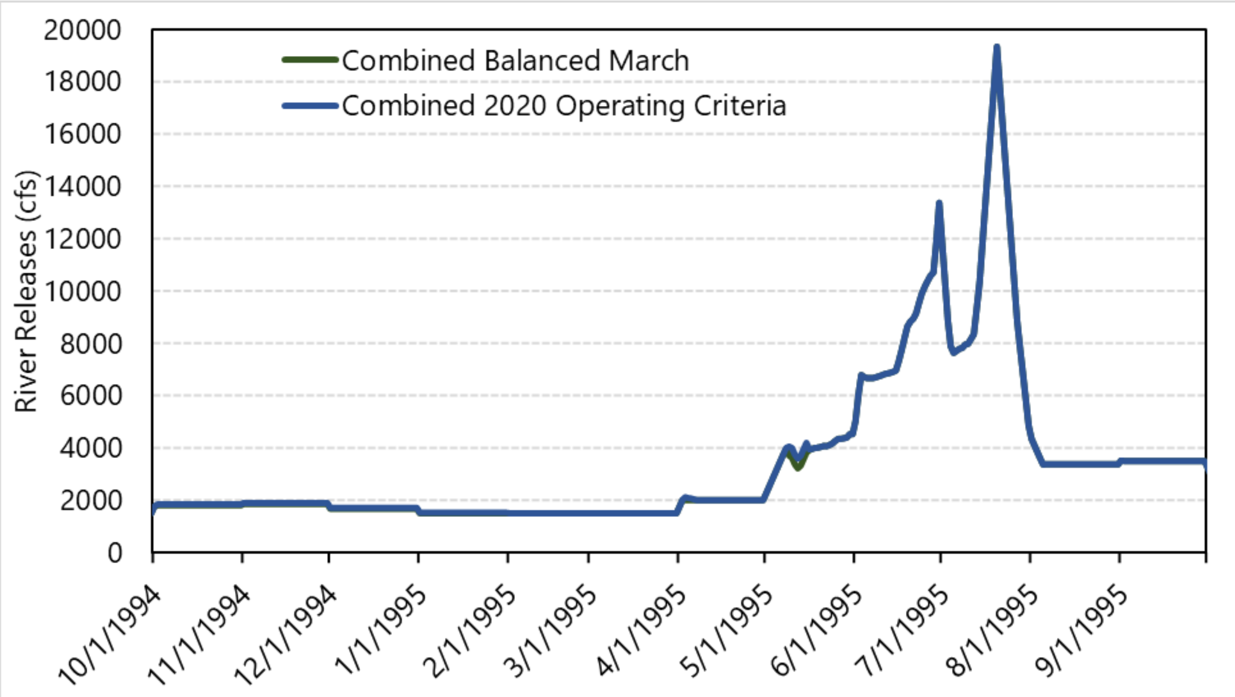


Figure 50. River releases and pool elevations for water year 1994. Differences between two cases caused by Balanced March Target logic.



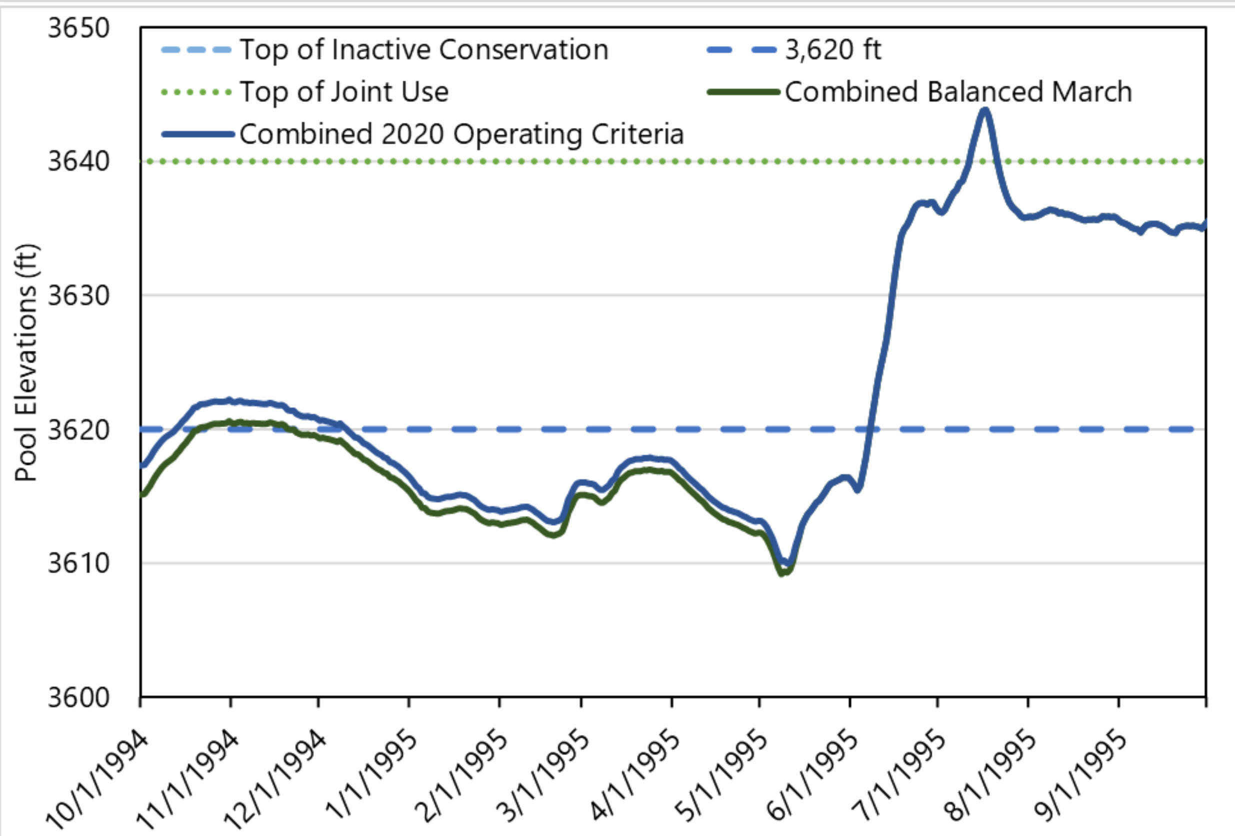


Figure 51. River releases and pool elevations for water year 1995. Differences between two cases caused by pool elevation differences from 1994.

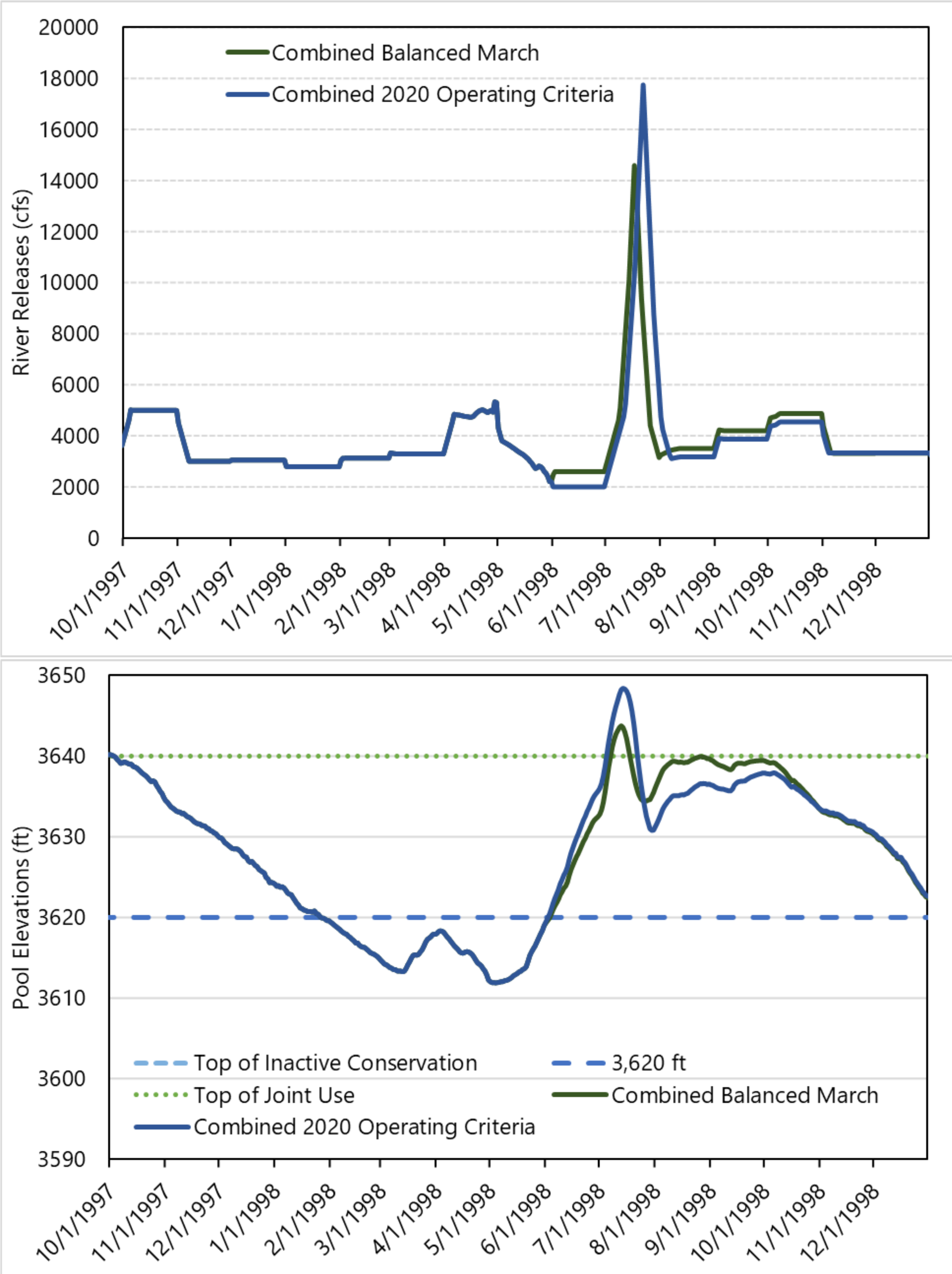


Figure 52. River releases and pool elevations for water year 1998. Differences between two cases caused by 2,000 cfs release cap.

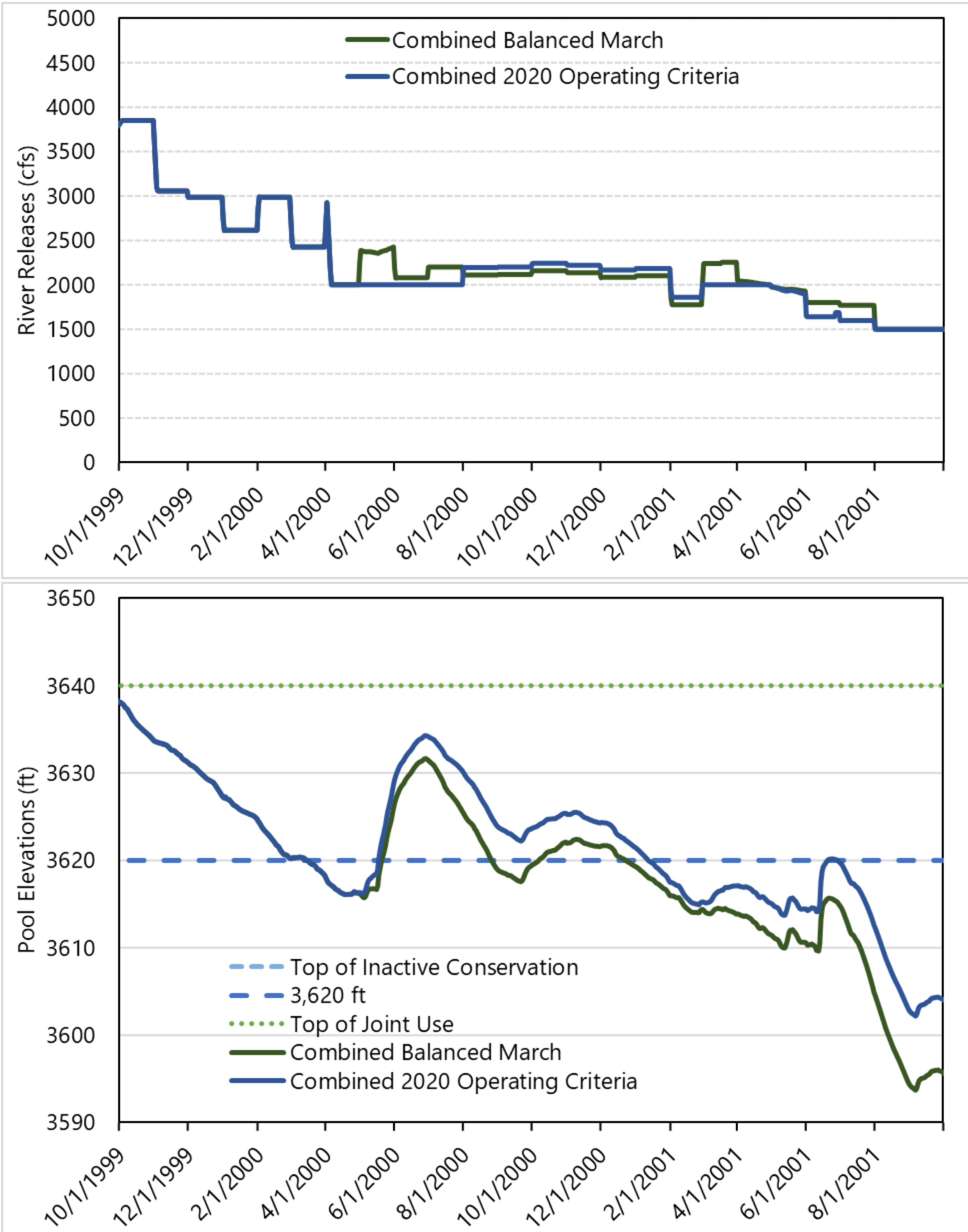


Figure 53. River releases and pool elevations for water years 2000 and 2001. Differences between two cases caused by 2,000 cfs release cap until June and July of 2001, when differences are caused by Balanced March release logic.

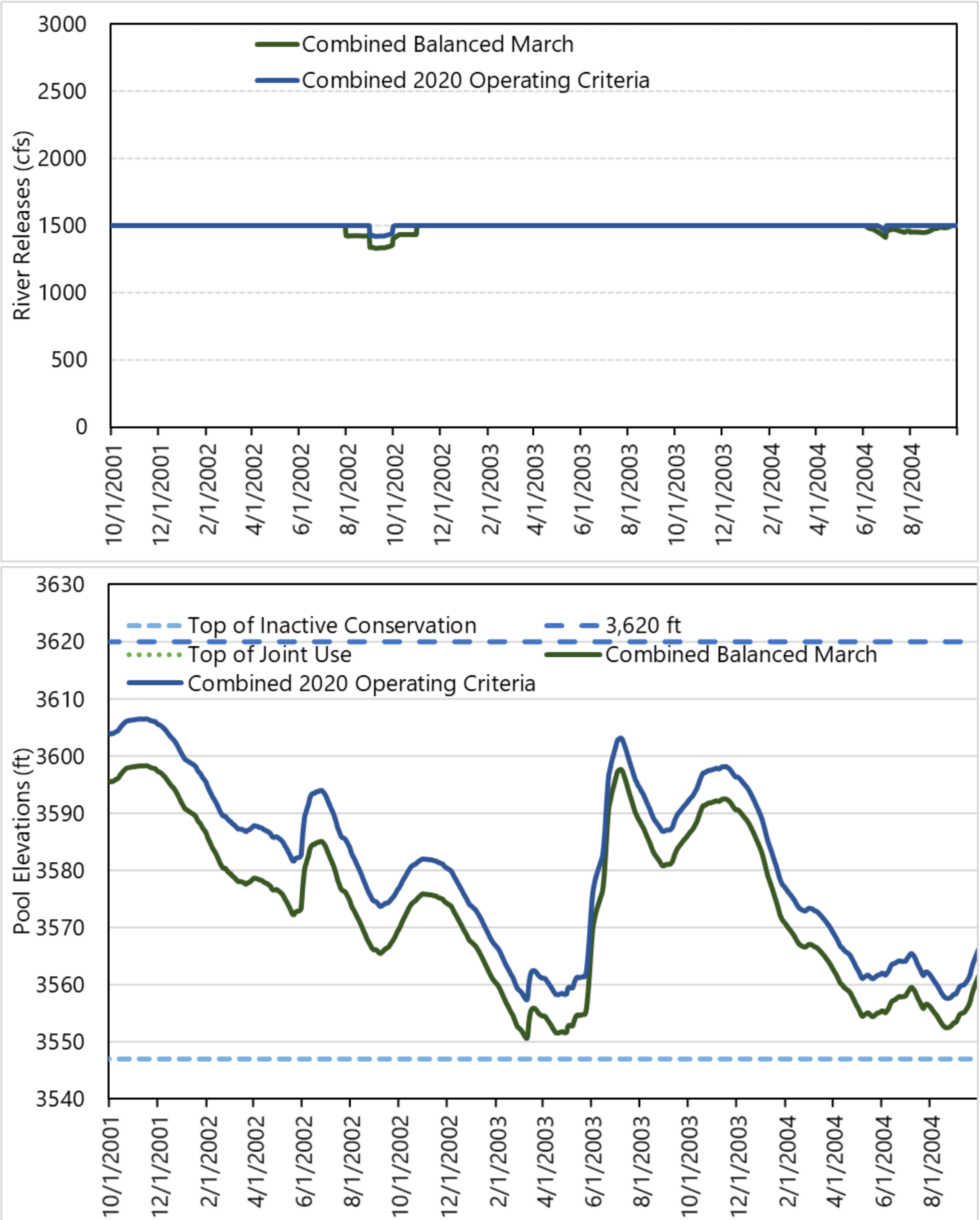
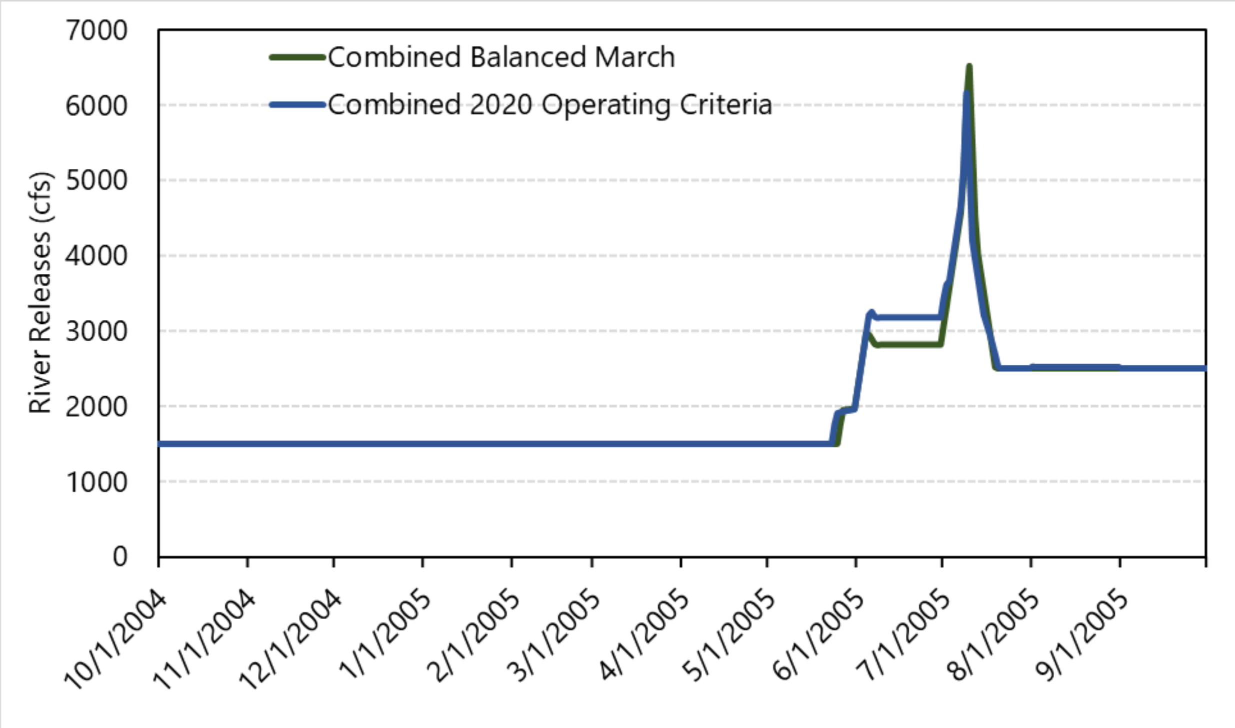


Figure 54. River releases and pool elevations for water years 2002-2003. Differences between two cases caused by differences in pool elevations from earlier water years.



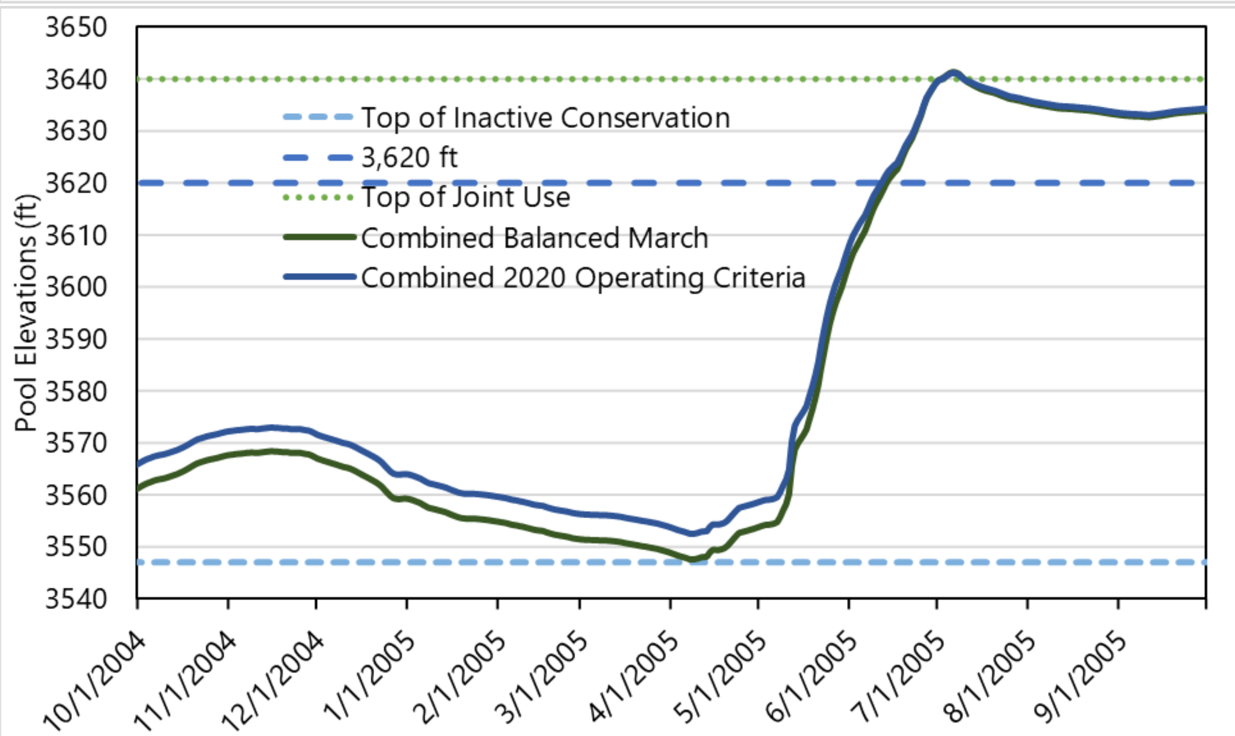


Figure 55. River releases and pool elevations for water year 2005. Differences between two cases caused by differences in pool elevations from earlier water years.

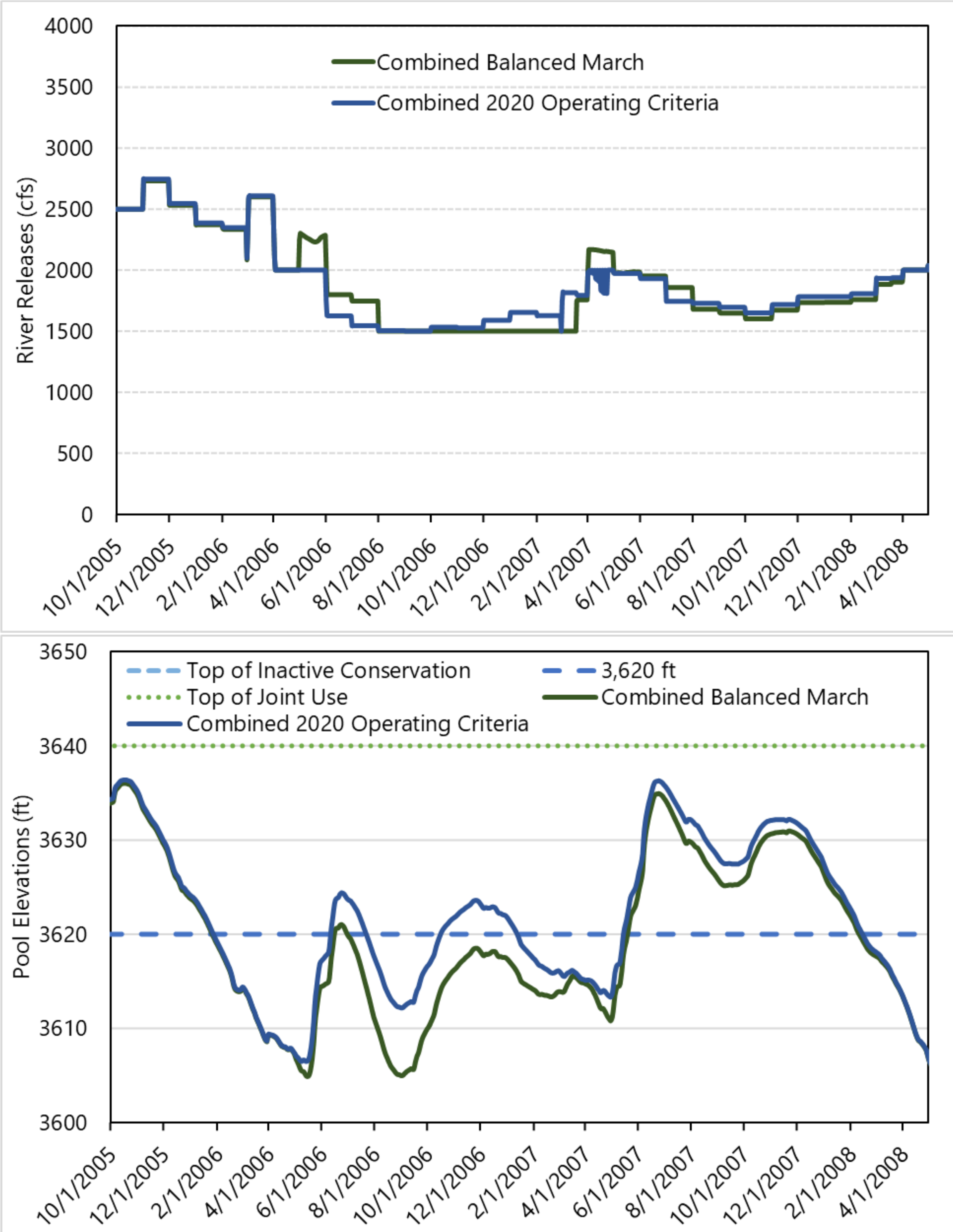


Figure 56. River releases and pool elevations for water year 2006 through 2008. Differences between two cases caused by 2,000 cfs release cap in May of 2006 and April of 2007, by Balanced March Target logic in June and July of 2006 and 2007, and by differences in pool elevations for the remaining differences.

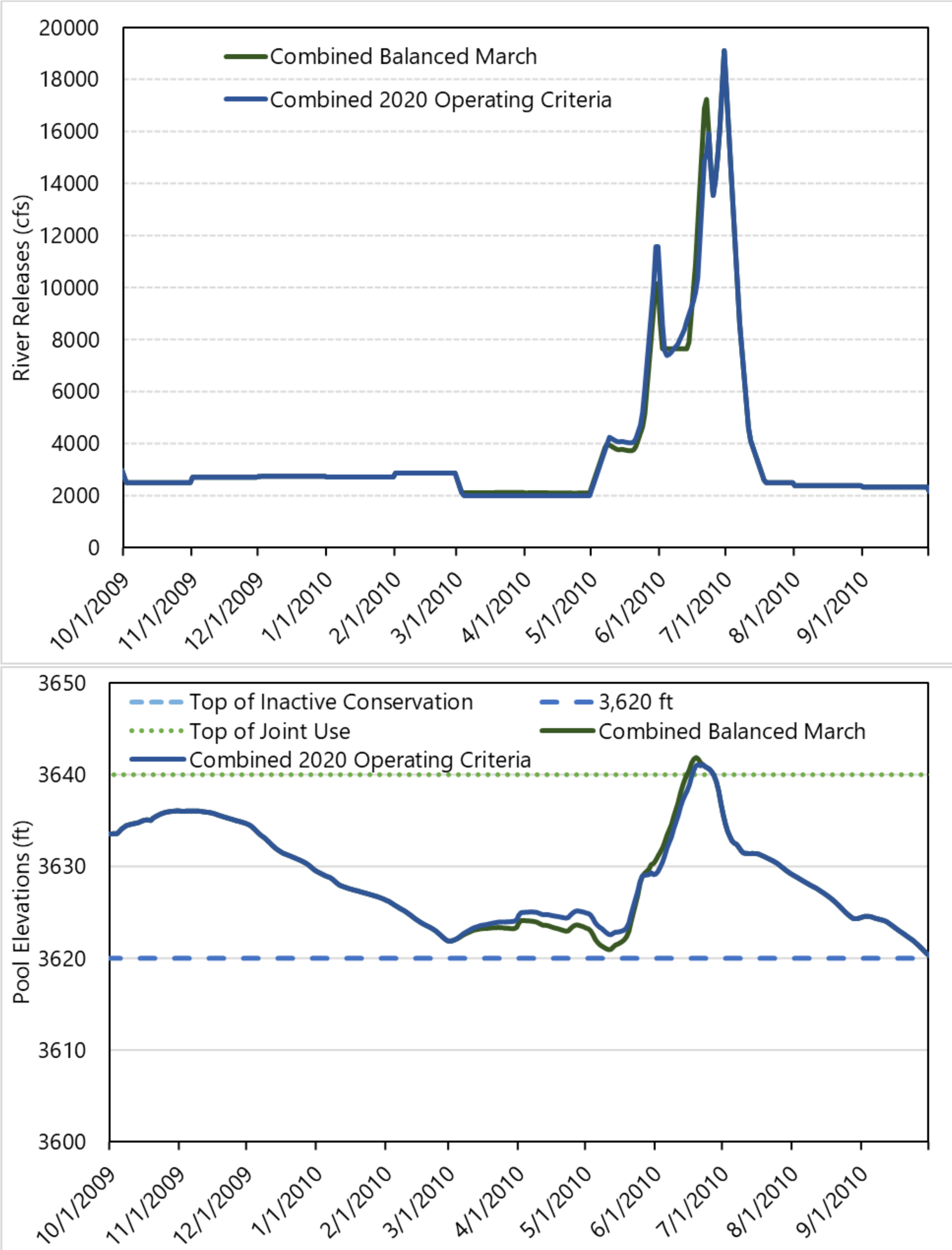


Figure 57. River releases and pool elevations for water year 2010. Differences between two cases caused by the 2,000 cfs release cap.

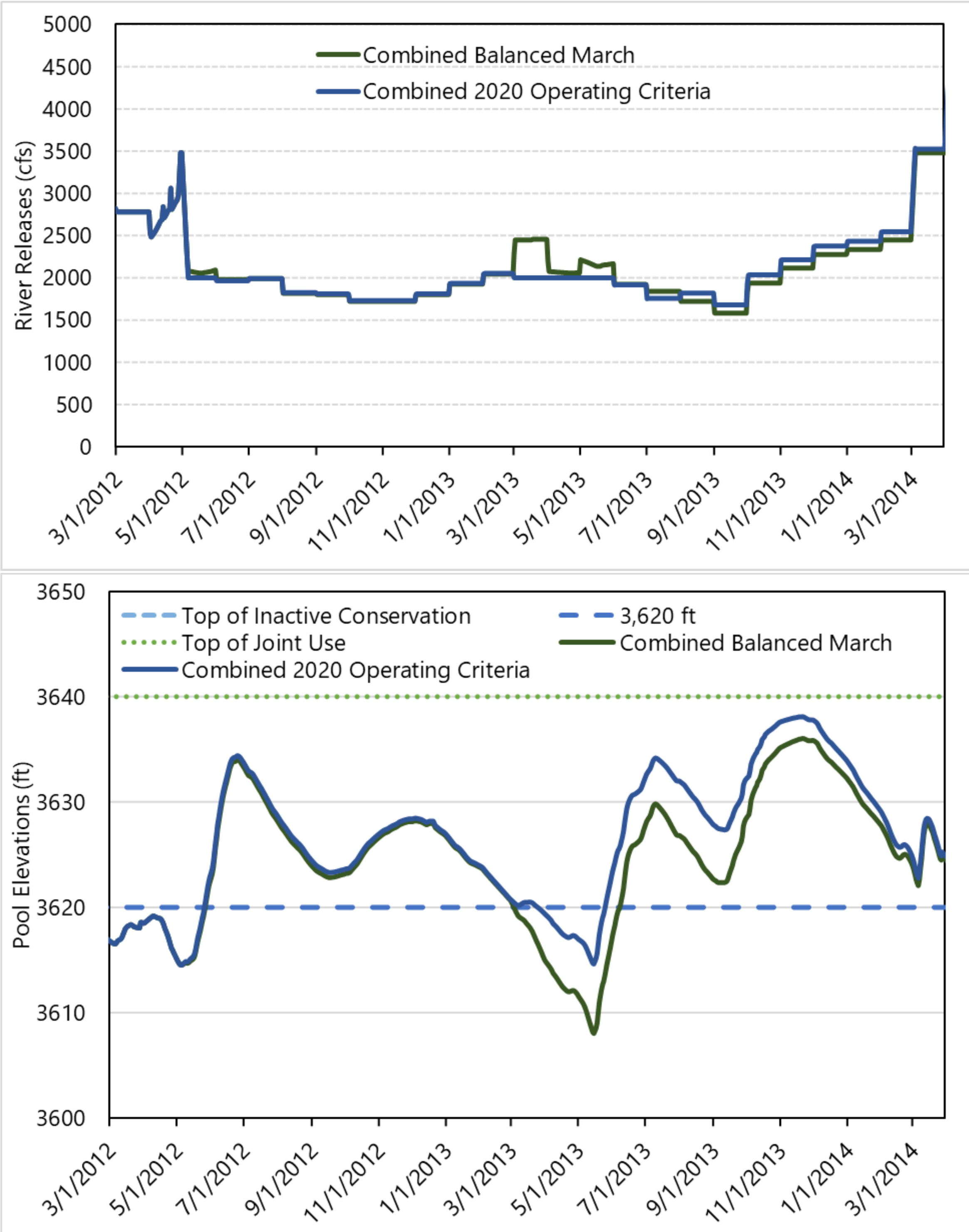


Figure 58. River releases and pool elevations for water years 2012 through 2014. Differences between two cases caused by 2,000 cfs release cap in May of 2012 and March, April, and May of 2013, by Balanced March Target logic in June and July of 2013, and by differences in pool elevations for the remaining months.

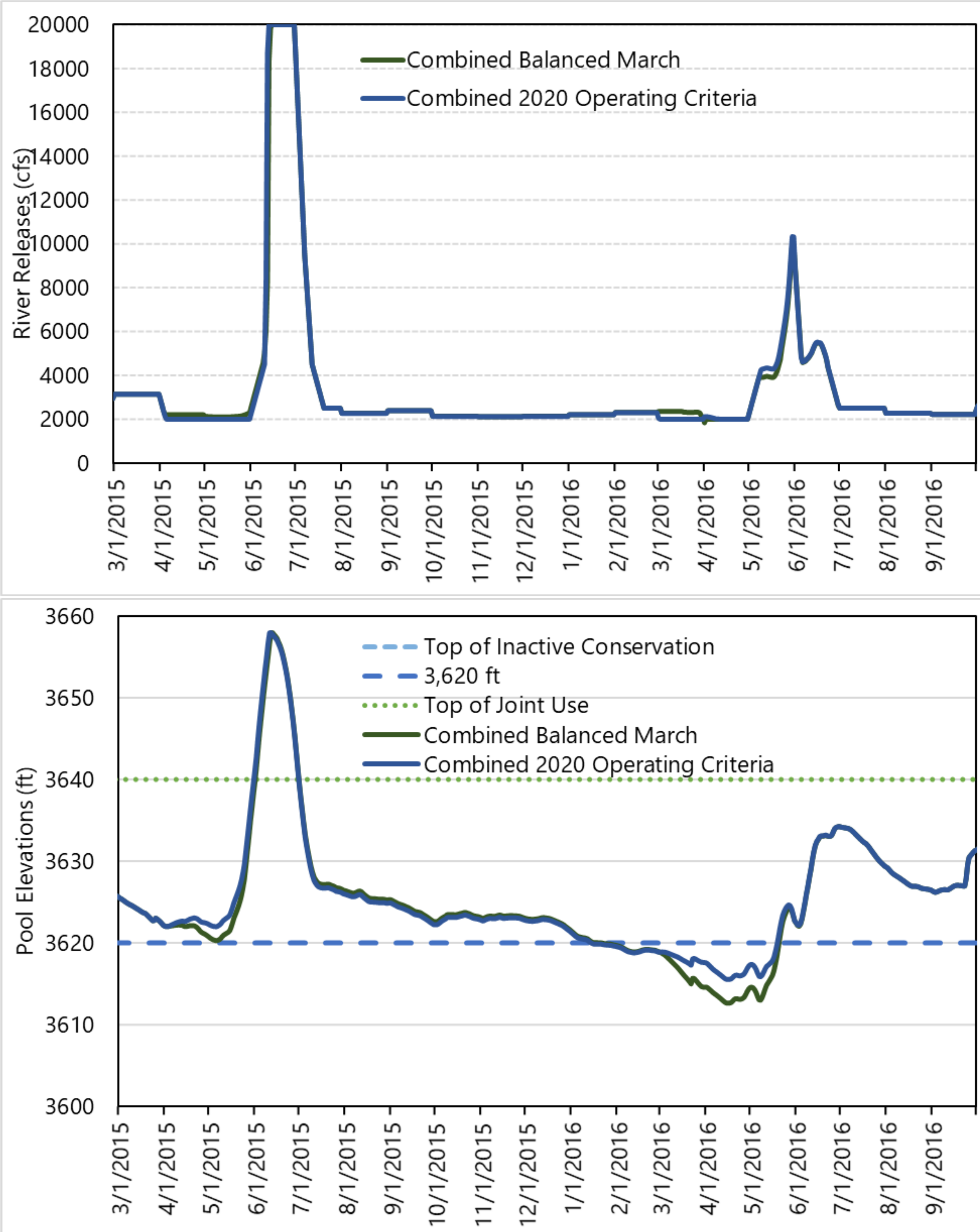


Figure 59. River releases and pool elevations for water years 2015 and 2016. Differences between two cases caused by 2,000 cfs release cap.