Truckee Basin Water Management Options Pilot Viability Assessment

Truckee Basin Project, California and Nevada
California-Great Basin Region

BUREAU OF RECLAMATION

TRUCKEE MEADOWS WATER AUTHORITY

PYRAMID LAKE PAIUTE TRIBE

U.S. DISTRICT COURT WATER MASTER

DEPARTMENT OF WATER RESOURCES STATE OF CALIFORNIA

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Cover Photograph – Truckee River in Reno, Nevada during a high flow event on December 16, 2016 (Mitch Barrie, Flickr).

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Prepared by:

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Acronyms and Abbreviations

1985 WCM	1985 *Truckee River Basin Reservoirs, Truckee River, Nevada and California: Water Control Manual*
1D	one-dimensional
2D	two-dimensional
Accounting Model	Truckee River Operating Agreement Operations and Accounting RiverWare® Model
BAM	By-a-Model Forecast-Informed Reservoir Operations
basin	Truckee Basin/Truckee River Basin
CA-DWR	California Department of Water Resources
CADSWES	Center for Advance Decision Support for Water and Environmental Systems, University of Colorado Boulder
cfs	cubic feet per second
CMIP5	Coupled Model Intercomparison Project Phase 5
CNRFC	California-Nevada River Forecast Center
DAS	Digital Aerial Solutions, LLC
DOI	U.S. Department of the Interior
dSRD	dynamic Storage Reservation Diagram
EOWY	end of water year
ESA	Endangered Species Act
FEMA	Federal Emergency Management Agency
FIRO	Forecast-Informed Reservoir Operations
Flood Project	Truckee River Flood Management Project
GEFSv12	Global Ensemble Forecast System, Version 12
GNSS	Global Navigation Satellite Systems
GRR	Truckee Meadows General Reevaluation Report
HEC	U.S. Army Corps of Engineers Hydrologic Engineering Center
HEC-DSS	Hydrologic Engineering Center’s Data Storage System
HEC-HMS	Hydrologic Engineering Center’s Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HEFS	Hydrologic Ensemble Forecasting System
IR	infrared
kAF (or TAF)	thousand acre-feet
10kyr	ten thousand years

Key Stakeholders	Technical Team members and other key stakeholders including Truckee River Flood Management Authority, California Nevada River Forecast Center, and U.S. Army Corps of Engineers
LBAO	Lahontan Basin Area Office, Bureau of Reclamation
LCT	Lahontan Cutthroat Trout
LiDAR	Light Detection and Ranging
LOCA	Localized Constructed Analogs
LVC	Long Valley Creek
M&I	municipal and industrial
MAE	Mean Absolute Error
MAF	million acre-feet
MEFP	Meteorological Ensemble Forecast Processor
MOA	Memorandum of Agreement
MOEA	multi-objective evolutionary algorithm
NAD83	North American Datum of 1983
NAIP	National Aerial Imagery Program
NAVD88	North American Vertical Datum of 1988
NGVD29	National Geodetic Vertical Datum of 1929
NRCS	National Resources Conservation Service
NSE	Nash-Sutcliffe Efficiency
NTD	North Truckee Drain
NV-DWR	Nevada Division of Water Resources
OCAP	Operating Criteria and Procedures for the Newlands Project, Nevada; a Federal rule governing the diversion of water from the Truckee River to supplement water supply in the Carson River Basin
Planning Model	Truckee River Operating Agreement Planning RiverWare® Model
PLPT	Pyramid Lake Paiute Tribe
PMF	Probable Maximum Flood
Quantum	Quantum Geospatial
RCP	Representative Concentration Pathways
Reclamation	Bureau of Reclamation
RMS	root mean squared
RMSE	root mean squared error
SECURE Act	Science and Engineering to Comprehensively Understand and Responsibly Enhance Water Act
SNOTEL	snow telemetry network (NRCS)
SRD	Storage Reservation Diagram
SWE	snow water equivalent
TSC	Technical Service Center, Bureau of Reclamation

Technical Team	Collaborative partners who are bearing the costs of this study, also referred to as the cost-share partners, including the Bureau of Reclamation, Lahontan Basin Area Office; California Department of Water Resources; Pyramid Lake Paiute Tribe; Truckee Meadows Water Authority; Truckee River Operating Agreement Administrator/U.S. District Court Water Master
TIN	Triangulated Irregular Network representation of the terrain surface
TIS	TROA Information System
TMWA	Truckee Meadows Water Authority
TMWRF	Truckee Meadows Water Reclamation Facility
TRFMA	Truckee River Flood Management Authority
TROA	Truckee River Operating Agreement
TROA Parties	Scheduling Parties of the Truckee River Operating Agreement—City of Fernley, City of Reno, City of Sparks, Pyramid Lake Paiute Tribe, State of California, State of Nevada, Truckee Meadows Water Authority, U.S. Department of the Interior, U.S. District Court Water Master, and Washoe County
TROM	Truckee River Operations Model
USWM	U.S. District Court Water Master
U.S.	United States
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VA	Viability Assessment
W/m^2	watts per square meter—unit of energy per surface area
WaterSMART	Sustain and Manage America’s Resources for Tomorrow
WCM	Water Control Manual
WMOP	Truckee Basin Water Management Options Pilot
WSE	water surface elevation
WY	water year
XS	cross section

Symbols

>	greater than
<	less than
%	percent

Contents

Appendices (available as separate documents)

Appendix A - Alternative Operational Scenarios Development Report

Appendix B - TROA Planning Model Verification

Appendix C - Truckee River Basin Historical Data Development Methodologies: Water Years 2001-2021

Appendix D - Truckee River Basin Historical Data Development Methodologies: Water Years 1986-2000

Appendix E - Truckee River Basin Historical Hourly Data Development Methodologies: Water Years 1986-2021

Appendix F - WMOP Truckee River Hourly River Model Time Lag Routing

Appendix G - Truckee River Hourly Model Verification for WMOP

Appendix H - Truckee Basin Water Management Options Pilot Study—Rain Flood and Snowmelt Flood Frequency Curve Update

Appendix I - Truckee Basin Water Management Options Pilot Study—Channel Capacity Analysis

Appendix J - Truckee River Flood Management Authority and National Weather Service Memorandums and Presentation

Appendix K - Revised Guide Curve Modeling, Improving Current Guide Curves with dSRD Approach

Appendix L - Inflow Uncertainty Analysis

Appendix M - Action and Alternative Operational Scenario Modelling in the WMOP

Appendix N - Multi-Objective Evolutionary Algorithm (MOEA) Tool Utilization and Development

Appendix O - Preferred Operational Scenario Selection Process

Appendix P - Preferred Operational Scenario Probable Maximum Flood Routings Analysis

Appendix Q - Preferred Operational Scenario with Martis Creek Reservoir Operational Analysis

Tables

Figures

Truckee Basin and Water Management Options Pilot—Introduction

The Truckee Basin is a microcosm of water management challenges in the American West, with highly variable intra- and inter-annual runoff and limited capacity to store water from year to year. Meeting basin water demands requires a system of dams, reservoirs, canals, and additional flood management structures, along with rules and requirements that guide the operations of the complex system. The construction and operation of this system contributed to the listing of the threatened Lahontan cutthroat trout (LCT) (*Oncorhynchus clarkii henshawi*) and endangered Cui-ui (*Chasmistes cujus*) fish species under the Endangered Species Act (ESA) (U.S. Fish and Wildlife Service, 2003). Urbanization and uncertain future conditions due to climate change, along with related shifting water demands, may create more water management challenges for the fully allocated system—challenges that could be mitigated with increased operational flexibility.

Water management studies and stakeholders in the Truckee Basin identified the 1985 Truckee Basin Water Control Manual (WCM) (1985 WCM) that currently guides reservoir flood operations as a key constraint to water management. A team of stakeholders comprised of the Bureau of Reclamation (Reclamation), California Department of Water Resources (CA-DWR), Pyramid Lake Paiute Tribe (PLPT), Truckee Meadows Water Authority (TMWA), and the U.S. District Court Water Master (USWM), known as the "Technical Team," came together in 2019 to develop a proposal to devise and test new, more flexible flood risk management criteria that could help address the growing water management challenges in the basin, termed the Truckee Basin Water Management Options Pilot (WMOP). The Technical Team received funding for this work under Reclamation's WaterSMART Program, signing a Memorandum of Agreement (MOA) in June 2021. Since then, the Technical Team has collaborated to develop five Action Alternative Operational Scenarios (Action Alternatives) and evaluated their impact on flood risk, water supply, and environmental flows compared to the 1985 WCM (No Action Alternative, Baseline). Through a series of technical studies, meetings, workshops, and collaborative discussions (Figure 1), the Technical Team selected a Preferred Operational Scenario that updates the WCM to incorporate streamflow forecasts, revised guide curves, reproportioning of flood space between reservoirs, and an increase in the downstream flood flow target. This Viability Assessment (VA) represents the culmination of the WMOP effort.

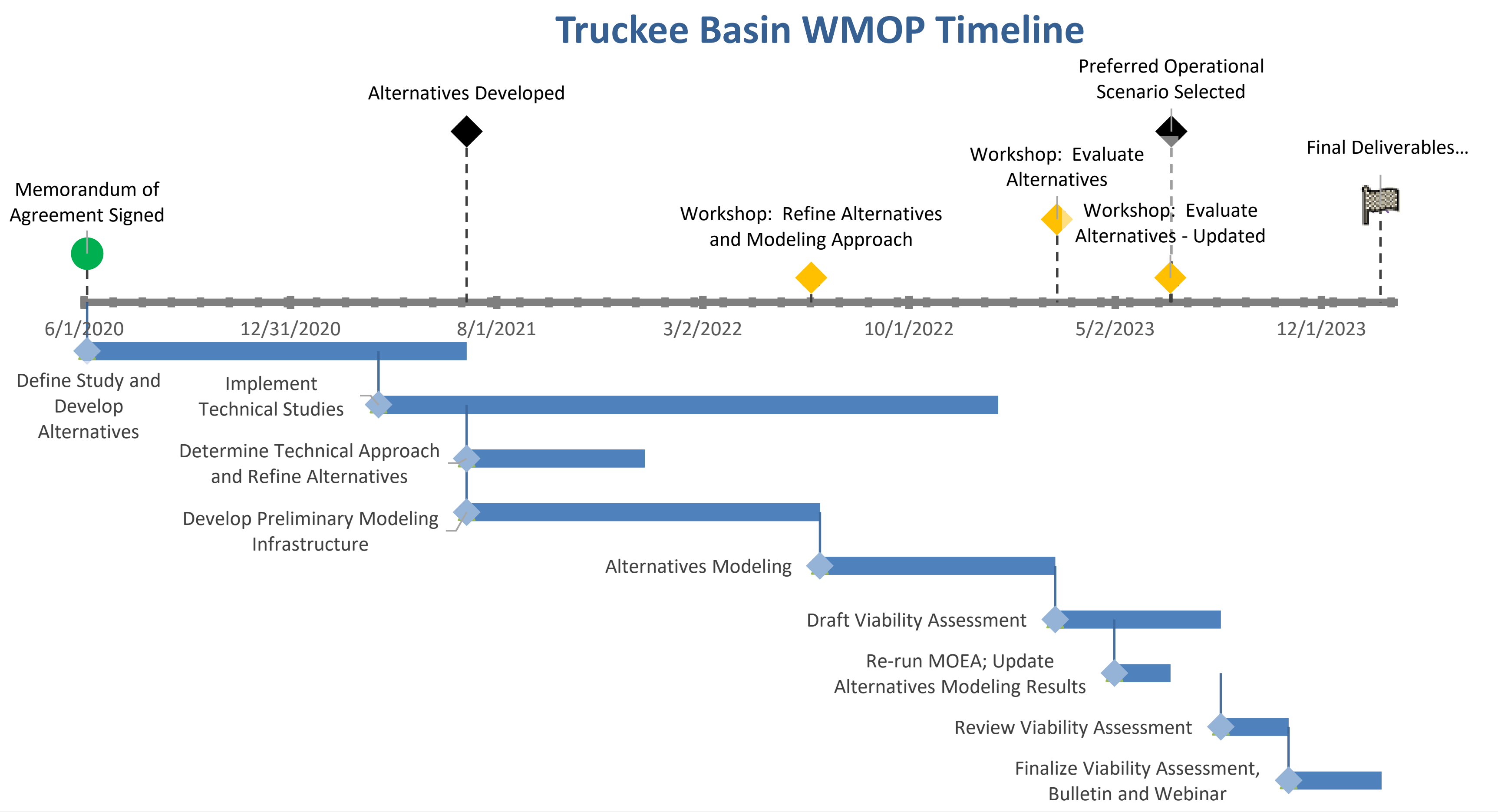

Figure 1.—Timeline of activities conducted during the WMOP.

This introductory section provides the context for the WMOP. It describes the existing conditions in the Truckee Basin and makes a case for improving reservoir operations for the benefit of flood risk management, water supply, and environmental flows. From there, this VA details each of the six Alternative Operational Scenarios (alternatives) developed by the Technical Team, which include five Action Alternatives and the Baseline, No Action Alternative. Building out these alternatives and the technical foundation from which to evaluate them required substantial effort, which is summarized in this VA and included as appendices. This VA then provides results from the modeling of the alternatives, including a discussion of the Technical Team's evaluation process. Lastly, this VA outlines recommendations for implementing and incorporating the Preferred Operational Scenario in a WCM update, followed by a concluding summary.

Current Water Supply and Demands

The Truckee Basin is a closed system (i.e., it does not drain into an ocean) spanning approximately 3,060 square miles between California and Nevada (Figure 2). The river flows 121 miles from Lake Tahoe northeast to its terminus in Pyramid Lake, encompassed in the PLPT Reservation. Along the way, the Truckee River gains additional flows from several tributaries, including Martis Creek, Prosser Creek, and Little Truckee River in California and Steamboat Creek in Nevada. The river crosses the California-Nevada border near Floriston, California, and then it travels through Reno, Nevada, where a variety of municipal and agricultural diversions extract water from the river.

Approximately 90% of the basin's precipitation falls in the California headwaters, while most water use occurs downstream in Nevada. The headwaters of the Truckee Basin lie in the mountains surrounding Lake Tahoe, which can receive well over 70 inches of precipitation annually, almost exclusively as snow from November to April. On the other hand, the lower Truckee Basin in Nevada receives less than 7 inches of precipitation each year, on average (National Centers for Environmental Information, National Oceanic and Atmospheric Administration, 2023).

Hydrologic conditions in the Truckee Basin have increased in variability in recent decades to the point where water managers recognize that hydrologic stationarity is no longer a valid assumption (Truckee Meadows Water Authority, U.S. District Court Water Master, Truckee River Flood Management Authority, and Bureau of Reclamation, 2019; Sterle, Hatcheet, Singletary, and Pohll, 2019; Bureau of Reclamation, 2020). From 2012 to 2015, the Truckee Basin experienced the most severe drought on gaged record. The drought was so severe that it was considered abnormal compared to a historical 500-year reconstructed flow record (Biondi and Meko, 2019). The extreme drought preceded the wettest hydrologic year on record in 2017 (Truckee Meadows Water Authority, U.S. District Court Water Master, Truckee River Flood Management Authority, and Bureau of Reclamation, 2019; Sterle, Hatcheet, Singletary, and Pohll, 2019; Harris, 2021). Further, water year 2023 broke or nearly broke snow water equivalent (SWE) records throughout the Sierra Nevada Mountains (California Department of Water Resources, 2023). Water managers must plan and adapt for the extreme swings between dry and wet periods—storing as much water as possible for dry periods and safely operating the reservoirs to protect life and property downstream during wet periods (U.S. Army Corps of Engineers, 1991).

The Truckee Basin's water has been fully appropriated to support agricultural, municipal, industrial, and environmental uses. In other words, every drop of water from the Truckee River's headwaters in the Sierra Nevada Mountains to its terminus at Pyramid Lake serves important beneficial uses for humans and the environment (Bureau of Reclamation, 2015). Water from the Truckee helps irrigate over 50,000 acres of farmland in Reclamation's Newlands Project; generates 50 million kilowatt-hours of hydroelectric power per year; serves the domestic needs of more than 440,000 residents of Reno, Sparks, and Washoe County, Nevada; and supports ESA-listed fish species of great importance to the PLPT (Bureau of Reclamation, 2015).

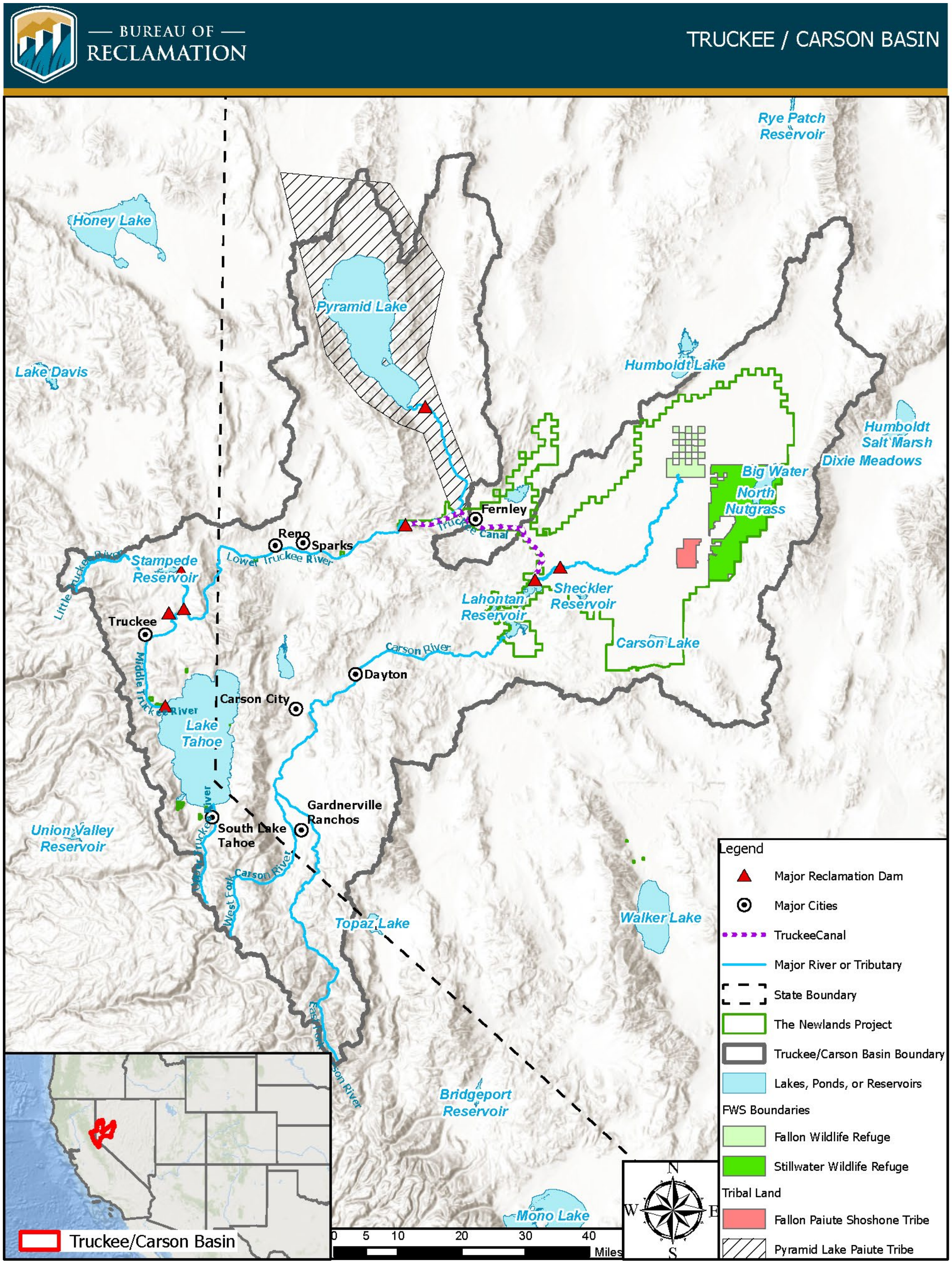

Figure 2.—Map of the Truckee and Carson Basins, including the reservoirs and other Reclamation project features.

Water Management and Facilities

Meeting water demands with the limited, variable water supply from the Truckee River requires extensive engineering works and coordinated operating procedures. Reclamation and the U.S. Army Corps of Engineers (USACE) manage multiple Federal projects on the Truckee River, dating back to the turn of the 20th century. Features in Reclamation's Newlands Project, authorized in 1903, include Lake Tahoe Dam, Derby Dam, Truckee Canal, and Lahontan Dam and Reservoir (Simonds, 1996) (Figure 2). The Truckee Canal hydrologically connects the Truckee and Carson Rivers to provide irrigation water to lands near Fernley and Hazen, Nevada, in the Truckee Division and Lahontan Reservoir for use in the Carson Division, Fallon Paiute-Shone Tribe Indian Reservation, and the Stillwater National Wildlife Refuge. In 1939, Reclamation's Truckee Storage Project added Boca Dam and Reservoir as additional water storage in the Truckee River (Hartl, 2001a). Further, Reclamation added two additional storage reservoirs (Prosser Creek and Stampede Reservoirs), an erosion control dam (Marble Bluff Dam), and a fish passage structure in 1970 as part of the Washoe Project (Hartl, 2001b). Three other dams operate within the Truckee Basin: Donner and Independence Lake Dams, owned and operated by the Truckee Meadows Water Authority (TMWA) for water supply, and Martis Creek Reservoir, owned and operated exclusively by USACE for flood control. The WMOP focused on developing recommendations for updating operations at the three flood control dams owned by Reclamation: Prosser Creek Dam (Prosser), Boca Dam (Boca), and Stampede Dam (Stampede), and then assessed the potential benefits of operationalizing Martis Creek Dam (Martis), which is currently inoperable for flood management due to safety concerns, as described subsequently.

Operations for the Truckee River have evolved in complexity over time, with increasing demands and legal challenges for water rights. One of the first agreements on Truckee River operation in 1908 established the Floriston Rates among the Truckee River General Electric Company, Floriston Land and Power Company, and Floriston Pulp and Paper Company. The Floriston Rates set a required average daily flow rate at the Farad Gage near the California-Nevada border. The agreement required that if there was insufficient flow from the remaining portion of the Truckee River system to meet these Floriston Rates, then, if possible, water would be released from Lake Tahoe to maintain the specified rates of flow. These original Floriston Rates were formalized in the 1915 Truckee River General Electric Decree and then modified in the Truckee River Agreement of 1935 (Table 1). Today, the water used to meet Floriston Rates provides water serving municipal and industrial (M&I) use in Truckee Meadows, instream flow, numerous agricultural water rights, and hydroelectric power generation.

Table 1.—Floriston Rate Targets (Floriston Rates) for the Truckee River Near Farad, California (TROA - Truckee River Operating Agreement, 1935)

Lake Tahoe Elevation (feet)	Floriston Rate Targets at Farad Gage (cfs)			
	October	November–March	March	April–September
< 6,225.25	400	300	300	500
6,225.25 – 6,226.00	400	350	350	500
> 6,226.00	400	400	500	500

Importantly, the Floriston Rates are based on water supply *availability* instead of a demand-driven system. As such, the targets fluctuate based on season and Lake Tahoe's water surface elevations rather than fluctuating based on water demands (Table 1). In 1944, the U.S. District Court of Nevada issued the Orr Ditch Decree to adjudicate the water rights for the Truckee Basin and further fortify the Floriston Rate Targets. Even though conditions in the Truckee Basin have changed over time, the Floriston Rates' minimum flow operating criteria have remained the same.

USACE's 1985 WCM dictates the flood operations of the basin's four flood control reservoirs: Prosser, Boca, Stampede, and Martis Reservoirs. The WCM guides operations to meet six main objectives that balance flood storage requirements, flow rates, and water supply needs (Table 2). The flood risk objectives focus on maintaining enough flood space in upstream reservoirs to protect the Reno-Sparks metropolitan area, colloquially known as Truckee Meadows. The WCM explicitly attempts to balance flood risk management with water supply objectives, supporting the beneficial uses of water.

Table 2.—Truckee Basin WCM Objectives (U.S. Army Corps of Engineers. 1985)

WCM Objectives
1. Protect the Truckee Meadows against reasonably probable rain floods. 2. Reduce damages in all but very large floods. 3. Restrict downstream Truckee River flows at the Reno, Nevada Gage to 6,000 cfs, insomuch as possible. 4. Provide the maximum conservation (flood) storage practical, without harming downstream water rights. 5. Allow for the maximum amount of power generation practical while balancing the flood storage needs. 6. Provide releases to preserve and enhance the Lower Truckee River habitat for threatened and endangered fish species.

Guide curves, also known as rule curves or Storage Reservation Diagrams (SRDs), dictate the amount of space that dam operators must reserve exclusively for flood control in the four flood control reservoirs: Prosser, Boca, Stampede, and Martis Reservoirs. The WCM reserves a total of 65,000 acre-feet of flood control storage distributed across the four reservoirs (Table 3). During flood events, any necessary encroachment into each reservoir's flood space should, as much as possible, match the percentage of total basin flood space in that reservoir so that one reservoir is not overly stressed compared to another. The total volume of required flood storage must be maintained from November 1st through at least April 10th and as late as June 1st. The flood storage requirement then steadily decreases, allowing the reservoirs to refill to meet spring and summer water demands. The date and rate of allowable refill in the spring depend on the forecasted Farad natural flow volume through July 31st, known as the snowmelt parameter. Storage reservation diagrams with this type of dynamic option to operate on different curves based on a snowmelt parameter are referred to as dynamic Storage Reservation Diagrams (dSRDs). Figure 3 shows the spring refill portion of the 1985 WCM guide curve for Prosser Reservoir, as an example.

The 1985 WCM authorizes the use of Martis Creek Reservoir to store water for flood control when flows at the Reno Gage are forecasted to equal or exceed 14,000 cfs. However, Martis Dam is experiencing underseepage and other failure patterns, leading USACE to characterize it as a “moderate risk” in 2015. As such, the reservoir is not currently operated as intended in the WCM.[1] Rather, Martis is currently operated with the gates fully open, only allowing for 800 acre-feet of dead pool storage (Moen, 2023).

Table 3.—Required Flood Space Between November 1 and April 10 in the Truckee Basin Flood Control Reservoirs

Reservoir	Required Flood Space November 1–April 10	Percent of Truckee Basin’s Flood Space
Prosser	20,000 acre-feet	30.8%
Martis	15,000 acre-feet*	23.1%
Little Truckee Total:	30,000 acre-feet	46.2%
• Boca	8,000 acre-feet	Approximately 27% of the Little Truckee total flood space
• Stampede	22,000 acre-feet	Approximately 73% of the Little Truckee total flood space
Total	**65,000 acre-feet**	**100%**

*Under the current restrictions, 800 acre-feet of dead pool storage is available in Martis, and the dam only provides minimal passive or incidental flood storage, yielding a total upper Truckee flood storage of 50,000 acre-feet.

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[1] Seepage issues were discovered on Martis Creek Dam in 1995 during a fill test. Further, a spillway capacity study in 2002 determined that the spillway capacity of Martis was inadequate. As a result, USACE determined in 2005 that Martis was one of the top six most high-risk dams in the Nation (U.S. Army Corps of Engineers, No date). After a more rigorous assessment in 2015, USACE changed Martis’ rating from “high risk” to “moderate risk” (Moen, 2023).

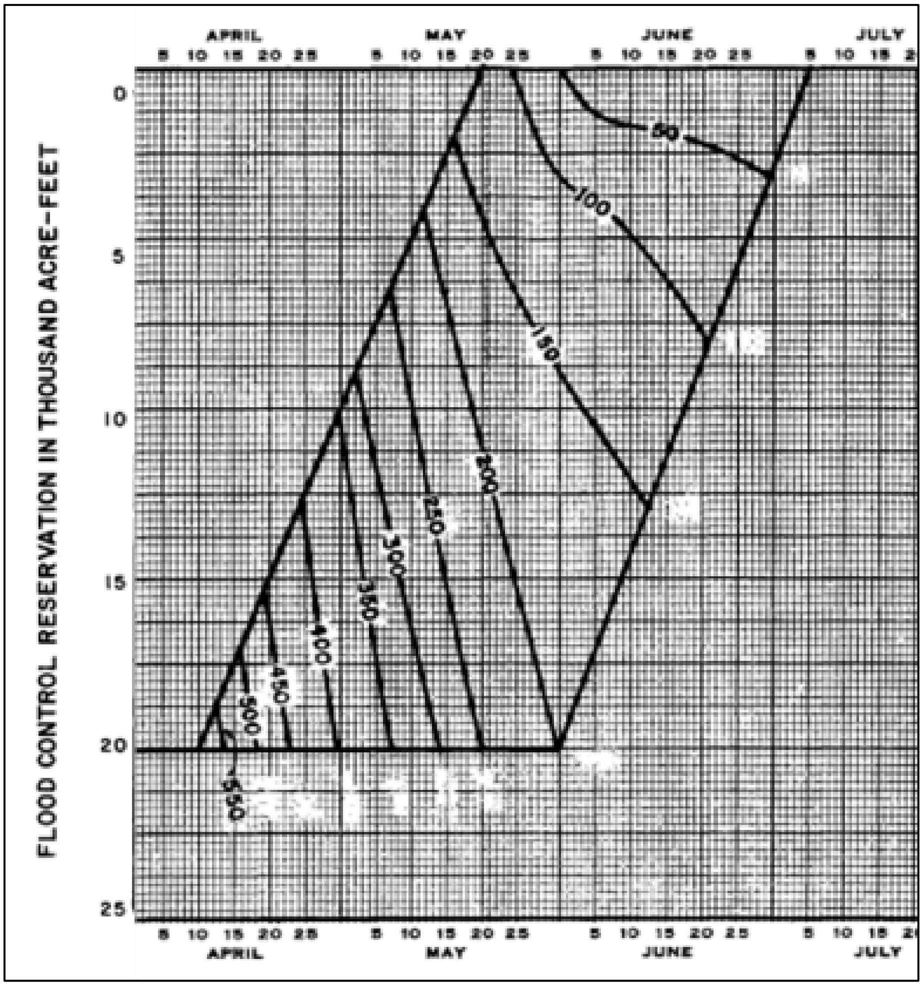


Figure 3.—Spring refill portion of the 1985 WCM Prosser Reservoir dSRD showing the required flood space (flood control reservation) based on the day of year and a snowmelt parameter of the forecasted Farad natural flow volume through July 31st (downward sloping lines from April through July, kAF).

Note**:** Figure 3 is a photocopy of the 1985 WCM guide curve, while a recreated, clearer version is included in Figure 28 (U.S. Army Corps of Engineers, 1985).

Important for the WMOP, the WCM restricts Truckee River flows, insofar as possible, to a 6,000-cfs instantaneous flow rate at the Reno Gage to protect Truckee Meadows from flooding. Although USACE completed substantial work to increase the Truckee River channel capacity to 14,000 cfs before the 1985 WCM, encroaching development within Truckee Meadows at that time was increasing flood risk by increasing the potential consequences should a flood occur. As such, the 1985 WCM set the target flood flow rate to 6,000 cfs to minimize the chance of flooding any encroaching development.

In 2011, the Truckee River Flood Management Authority (TRFMA) was established with the goal to create a more resilient community by reducing flood damage resulting from large flood events. TRFMA oversees the Truckee River Flood Management Project (Flood Project), which includes a substantial amount of work to reduce the impact of flooding in Truckee Meadows (Truckee River Flood Management Authority, 2017). TRFMA has already completed several portions of the Flood Project, including constructing multiple levees, purchasing and developing land in the floodplain, and raising bridges that span the Truckee River to increase flow capacity.

Since the early 1980s, the Truckee River has also been managed to provide environmental flows that benefit threatened and endangered fish species. The U.S. Fish and Wildlife Service developed a set of ecosystem flow regimes to supplement flows in the lower river with water from Stampede and Prosser Reservoirs, and PLPT leads the management of environmental flows for the lower Truckee River under TROA (TROA - Truckee River Operating Agreement, 2008; HDR, 2004). These environmental flows are designed to provide suitable river stages and Pyramid Lake conditions during spawning (April to July) and improve overall instream and riparian habitat. The selection of which flow regime to follow in any given year depends on water availability and ecosystem needs. Further, the California Department of Fish and Wildlife aims to maintain preferred flow conditions in the California portion of the Truckee River with the intent to mimic the natural hydrograph in these streams as much as possible (California Department of Water Resources and California Department of Fish and Wildlife, 2018).

The Case for Change

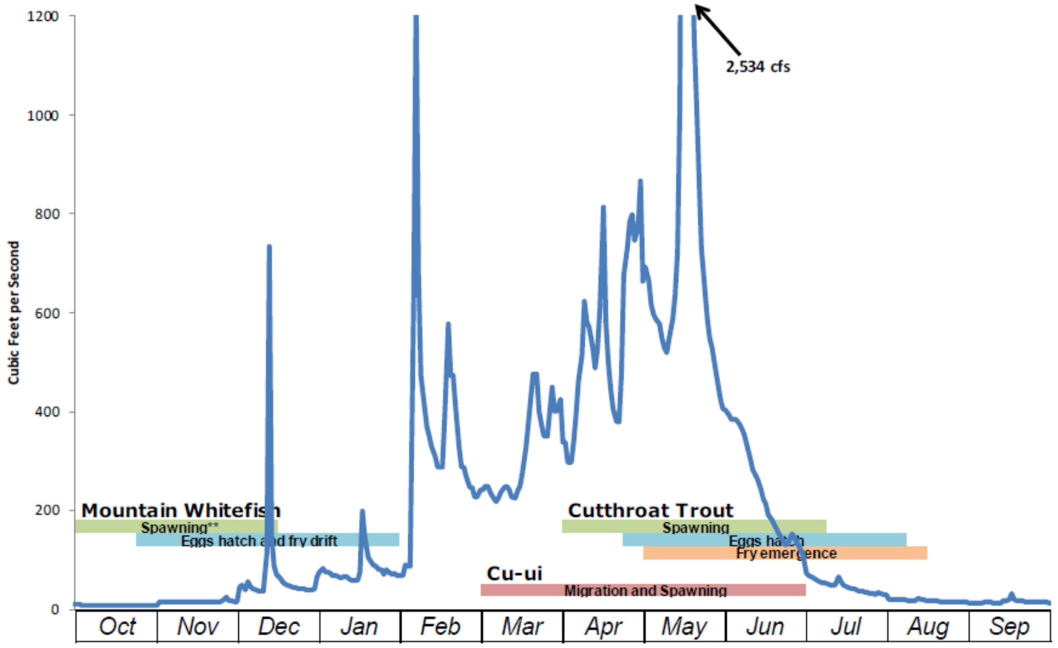
The WCM was innovative for its time and likely represented an optimal balance between basin objectives to the extent feasible when USACE produced it. However, significant changes have occurred in the Truckee Basin in almost 40 years since USACE developed the regulation criteria, and the manual is outdated for modern conditions. The changes in the basin and lessons learned from operating under the 1985 WCM drive the need to re-examine the operating rules in the WCM. These drivers include:

- Inflexible guide curves,
- Changes in supply and demand,
- Improved data and forecasting,
- Facility upgrades, and
- Changes in the rules governing operations (subsequently described in further detail).

Inflexibility in Guide Curves

The inflexibility of the current guide curves can restrict or prohibit operations that would otherwise lead to more effective and efficient water management in the Truckee Basin. The extreme variability from year to year in terms of winter precipitation, snowpack, and runoff makes it very challenging for water managers, including Reclamation and its partners, to adapt and plan for water supplies within the constraints governing how the reservoirs must be operated for flood risk management. Each component of the guide curves—fall drawdown, winter flood operations, and spring refill—exhibited inflexibility to some extent, as described subsequently.

In the fall, the WCM requires dam operators to evacuate flood space by October 31st before that space is necessary and any real threat of flooding exists (Appendix K). This can harmfully impact riverine species that have adapted to relatively low natural flows during this time of year. Fall flood operations can result in rapidly changing flows, with unnaturally high flows to evacuate flood space followed by steep drops in flows once the reservoirs get to their flood control levels. Drawdown under the 1985 WCM occurs during the spawning of native mountain whitefish and non-native brown trout, popular for recreational fishing. Mountain whitefish typically spawn from October to early December, but the spawning timeframe can vary depending on hydrology and temperature (Figure 4) (California Department of Water Resources and California Department of Fish and Wildlife, 2018). Exceptionally high flows and long-sustained high flows during drawdown can potentially disturb redds and flush eggs and juveniles into less ideal habitats. Flow drops in October and November can expose redds resulting in egg mortality, and flow drops after emergence can lead to fish stranding (California Department of Water Resources and California Department of Fish and Wildlife, 2018). Allowing for the flexibility to evacuate to the flood control level later in the year—more in line with historical flood risks—could help avoid some of the negative impacts on fish species by spreading out flood control releases over a longer period to create more backwater for spawning and to avoid drops in flow during spawning.



Mountain Whitefish and Cutthroat trout life history timing adapted from Moyle, 2002.
Cui-ui life history timing from U.S. Fish and Wildlife Service http://www.fws.gov/nevada/protected_species/fish/species/cuiui.html
Hydrology data from the TROA Planning Model - Local inflow to Stampede Reservoir without inflow from Independence - 1995-1996 water year
**Mountain whitefish spawn in waters with temperatures between 1°C and 11°C. High embryo mortality occurs above 9°C (Moyle, 2002)

Figure 4.—Mountain whitefish, Cui-ui, and cutthroat trout life history (California Department of Water Resources and California Department of Fish and Wildlife, 2018).

In addition, the WCM requires reservation of the full flood space throughout the entire winter, even when there is a low snowpack. This prevents carrying over water storage from wet to dry years to help manage the intra- and inter-annual variability characteristic of the Truckee Basin. In the basin, flows for threatened and endangered fish species are supported by transferred and decreed water rights, which rely on storage during wet periods for later release to maintain instream flows, making efficient storage during these periods critical. Reclamation expressly authorized Stampede and Prosser Reservoirs to support the fisheries of the PLPT. These two reservoirs constitute approximately 84% of the flood space that the WCM currently regulates (42,000 of 50,000 acre-feet), and the ability to store into some of this flood space during years with lower flood risk could provide operational flexibility to better meet environmental flows for threatened and endangered fish species and other water demands.

The current guide curves can sometimes prohibit the reservoirs in the Truckee Basin from filling in the spring. The guide curves and snowmelt parameters that dictate when and how reservoirs can be filled can require dam operators to maintain empty flood space in reservoirs late into spring. Even during years with high runoff, by the time filling is finally allowed into the flood space, the snowmelt runoff has often receded to a level that some reservoirs do not fill (Bureau of Reclamation, 2021a). For example, in 2017, the largest water year in the historic gage record, the guide curves prohibited Prosser Reservoir from filling (Truckee Meadows Water Authority, U.S. District Court Water Master, Truckee River Flood Management Authority, and Bureau of Reclamation, 2019). The cascading effects of failing to fill the reservoirs will impact operations for years to come, especially releases made for threatened and endangered fish species. Further, during medium to large water years, the WCM allows some encroachment into the flood space due to the ranges of the snowmelt parameter and the shape of the refill curves, but then forces operators to evacuate that space as the system shifts to a lower snowmelt parameter curve with the natural decline in the remaining water year Farad natural flow through the spring.

In addition, spring refill under the WCM requires minimum downstream flow releases during times of naturally high runoff, to which the native aquatic species have evolved. Lahontan cutthroat trout and rainbow trout spawn between February and July, and Cui-ui spawn between March and June. The timing and extent of spawning depends on streamflow and water temperature, both of which dam operations can alter. Releases made specifically for fish species attempt to counterbalance the negative impact of WCM operations' alteration of the natural flow regime.

Changes in Water Supply and Demands

The current challenges water operators face in trying to balance flood risk management with meeting water demands are projected to grow in the future—although the basin is fully allocated, water users do not currently exercise full use of their water rights, which is expected to change in the future (Bureau of Reclamation, 2015). Subject area experts have conducted numerous studies to better understand the current trends in water supplies and demands in the Truckee Basin, as well as how these may change under future scenarios. Among these, Reclamation published three prominent reports:

- **Truckee Basin Study (2015)**.—Funded through the U.S. Department of the Interior's WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program, Reclamation initiated a series of studies to assess current and future water supply and demand in the Truckee Basin and to identify a range of potential strategies to address any projected imbalances. The 2015 Truckee Basin Study was conducted by Reclamation in partnership with four non-Federal cost-share partners: Placer County Water Agency, Tahoe Regional Planning Agency, TMWA, and TRFMA (Bureau of Reclamation, 2015).

- **Truckee and Carson River Basins SECURE Water Act Section 9503(c) Report to Congress (2021)**.—Through WaterSMART and the Science and Engineering to Comprehensively Understand and Responsibly Enhance (SECURE) Water Act of 2009, Reclamation developed this report to characterize the impacts of warmer temperatures, changes to precipitation and snowpack, and changes to the timing and quantity of streamflow runoff in the Truckee and Carson River Basins (Bureau of Reclamation, 2021c). The 2021 SECURE Water Act Report to Congress compared paleo-hydrology and Coupled Model Intercomparison Project Phase 5 (CMIP5) climate change predictions to historic (gaged) hydrologic records to quantify how hydrologic conditions have shifted in the gage record and how they may continue to shift into the future.

- **West-Wide Climate and Hydrology Assessment (2021)**.—The 2021 West-Wide Climate and Hydrology Assessment is the technical companion document to the 2021 SECURE Water Act Report to Congress (Bureau of Reclamation, 2021d)**.**

These reports, along with other work produced outside of Reclamation, form the basis for assessing hydrologic trends and climatic changes in the Truckee Basin, namely, those related to:

- Water supply volume and seasonality shift,
- Water demands, and
- Inter-annual variability and extremes.

These potential climatic changes have far-reaching ramifications for individuals, businesses, agriculture, critical habitats for ESA-listed species, and Tribal or cultural resources dependent on the Truckee River, as described subsequently.

Water Supply Volume and Seasonality

Future changes in precipitation remain highly uncertain, with climate models projecting an increase, decrease, or no change in average annual precipitation in the Truckee and Carson Basins (Bureau of Reclamation, 2015). Greater consensus surrounds the expectation for the regional climate to warm 5 to 6 degrees Fahrenheit by the end of the 21st century (Bureau of Reclamation, 2015). Hotter summers will increase evaporation at all Truckee Basin lakes and reservoirs, most notably at Lake Tahoe and Pyramid Lake, because of their vast surface areas. Warmer winters would also reduce snowpack or cause earlier runoff in the Truckee River's high Sierra headwaters (Bureau of Reclamation, 2021c). Even without a change in annual precipitation volumes, this increase in temperature may reduce water supplies (Bureau of Reclamation, 2015), while other studies project no significant changes in annual water supply volumes (Sterle et al., 2020).

Increases in temperature and reductions in snow accumulation can cause a phenomenon referred to as a seasonality shift, where peak runoff and flows occur earlier in the season than they have historically. Peak snowmelt runoff in the Truckee River at Farad has historically occurred in April and May (Bureau of Reclamation, 2015). Studies have found a seasonality shift evident in the historic gage record (Sterle, Singletary, and Pohll, 2017; Sterle, Hatcheet, Singletary, and Pohll, 2019), while future projections in the 2015 Truckee Basin Study did not reveal large shifts in the peak runoff timing until the 2070s (Figure 5). These future projections also show a steady decreasing trend in the monthly peak runoff volume from the 1990s into the future (Figure 5) (Bureau of Reclamation, 2015).

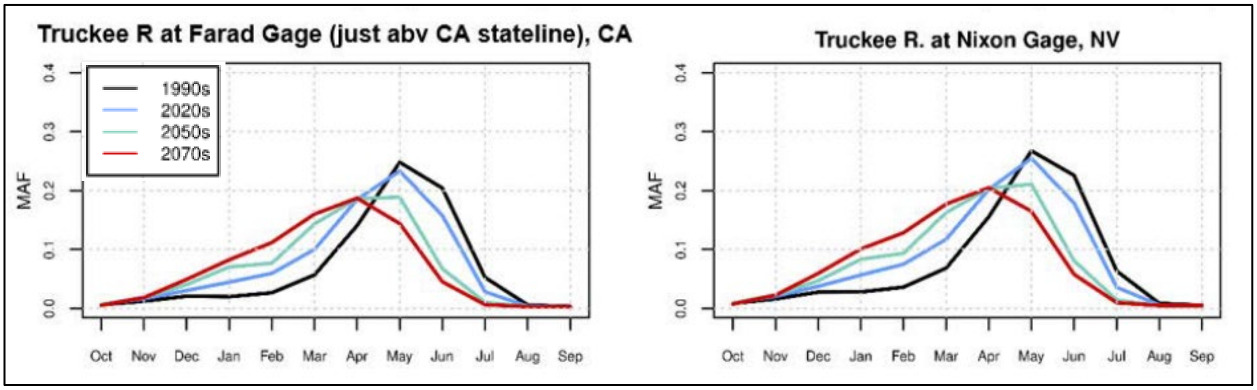


Figure 5.—Monthly mean flows for the Truckee River at Farad Gage and Truckee River at Nixon Gage. Mean flows were generated into the future using the CMIP5 climate change downscaling routed through a Variable Infiltration Capacity model. Monthly volumes are shown in million acre-feet (MAF) (Bureau of Reclamation, 2021d).

Seasonality shifts can complicate the ability of existing reservoirs to refill and the ability of managers to satisfy water demands. Climate change is projected to shift the peak runoff to earlier in the year, when reservoir storages are constrained by flood management rules that specify how much and when storage must be available to capture inflow from anticipated winter floods. This condition would force dam operators to forego capturing runoff that could help refill reservoirs and replenish stored supplies, resulting in lower stored water availability through the high-demand summer months and less carryover for drought periods.

Warmer temperatures and seasonality could also alter the timing of the breeding patterns of aquatic species in the Truckee River (Bureau of Reclamation, 2015). High, cold, turbid snowmelt-derived runoff triggers the spawning season of the LCT and Cui-ui (U.S. Fish and Wildlife Service, 2003). Earlier runoff may shift the natural timing of the spawning season. Further, LCT fingerlings and fry are sensitive to water temperature and are only viable in water temperatures below 20.2 degrees Celsius (Vigg and Kock, 1980). Lower summer flows and warmer stream temperatures could add further stress to the threatened and endangered fish species. Currently, the PLPT manages water rights specifically to support threatened and endangered fish species propagation and recovery. Overcoming the shifts in natural runoff timing and increased temperatures would likely require larger volumes of water to be stored in reservoirs to maintain environmental flows. However, regulatory and operational conditions may constrain the water managers' ability to maintain suitable conditions for fish species under climate change.

Water Demand

Climatic changes, along with the projected increase in regional population and socio-economic changes, would increase and alter the timing of demand, placing further stress on water resources within the Truckee Basin. Although the basin is fully appropriated, on average, water users demand and divert less water than allocated in their water rights. As such, the 2015 Truckee Basin Study examined how water demands might increase and shift between uses and estimated the date at which water users reach their full use of water rights (Bureau of Reclamation, 2015).

The 2015 Truckee Basin Study examined future demands under an Existing Trends storyline with a slow regional economy as well as demands under a Robust Growth storyline. Both storylines indicate a significant increase in water demands over the Baseline; however, due to the highly planned and regulated nature of water rights in the Truckee Basin, by 2100, total annual water demand in the basin only differs between the storylines by about 25,000 acre-feet (Figure 6). Importantly, water user communities reach their full use of water rights sooner under the Robust Economy storyline than under the Existing Trends storyline.

Under the Robust Economy storyline, the Truckee Basin is expected to experience an overall increase in annual water demands of 95,754 acre-feet over baseline, a 26% increase over current demands (Bureau of Reclamation, 2015) (Figure 6). Population growth in urban areas and industrial expansion in Nevada drive the increase in demand. Relatedly, the urban expansion is projected to absorb agricultural lands in Truckee Meadows, leading to a projected overall decrease in agricultural water demands.

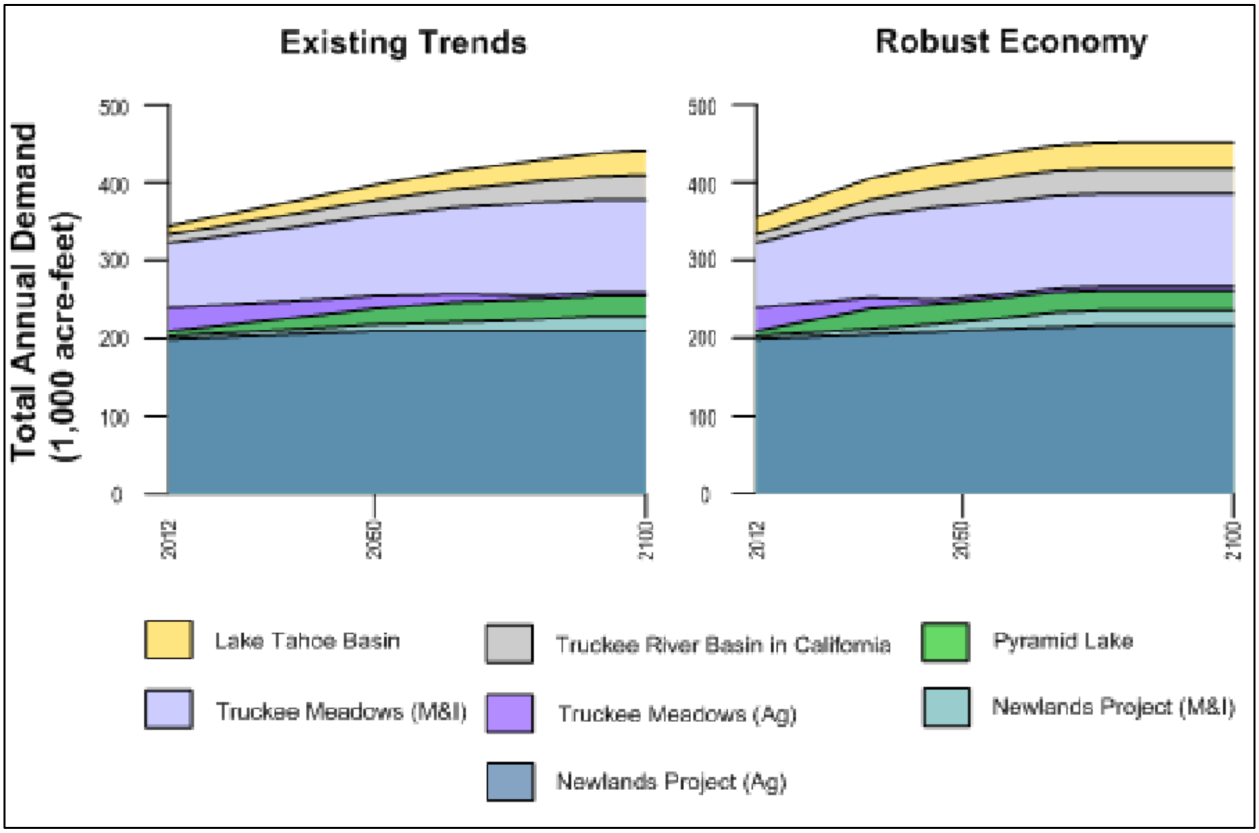


Figure 6.—Projected changes in water demand in the Truckee Basin due to population growth and socio-economic changes under different future storylines (Bureau of Reclamation, 2015).

Despite the projected decrease in the acreage of irrigated agriculture, projected climatic changes will increase crop water demands and irrigation requirements to meet those demands, not accounted for in Figure 6. Higher year-round temperatures would increase evapotranspiration rates and provide for longer summers and earlier spring conditions, lengthening the growing season and increasing irrigation demands. Natural runoff patterns currently match agricultural water demand schedules, where the highest demand for irrigation water occurs during the summer months when the rivers naturally peak. As the peak streamflow timing shifts to earlier in the season, the agricultural demand for water stored in reservoirs will increase. The net effect of climate change on irrigation demand is a greater reliance on water stored in reservoirs from earlier in the spring through the end of the summer or the beginning of the fall.

Similar to agricultural demands, climate change may also affect ecological water demands. Warmer temperatures could lead to earlier plant growth and greater water needs for wetlands, riparian areas, and meadows along the Truckee and Carson Rivers. These ecosystems support migratory birds that use the Lahontan Valley as a resting point along the Pacific Flyway.

Interannual Variability and Extremes

The 2021 SECURE Report to Congress quantifies historical and future hydrologic changes by comparing paleo-hydrology and climate change predictions to historical (gaged) hydrologic records. The report indicates that water supply variability has increased over the historic record and will continue to increase under future climatic changes (Bureau of Reclamation, 2021d). Droughts and flooding recorded in the last 120 years of the gage record are greater than any of the events in the 261-year paleo-record used in the report (1650–1910) (Bureau of Reclamation, 2021d), as well as a more recently developed 400 years of the paleo-record (1491–2003) (Harris and Adam, 2023). Further, in the 2021 West-Wide Climate and Hydrology Assessment report, the Truckee-Carson was the only basin that experienced more severe droughts and flooding in the gaged record compared to the paleo-record (Bureau of Reclamation, 2021d).

Of the three droughts noted in the SECURE Report paleo-hydrographs, the drought starting in 1841 was considered the largest drought event in the paleo-record, lasting 11 years and resulting in the largest cumulative deficit of average streamflow (Figure 7) (Bureau of Reclamation, 2021d). However, the 1923 to 1936 drought was more severe than any of the paleo-droughts in terms of both magnitude and duration (Bureau of Reclamation, 2021d). Using a different drought definition (Harris and Adam, 2023), it was also found that the 1917 to 1937 drought exceeded all droughts in the paleo-record in terms of a combination of length, magnitude, and severity. Of importance for water management and dam operations, during the 1923 to 1936 drought, Lake Tahoe's April 1st elevation was lower than during any of the paleo-drought periods (Bureau of Reclamation, 2021d).

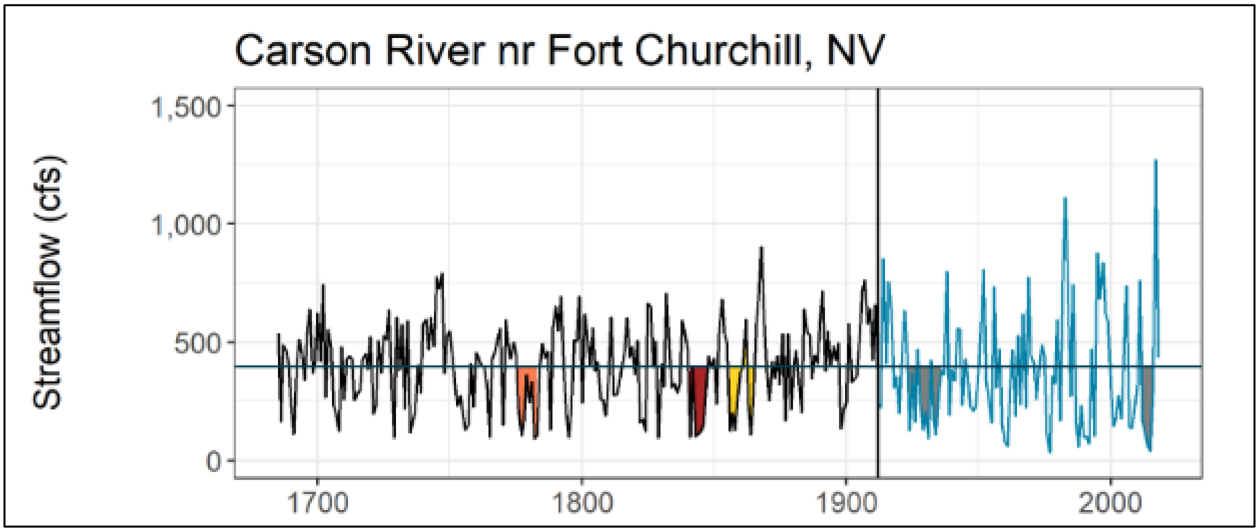


Figure 7.—Carson River flow at Fort Churchill constructed by appending the paleo-hydrographs (left of the black vertical line; shown in black) to the historical gage record (right of the black vertical line; shown in blue). The paleo-droughts are highlighted in orange, red, and yellow, whereas the historic droughts are highlighted in grey. The black horizontal line represents the long-term median streamflow calculated using the historical record (Bureau of Reclamation, 2021d).

The gage and paleo-records also indicate that the once multidecadal periods of higher-than-average Truckee streamflow have been decreasing in length over time, with a marked hydroclimatic shift centered around the 1850s (Harris and Adam, 2023). Since that time, consecutive years of high streamflow reduced in length from 8 years (1872–1879) to 6 years (1906–1911) and finally to 2 to 4 years since the 1930s (Harris and Adam, 2023).

The historical trends of increasing water supply variability are expected to increase further into the future under climate change (Bureau of Reclamation, 2021c; Bureau of Reclamation, 2015). The 2015 Truckee Basin Study indicates that annual precipitation, annual runoff, and seasonal runoff are all likely to increase in variability (Bureau of Reclamation, 2015).

Improved Data and Forecasting

In addition to an improved understanding of long-term climatic changes, there have also been significant advances in forecasting technology since 1985, warranting consideration of whether or not and how the Truckee Basin stakeholders can use these forecasts to improve water management. The establishment of the Natural Resources Conservation Service's (NRCS) automated snow telemetry (SNOTEL) network, improvements to integrate snow data into the forecasting process, and increased accuracy of hydrology models have resulted in significantly more accurate weather and runoff forecasts (Harpold, Sutcliffe, Clayton, Goodbody, and Vazquez, 2017; Gichamo and Tarboton, 2019). The California-Nevada River Forecast Center (CNRFC) produces deterministic flow and ensemble forecasts using the Hydrologic Ensemble Forecasting System (HEFS). These forecasts have significantly improved runoff estimates and extended lead times for runoff events in recent years. A complex, state-of-the-art operations model of the Truckee River and its reservoirs was developed in the early 2000s using RiverWare, providing USWM and the region with much-improved water accounting, operational, and forecasting tools.

Facility Upgrades

During the last 30 years, there have been several important flood-related changes within the Truckee Basin that are not considered in the 1985 WCM. Reclamation has implemented multiple facility improvements, including the Stampede Reservoir Safety of Dams Project, which recently raised Stampede's crest by 11.5 feet to increase its capacity to safely manage floodwaters. Reclamation also recently added a parapet wall to the crest of Prosser, which decreases the chance of overtopping in an extreme flood event.

The creation of the TRFMA in 2011 has also improved the river system through several projects designed to mitigate flooding on the Truckee River through Reno and Sparks, including the replacement of the Virginia Street Bridge, which was constructed to allow a greater conveyance of flood waters, removal and/or replacement of old rock and rubble agricultural diversion dams, and the realignment of the North Truckee Drain in Sparks (TRFMA, Flood Project Elements along the Truckee River Past, Present, Future, 2023). These recent flood risk management improvements avert impacts to the Reno and Sparks metropolitan area until significantly higher river flows are reached. Nonetheless, the WCM still constrains release thresholds through downtown Reno based on the physical system that existed in the 1980s, without consideration of all the upgrades that have occurred since that time.

Changes in Rules Governing Operations

The Truckee River Operating Agreement (TROA) is currently the controlling operating agreement within the Truckee Basin. TROA was signed in 2008 and implemented in December 2015, 30 years after the enactment of the 1985 WCM. TROA was required by Public Law 101-618 to settle numerous litigation cases, satisfy all dam safety and flood requirements, enhance water management for threatened and endangered fish species, determine the allocation of California and Nevada's water rights, and create a flexible operating criterion that allows for enhanced water management (Public Law 101-618, 1990).

One of the main tenets of TROA is to increase the operational flexibility of the Truckee River system. The increased flexibility allows for more efficient coordination to meet the TROA parties' water management goals. TROA parties are allowed to store credit water in the Truckee Reservoirs; this is Truckee River water to which a TROA party is entitled but chooses not to divert from the river. The storage of credit water allows the parties to optimize the timing of when they use their water versus using the water only when it is available (TROA - Truckee River Operating Agreement, 2008). Additionally, the parties are allowed to move water between Truckee River reservoirs through a variety of accounting transactions known as trades and exchanges. Exchanges provide the TROA Administrator with the flexibility to try to meet multiple parties' objectives. For example, CA-DWR is responsible for maintaining fish flows below Prosser Reservoir. If a TROA party is releasing their water from Stampede, an exchange can change the release of water from Stampede to Prosser to meet both parties' objectives. Trades of water can occur between two TROA parties that may want to change the location of their water storage without a physical transfer of water (Bureau of Reclamation, 2021c).

WMOP – Catalyzing Change Through Collaboration

The 1985 WCM was an innovative water management tool that implemented semi-flexible guide curves. However, conditions in the Truckee Basin have substantially changed in recent decades. Numerous Federal, State, Tribal, and local agencies have collaboratively developed a new flexible operating system and put forth an enormous effort to increase the Truckee River flood capacity to better protect people and property. Additionally, meteorological and river runoff forecasts have substantially improved since 1985. The current WCM was not designed to integrate the type and extent of changes that have taken place in the Truckee Basin, making it antiquated. More recently, water managers have been looking for regulation criteria that routinely adjust for improving technology, such as runoff forecasting.

The 2015 Truckee Basin Study identified the modification of the WCM as one strategy to adapt to climate change while balancing water supply benefits with flood risks (Bureau of Reclamation, 2015). The study evaluated this option by considering an upper bound of potential gains in the water supply that would result from fully removing all flood management requirements from Truckee River reservoirs. The preliminary analysis found that removing or relaxing the guide curves mitigated some seasonality shifts by capturing runoff when it was most available and releasing it as needed. Following the recommendations of the 2015 Truckee Basin Study, the WMOP brought together key stakeholders to further investigate the potential to update the 1985 WCM.

The parties involved in the 2015 Truckee Basin Study and TROA best understand the basin's varying hydrology, water demands, and need for environmental flows and flood risk management. Through this understanding, they recognize the urgent need to continue to work together to enhance water management in the basin. The development of TROA greatly improved operations, leading to a more resilient water supply that allows TROA parties to meet their operational objectives more frequently—especially during periods of drought (TMWA, 2020). With the predicted changes in hydrologic conditions and general improvements in forecasting, the basin's stakeholders recognized the need to review the current WCM to determine if there are ways to apply the best available science, enhance operation modeling, and improve understanding of the current system to identify paths to modernize the WCM. To do so, a group of TROA parties, jointly called the Technical Team (Table 4), joined forces in a cost-share agreement supported by Reclamation under the WaterSMART Program to develop a preferred WCM update solution. As stated in the WMOP MOA:

> "[The purpose of the] Truckee Basin Water Management Options Pilot Study is to develop flexible flood risk reduction criteria without increasing downstream flood risk. The study will evaluate Forecast Informed Reservoir Operations, flexible guide curves, and changes to downstream regulation goals. This study will then be documented in a Viability Assessment document and provided to the United States Army Corps of Engineers for a subsequent update to the Water Control Manual" (Bureau of Reclamation, 2020).

The Technical Team also invited a group of "Key Stakeholders" to participate in some WMOP activities (Table 4). When any member of the Key Stakeholders participated in a WMOP activity (e.g., workshops, meetings, decisions, etc.), this report uses the term "Key Stakeholders."

Table 4.—Key Stakeholders Comprised of the Technical Team (Yellow Shading) and Additional Key Stakeholders That Participated in WMOP Workshops and Meetings

Group / Agency	Expertise in the Truckee Basin
Bureau of Reclamation (Reclamation)	Owners and operators of numerous Federal projects in the Truckee Basin, including the active Truckee River flood control reservoirs (Prosser, Stampede, and Boca)
Truckee Meadows Water Authority (TMWA)	Water purveyors for the Truckee Meadows, including the North Valleys area (North of Reno); owners and operators of Donner and Independence Reservoirs
TROA Administrator / U.S. District Court Water Master (USWM)	Administrator of TROA and responsible party for the administration and operations of the Orr Ditch Decree; determines the day-to-day storage, release, and accounting for all surface water rights in the Truckee Basin
California Department of Water Resources (CA-DWR)	TROA party responsible for managing California's portion of water for the benefit of municipal and industrial needs, environmental flows, and recreational purposes
Pyramid Lake Paiute Tribe (PLPT)	Managers of numerous surface water rights for the benefit of agricultural irrigation and instream flow rights to enhance the protection and propagation and recovery of threatened and endangered fish species
NOAA California - Nevada River Forecast Center (CNRFC)	Developer of runoff forecasts for the Truckee River system
Nevada Division of Water Resources (NV-DWR)	TROA party responsible for the managing Nevada Water Rights
Truckee River Flood Management Authority (TRFMA)	Authority who manages and oversees the Truckee River Flood Management Project, which aims to reduce flood damages, safeguard the community, and enhance resiliency with the Truckee Meadows
U.S. Army Corps of Engineers (USACE)	Regulatory authority over the Truckee River flood management, including the WCM
Washoe County Water Conservation District	Operators and co-owners of Boca Dam

Meeting the objectives of the WMOP depended on open, consistent communication and effective collaboration. The Key Stakeholders brought a range of expertise and experience to the WMOP, from on-the-ground reservoir management and regulatory oversight to technical modeling to Tribal and municipal water and flood risk management planning. These parties met biweekly to discuss project status updates, coordination/planning of current and upcoming activities, review of assigned project tasks, and review of the risk register, with additional meetings scheduled as needed. In addition, multiple workshops were held throughout the WMOP to bring the Key Stakeholders together in one setting, with sufficient time allowed to look in depth at the technical work performed, generate active discussions, and come to a consensus regarding major decisions:

- **Action Alternatives Development Workshop Series (2021)**.—The process for developing the Action Alternatives involved four virtual workshops during which the Key Stakeholders documented current conditions and management, identified problems and opportunities and actions for addressing them, created screening criteria based on objectives and constraints for flood risk management, screened potential actions, and combined actions into alternatives.

- **Modeling Workshop (June 2022)**.—Workshop for Key Stakeholders to collaborate on the modeling efforts related to the multi-objective evolutionary algorithm (MOEA), revised guide curve, and flood flows and inundation.

- **Planning Model Review Sessions (December 2022 and January 2023)**.—Technical Team meetings to review the RiverWare model used for water management planning in the Truckee Basin and to make necessary changes.

- **Evaluation Framework Sessions (February 2023)**.—Technical Team meetings to develop a framework for evaluating the MOEA scenarios and Action Alternatives.

- **Preferred Operational Scenario Selection Workshop No. 1 (March 2023)**.—Workshop for the Key Stakeholders to collaboratively come to a consensus on the Best-Performing MOEA, Preferred Operational Scenario, and recommended flood flow target at Reno.

- **Preferred Operational Scenario Selection Workshop No. 2 (June 2023)**.—Workshop for the Key Stakeholders to collaboratively come to a consensus on the *new* Preferred Best-Performing MOEA Scenario, *new* Preferred Operational Scenario, and the recommended flood flow target at Reno after correcting a coding error in the MOEA detected after the Preferred Operational Scenario Selection Workshop No. 1.

In alignment with these workshops, assessing a potential WCM update entailed multiple coordinated phases led by the Technical Team and their contractors. Early efforts focused on identifying the objectives, constraints, and desired outcomes of the project, which were then used to develop the Action Alternatives to study as part of the WMOP. Getting to a position to evaluate these Action Alternatives required a substantial effort to build the technical foundation through dataset development and model updates, calibration, and validation. Having all these pieces in place allowed for analyzing and evaluating the developed alternatives. Lastly, the Key Stakeholders came together to select a Preferred Operational Scenario to the 1985 WCM and documented the process in this VA and associated reports. This VA describes each of these project phases with additional detail provided in the appendices.

Development of Alternative Operational Scenarios

As part of the WMOP, Reclamation documented the development of alternative scenarios in the "Alternative Operational Scenarios Development Report" (Appendix A), and Precision Water Resources Engineering further described the modeling of these alternatives in the "Action and Alternative Operational Scenario Modelling in the WMOP" report (Appendix M). An abridgment of the analyses, results, and conclusions follow.

The Key Stakeholders participated in a series of four workshops in 2021 to formulate a plan for developing a set of Action Alternatives to continued operations under the No Action Alternative (Bureau of Reclamation, 2021a). This process included:

1. Identifying Problems and Opportunities
2. Identifying Study Constraints and Objectives
3. Defining Actions
4. Defining Action Alternative Operational Scenarios

During the plan formulation, the Key Stakeholders determined four problems with the regulation criteria of the WCM that represent "opportunities" for improving water management in the Truckee Basin (Table 5).

Table 5.—Summary of Problems and Opportunities Identified in the Plan Formulation (Appendix A)

Summary of Problems and Opportunities Identified		
Reservoir Refill	**Problem Description**	The current guide curves miss opportunities for storing inflow.
	Opportunity	Under updated guide curves, inflow that would have been passed under current guide curves to maintain flood space in the winter could be stored for later use.
Fall Drawdown	**Problem Description**	The current timing of drawdown, which has reservoirs fully drawn down by November 1st, can require water to be released from reservoirs that is not demanded downstream. This problem can also make it difficult to meet instream flow requirements resulting in biological impacts on factors such as water temperature in the Truckee River or exposing fish species in the river.
	Opportunity	Under updated guide curves, water that would have been released to maintain flood space requirements could instead be conserved for later use when it is demanded.
Normal Flood Operations	**Problem Description**	The set flood operations target flow at the Reno Gage of 6,000 cfs may no longer be the reasonable threshold that should govern operations.

Summary of Problems and Opportunities Identified		
	Opportunity	If the flow target could be increased, flood space could be evacuated more efficiently, helping minimize risk of downstream flooding.
Little Truckee Flood Space	**Problem Description**	The WCM has not been updated to account for 2017 improvements to Stampede.
	Opportunity	Leveraging these improvements, reproportioning the flood space between the Boca and Stampede Reservoirs could benefit water supply or help minimize risk of downstream flooding.

The Key Stakeholders also determined the objectives and constraints of the WMOP. The objectives fall under a set of overarching goals for the WMOP; namely, the Preferred Operational Scenario should:

- Maximize water supply,
- Reduce flood risk, and
- Enhance environmental flows in the Truckee River.

The Key Stakeholders refined these general goals into quantifiable and non-quantifiable objectives that allow for a relative comparison between alternatives (Table 6). The quantifiable objectives can be calculated from model results for a given alternative. Non-quantifiable objectives represent those that are more subjective and that could not be directly calculated from the model results of a given alternative. Both sets of objectives played a significant role in the process of selecting a Preferred Operational Scenario.

Table 6.—Objectives Defined for the WMOP During the Plan Formulation (Appendix A)

Objective Description
Quantifiable Objectives
Maximize the number of Floriston Rate days or the amount of Floriston Rate water in storage.
Maximize flexibility for timing of drawdown under flood control measures.
Maximize flexibility for refill in reservoirs up to the maximum conservation elevations.
Improve environmental instream flows downstream from reservoirs.
Minimize use of surcharge space above the spillway.
Reduce risk of damage from flooding downstream.
Optimize storage to satisfy water demands through the year.
Non-Quantifiable Objectives
Bring the WCM up to date with current technologies and capabilities and allow for flexibility for future improvements in data availability/forecasting of future climate conditions.
Allow flexibility for varying future operating conditions of Martis.
Allow flexibility for future increases in flood thresholds because of flood improvements downstream.
Develop methodologies that are implementable in an operational mode.

To further restrict the development of alternatives, the Key Stakeholders identified 10 study constraints that any action must meet for consideration in the range of alternatives (Table 7).

Table 7.—Constraints Defined for the WMOP During the Plan Formulation (Appendix A)

Constraint Description
Do not increase damage from flooding as a result of changed reservoir operations.
Comply with requirements of TROA and other governing agreements.
Can be addressed through updates to the WCM.
Do not change the total among authorized flood control space (e.g., 30,000 acre-feet between Boca and Stampede).
Do not increase probability of dam failure from overtopping or internal failure.
Must be technical feasible to implement.
Must not decrease the number of projected Floriston Rate days compared with continuing management under the No Action Alternative.
Do not negatively impact the threatened and endangered fish species.
Do not change water rights.
Must be within the scope of this pilot study as defined in the WMOP MOA.

With these constraints and objectives in mind, the Key Stakeholders identified actions to address each of the identified problems and opportunities (Table 8).

Table 8.—Actions Defined for Each Problem Identified in the Plan Formulation

Problem	Action 1	Action 2
Reservoir Refill	Revised Guide Curve	"By a Model" Method
Fall Drawdown	Revised Guide Curve	"By a Model" Method
Normal Flood Operations	Updated Target Flow	Updated Target Location
Little Truckee Flood Space	Reproportion	–

The actions to address problems with the WCM's refill and drawdown requirements entail 1) revising the guide curves based on updated historical data and methodology and 2) using runoff forecasting technology to determine the required flood space. For the second action, the Technical Team devised the By-a-Model (BAM) method that employs forecasting technology as a component of Forecast-Informed Reservoir Operations (FIRO), described in more detail in the "Forecast-Informed Flood Space Requirements: By-a-Model Method" section of this VA. FIRO is a water management strategy that employs forecasts to inform reservoir operations (National Integrated Drought Information System, National Oceanic and Atmospheric Administration, No date).

The Key Stakeholders also identified two actions to address problems with the current Reno flood flow target for normal flood operations. First, the Updated Target Flow action sought to identify benefits associated with increasing the downstream flood target to greater than 6,000 cfs at the Reno Gage. Secondly, the Technical Team explored whether operating reservoirs during floods on both the Reno Gage *and* the downstream Vista Gage provided benefits to reducing downstream flood damages. During a storm event, reservoir managers will dynamically operate dams to meet the limiting threshold, depending on where the water is coming from. For example, if the precipitation is occurring in the upstream portion of the basin, the threshold at the Reno Gage may provide the appropriate basis for reservoir management to avoid flooding impacts downstream. However, if the precipitation is occurring primarily downstream of Reno, the threshold at the Vista Gage would be the limiting threshold for releases from reservoirs. Further, ongoing and planned flood risk management projects near Reno and Vista will retain more water instream, increasing flood flows downstream and potentially supporting the inclusion of a downstream flood flow target. Due to the lack of forecasting data in the lower river, this action first evaluated a flood flow target at the Vista Gage. Of note, implementing this management action would place a heavier emphasis on modeling to account for the two different flow threshold locations and the tributaries feeding into each.

Lastly, one action was identified for the Little Truckee Flood Space problem. Boca and Stampede Reservoirs on the Little Truckee River operate as a unit and in a series 7 miles apart. The current WCM regulation criterion reserves roughly 27% of the total Little Truckee Flood Space in Boca Reservoir and the remaining 73% in Stampede Reservoir. The reproportion action explores the benefits to the objectives achieved from adjusting the flood space allocation percentages between Boca and Stampede Reservoirs.

With these actions identified, the Key Stakeholders initially developed four Alternative Operational Scenarios to the WCM comprised of different combinations of actions to address the identified problems, termed, "Action Alternatives." An additional alternative was added after the first workshop to select a Preferred Operational Scenario (March 2023), totaling five Action Alternatives and the No Action Alternative (alternatives). The alternatives combine various approaches for addressing the problems with reservoir refill, fall drawdown, normal flood operations, and Little Truckee flood space allocation (Table 9). Alternatives 2 and 3 represent the most comprehensive FIRO approach identified by the Technical Team, while Alternatives 5 and 6 represent variations on Alternative 2 and use the BAM method to a lesser degree. Alternative 5 restricts the use of the BAM method to spring refill, while Alternative 6 restricts encroachment into flood space using the BAM method, based on the forecasted water year runoff volume. Alternative 4 would update the WCM guide curves without implementing any new FIRO components. These alternatives, as described subsequently, are defined in more detail in the *Alternative Operational Scenarios Development Report* (Bureau of Reclamation, 2021a) (Appendix A).

Table 9.—Overview of the Actions Included in Each of the Alternative Operational Scenarios (Appendix A)

	Alternative Operational Scenarios		**Problems/Opportunities**			
	Alternative (No.: Description)	**Short Name**	**Reservoir Refill**	**Fall Drawdown**	**Food Flow Target (Location: Flow)**	**Little Truckee Flood Space**
	1: No Action	Baseline	Current Guide Curve	Current Guide Curve	Reno: 6,000 cfs	Current Proportion
Action Alternatives	2: By-a-Model All Seasons	BAM:All	By-a-Model Method	By-a-Model Method	Reno: 6,500 cfs	Reproportion
	3: By-a-Model All Seasons $^{+}$Vista Flood Criteria	BAM $^{+}$Vista	By-a-Model Method	By-a-Model Method	Reno: 6,500 cfs Vista: 8,500 cfs	Reproportion
	4: Revised Guide Curves	dSRDs	Revised Guide Curve	Revised Guide Curve	Reno: 6,500 cfs	Reproportion
	5: By-a-Model in Spring	BAM:Spring	By-a-Model Method	Revised Guide Curve	Reno: 6,500 cfs	Reproportion
	6: Variable By-a-Model Space	BAM:Var	Variable By-a-Model Space	Variable By-a-Model Space	Reno: 6,500 cfs	Reproportion

Note: Each Action Alternative is a combination of different actions in response to the identified problems and opportunities.

1: No Action (Baseline)

The No Action Alternative (Baseline) would carry forward current management in the 1985 WCM. Fall drawdown, winter flood operations, and spring refill would be governed by the WCM guide curves and snowmelt parameters. Downstream flows would continue to be regulated to 6,000 cfs as measured at the Reno Gage, insofar as possible. Flood space allocations between the reservoirs in the basin would remain the same. This would include the 30,000 acre-feet joint flood space allocation between Boca and Stampede reservoirs, at least 8,000 acre-feet of which must be reserved in Boca Reservoir. Martis Creek Reservoir would continue to be authorized to store water for flood control once flows at the Reno Gage reached 14,000 cfs as described in the WCM; however, Martis Creek dam will not be operated again until dam safety concerns are addressed. Until then, Martis Creek Reservoir will continue to provide only passive or incidental flood control. Regarding ramping rates, releases from Truckee Basin reservoirs would continue to be prohibited from increasing or decreasing by more than 1,000 cfs per hour.

2: By-a-Model All Seasons (BAM:All)

Alternative 2 is comprised of the actions that would best meet the objectives related to satisfying water demands throughout the year and increasing flexibility to account for changing precipitation and runoff conditions. Fall drawdown, winter flood operations, and spring refill would all be governed by a dynamic FIRO model, the BAM method, to determine flood space. The downstream regulation goal at the Reno Gage would be updated to a threshold of 6,500 cfs. This alternative would also reproportion the joint flood space distribution between Boca and Stampede reservoirs. Providing more flexibility to account for changing conditions, such as the 2017 improvements to Stampede Dam that increased the surcharge space in the reservoir.

3: By-a-Model All Seasons $^{+}$Vista Flood Criteria (BAM $^{+}$Vista)

Alternative 3 was created by combining the actions that would provide the most flexibility for dynamic management based on the conditions occurring at the time. This alternative includes actions that emphasize real-time modeling based on forecasted conditions. Under the BAM $^{+}$Vista Alternative, fall drawdown, winter flood operations, and spring refill would be managed using the BAM method, as operated in the BAM:All Alternative. In addition to updating the flow threshold at the Reno Gage to 6,500 cfs, the BAM $^{+}$Vista Alternative also operates to a flood flow target of 8,500 cfs at the Vista Gage. Like BAM:All, the BAM $^{+}$Vista Alternative would also reproportion the joint flood space distribution between Boca and Stampede Reservoirs.

4: Revised Guide Curves (dSRDs)

Alternative 4 was created by combining the actions that focus on the objective of reducing flooding risk downstream and that are the easiest to implement. Under Alternative 4, reservoir refill and drawdown would be governed by a new, expanded set of revised dSRDs based on a range of scenarios or periods. The revised dSRDs are based on historical unregulated flows over the Reno flood flow target and allow for dynamically operating at different refill curves based on the remaining water year forecasted runoff volume (snowmelt parameter). The downstream regulation goal at the Reno Gage would be updated to a threshold of 6,500 cfs. This alternative would also reproportion the joint flood space distribution between Boca and Stampede Reservoirs.

5: By-a-Model in Spring (BAM:Spring)

Alternative 5 was developed by combining the actions that robustly address the most objectives, rather than trying to optimize one or two objectives. This alternative includes a hybrid approach to reservoir management, using the BAM method to determine required flood space during spring refill and the revised dSRDs during fall drawdown and winter flood operations. The downstream regulation goal at the Reno Gage would be updated to a threshold of 6,500 cfs. The BAM:Spring Alternative would also update the joint flood space distribution between Boca and Stampede Reservoirs.

6: Variable By-a-Model Space (BAM:Var)

Alternative 6 was added to the study after the first workshop to select a Preferred Operational Scenario (March 2023) and address concerns of large fluctuations of reservoir releases required by some alternatives that were discovered. The Technical Team developed this alternative to maximize the water supply benefits of the BAM:All Alternative while operating more conservatively in large snowpack years, resulting in less flashiness.

To accomplish these objectives, the percentage of flood space determined using the BAM method is variable, dependent on the median forecasted water year Farad natural flow volume (WY FNF) (California Nevada River Forecast Center, National Oceanic and Atmospheric Administration, 2023a). Based on the model result using the historical dataset, when water year Farad natural flow is greater than 600 thousand acre-feet (kAF), all reservoirs fill (refer to Appendix O for more details). As such, with forecasts of 600 kAF or more, the BAM:Var Alternative conservatively maintains 100% of the revised dSRDs' flood storage (Figure 8). When the forecasted volume is 300 kAF or less, the BAM:Var Alternative maintains 30%[2] of the revised dSRDs' required flood space and operates the remaining space using the BAM method. Between 300 and 600K, the reserved percentage of the revised guide curve flood space varies linearly between 30 and 100.

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[2] It is important to note that, regardless of the magnitude of the water year Farad natural flow forecast, at no point will the percentage of the revised dSRD fall below the percentage used in the BAM:All Alternative.

To minimize flashiness and daily changes in flood space requirements due to day-to-day fluctuations observed in the water year Farad natural flow forecasts, the Technical Team opted to limit the percentage of the revised guide curve flood space to:

- Change by at most 2% per day, and
- Be based upon the forecasted water year Farad natural flow volume rounded to the nearest 50,000 acre-feet.

To illustrate operations under this alternative, Figure 8 shows the percentage and volume of the revised dSRDs' flood space to exclusively reserve during water year 2023 (y-axes), based on the median water year Farad natural flow forecasts from the CNRFC (blue line). Due to low water year Farad natural flow forecasts early in the water year, the BAM:Var Alternative only reserves 30% of the revised guide curve in the fall and operates the remainder of the flood space above the orange line using the BAM method). As the flood season progresses and the water year Farad natural flow increases with increasing snowfall, BAM:Var operates an increasingly smaller portion of the flood space BAM, and eventually reserves 100% of the revised dSRDs' flood space from the beginning of March onward.

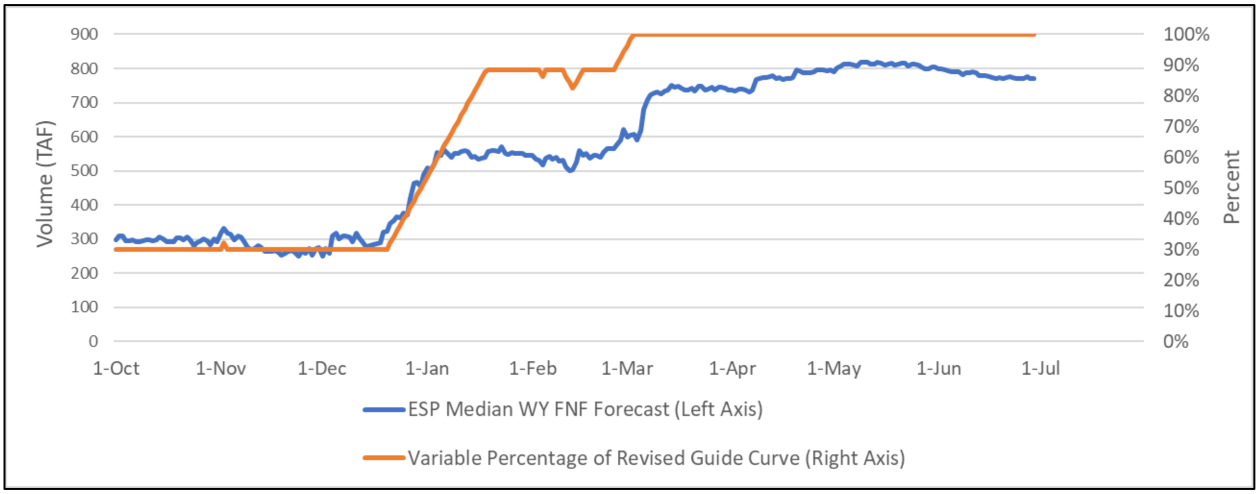

Figure 8.—Example of the Percentage of the Revised Guide Curve flood space reserved in the Variable By-a-Model Space (BAM:Var) Alternative, based on the median forecasted water year Farad natural flow volume (WY FNF). The orange line represents the minimum required flood space in the BAM:Var Alternative, with no floods in the forecast, as a percentage of basin flood space (right axis). The BAM method uses stream flow forecasts to determine if additional storage is required above orange line.

Building the Technical Foundation

The WMOP benefited from a strong foundation of data, models, and technical capacity to support water management initiatives in the Truckee Basin; however, assessing the identified alternatives and achieving the objectives of this innovative WMOP required the development of additional datasets, updating and verifying models, and conducting multiple technical studies. All the technical information, data, models, analyses, and conclusions of the WMOP underwent a thorough, methodological review for accuracy and validity, as described in the Technical Sufficiency Review Plan of the MOA (Bureau of Reclamation, 2020).

While the technical studies were designed to support the larger WMOP, they also benefit water management and planning in the Truckee Basin, more generally. For example, the WMOP developed a new hourly RiverWare model and hourly discharge data to assess the flood impacts of the alternatives. This work, in combination with updating the seasonal flood frequency curves and completing a channel capacity analysis, added to the overall ability to manage and plan for floods in the basin. The WMOP also took advantage of an updated daily Planning Model dataset and produced an ensemble of hindcasts based on historical conditions, as well as scaled hindcasts to simulate larger floods.

This VA provides an overview of the technical work completed for the WMOP, while the appendices (available as separate documents) provide detailed, in-depth information on the developed data, models, and studies undertaken as part of the WMOP or directly related to it:

- Appendix A - Alternative Operational Scenarios Development Report
- Appendix B - TROA Planning Model Verification
- Appendix C - Truckee River Basin Historical Data Development Methodologies: Water Years 2001-2021
- Appendix D - Truckee River Basin Historical Data Development Methodologies: Water Years 1986-2000
- Appendix E - Truckee River Basin Historical Hourly Data Development Methodologies: Water Years 1986-2021
- Appendix F - WMOP Truckee River Hourly River Model Time Lag Routing
- Appendix G - Truckee River Hourly Model Verification for WMOP
- Appendix H - Truckee Basin Water Management Options Pilot Study—Rain Flood and Snowmelt Flood Frequency Curve Update

- Appendix I - Truckee Basin Water Management Options Pilot Study—Channel Capacity Analysis
- Appendix J - Truckee River Flood Management Authority and National Weather Service Memorandums and Presentation
- Appendix K - Revised Guide Curve Modeling, Improving Current Guide Curves with dSRD Approach
- Appendix L - Inflow Uncertainty Analysis
- Appendix M - Action and Alternative Operational Scenario Modelling in the WMOP
- Appendix N - Multi-Objective Evolutionary Algorithm (MOEA) Tool Utilization and Development
- Appendix O - Preferred Operational Scenario Selection Process
- Appendix P - Preferred Operational Scenario Probable Maximum Flood Routings Analysis
- Appendix Q - Preferred Operational Scenario with Martis Creek Reservoir Operational Analysis

Planning Model Data Development and Verification

Truckee Basin stakeholders regularly use two related, but different, RiverWare models to help manage water in the basin—one designed for short-term operations and the other for long-term planning, both operating on a daily timestep. The USWM uses the forward- and backward-looking TROA Operations and Accounting RiverWare® Model (Accounting Model) to schedule reservoir releases and diversions in the Truckee and Carson Basins (Table 10). The backward-looking period allows the USWM to account for water diversions to ensure that releases and diversions meet TROA party and water right holder requests and schedules, while the forward-looking period allows for short-term planning and scheduling, for up to 15 months. Alternatively, Truckee Basin stakeholders regularly use the RiverWare TROA Planning Model (Planning Model) for planning studies, such as the WMOP, to develop long-term management practices in the Truckee and Carson Basins. While the Planning Model is very similar to the Accounting Model, the Planning Model operates exclusively in a forward-looking mode and simulates the system according to coded logic that captures the TROA operating criteria and water operation scheduling parameters provided by the TROA Parties. The Planning Model allows TROA parties to ask “what if” questions about the system by varying hydrology, demand, policy, or a TROA party’s schedule.

The existence of these models provided a significant leg-up to the WMOP, but taking advantage of these models to evaluate the developed alternatives required the following tasks, as described in this section:

- Verifying the Daily Planning Model results against the Accounting Model results,
- Updating the Daily Planning Model Dataset used to run the TROA Planning Model,
- Developing an Hourly Model Dataset, and
- Developing and validating an Hourly Model for the Truckee River.

Table 10.—Truckee Basin Planning and Accounting Models and Input Data Accessed for the WMOP

TROA Planning Model (Planning Model).—Forward-looking, daily time-step RiverWare model that simulates TROA operations in coded logic to ask "what if" questions for long-term planning.

TROA Operations and Accounting RiverWare® Model (Accounting Model).—Backward- and forward-looking, daily time-step RiverWare model used by the USWM to complete water right accounting, plan short-term reservoir operations, and aid TROA parties in short-term planning and scheduling.

Truckee River Hourly Model (Hourly Model).—Forward-looking, hourly time-step RiverWare model developed for the WMOP to simulate flood events and operations.

Daily Planning Model Dataset.—Historical dataset of daily inflows, demands, and other hydrologic data needed to run the Planning Model – updated as part of a projected related to the WMOP.

Hourly Model Dataset.—Historic dataset of hourly inflows, demands, and other hydrologic data needed to run the Hourly Model – developed as part of the WMOP.

Daily Planning Model Verification

As part of a project relevant to the WMOP, PWRE verified the TROA Planning Model and documented the results in the "TROA Planning Model Verification" report (Appendix B). Below is an abridgment of the analysis, results, and conclusions.

LBAO maintains and continuously updates the Planning Model, however, it has not been verified against observed operations since the TROA was implemented in 2015. The long-term Planning Model operates the system according to logic coded into the RiverWare platform that captures the requisite operating rules and criteria. On the other hand, the Accounting Model operations are requested by a TROA Party and scheduled in the model by the USWM, making it a more accurate representation of on-the-ground operations and observed conditions. The high-stakes decisions made leveraging the TROA Planning Model necessitated a thorough evaluation and verification effort of the model to support its use in the WMOP and other planning studies in the basin.

The verification study compared the six archived Accounting Models for each water year between 2016 and 2021 (observed data) to a Planning Model run performed in a forward-looking forecast mode within the same run period (simulated data). Each Planning Model was input with historical initialization conditions, water year hydrology (i.e., inflows to the Truckee Basin), and actual demands from the respective water year. The input hydrology used in the verification effort was developed as a part of the update to the daily Planning Model dataset (Appendix C).

Relevant model data was exported for quantitative and qualitative comparison of simulated and observed data for several key metrics in the Truckee Basin:

- Floriston Rate and Annual Volumes at the Farad Gage;
- Annual Flow Volumes for the Truckee River at Nixon, Nevada Gage;
- Truckee Canal Annual Diversion Volumes;
- End-of-year (EOY) storage volumes in Lake Tahoe, Doner Lake, Prosser Creek, Reservoir, Independence Lake, Stampede Reservoir, Boca Reservoir, Lahontan Reservoir, and Pyramid Lake; and
- Summary of Stakeholder (TROA Party) Volumes for each water year

Comparisons between the Accounting and Planning Models for each water year included several methods to evaluate the model's performance, including comparisons of annual volumes for different metrics between the two models, calculations of Nash-Sutcliffe efficiency (NSE), scores of time-series data, and comparison of end-of-year reservoir storages.

The American Society of Civil Engineers (ASCE) recommends the use of NSE to assess the overall fit of a hydrograph (McCuen et al, 2006). The NSE evaluates how well the observed versus simulated data points match the 1:1 line, indicating a perfect match. Equation 1 displays the NSE formula with the variable Y representing the dataset being evaluated. NSE is calculated as 1 minus the ratio of the error variance of the observed and simulated values. The NSE ranges from -∞ to 1, with 1 indicating a perfect match between the model results and the observed data. Typically, an NSE between 0 and 1 is viewed as an acceptable level of performance; however, a stricter criterion proposed by Moriasi et al. (2007) sets grading criteria for the NSE[3] (Table 11) (Moriasi et al., 2007). NSE and the associated grading criteria in Table 11 are used throughout the WMOP technical studies to evaluate how well-simulated data points match those observed.

Formula for Nash Sutcliffe Efficiency: Equation 1

$$NSE = 1 - \left[\frac{\sum_{I=1}^{n}\left(Y_i^{obs} - y_i^{sim}\right)^2}{\sum_{I=1}^{n}\left(Y_i^{obs} - y_i^{mean}\right)^2}\right]$$

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[3] Note, the paper *Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations* (Moriasi et al., 2007) is referenced throughout when making qualitative judgements on NSE scores.

Table 11.—Nash Sutcliffe Efficiency Grading Criteria (Moriasi et al., 2007)

NSE Score Range	Performance Description
0.75 – 1.00	Very Good
0.65 – 0.75	Good
0.50 – 0.65	Satisfactory
< 0.50	Unsatisfactory

The verification effort undertook an iterative approach to making improvements to the Planning Model using these comparison metrics. When comparisons yielded areas of the Planning Model that did not agree with the Accounting Model, the Planning Model was improved, primarily through changes to the model logic, then compared against the Accounting Model again. This iterative process occurred multiple times as a part of the verification effort to improve the performance of the Planning Model.

Overall, the verification effort identified areas of the model that verified well, along with some deviations between the simulated and observed data, as described below. Floriston Rate operations verified well between the two models in all years, whereas Operations in the Nixon Gage, Truckee Canal, and end-of-year reservoir storage volumes verified well in some years and not in others, as described below (Table 12).

Table 12.—NSE Scores of Daily Planning Model Metrics Compared to Daily Accounting Model Metrics by Water Year

Metrics	2016	2017	2018	2019	2020	2021	Legend
							Very Good
Floriston Rate	0.96	0.96	0.99	1.00	1.00	0.87	Good
Nixon Gage Flow	0.72	0.91	0.71	0.86	0.57	0.33	Satisfactory
Truckee Canal Diversions	0.25	0.63	0.74	-0.30	0.90	0.13	Unsatisfactory

Floriston Rate

Floriston Rate is one of the fundamental operational criteria in the Truckee Basin. Throughout the period of record, results of the Planning Models for annual Floriston Rate delivery volumes did not differ from that of the Accounting Models by more than 3%. Figure 9 demonstrates the similarity between the daily Floriston Rate volume recorded in the Accounting and Planning Models for water year 2021. Furthermore, NSE scores show “very good” scores for daily

Floriston Rate volumes for each year in the period of record (Table 12). Floriston Rate targets are well prescribed by TROA and are less subject to scheduling, contributing to the high NSE scores in this metric.

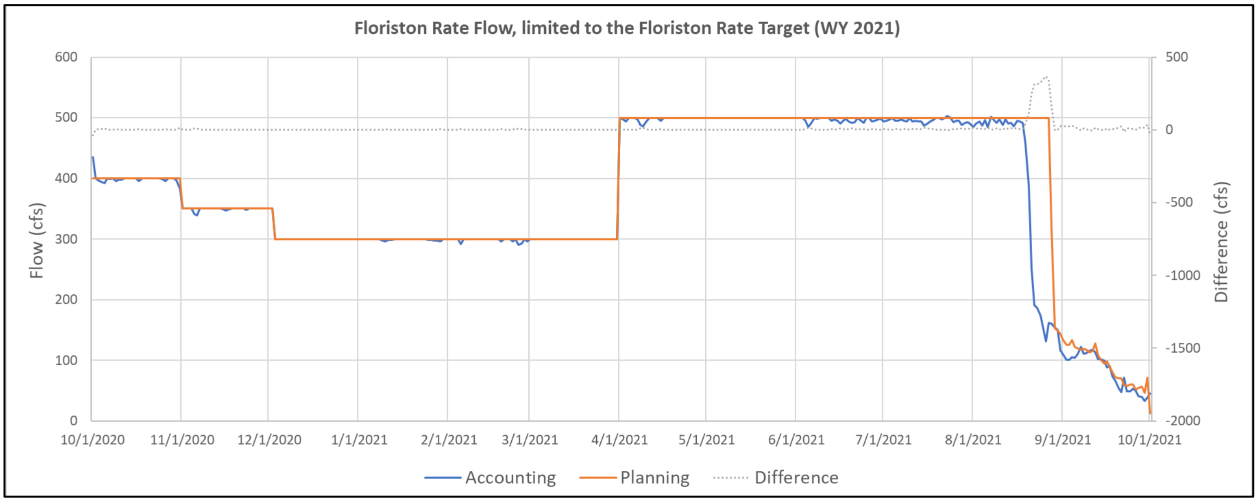

Figure 9.—Daily Floriston Rate flow (limited to the Floriston Rate Target) in the Accounting Model (blue) and Planning Model (orange) during water year 2021 (left axis), and the daily difference between the two models (dotted, right axis) (Appendix B).

Nixon Gage Flow and Annual Volume

Flow and annual delivery volumes for the Truckee River at Nixon Gage serve as important environmental flow criteria to assess the waters entering Pyramid Lake. Annual volumes at the Nixon Gage showed less than 4% differences for most years, but water years 2016 and 2021 showed more noticeable discrepancies in the annual volumes at Nixon. Time-series data resulted in “satisfactory” or better NSE scores for all water years except 2021 (Table 12, Figure 10). This largely stems from the Planning Model’s strict adherence to hitting flow targets at Nixon Gage defined by runoff forecasts and Stampede storage, whereas, Nixon flow targets are set and met more adaptively in practice, considering hydrologic, environmental (e.g., fish runs), and operational variability.

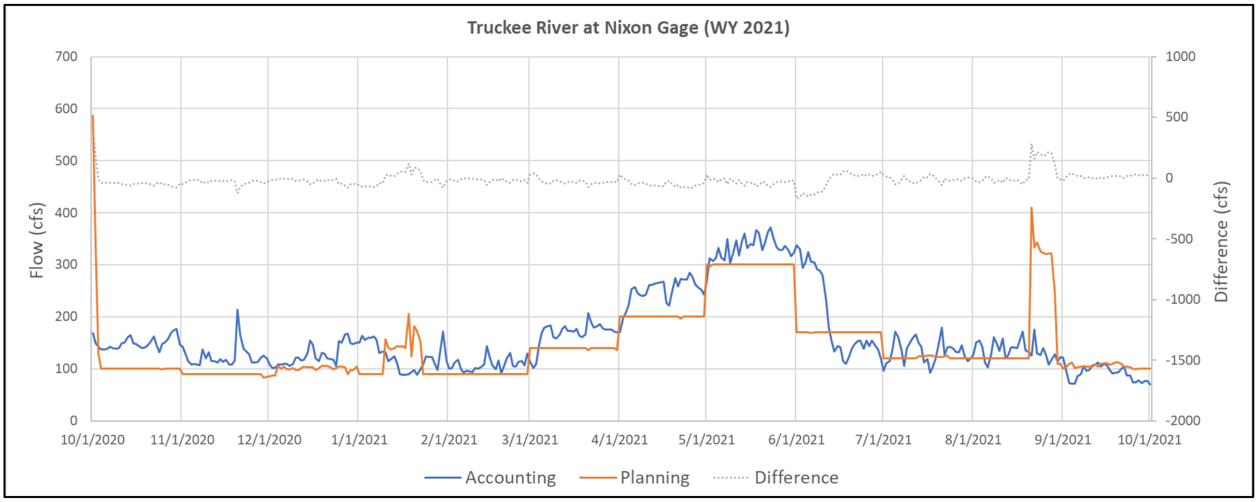

Figure 10.—Daily Truckee River flows at the Nixon Gage in the Accounting Model (blue) and Planning Model (orange) during water year 2021 (left axis) and the daily difference between the two models (dotted, right axis) (Appendix B).

Truckee Canal Diversion Rates

The Truckee Canal delivers water to Reclamation’s Newlands Project and diversion volume serves as an important criterion for meeting and accurately accounting for agricultural, wetland, and M&I demand and use. Operations in the Truckee Canal verified well in some years and not in others (Table 12). Years with poor verification performances were largely caused by the dependence of the Accounting Model’s canal operations on uncertain NRCS forecasts, while the Planning Model uses input hydrology, such that it has perfect knowledge of the forecast. In years with poor performance, 2016 and 2021, the Planning Model allowed much higher diversions, than that diverted historically (Figure 11).

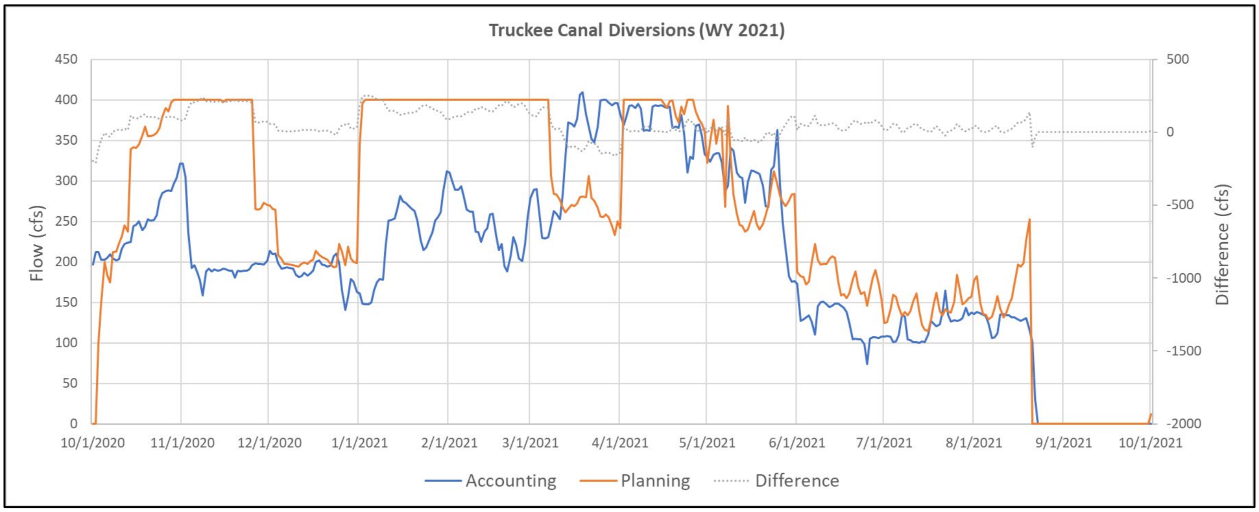

Figure 11.—Daily Truckee Canal Diversions in the Accounting Model (blue) and Planning Model (orange) during water year 2021 (left axis) and the daily difference between the two models (dotted, right axis) (Appendix B).

End-of-Year Reservoir Storage

Effective water resource management requires an accurate accounting of storage volumes in the Truckee Basin reservoirs. End-of-year storage values on reservoirs verified well, overall, but in some years, Boca Reservoir, Lahontan Reservoir, and Prosser Creek Reservoir showed deviations. One source of these deviations traces back to the deviations in the Truckee Canal and Nixon Gage flow, previously noted. For example, the discrepancy between the models on Prosser Creek Reservoir in water year 2016 relates to differences in demand for ecological flows, as reflected in the difference in Nixon Gage flow (Figure 12). Secondly, reservoir drawdown operations differed subtly between models, causing differences in end-of-year reservoir elevations. These differences in operational/ planned drawdown were noted as areas for improvement in the Planning Model.

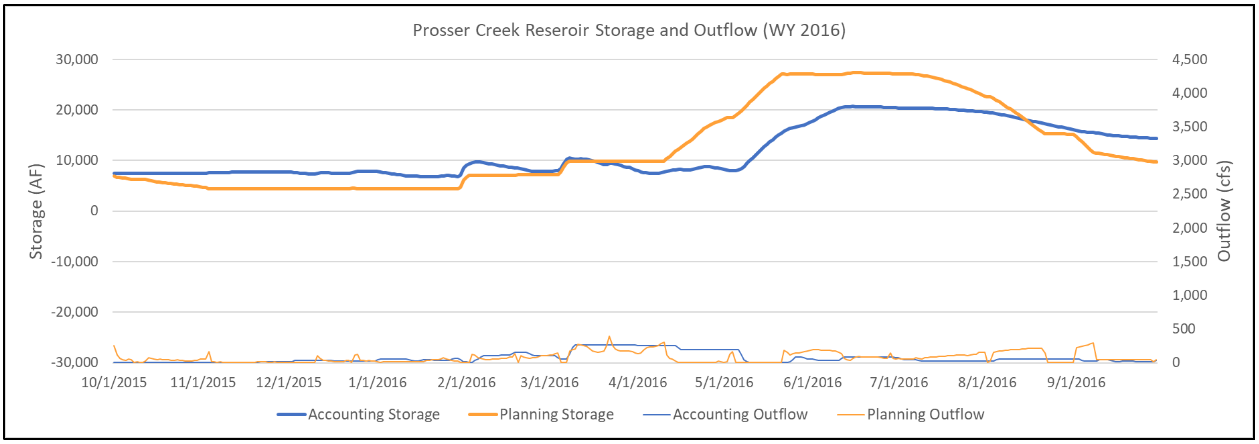

Figure 12.—Prosser Creek Reservoir storage (left axis) and outflow (right axis) in the Accounting Model (blue) and Planning Model (orange) during water year 2016 (Appendix B).

TROA Party Volumes

TROA allows parties to perform different operations, which are coded into the Planning Model logic. This includes establishing, accumulating, and releasing Credit Water stored in reservoirs. Operations performed by TROA Parties in history were largely recreated, in part or in full, by the Planning Model. However, the verification effort revealed that improvements could be made in how the Planning Model determines *when* a TROA party would establish Credit Water and *how much* water a TROA party would release under different conditions. Capturing these subtle operations more precisely in the Planning Model would require input from the TROA Parties; this was beyond the scope of WMOP but may be an area for future work.

Overall, the verification study showed that the Planning Model represents operations in the basin that adhere to TROA and simulate operations of the TROA Parties well. As such, the verification effort found the Planning Model to be an adequate tool by which to model operations in the Truckee Basin for planning-type studies like the WMOP. However, the verification effort did uncover areas of the model that should be further developed to enhance model operations, as described in the “Additional Studies and Future Work” section of this VA and in Appendix B.

Daily Planning Model Dataset Development

As part of a project related to the WMOP, PWRE developed a method to update the daily hydrologic dataset for use in the Planning Model, described in the report, "Truckee River Basin Historical Data Development Methodologies: Water Years 2001-2021" (Appendix C). Stetson Engineers applied the same methodology to update the 1986–2000 daily hydrologic dataset used in the Planning Model (Appendix D). Below is an abridgment of the analysis, results, and conclusions.

High-quality data are an essential component of using the Planning Model to comprehensively assess the Action Alternatives. Identified inconsistencies and inadequacies in existing hydrology data necessitated the development of a new, robust hydrology dataset for planning studies in the Truckee Basin. This offered the opportunity to not only create a historical dataset, but also develop a methodology by which the hydrologic dataset can (1) continue to grow year-by-year into the future, (2) be developed further into the past, and (3) be redeveloped when changes occur to the underlying water balance assumptions in the modeling.

The development of the datasets needed to run the Planning Model, referred to as the Planning Model dataset, built upon prior efforts to develop datasets for the TROA models. Previously, Fulwiler and Lawler (2012) disaggregated monthly data to develop a daily Planning Model dataset for water years 1901–2000 from the Truckee River Operations Model (TROM), a Fortran-based predecessor to the RiverWare models used today (Fulwiler and Lawler, 2012). The water balance of the Truckee Basin represented in the TROA Planning Model is like that of the TROM, but they are not identical. Importantly, the disaggregated datasets used in the TROM do not preserve precise daily peaks and volumes that were needed to effectively analyze flooding impacts in the Action Alternatives. In contrast, the methodology used to develop an updated daily Planning Model dataset used daily gage data, preserving daily peaks and volumes.

The methodology to develop the daily Planning Model dataset assumed two water balance equations—one for reservoirs and one for river reaches. Equation 2 provides the water balance equation for reservoirs, where **Total Inflow** refers to all of the water entering a reservoir. This includes the instream flows entering the reservoir, **Upstream Inflow**, usually measured with a gage, and all other potential **Local Inflow**, such as groundwater inflow, bank discharge, runoff, etc., calculated using the water balance equation, as well as direct **Precipitation** on the reservoir. Based on the conservation of mass, inflows equal **Total Outflow** plus **Change in Storage** in the reservoir. Reservoir outflows include **Downstream Outflow** released to a stream, any **Diversion(s)** from the reservoir, and **Evaporation** from the reservoir's surface.

Reservoir water balance equation: Equation 2

$$Total\ Inflow = Total\ Outflow + \Delta Storage$$

$$\begin{aligned} &Upstream\ Inflow + Local\ Inflow + Precipitation \\ &= Downstream\ Outflow + Diversions + Evaporation + \Delta Storage \end{aligned}$$

Similarly, equation 3 provides the water balance equation for river reaches. In addition to upstream inflow and local inflow, total reach inflow includes flow from any **Tributaries** that enter the reach.

River reach water balance equation: Equation 3

$$Total\ Inflow = Total\ Outflow$$

$$Upstream\ Inflow + \ Local\ Inflow\ + Tributaries = \ Downstream\ Outflow + Diversion$$

All data to populate the variables in equations 2 and 3 were derived from either USGS daily gage data or the TROA Information System (TIS) (TROA - Truckee River Operating Agreement, 2021) and used to solve the equations for Local Inflow, the one unknown variable. The data sources and method for developing the Daily Planning Model Dataset for locations upstream of the Farad Gage differed from that used to develop data downstream of the Farad Gage for the following two reasons.

First, accurately calculating Local Inflow upstream of Farad, referred to as “Sidewater” in the TROA, requires accounting for the travel time of release changes from the five upstream reservoirs. The daily value of the Sidewater flow is a critical parameter for Truckee River operational policy, and, thus, additional effort was taken to account for travel time in the upper basin. As such, upstream of Farad, Local Inflows were calculated using the RiverWare Accounting Model with data sourced from the TROA Information System, which accounts for travel time. The observed data were input to the model, at which point RiverWare performed pre-processing on reservoir elevation and precipitation data before solving the water balance. This included smoothing pool elevation measurements and adjusting erroneous precipitation measurements to reduce uncertainty due to instrumentation measurement inaccuracies. Once the data preprocessing was complete, RiverWare computed the water balance utilizing equations 2 and 3 for each reservoir and reach between gages above the Farad Gage.

Changes in reservoir releases have less impact on flows downstream of the Farad Gage due to attenuation, thus it is not as important to account for the travel time of releases. Further, Local Inflows downstream of Farad are significantly smaller than upstream and constitute a small percentage of the Total Inflow in the reaches. As a result, additional measures were necessary to address the gaging uncertainty in the lower river to develop meaningful inflow data. Downstream of Farad, USGS-approved daily data were used where available, and TIS data was used for sites not monitored by USGS. Gaging uncertainty caused significant challenges, requiring the development of a methodology to minimize the uncertainty in the Local Inflow estimates, as follows:

1. Equation 3 was applied to each river reach (or sub-reach) between successive stream gages on the Truckee River from the Farad Gage downstream to the Truckee River at Nixon Gage to calculate Local Inflow for each sub-reach.

2. The monthly average Local Inflow for each sub-reach was calculated for the entire period.
3. All sub-reaches were spatially aggregated into one reach, Farad to Nixon, and the daily and the monthly average Total Inflow from Farad to Nixon were calculated.
4. The ratio of the monthly average Local Inflow (Step 2) for each sub-reach to the monthly average Total Inflow from Farad to Nixon (Step 3) was calculated.
5. Sub-reach Local Inflow was calculated by multiplying the daily Total Inflow from Farad to Nixon by the appropriate distribution ratio (Step 4) based on month and sub-reach.

This methodology was initially applied to water years 2001–2021 and then Stetson Engineering applied the same methodology to water years 1986–2000, also using USGS gage data and TIS data.

Lastly, the developed daily unregulated datasets upstream and downstream of Farad were manually reviewed and then verified. The review identified irregularities and anomalies in the data that did not follow anticipated hydrologic behavior within the basin. When necessary, corrections were implemented on identified issues. The resulting data from above Farad was verified by comparing the USGS and TIS *measured* net inflow at Farad from 2001–2016 to the net inflow *computed* using the data development methodology during this time. The verification process examined the NSE, as well as the percent and absolute difference, between the computed Total Inflows and observed (gaged) flows at Farad and four gages below Farad. Each test gage—Glendale, Tracy, Wadsworth, and Nixon—registered NSE scores of 0.9 or greater, or a "Very Good" performance rating (Moriasi et al., 2007). The computed and measured net inflows above Farad over the 15-year verification period agree within 0.05% (2,800 acre-feet), confirming that volume is conserved in the computed Local Inflows, Evaporation, and Precipitation volumes throughout the verification period.

The development of the daily hydrologic Planning Model dataset established a process to compute the hydrologic inflows to the Truckee and Carson Rivers, which are necessary to run the associated RiverWare models. These computed inflows are specific to the water balance assumed in the RiverWare models and were developed to allow for the regular extension of the dataset in years to come. Furthermore, the inclusion of the 2012–2015 drought in the updated dataset improves upon the ability to analyze scenarios for drought planning.

Hourly Model Dataset Development

As part of the WMOP, Stetson Engineers developed an hourly hydrologic dataset to model floods in the basin on an hourly timestep, described in the report, "Truckee River Basin Historical Hourly Data Development Methodologies: Water Years 1986–2021" (Appendix E). Below is an abridgment of the analysis, results, and conclusions.

Early on, the Technical Team constrained the WMOP so that the Preferred Alternative must not increase the frequency or magnitude of flooding. As such, the ability to model flood events in the

Truckee Basin and to make comparisons of how different alternatives performed was essential to the selection process. In particular, the flood target in the WCM is set based on an instantaneous flow rate at the Reno Gage (6,000 cfs), requiring an hourly dataset and a model with an hourly timestep for analysis. However, capable modeling technology available to the basin at the onset of the WMOP was limited to the daily timestep of the Planning Model, which is not configured to route flood events to an adequate degree of detail necessary for the study. As a result, the WMOP developed an Hourly Planning Model Dataset and the Truckee River Hourly Model (Hourly Model) to route floods through the basin and assess how well alternatives of the study performed for the flood objective.

The hourly dataset focuses only on the major runoff events in the period of water years 1986 through 2021 to simulate conditions when the instantaneous flow rate is at or above the Reno flood target. For all other periods, the system is operated at a daily timestep to allow for the complications of TROA operations which would not be feasible at an hourly timestep. A major runoff event is classified as any period within 2 weeks of either:

1. Hourly observed flows at the Truckee River at Reno Gage (USGS gage number 10348000) exceeding 5,000 cfs,
2. Daily Farad natural flow exceeding 5,000 cfs, or
3. RFC hindcasts showing the flow at Reno exceeding 6,000 cfs.

Based on these criteria, the WMOP developed hourly data for 15 historical events. The hourly dataset is designed to run in an hourly RiverWare model and in tandem with the daily timestep Planning Model (described below). Hourly inflow data was generated for 12 input locations in the hourly RiverWare model using all available gaged data during all major flood events in the 35-year period of record ending 2021. Any missing data points were estimated from available daily data and nearby gage stations. This data was then adjusted to match the timing and volume of the daily inflow input parameters and then run through the hourly RiverWare model to calculate Local Inflows.

Hourly Model Development and Verification

As part of the WMOP, PWRE developed, calibrated, and validated an hourly RiverWare model described in the reports, "WMOP Truckee River Hourly River Model Time Lag Routing" (Appendix F) and "Truckee River Hourly Model Verification for WMOP" (Appendix G). Below is an abridgment of the analysis, results, and conclusions.

Alongside the development of the Hourly Planning Model Dataset, the Truckee River Hourly Model (Hourly Model) was developed as a part of the WMOP to route floods through the basin and assess how well the alternatives performed for the flood objective. The Hourly Model was built using RiverWare and routes water from the upper basin reservoirs through Reno to the Truckee River at Wadsworth, Nevada Gage. Two key pieces of development were necessary for the Hourly Model, namely, reach routing and flood control operations modeling:

- **Reach routing** enables a model to simulate the physical processes of water moving through a basin, using the principle of conservation of mass. While several reach routing methods exist, the Hourly Model uses the Muskingum Routing Method (McCarthy, 1938; Gill, 1978), following the USACE's Truckee River Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) (U.S. Army Corps of Engineers, 2020), which was utilized in previous models of this region (U.S. Army Corps of Engineers, 2021).

- **Flood control operations modeling** in the Hourly Model followed the WCM regulation criteria of Flood Control Reservoirs in the Truckee Basin (U.S. Army Corps of Engineers, 1985). These criteria include, among other things, prescriptive requirements of flood space in reservoirs based on a remaining runoff parameter, downstream flood flow targets, and operational requirements of both storing into and evacuating reservoir flood space. These criteria represent the No Action Alternative in the WMOP, and the Hourly Model was developed to adequately simulate the basin under these criteria during floods.

The Muskingum Routing Method is built into the software, allowing for easy integration of the method in the Hourly Model. To implement the Muskingum Routing Method, the Truckee Basin was delineated into routing groups associated with gaging locations within the RiverWare workspace. Each routing group required three parameters that necessitated calibration:

- K, a lag time in hours.
- X, a variable describing attenuation in the river.
- N, the number of segments, which is used by RiverWare to further discretize the reach (Appendix F).

An MOEA was utilized to facilitate model calibration by optimizing the Normalized Nash-Sutcliffe Efficiency (NNSE) between downstream gage flow and routed flow.[4] Each reach was calibrated individually through the MOEA process and optimal routing parameters were recorded. In some instances, the MOEA calibration process was not effective over multiple efforts due to complications with events, local inflows, and a lack of additional gage station records. These reaches were manually calibrated through trial and error for a visual best fit.

Satisfactory routing parameters were recorded and then each validation event was run with the Hourly Model to determine the validation event NNSE value for each reach, routing parameter set, and event combination. The lowest calibration and validation NNSE values were 0.58 and 0.76, respectively. This indicates that the parameter configuration for each reach within the model performed well in terms of NNSE scores. Furthermore, an estimation of routing parameter performance over larger flow events gives confidence in utilizing the routing parameters to simulate flood events in the Truckee Basin accurately.

Once the routing parameters were calibrated and validated, the operational criteria of the WCM were codified into the Hourly Model using RiverWare Policy Language. Simulated operations

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[4] The NNSE and the Nash Sutcliffe Efficiency (NSE) performance metrics are very similar, except that NNSE is bounded between 0 and 1 and NSE is bounded between $-\infty$ and 1. NNSE was selected for use in the calibration of routing parameters because of its improved functionality in an automated calibration application.

were then verified over six historical flood events using qualitative analysis of plots that compared simulated operations to historical operations. Two quantitative metrics that make analytic comparisons of simulated to historical values were used for verification the: NSE and Percent Bias (PBIAS). All but one of the calibration events yields "very good" NSE scores, while the April 2018 event yields a "poor" score (Table 13). On the receding limb of the 2018 event, the Hourly Model evacuated flood space as efficiently as possible, strictly adhering to the criteria outlined in the WCM; on the other hand, dam operators applied human discretion to hold onto the encroached water longer than the model projected, in anticipation of a decrease in the WCM required flood space within a few days of the event. Further, three events had significant positive biases of modeled Reno Gage flows over historical values (Table 13). These deviations are due to the model's ability to evacuate flood storage more efficiently than it can be evacuated in real-time operations while adhering to the operational criteria of the WCM. For example, Figure 13 demonstrates a "very good" match between modeled and observed flows during the January 2006 event, but a positive bias.

Table 13.—NSE Scores and Performance Descriptions for Each of the Verification Events (Appendix F)

Event	NSE Score	Performance Description	Percent Bias
April 2018	-4.41	Unsatisfactory	16.65%
March 1995	0.81	Very Good	11.15%
February-March 1986	0.88	Very Good	0.45%
February 2017	0.94	Very Good	0.01%
1997 Flood	0.76	Very Good	0.86%
January 2006	0.94	Very Good	9.11%

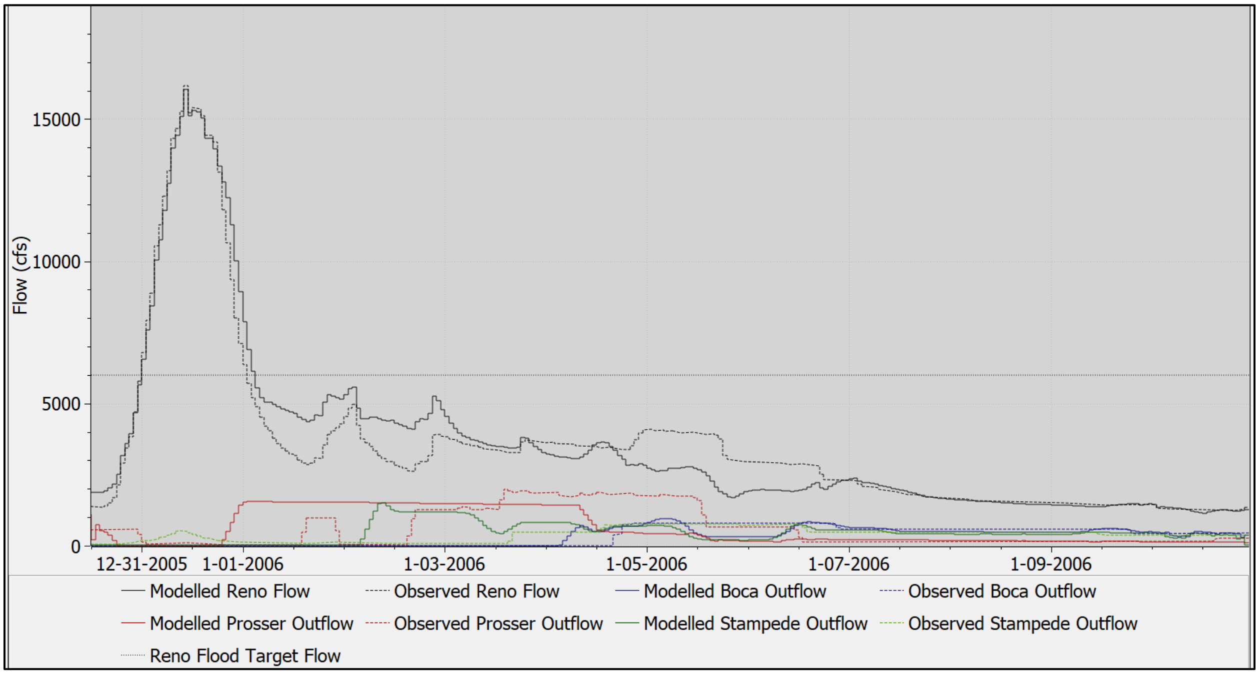

Figure 13.—Modeled (solid lines) and observed (dashed) flood flows during the January 2006 flood event.

Overall, the Hourly Model performed well at operating reservoirs during floods following the WCM. In particular, the model was able to:

- Replicate historical operations well.
- Maintain flood control reservoir storages at their required flood control capacities before events and after flood space was evacuated.
- Store into flood control reservoir flood space to reduce flows in the river at the Reno Gage to 6,000 cfs or reduce flows at the Reno Gage as much as possible.
- Maintain, when possible, proportional encroachment into flood space between Prosser Creek and Little Truckee Reservoirs.
- Limit hourly release changes on flood control reservoirs to 1,000 cfs or less.

The results of the routing method calibration and validation effort and the flood control operations verification demonstrate that the Hourly Model performed well at simulating the Truckee Basin during flood events. As a result, the Hourly Model represents a robust modeling tool by which to assess flooding objectives in the Truckee Basin.

Flood Frequency and Channel Capacity

In addition to validating an hourly model and data to assess the flooding impacts of the alternatives, the WMOP also updated the flood frequency curves in the 1985 WCM using the most up-to-date hydrologic data and details of the physical system to analyze the channel capacity through Truckee Meadows and downstream. These updated flood frequency curves were also the basis for 1%, 0.5%, and 0.2% annual exceedance (100-, 200-, and 500-year recurrence) flows used for the scaled hindcast development.

Rain and Snowmelt Flood Frequency Analysis

As part of the WMOP, River Focus, Inc. and HDR, Inc., updated the Truckee Basin flood frequency curves, documented in the report, "Truckee Basin Water Management Options Pilot Study—Rain Flood and Snowmelt Flood Frequency Curve Update" (Appendix H). Below is an abridgment of the analysis, results, and conclusions.

The flood frequency curves used to develop the 1985 WCM no longer reflect the best available data, nor do they accurately represent current conditions in the Truckee Basin. While the curves developed for the 1985 WCM used a relatively long data record (over 81 years from 1901 through 1982) (U.S. Army Corps of Engineers, 1985), 40 years of data have been collected since that time. The additional data are particularly important for flood frequency analyses that typically only look at one recorded flood per water year of data collected, representing the maximum annual flood. For example, the 1997 flood resulted in an unregulated annual peak daily average flow of 32,803 cfs at Reno, 35% larger any peak daily flow considered in the

WCM, which shifts the updated flood frequency curves upward significantly. Climatic changes over time have also altered the flood frequency curves (Meyers, Dobrowski, and Tauge, 2010), with the region experiencing an increasing trend in the magnitude of floods over time (Bureau of Reclamation, 2015; Bureau of Reclamation, 2021c). Lastly, land use trends, including an increase in development can alter precipitation-runoff curves and lead to an increased proportion of runoff during precipitation events.

To better represent current flood exceedance relationships, the WMOP developed updated flood-frequency curves that incorporated an additional 37 years (1983 to 2020) of the most recent daily flow data. The climate in the Sierra Nevada mountains necessitates the development of separate annual maximum datasets for rain (no-snow) flood flows and snowmelt flood flows since these entail distinct physical processes and meteorological events (U.S. Army Corps of Engineers, 1993; England et al., 2019). Updated flood frequency curves were developed at five basin locations in the Truckee Basin – Martis Reservoir, Prosser Reservoir, Boca Reservoir, Truckee R. at Farad, and Truckee R. at Reno – following the USGS Guidelines for Determining Flood Flow Frequency Bulletin 17C (Bulletin 17C) (England et al., 2019).

The guidance in Bulletin 17C requires identification of the annual maxima unregulated daily and instantaneous flow at each site. Some of the study locations and associated gage data represent regulated flow, requiring further processing. As such, assembling the data set used to fit flood frequency curves required collection and collation of raw flow and reservoir storage data, performing QA/QC on the data, and data manipulation to deregulate flow, i.e., estimate natural flow, where needed.

To determine daily flow, data were collected primarily from three sources, the:

- USGS Water Data website (U.S. Geological Survey, 2023),
- 1985 WCM (U.S. Army Corps of Engineers, 1985), and the
- USACE Sacramento District Water Control Data System website (U.S. Army Corps of Engineers, No date b).

Additional data sources included the California Data Exchange website and daily worksheets from the USWM Office, with priority given to the USGS sources as they provided the longest continuous record at most sites. Following data collection and compilation, each daily dataset was carefully reviewed to identify erroneous or incomplete data. As with most long-term datasets compiled using data from a variety of sources, dataset completeness and quality needed to be addressed. Many of the data sources reflected apparent quality control screening issues and required some adjustments and/or corrections. Refer to Appendix H for a complete description of the key data challenges and methods used to adjust and clean the compiled data.

The procedures for computing flood flow frequency outlined in Bulletin 17C (England et al., 2019) do not cover watersheds with flows altered by reservoir regulation, and there is currently no consistent national guidance on methods for estimating flood flow frequency curves at stream locations affected by regulation. This study adopted a similar approach to that used in the 1985 WCM. Namely, the unregulated mean inflow at each flood control reservoir location (cfs) was estimated by adding the storage-equivalent flow of that reservoir (and any upstream flood control reservoirs) to the daily mean reservoir outflow (cfs) recorded at a downstream USGS gaging station (Figure 14). Calculating storage-equivalent flow requires a conversion from acre-feet per day of stored water to cfs. The rain and snowmelt flood annual maximum datasets compare well with those computed in the 1985 WCM analysis for most years. Of note, the methodology used to develop the unregulated flows for the flood frequency analysis is similar, but a more simplified method than that used to develop the Daily Planning Model Dataset, resulting in some differences in flow estimates.

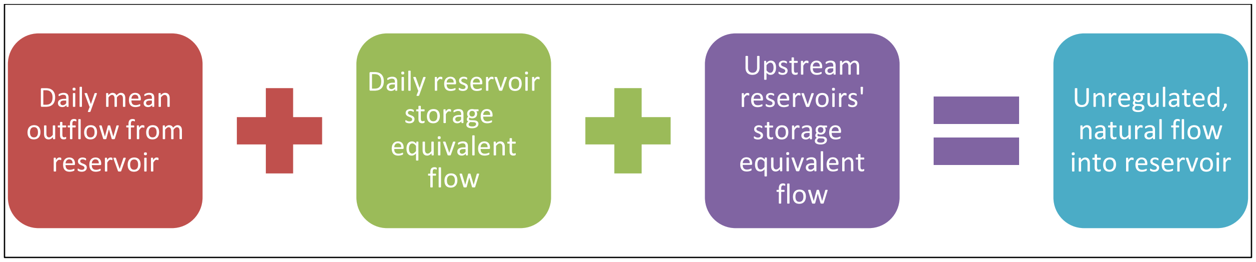

Figure 14.—Example routing math used to compute the unregulated daily mean inflow at regulated reservoir locations. Unregulated daily mean flow for reservoir locations was computed as the sum of the outflow from the reservoir and storage-equivalent flows from all upstream reservoirs.

To capture the seasonal and regional characteristics of different types of floods in the basin, separate annual maximum datasets were developed for rain flood flows and snowmelt flood flows at each of the five study sites. Floods occurring from October through March were categorized as rainfall floods, while floods occurring from April through July were categorized as snowmelt flows (England et al., 2019). To ensure that the flood frequency could be computed for all purposes, curves were developed for the Truckee River at Farad and the Truckee River at Reno locations that both included and excluded flow from the Truckee River at Tahoe City[5] in the computations, in line with the flood frequency curves in the 1985 WCM. To demonstrate the annual distribution of flows, Figure 15 shows the daily average unregulated flow at Reno plus the releases from Lake Tahoe measured at Tahoe City by day of year (Appendix Q). The annual maximum series were subsequently used to compute flood frequency curves for the study sites.

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[5] Lake Tahoe is a large natural lake at the headwaters of the Truckee River Basin with a dam that allows control of 6 feet of the lake level above the natural rim. TROA prescribes when release will be made to maintain the maximum elevation of 6,229.1 feet (TROA - Truckee River Operating Agreement, 2008). These releases can be up to 3,000 cfs when the lake is full and thus can make up a large portion of the flood target downstream at Reno. As such, releases from Lake Tahoe (measured at the Truckee River at Tahoe City) are included in the unregulated flow at Reno for computation of the revised dSRDs as it is a better indicator of the volume that would need to be stored in Truckee River flood control reservoirs to eliminate flooding (Appendix K).

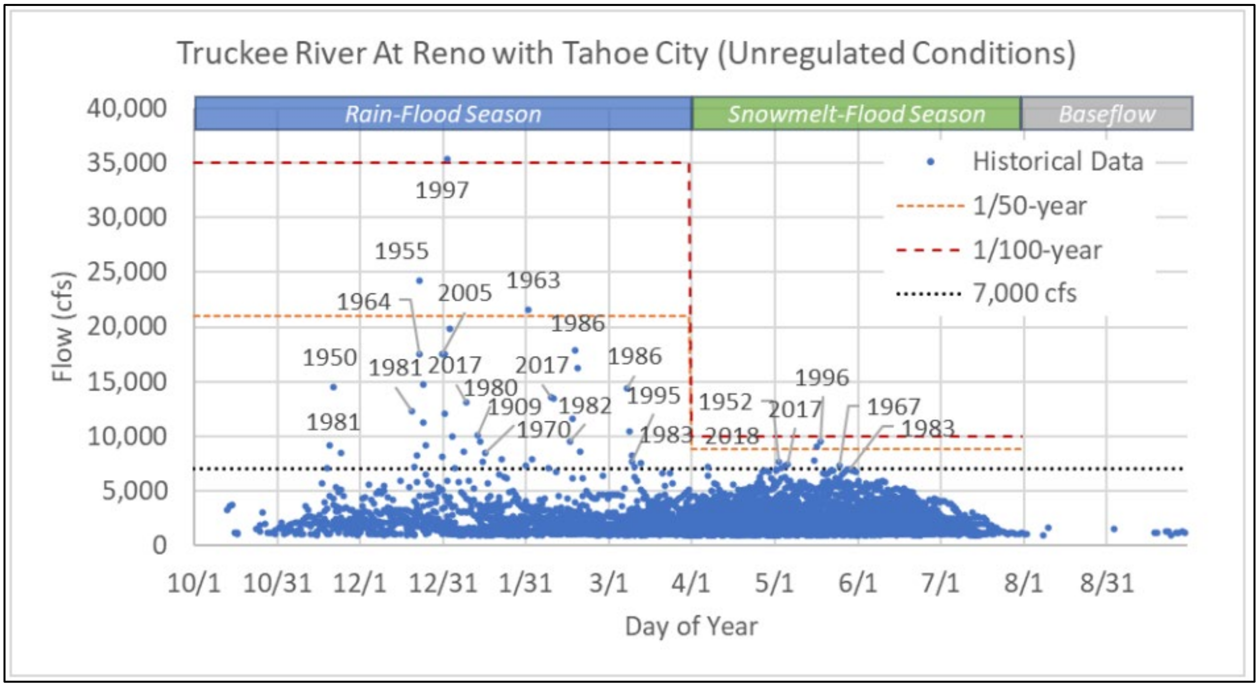

Figure 15.—Summary of historical daily average Reno unregulated flows including Lake Tahoe releases measured at Tahoe City and established seasonal flow recurrence intervals. Flows less than 1,000 cfs were omitted (Appendix Q).

Flood-frequency curves were fit to the adjusted annual maximum rain and snowmelt flood datasets using HEC-SSP and the software's built-in Bulletin 17C Expected Moments Algorithm (EMA) and the Log-Pearson Type III (LP3) probability distribution function. HEC-SSP was used to develop volume-duration datasets for the annual maximum rain flood flows and snowmelt flows for the five study locations, where runoff volumes are expressed as average flow (in cfs) over a specified time duration. The specified time durations for rain-driven flows were 1-, 2-, 3-, 5-, 7-, 15-, and 30-day annual peak flow events and the specified time durations for snowmelt-driven flows were 1-, 15-, 30-, 60-, 90-, and 120-day annual peak flow events. Flood frequency curves were fitted to the annual maximum datasets for all locations and flow durations for both the rain and snowmelt seasons, and separate sets of curves were fit for the Truckee River at Farad and Reno locations including and excluding the Tahoe City flows (refer to Appendix H for all flood frequency curves and LP3 function parameters).

This work supported the WMOP study by enhancing and expanding the unregulated flow time series at key locations, annual maximum flood datasets, and sets of flood frequency curves. While an analysis and full comparison of the flood-frequency curves presented in the 1985 WCM and those developed as part of the current study is not within the scope of this project, the updated curves did reveal the following key points, shown in Figure 16 and Figure 17:

- The **largest rain-driven flood events were greater in magnitude than the largest snowmelt events**, though the largest snowmelt flows tended to have a much longer duration. Large rain-driven floods did not occur during many years.

- The predicted 10-year and 100-year, 1-day **rain flood flows increased at all locations relative to the 1985 WCM** rain flood curves. All locations except Boca Reservoir saw increases in predicted flood flows of over 30% for both the 10- and 100-year floods.

- The predicted 10-year and 100-year, 1-day **snowmelt flood flows match or are very similar to the 1985 WCM** snowmelt flood curves, except at the Martis Reservoir location. The apparent increase in snow-melt magnitude in the revised curves for Martis Reservoir is a result of the uncertain, differing 1-day annual snowmelt flow maxima for 1982 and does not reflect an actual change in the mean 1-day maximum snowmelt, as described further in Appendix H.

This work enhanced and expanded the unregulated flow time series at key locations, annual maximum flood datasets, and sets of flood frequency curves. It is important to note that the observed changes in the upstream unregulated flood frequency curves do not directly correlate to changes in flood risk, as defined by FEMA mapping that uses regulated downstream flows to determine flood inundation. The updated flood frequency curves were used to develop revised dSRDs for the Truckee Basin reservoirs, as described in the "Dynamic Storage Reservation Diagrams Development" section of this VA. The updated flood frequency curves were also used to determine the target flows for the scaled hindcasts which provided synthetic events larger than the historical record to test proposed scenarios against.

While flood frequency curves developed for this project improve upon those developed for the 1985 WCM, noteworthy uncertainty still exists. The Bulletin 17C procedures are intended to develop the best and consistent estimates of flood-flow frequency up to the 0.002 annual exceedance probability, and significant uncertainty exists in extrapolating values beyond the fitted datasets and this range, especially given the positive skew values in the fitted distributions. This study did not address the uncertainty of these extreme probabilities. Another key uncertainty is the extent to which rain and snowmelt-driven floods truly are segregated by calendar month for the Truckee Basin during the study period. Future development of the HEC-SSP software may permit more flexibility in the "look-back" versus "look-forward" methodology; this could help mitigate the challenges observed in this study and allow for more consistent segregation of events by calendar month.

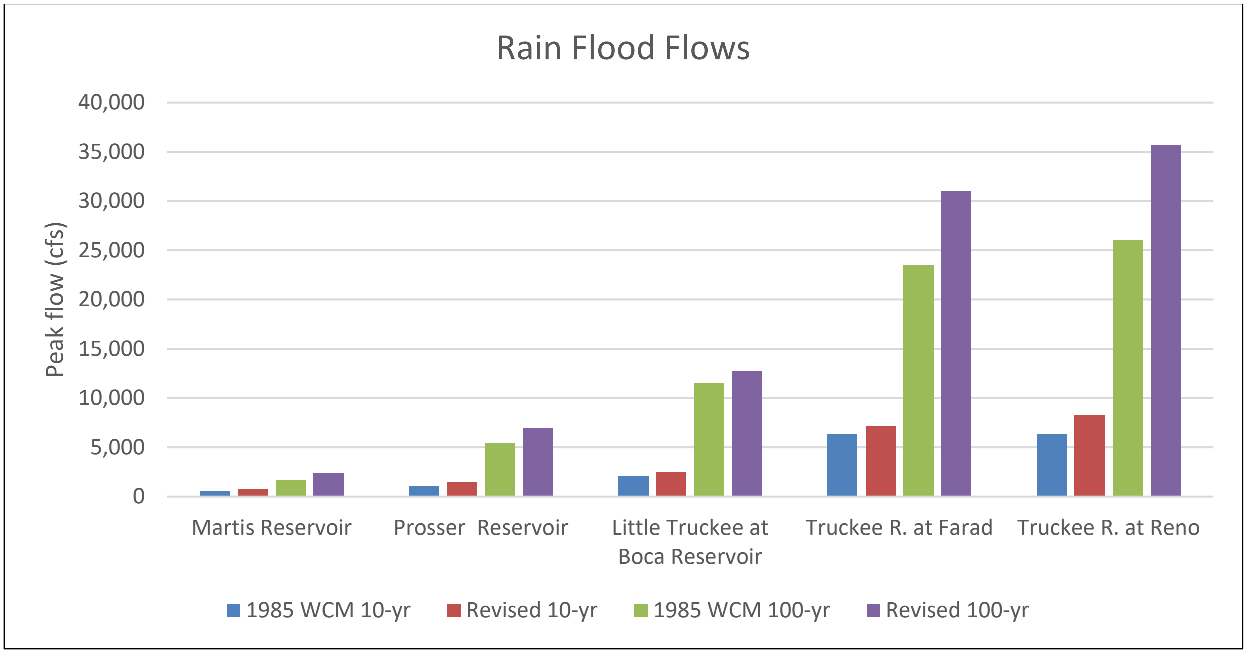

Figure 16.—Comparison of the predicted 1-day annual maximum 10-year and 100-year rain flood flows from the current study to curve predictions from the 1985 WCM.[6]

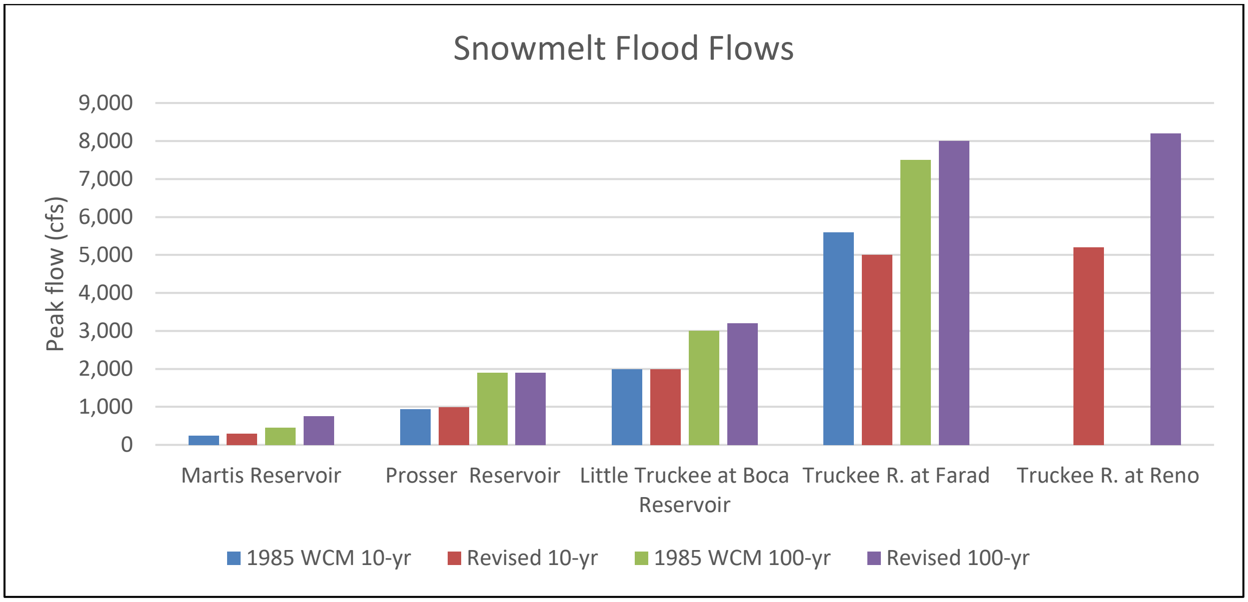

Figure 17.—Comparison of the predicted 1-day annual maximum 10-year and 100-year snowmelt flood flows from the current study to curve predictions from the 1985 WCM.[7]

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[6] Note that equivalent 1985 WCM and revised rain flood flows for the Truckee River at Farad and Reno are presented with Tahoe City flows included, while the equivalent snowmelt flood flows are presented with Tahoe City flows removed. Appendix H includes results with and without Tahoe City flows for both seasons.

[7] The 1985 WCM does not include snowmelt flood frequency curves for the Truckee River at Reno.

Channel Capacity Analysis

As part of the WMOP, HDR, Inc. and River Focus, Inc. analyzed the channel capacity of the Truckee River at Reno, herein referred to as Channel Capacity Analysis (Appendix I). Below is an abridgment of the analysis, results, and conclusions.

The WCM mandates a maximum instantaneous flood flow target of 6,000 cfs at the USGS stream gage on the Truckee River at Reno, however, the Technical Team believes this target may be outdated due to recent infrastructure upgrades, increased accuracy and precision of data and modeling, and observed flood conditions at flows at and above 6,000 cfs. The current 6,000-cfs target constrains the release of upstream reservoir outflows and thus the evacuation of the flood pool before, during, and after floods. If the channel from Reno to Wadsworth can safely convey a higher flow, increasing the target maximum flow would allow for greater flexibility in operating the upstream reservoirs.

Channel Capacity Hydraulic Models

To assess channel capacity, HDR and River Focus developed synthetic flow hydrographs and routed these through existing HEC-RAS hydraulic models developed in support of a Federal Emergency Management Agency (FEMA) Physical Map Revision. Importantly, these models were developed with a focus on modeling and mapping the 1% annual exceedance event, which has a peak flow of over 20,000 cfs on the Truckee River at Reno; this is significantly higher than the range of potential Reno flood flow targets (6,000 to 8,000 cfs) of primary interest in the WMOP. The model uses a 150-foot grid cell and refining the level of detail in the model was outside the scope of the WMOP project. As such, smaller conveyance structures, such as local storm drains are not represented by the model, nor obstructions to flow such as Jersey barriers and earthen berms. While the higher flows associated with the FEMA mapping are sufficient to overwhelm these structures, they mitigate flooding at lower flows, such as those examined in the WMOP. These limitations of the channel capacity modeling are discussed in more detail later in this section.

The Truckee River near Reno exhibits markedly different hydraulic behavior upstream of and downstream from Vista, requiring two different hydraulic modeling approaches. To capture the wide floodplain within the upstream Truckee Meadows Reach, this study used a fully two-dimensional (2D) model with unsteady state flow conditions for the region upstream of Reno to an endpoint approximately 2.5 miles downstream of Vista (Figure 18). Three tributaries, Steamboat Creek, Long Valley Creek, and the North Truckee Drain (NTD), contribute to this study reach. In contrast, the reach of the Truckee River from Vista to Wadsworth (Lower Reach) flows through a relatively narrow canyon and has a comparatively small floodplain. Due to these conditions, a one-dimensional (1D) model can accurately represent hydraulic conditions within this reach (Figure 19).

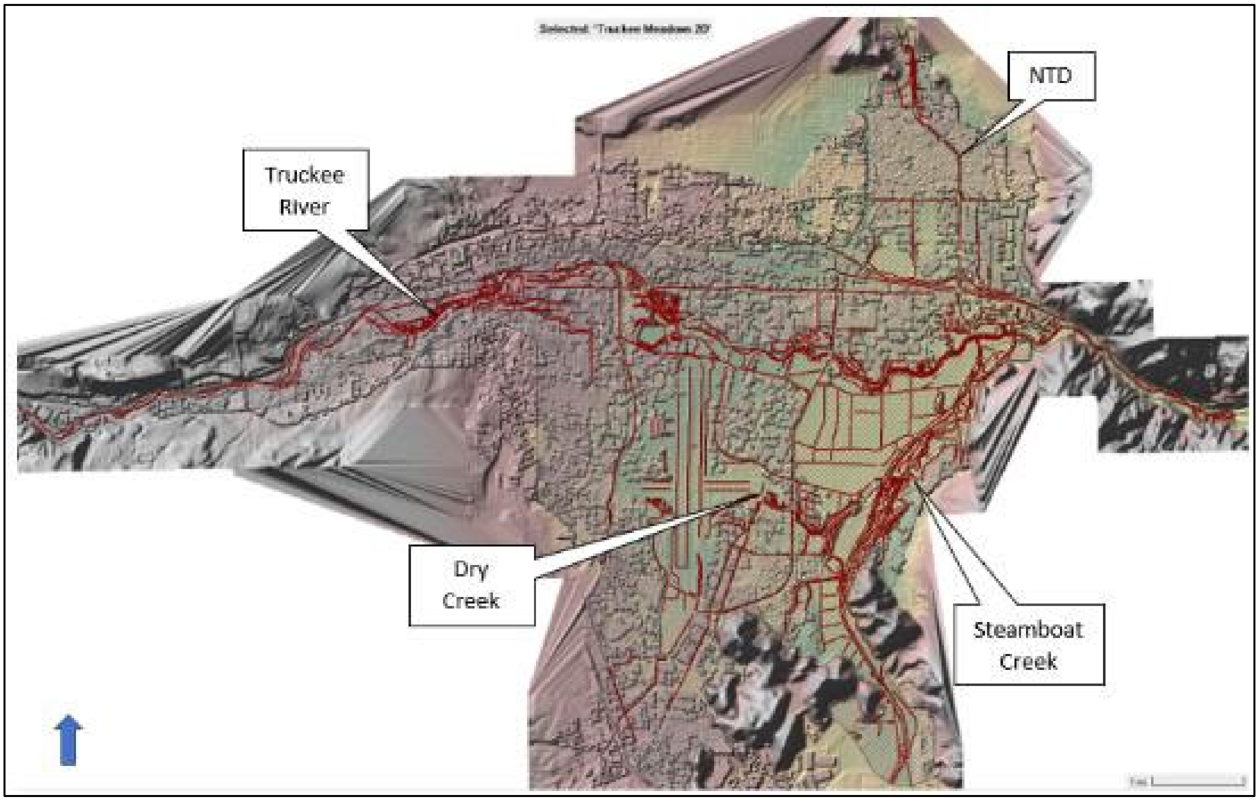

Figure 18.—Truckee Meadows 2D HEC-RAS Model Configuration (Appendix I).

Figure 19.—Lower Reach 1D HEC-RAS Model Configuration (Appendix I).

The models were calibrated and validated using five high-flow events—three events for calibration (2005, 2017, and 2019) and two for validation (1997 and 2018). These events were selected based on data availability and reliability, as described further in Appendix I. The calibration process updated the Manning's n roughness values used to represent the hydraulic resistance to flow. The Manning's n roughness values developed for each calibration flood event were averaged to create a final set of Manning's n roughness values for each model. The calibrated hydraulic models were then validated by simulating two other historical flood events that occurred in 1997 and 2018.

The calibration and validation process used NSE statistics to assess the model's goodness of fit relative to discharge and water surface elevation (WSE) at five gage locations on the Truckee River located at Reno, Vista, Tracy, Derby Dam, and Wadsworth. During the calibration and validation process, the NSE for the five flood events and five gage locations primarily fell into the "very good" range, with a few notable exceptions. The 2018 validation event produced "unsatisfactory" results in the lower reach; for this event, the difference between the modeled and observed peak WSE is relatively small but, the WSE hydrographs are offset by a similar amount for the entire event simulation, resulting in the "unsatisfactory" calculated NSE value. In addition, the NSE for WSE at Reno produced "unsatisfactory" results during the 2019 calibration event and 2018 validation event, where the model projected WSE approximately 1 foot below the gaged WSE during the peak of the hydrograph. During these events, the simulated discharge at the Reno Gage matches the observed discharge well, with NSE results rated as "very good." Further, both the WSE and discharge at the Vista Gage produced "very good" NSE results during the 2018 and 2019 events, indicating that any modeling discrepancies at the Reno Gage are not propagated through the model.

HDR and River Focus noted several possible reasons for the "unsatisfactory" results for WSE at the Reno Gage. One possible reason for this discrepancy could be a backwater effect taking place in the region of the Reno Gage location that the HEC-RAS model does not capture. Another possible reason is that the modeled conditions in this reach of the river may be different than the specific conditions during the flood event modeled. Further, HDR and River Focus encountered unreliable rating curve data at Reno after the gage was relocated in 1998 through and including the 2005 hindcast event. While HDR and River Focus revised the peak flow estimates to address the rating curve issue, it may have affected the calibration. as such, the Key Stakeholders do not believe the isolated "unsatisfactory" NSE results for the WSE at the Reno Gage significantly affect the overall validity of the channel capacity modeling results, however, they do prompt an appropriate scrutiny of results.

Assessment of Channel Capacity

The study took two approaches to assess channel capacity and areas of breakout flow. First, HDR and River Focus routed synthetic hydrographs developed from historical gaged flow patterns through the HEC-RAS models. Secondly, channel capacity was assessed under sustained, fixed high flows for 21 days, representing reservoir drawdown post-high flow event. The sustained flow assumptions allow for assessment of a flood flow target to which the dams could be operated indefinitely, without causing damages, a primary objective of the WMOP.

To assess channel capacity, HDR and River Focus developed a series of synthetic flow hydrographs representing peak flow rates at the Reno Gage. A total of 17 events, ranging in peak flow from 6,000 up to 14,000 cfs, at an increment of 500 cfs, were developed. The flow patterns for the synthetic inflow hydrographs for the Truckee River and associated tributaries are based on the 100-year event hydrographs. Each of the synthetic hydrographs was routed through the Truckee Meadows and Lower Reach HEC-RAS models to produce inundation boundaries for each of the target flows, which were then examined in HEC-RAS Mapper and ESRI ArcMap.

The WMOP study focused on breakout locations and inundation extent occurring at peak flows between 6,000 and 8,000 cfs since these provide the most pertinent information when considering potential adjustments to the target maximum flow rate at the Reno Gage. Within the Truckee Meadows reach, channel capacity was exceeded at the 6,000 cfs peak flow rate in two separate areas. One was a minor breakout at Oxbow Park, upstream of downtown Reno, that does not impact constructed park features aside from walking trails. Additionally, at the 6,000 cfs peak flow, channel capacity is exceeded at two locations into the south, river right overbank in the area between S. Rock Boulevard and S. McCarran Boulevard near N. Edison Way (Figure 20). The number of breakouts and extent of inundation in this region increases with each incremental increase in peak flow; however, up to the 8,000 cfs flow rate, the flooding does not appear to threaten any roadways or structures. In the Lower Reach, channel capacity was exceeded in numerous locations, beginning at the 6,000 cfs flow rate and increasing with higher discharge, but no existing roads or structures appeared to be threatened by flows up to 11,500 cfs.

An additional set of model runs simulated peak flow rates of 6,500; 7,000; and 7,500 cfs at the Reno Gage, held steady for 21 days each. These simulations better represent the expected conditions during reservoir-controlled operations than the incremental hydrographs based on gaged flow patterns, which contain a relatively short period of peak flow. In general, no new channel breakouts occurred with the sustained flow runs, relative to the simulated pattern hydrographs with equivalent peak flows. However, there is potential for additional flow volume in the overbank areas, increasing ponding and the maximum Inundation extents.

The channel capacity assessment revealed that the reach between S. Rock Boulevard and S. McCarran Boulevard near N. Edison Way is a critical flood area within the Truckee Meadows Reach and a crucial location for the WMOP study (Figure 20). Up to 8,000 cfs, this is the only reach where the modeling shows breakouts with the potential to affect infrastructure, although this is still confined to inundation of roadways and parking areas. According to the sustained flow simulations, there are breakouts along this stretch beginning at Truckee River flows as low as 6,000 cfs. As the flow increases to 6,500 cfs, the size of this breakout increases to 1.8 acres, and there is enough water breaking out into the floodplain north of S. Mill Street to cause ponding against S. Mill Street. The 7,000-cfs results indicate actual overtopping of S. Mill Street and an increase in inundated area from 6.2 acres up to 41.4 acres, with significant flooding north of S. Mill Street near the Truckee River, along N. Edison Way, and south of S. Mill Street, moving into the commercial area. The 7,500-cfs simulation results indicated an increase in inundated areas to 49.8 acres.

Figure 20.—Truckee River Truckee Meadows Reach, 6,000-cfs Peak Flow Inundation Boundary for Channel Capacity Analysis. Blue shading indicates areas inundated in the 2D HEC-RAS during the routing of the 6,000-cfs peak flow synthetic hydrograph, and the yellow lines indicate breakout locations.

Note: The first six rectangles/trapezoidal shapes along N. Edison Way are concrete pads, not buildings. TRFMA purchased these properties for the purposes of flood risk reduction (Appendix I).

While these modeling results present some reasons for caution, several other factors must be considered. In general, the channel capacity modeling effort took a conservative approach, and several key assumptions and factors may affect the extent to which the HEC-RAS results reflect on-the-ground flood conditions:

- **FEMA Models' Design**.—The HEC-RAS models used for the Channel Capacity Analysis were developed for updating the FEMA floodplain mapping, which focused on the 1% annual chance exceedance event, with a peak flow of over 20,000 cfs on the Truckee River; however, the WMOP is primarily interested in flows within the 6,000 to 8,000 cfs range. The model's grid size and geometries do not provide for inclusion of smaller flood barriers and conveyance structures, such as local storm drains. Unlike the large flood flows examined by FEMA that overwhelm these small structures, these features can perform important flood risk management functions at the lower flood flows of concern in the WMOP.

- **Synthetic Hydrograph Pattern**.—The Channel Capacity Analysis used the 100-year event hydrographs as the pattern hydrographs for all synthetic events simulated for this task (refer to Appendix I for discussion). This approach leads to a greater flow volume entering the model domain, relative to simulations using smaller USACE event flow hydrograph patterns.

- **Tributary Flows Assumptions**.—The synthetic hydrographs assume relatively high flow events taking place on tributaries at the same time or nearly simultaneously with high flows in the Truckee River. Examination of gage records indicates that large flows in Steamboat Creek and the NTD are rare, usually of short duration, and may not occur simultaneously with peak flows on the Truckee River.

- **One-Dimensional Model Limitations**.—Since the 1D model for the Lower Reach assumes a constant water surface across the length of each cross-section, the inundation boundaries produced by HEC-RAS Mapper can show low-lying areas as inundated, even though they are isolated from the river by berms or other elevated features.

- **HEC-RAS Model Detail**.—The mapped inundation extents do not account for potential impacts of storm drains, roadway crowns, and other physical features that could impact flow patterns and flood inundation and minor barriers to flow (unofficial floodwalls or berms) may not be represented by the models at all locations.

- **Truckee River Flood Management Project Features**.—The Flood Project includes numerous levees, floodwalls, and other features intended to reduce or eliminate flooding within Truckee Meadows. *Proposed* Flood Project features are not represented in the HEC-RAS model but have the potential to significantly alter the behavior of the Truckee River system if they were to be constructed. In general, the Flood Project features would better retain floodwaters within the river channel in the Truckee Meadows reach, thus increasing peak flows downstream. However, hydraulic analysis indicates that the overall Flood Project would have little to no impact on peak discharge downstream of Vista for events smaller than 10,000 cfs.

Supplemental Channel Capacity Information

The results of the Channel Capacity HEC-RAS modeling study were supplemented with flood stage designation by the National Weather Service (NWS), along with documented observations during flood events, and the expert opinion of the Executive Director of TRFMA, further documented in Appendix J.

The NWS designates flood stages for the Truckee River and has set the flood stage for the Truckee River at Reno far higher than the target maximum flood flow of 6,000 cfs in the WCM. The flood stage is commonly defined by NWS as the river stage at which overflow of the banks of a stream begins to cause flood damage in the local area. In 2018, the NWS, in coordination with the City of Reno, the City of Sparks, TRFMA, and others, raised the flood stage levels in all locations on the Truckee River—Truckee, Reno, Vista, and Wadsworth—by 0.5 to 2 feet due to both natural and manmade changes over the watershed (National Weather Service, National Oceanic and Atmospheric Administration, 2018) (Appendix J). At that time, the "minor" flood stage at Reno was raised from 11 to 12 feet, equivalent to an increase from 8,728 to 11,402 cfs of flow (National Weather Service, National Oceanic and Atmospheric Administration, 2018; California Nevada River Forecast Center, National Oceanic and Atmospheric Administration, 2023) (Figure 21). At Reno, NWS set the "warning" stage at 10 feet (6,496 cfs). From the warning stage up to the 12-foot minor flood stage, only minor flooding of the bike path and riverside parks is expected (California Nevada River Forecast Center, National Oceanic and Atmospheric Administration, 2023). In sum, the NWS projects much less significant and nominal flood risk at the river stages around the WCM target maximum flow than those produced by the HEC-RAS model used in the Channel Capacity Analysis (Appendix J).

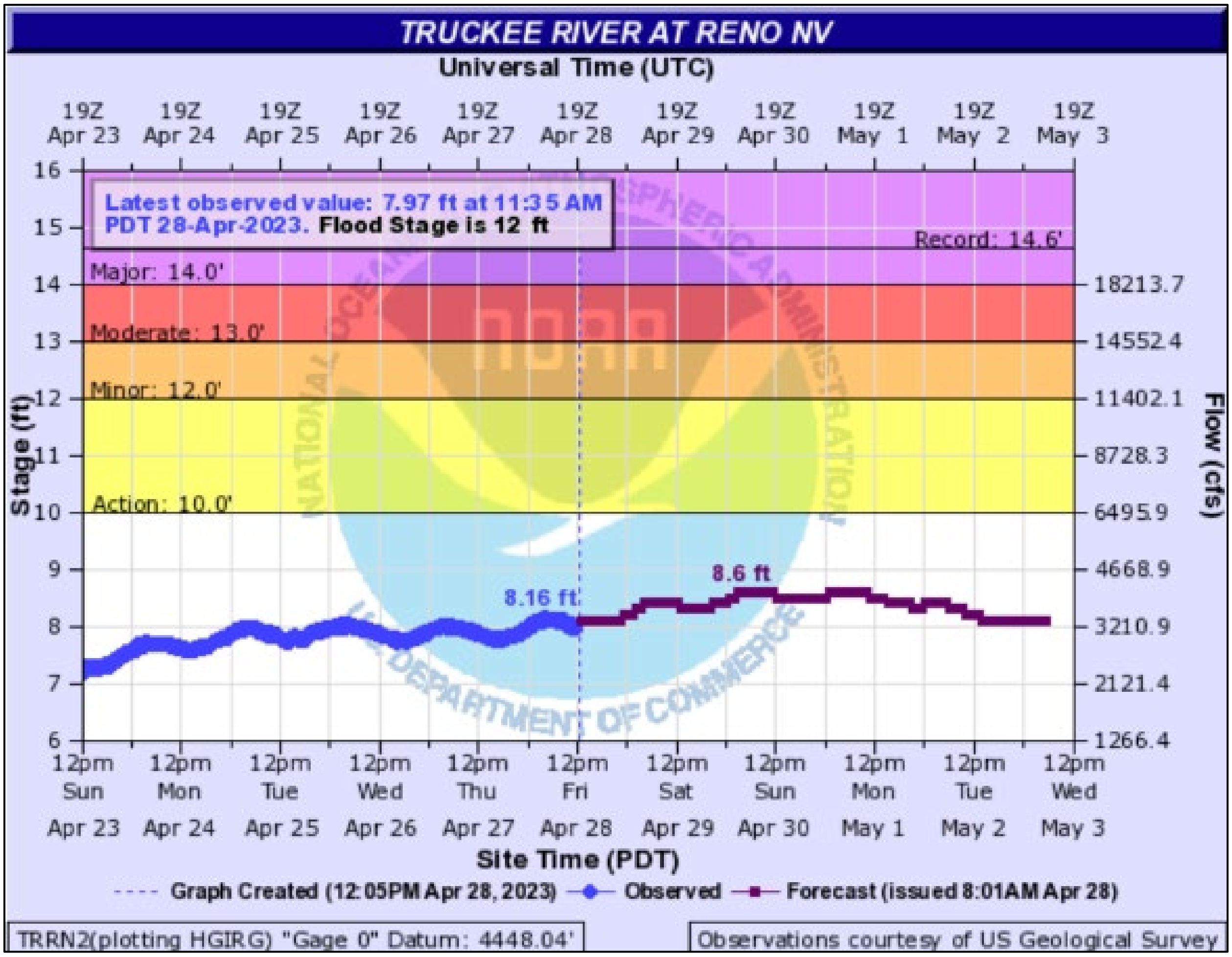

Figure 21.—National Weather Service flood stages and associated flow rates at Reno (National Weather Service, National Oceanic and Atmospheric Administration, 2023).

In addition to comparing the results of the Channel Capacity analysis to the NWS flood stages, TRFMA carefully evaluated the Channel Capacity Analysis, with a focus on the reach between S. Rock Boulevard and S. McCarran Boulevard along the south, river right, bank of the Truckee River, the critical flood area noted above (Figure 20). TRFMA serves as the official Local (Non-Federal) Sponsor working with the USACE to evaluate flood risk management alternatives and secure Federal funding via Congressional authorization and appropriations to construct the Flood Project (Truckee River Flood Management Authority, 2017). While TRFMA acknowledges the potential breakout flow and volume in this reach, they noted the need to balance the modeling results with two factors:

1. Observations of inundation and ponding during flood events, and
2. The Capacity of a storm drain that was not part of the HEC-RAS model used in the Channel Capacity Analysis.

In line with the NWS flood stages and contrasting with the HEC-RAS Channel Capacity Analysis, at flows around 7,000 cfs (April 2018), TRFMA staff have observed little or no water on N. Edison Way and no ponding against S. Mill Street. During significantly larger flood events in the range of 10,000–12,000 cfs (January and February 2017), TRFMA staff have observed ponding of water along N. Edison Way and S. Mill Street, but the water did not breach S. Mill Street (Figure 22).

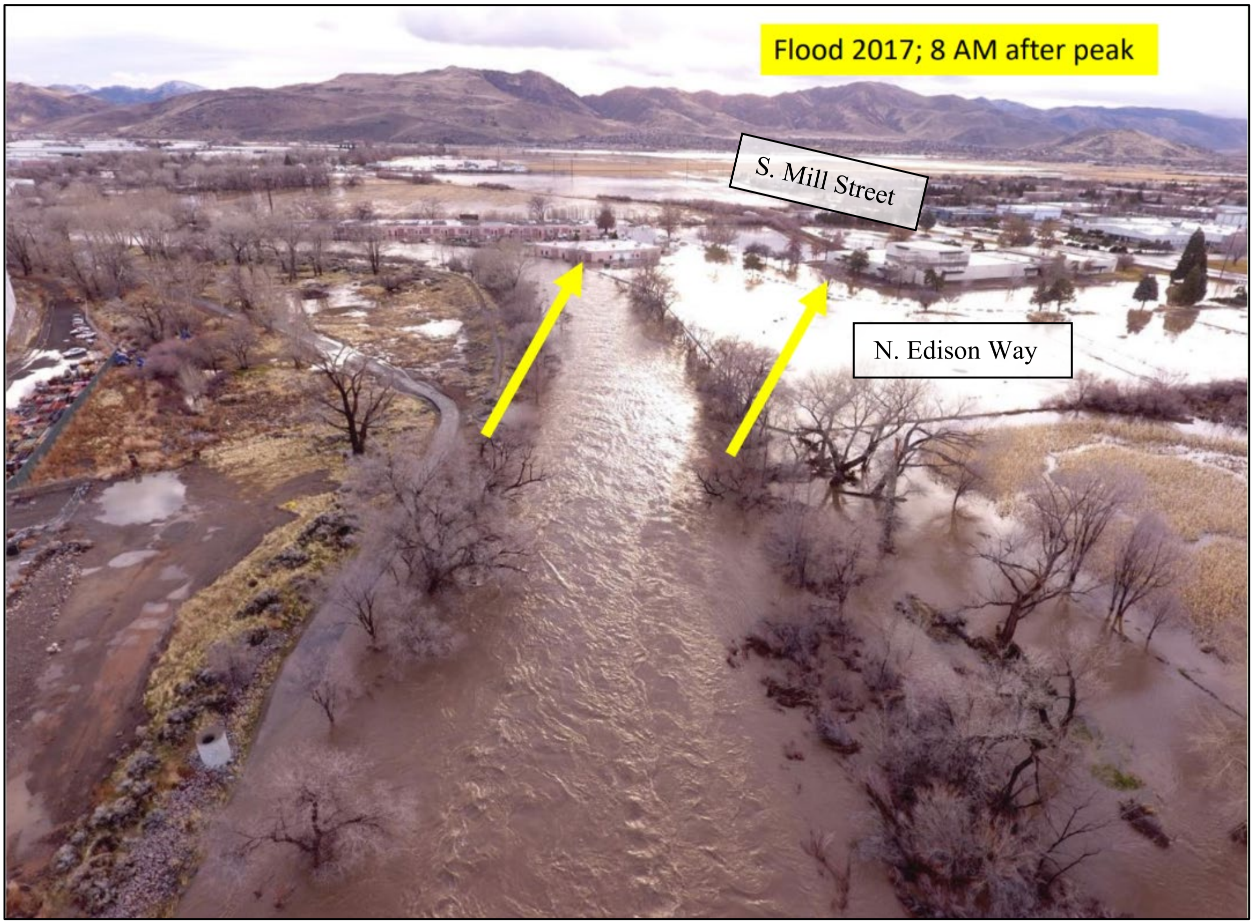

Figure 22.—Photograph taken above the Truckee River by N. Edison Way, looking southeast toward S. Mill Street and S. McCarran Boulevard. This photograph was taken around 8:00 a.m. on January 9, 2017, when the river was flowing at about 8,760 cfs at the Reno Gage, after peaking at 12,800 cfs the night before. At the time the photograph was taken, TRFMA staff observed ponding of water along N. Edison Way and S. Mill Street, but the water did not breach S. Mill Street (Appendix J).

In looking at the area of concern, TRFMA believes the presence of a storm drain that is not included in the HEC-RAS model, along with drainage along Pioneer Ditch, conveys considerable water during high-flow events (see Figure 23 and annotated photographs in Appendix J). According to City of Reno staff, this storm drain has a diameter of 48 inches and actively conveys water during high-flow events. Performing simplified calculations in the HY-8 Culvert Hydraulic Analysis Program and researching the flow rate of similarly constructed 48-inch pipe, results in a conservative estimate that the storm drain can pass more than 100 cfs when free-flowing. Relatedly, cursory calculations of the HEC-RAS profile cross-sections indicate that less than 100 cfs breaks out of the channel at this area, up to and perhaps beyond 7,000 cfs Truckee River flow. At 7,000 cfs, it appears the river stage is still low enough to allow for at least partial outflow from the storm drain. For higher flows, there may be backwatering that hinders sewer capacity. As such, breaching or ponding against S. Mill Street or significant inundation along N. Edison Way does not appear to occur at flows up to and perhaps beyond 7,000 cfs (Appendix J).

The Technical Team thoroughly considered all the information in the Channel Capacity Analysis alongside the NWS flood stage designations and TRFMA's presentation to agree upon a recommendation to increase the target maximum flow at the Truckee River in Reno from 6,000 cfs in the 1985 WCM to 7,000 cfs, as described further in the "Reno Flood Flow Target Update" section of this VA.

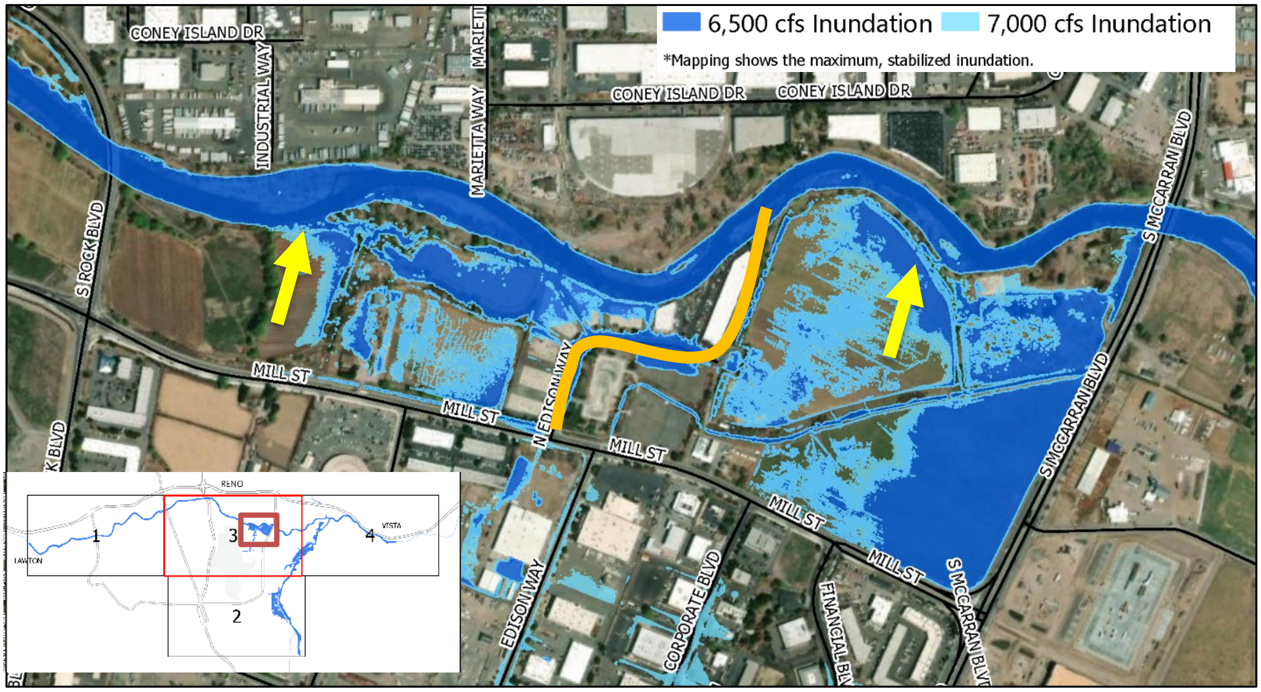

Figure 23.—Truckee River Truckee Meadows Reach, 6,500-7,000 cfs Sustained Flow Inundation Boundary for Channel Capacity Analysis. Dark blue shading indicates areas inundated in the 2D HEC-RAS model during the routing of the 6,500 cfs peak flow sustained for 21 days. Light blue shading represents the additional areas inundated under 7,000 cfs sustained flow. The yellow arrows point to breakout locations. The orange line represents the storm drain along N. Edison Way that is not included in the HEC-RAS model, but conveys flood flows, reducing inundation (Appendix J).

Action Alternatives Build-Out

The technical foundation developed as part of the WMOP provided the data and models to build out and assess the No-Action and Action Alternatives. This includes the development of revised dSRDs, following more conventional guidance from the USACE (U.S. Army Corps of Engineers, 2018) and NRCS (Natural Resources Conservation Service, 1991) and development of the BAM method used to incorporate forecasts into flood space determinations. The CNRFC produced hindcast ensembles as a precursor step to building out the BAM method, as described below.

Dynamic Storage Reservation Diagrams Development

As part of the WMOP, PWRE revised the dSRDs used in the 1985 WCM and documented the methodology in the report, "Revised Guide Curve Modeling" (Appendix K). Below is an abridgment of the analysis, results, and conclusions.

All of the Acton Alternatives build off the revised dSRDs to address the limitations of the outdated guide curves for the Truckee Basin. As a part of the WMOP, PWRE updated the 1985 WCM guide curves using the latest data and following USACE (U.S. Army Corps of Engineers, 2018) and NRCS (Natural Resources Conservation Service, 1991) guidance. The revised dSRDs were developed exclusively based on the data developed for the updated rain flood and snowmelt flood frequency curves associated with the WMOP, specifically, daily unregulated, natural flow at Reno and Farad from January 1909 through October 2021, ranging 112 years. Updating the guide curves required three steps, as described below:

1. Data processing to populate revised dSRDs
2. Storage envelope generation
3. Storage envelope compilation into revised dSRDs

This process produced revised dSRDs for Martis, Boca and Stampede, and Prosser Reservoirs, at five potential Reno flood flow targets: 6,000; 6,500; 7,000; 7,500; and 8,000 cfs, with and without Martis operational for flood control.

Data Processing to Populate Revised dSRDs

The first step to revising the guide curves required some preliminary calculations to determine the required flood space based on three different flow volume datum:

- Water year-to-date unregulated Reno natural flow over the flood target,
- Remaining water year unregulated Reno natural flow over the flood target, and
- Remaining water year Farad natural flow volume.

The first calculation helps determine the storage required early in the water year, i.e., the fall drawdown portion of the guide curve. This process calculated the *water year-to-date* flows over the Reno flood flow target, using equation 4, where I_t represents the calculated observed daily unregulated Reno flow at time, t (Figure 24). The equation is summed from the first day of the water year, October 1st ($t = 0$), through the date of interest, t_f, for every day of the water year.

Cumulative Storage over flood flow target.[8] Equation 4

$$Required\ Flood\ Space = \sum_{t=0}^{t_f} \max(I_t - T_{Reno}, 0)$$

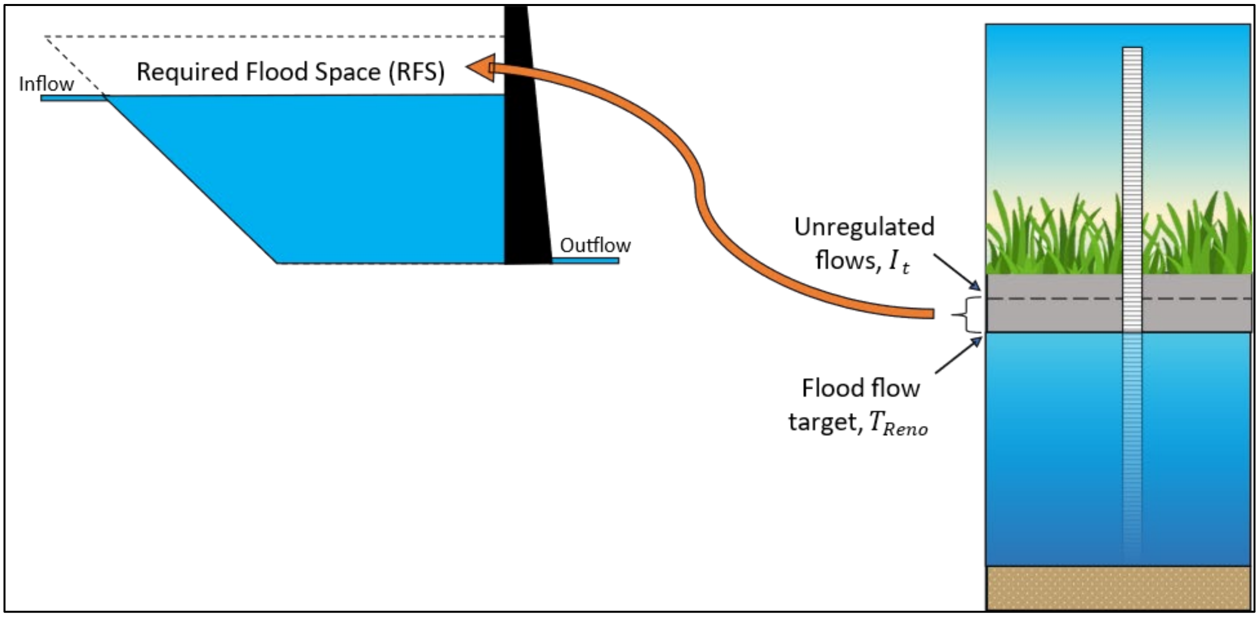

Figure 24.—Required flood space demonstration. The required flood space is a function of the difference between the unregulated flows at Reno and the Reno flood flow target. Equation 4 is summed over a specified period to ensure sufficient flood space is available to capture all flows above the target.

The second calculation also uses equation 4 but solves for the *remaining* unregulated water year volume over the Reno flood flow target to determine the storage required later in the water year, i.e., the spring refill portion of the guide curve. In this case, the equation is summed from the date of interest, $t = 0$, through the end of the water year, September 30th, t_f, for every day of the year.

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[8] Of note, equation 4 is used for several calculations to define the dSRDs as well as the BAM method. Differences between these calculations relate to different values used for I_t (e.g., observed versus forecasted flows) and the time period over which the equation is summed, t_0 to t_f (e.g., year-to-date, remaining water year, or full water year).

The last calculation solves for the remaining water year Farad natural flow volume. This calculation represents the snowmelt parameter on the dSRDs, that allows for dynamically operating at different curves during wet, normal, and dry years. F is used for this calculation instead of the Reno unregulated flow, following the snowmelt parameter used in the 1985 WCM.

Storage Envelope Generation

In the second step, storage envelope curves were generated using the results of the preliminary calculations. The maximum required flood space for each day of the water year is identified from the period of record, using each of the three calculations. For example, Figure 25 compares the day of the water year to its maximum water year to date Reno flow volume over the flood target during the period of record. To identify a fall drawdown curve, one can draw a storage envelope curve of required flood space where all points are slightly larger than each day's maximum observed remaining water year Reno unregulated flow volume over the flood target (dotted orange line in Figure 25). This ensures sufficient space is reserved to capture all of the largest fall flows in the period of record.

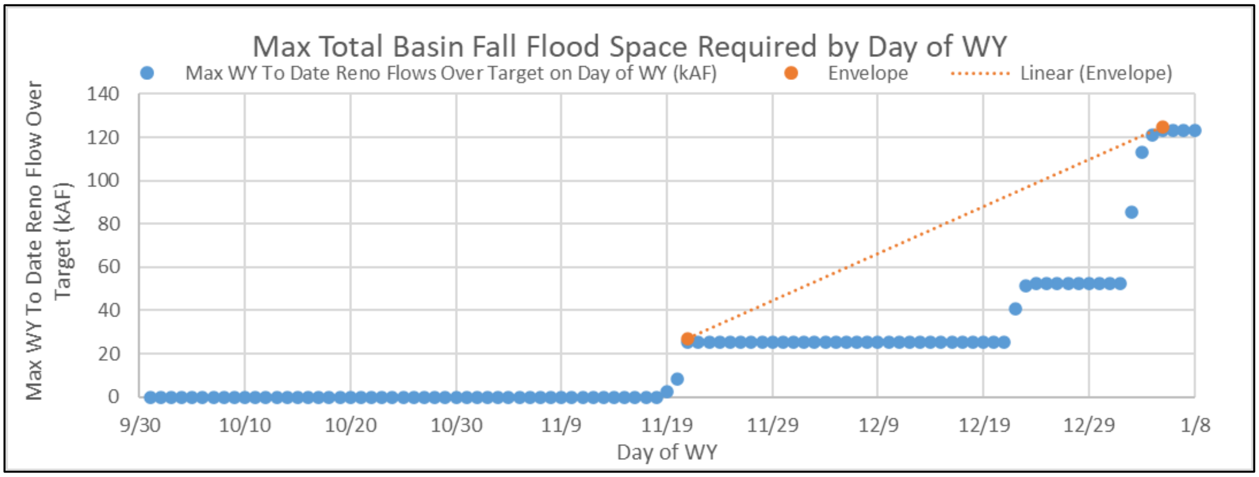

Figure 25.—Fall drawdown envelope with 6,000-cfs Reno flow target (Appendix K).

To determine the spring refill portion of the guide curve, a similar approach was taken with the maximum required flood space for each day of the water year, as determined by the remaining water year unregulated Reno flow over the flood target. In addition, the results of this calculation are grouped based on the Farad unregulated flow volume, snowmelt parameter, following the 1985 WCM. For example, Figure 26 shows the storage envelope based on the maximum remaining water year Reno flow volume over the flood target in the period of record. Similar storage envelopes were drawn for different bins of the remaining water year Farad natural flow, ranging from 50 to 600 kAF.

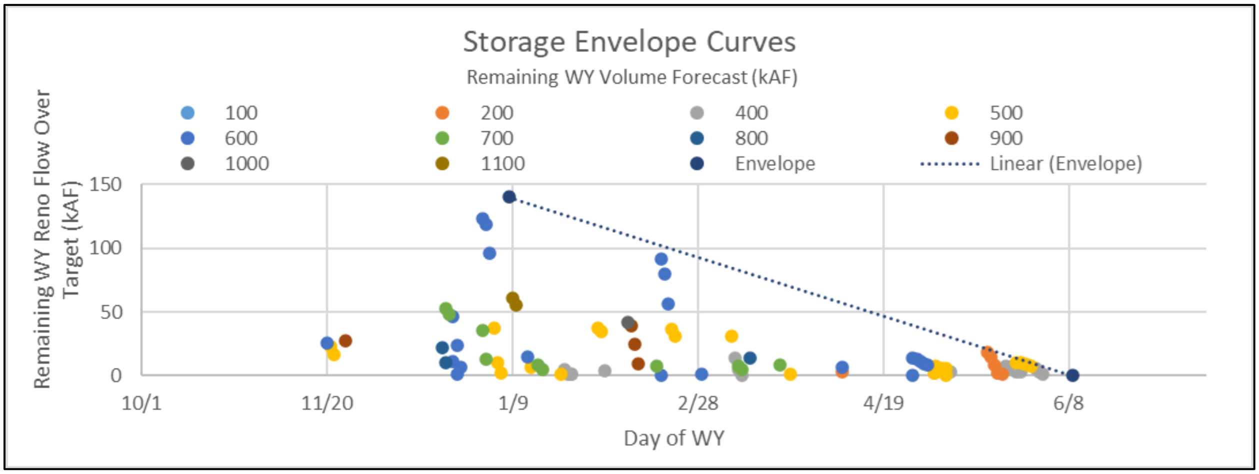

Figure 26.—Overall storage envelope with 6,000-cfs Reno flood flow target (Appendix K).

Storage Envelope Compilation in Revised dSRDs

The third step required the compilation of the storage envelopes into the revised dSRDs. This process involved superimposing all the storage envelope curves (e.g., Figure 25 and Figure 26) on the same plot. Straight line storage envelope curves were drawn to encompass the worst floods that occurred in the fall (e.g., Figure 25) and the largest floods that have occurred in the spring (e.g., Figure 26) for each remaining water year Farad natural flow bin. In any period when the historical required flood space exceeds the allocated flood space in the basin (e.g., 50,000 acre-feet without Martis and 70,000 acre-feet with Martis) the flood space in the fall and spring is limited to the basin allocated flood space to combine the fall and spring envelopes. This step resulted in dSRDs for total required flood space in the Truckee Basin.

Finally, sub-basin guide curves were determined by multiplying the total basin curves constructed in the previous step by the sub-basin's portion of the total flood space, with the y-axis coordinates representing daily total basin flood space requirements (Figure 27). This is achieved by multiplying the daily total basin flood space requirements by the ratio of each reservoir's flood space to the total basin flood space.

These aforementioned steps were repeated for five potential Reno flood flow targets: 6,000; 6,500; 7,000; 7,500; and 8,000 cfs. Each of these five sets is comprised of sub-basin revised dSRDs for Martis, Boca, and Stampede, and Prosser Reservoirs as required by the current WCM. Two sets of guide curves were developed for all flow targets; one set assuming Martis is not operational for flood control and one set assuming Martis is operational for flood control. Figure 27 and Figure 28 demonstrate the differences between the current and revised Prosser Reservoir guide curves.

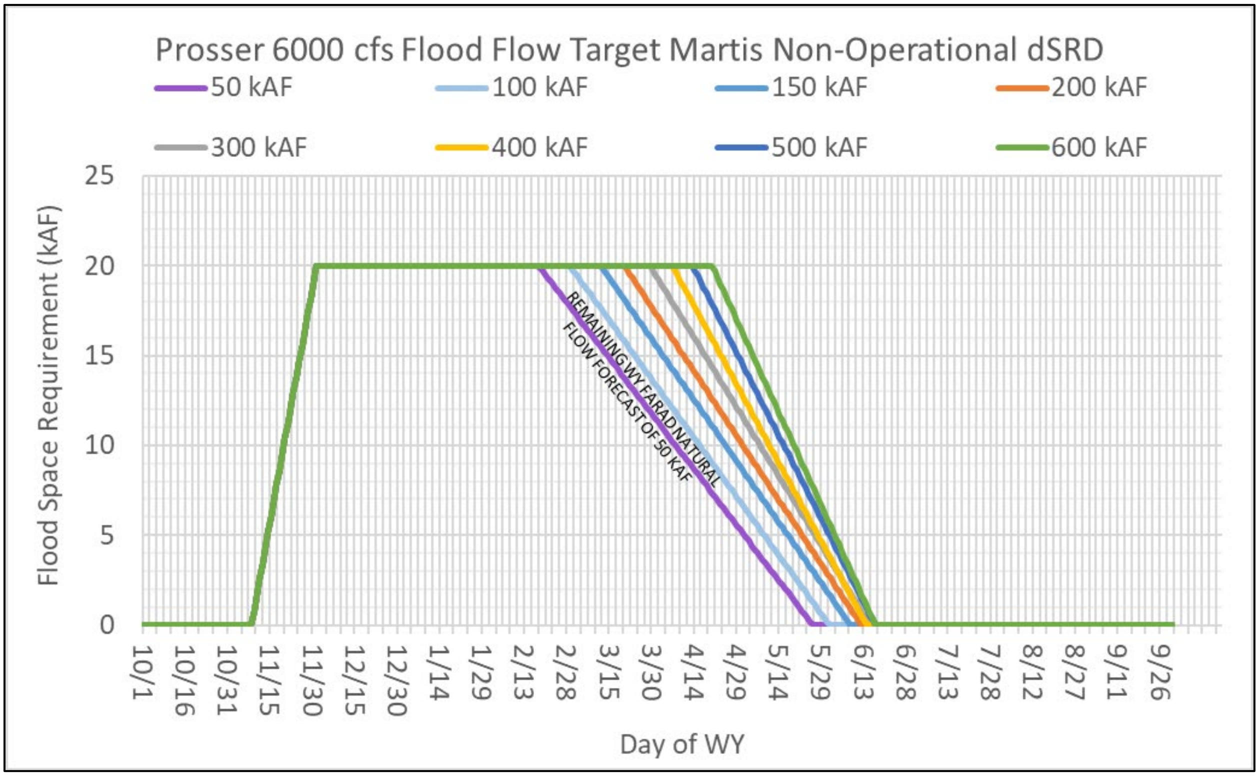

Figure 27.—Prosser revised dSRD with 6,000-cfs flood flow target showing the required flood space (flood control reservation) (y-axis, in thousand acre-feet [kAF]) based on the day of year (x-axis) and a snowmelt parameter of the forecasted remaining water year Farad natural flow (downward sloping lines from April through June, kAF) (Appendix K).[9]

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[9] Nuanced differences in appearance are apparent between the WCM and revised dSRDs. WCM guide curves' vertical axes increase from top to bottom, whereas those of revised dSRDs increase from bottom to top. Additionally, the x-axes of WCM guide curves are shown across the entire duration of the water year. On the other hand, those of the revised curves are shown through the summer. Any date not shown on the revised guide curve x-axis implies that no flood space is required for that date. These differences in appearance were approved by the Technical Team during the technical analysis phase of the project.

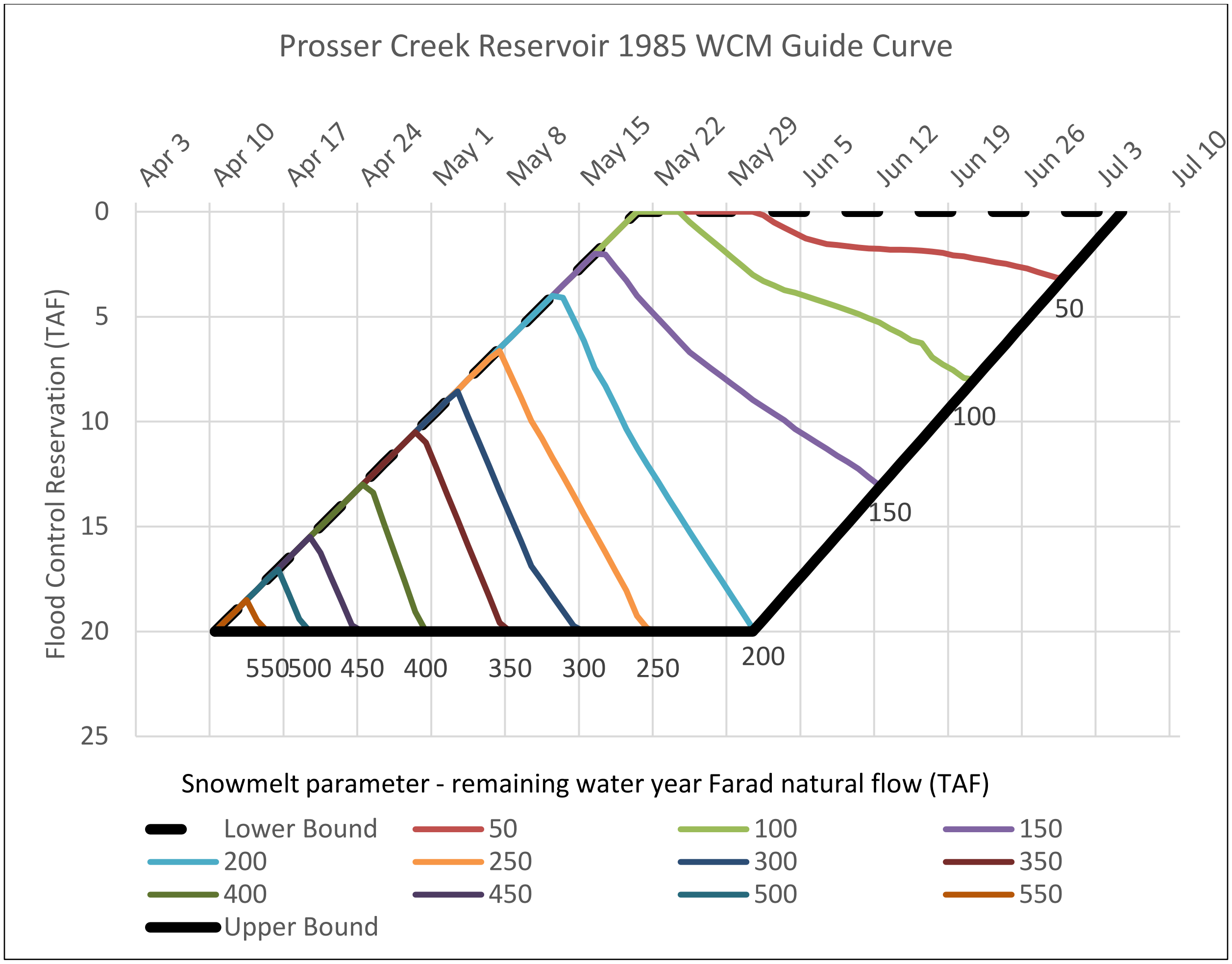


Figure 28.—Spring refill portion of the 1985 WCM Prosser dSRD showing the required flood based on the day of year and a snowmelt parameter of the forecasted remaining water year Farad natural flow (downward sloping lines from April through July) (U.S. Army Corps of Engineers, 1985).

In comparison to the 1985 WCM guide curves (e.g., Figure 28), the revised dSRDs (e.g., Figure 27) will increase fall drawdown and spring refill reservoir operational flexibility in the Truckee Basin, as follows:

1. The revised dSRDs no longer require all flood space to be available between November 1st and April 10th. There is no rationale for this current requirement discovered when reviewing the literature. This means that there may be more flexibility to fill reservoir flood space earlier in the year.

2. The earliest possible spring refill date in the revised dSRDs occurs earlier than in the current guide curve.

3. The latest possible spring refill date prescribed by the revised dSRDs occurs earlier than those required by the WCM.

4. In practice, the revised dSRDs allow some storage into existing guide curve flood space by April 1st for all downstream flow targets with a median RFC seasonal forecast of 300 kAF or less.

The updated curves were analyzed within the alternatives in the WMOP study to quantitatively and qualitatively compare what benefits, if any, existed in updating the WCM with the revised dSRDs (Bureau of Reclamation, 2021a).

Hindcast Dataset Development and Uncertainty Analysis

To increase the flexibility in the flood space requirement, the BAM method uses runoff forecasts as input data to determine flood space volumes. CNRFC regularly produces ensemble forecasts utilizing the Hydrologic Ensemble Forecasting System (HEFS). Whereas a single-value or "deterministic" forecast produces a single forecast, the HEFS produces an ensemble forecast based on a set of possible values of the forecast variables precipitation and temperature. Each runoff forecast in the ensemble is called a "trace." The short-term forecast is primarily influenced by weather forecasts from a combination of numerical weather prediction models and CNRFC forecasts. Long-term forecasts, beyond 2 weeks, are driven by historical climate patterns, which are then blended with the short-term forecast to produce an ensemble forecast out to 365 days. At the time of this report, each ensemble contained 41 traces representing historical climate data from water years 1980–2020. These traces provide information about forecast uncertainty that allows computation of the probability that a forecast runoff peak or volume will be exceeded.

To develop and assess the BAM Action Alternatives, the WMOP utilized hindcasts from the CNRFC. Hindcasts are an attempt to "replay" historical events using the most current technology and forecasting tools. Hindcasts are useful because they provide an opportunity to evaluate current forecast capabilities by comparing forecast flows to historical flows and then performing any necessary bias correction. This section describes the methodology used to develop the hindcasts and assess their uncertainty. The use of the hindcasts to develop and assess different alternatives is discussed in the "Forecast-Informed Flood Space Requirements: By-a-Model Method" section of this VA.

Hindcast Dataset Development

The hindcast development process follows the general flow of operational HEFS forecast development, which is described below and shown in Figure 29. HEFS translates an ensemble of meteorological inputs through hydrologic models to provide an ensemble of streamflow outputs. To create a meteorological ensemble, HEFS uses a Meteorological Ensemble Forecast Processor (MEFP) to statistically model the relationship between past forecasts and observations. The MEFP first calculates parameters for the statistical model based on a long and consistent record of paired forecasts and observations, using a MEFP Parameter Estimator (MEFPPE) (Figure 29). Secondly, the MEFP applies the estimated parameters to the "raw" operational forecasts from the CNRFC and/or the Global Ensemble Forecast System (GEFS) to create an equally likely meteorological ensemble time series (Figure 29). The short-term precipitation and temperature forecasts are driven by short-term weather forecasts, which are then blended with the historical weather climatology as the weather forecast skill decreases. Lastly, temperature and precipitation outputs from the MEFP are fed as inputs through hydrologic models one ensemble pair at a time, yielding an ensemble of streamflow forecasts (Figure 29).

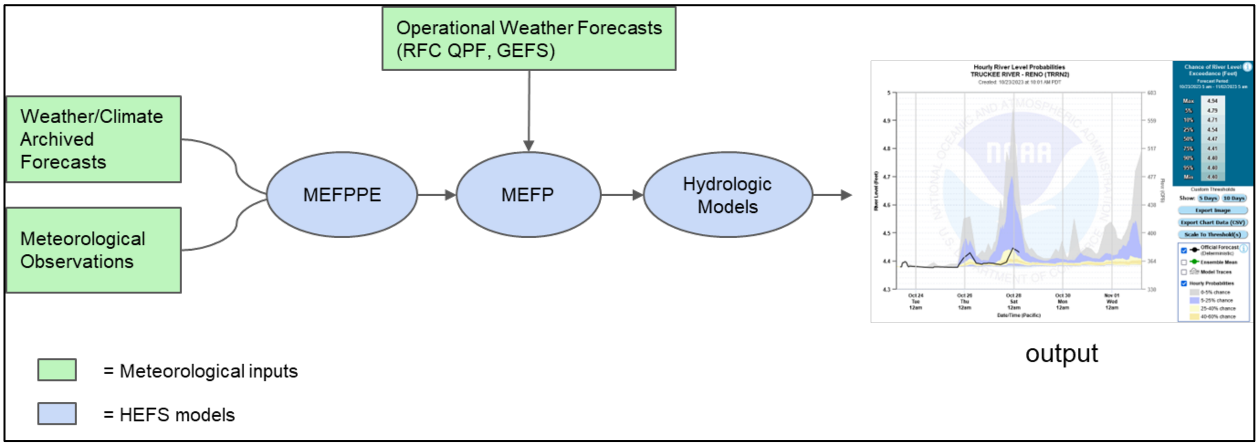


Figure 29.—Flow of the HEFS from parameter estimation to the final streamflow ensemble output (Yuba-Feather FIRO Steering Committee, 2022).

Similar to the development of ensembles forecasts using HEFS, hindcasts are generated by feeding meteorological forecasts from the GEFS to the MEFP. The ensemble forcings from the MEFP statistical models are then processed through hydrologic models initiated with antecedent conditions that represent basin conditions at the time of hindcast. For the Truckee hindcasts, the MEFP parameters were based on 1990 through 2020 GEFSv12 temperature and precipitation forecasts and the corresponding observations. The first step to generating hindcasts is to create antecedent watershed conditions for every day during the hindcast period by running the hydrologic model forced with observed historical precipitation and temperatures. Secondly, the HEFS hindcasts are processed one day at a time by processing the GEFSv12 hindcast precipitation and temperatures through the MEFP, resulting in forcing ensembles for that day. Last, the hydrologic models are initiated using the appropriate antecedent conditions, then the MEFP ensembles are processed through the hydrologic models, resulting in streamflow ensemble hindcasts for that day. The output from this hindcast process is a collection of ensemble streamflow forecasts using consistent meteorological inputs and hydrologic models.

Using the HEFS, CNRFC generated ensemble streamflow hindcasts for several locations in the Truckee Basin for the period spanning water years 1990 through 2020. Additional hindcasts were provided for the large flood event that occurred in February and March of 1986. The hindcasts include 41 traces of daily Planning Model data for a 365-day outlook and 41 traces of hourly Planning Model data for a 30-day outlook.

The hindcast Planning Model dataset includes 15 high-flow events, but the 6,000-cfs Reno flood target was only exceeded in seven of these events, providing few test cases on how the alternatives would have handled past floods (Figure 30). The average Reno unregulated flow in the historical events (denoted by solid lines in Figure 30) only exceeds the 2% exceedance flood flow (50-year flood) in two instances: the January 1997 event and May 1996 event. Thus, the historical dataset gives a limited sampling of the range of high flows that could occur in the rain and snowmelt seasons as summarized by the flood frequency analysis.

To facilitate testing the alternatives with events that matched the 1%, 0.5%, and 0.2% annual exceedance (100-, 200-, and 500-year recurrence) volumes identified by the flood frequency analysis for the rain and snowmelt seasons, CNRFC scaled up the precipitation forcing for select historical events in the hindcast to produce the desired volume, similar to the approach used when developing hindcast datasets for other FIRO projects (Yuba-Feather FIRO Steering Committee, 2022). These scale factors were then applied to the precipitation forecast to produce “scaled hindcasts” that are larger versions of the historical events. The January 1997 and February 1986 events were scaled to achieve the 1%, 0.5%, and 0.2% exceedance volumes for the rain season, and the January 2017 and May 1996 events were scaled to 1%, 0.5%, and 0.2% exceedance volumes for the snowmelt season. The simulated flow exceeded the target flow for all events, so the scaled hindcasts represent a conservative estimate of the 1%, 0.5%, and 0.2% exceedance flows.

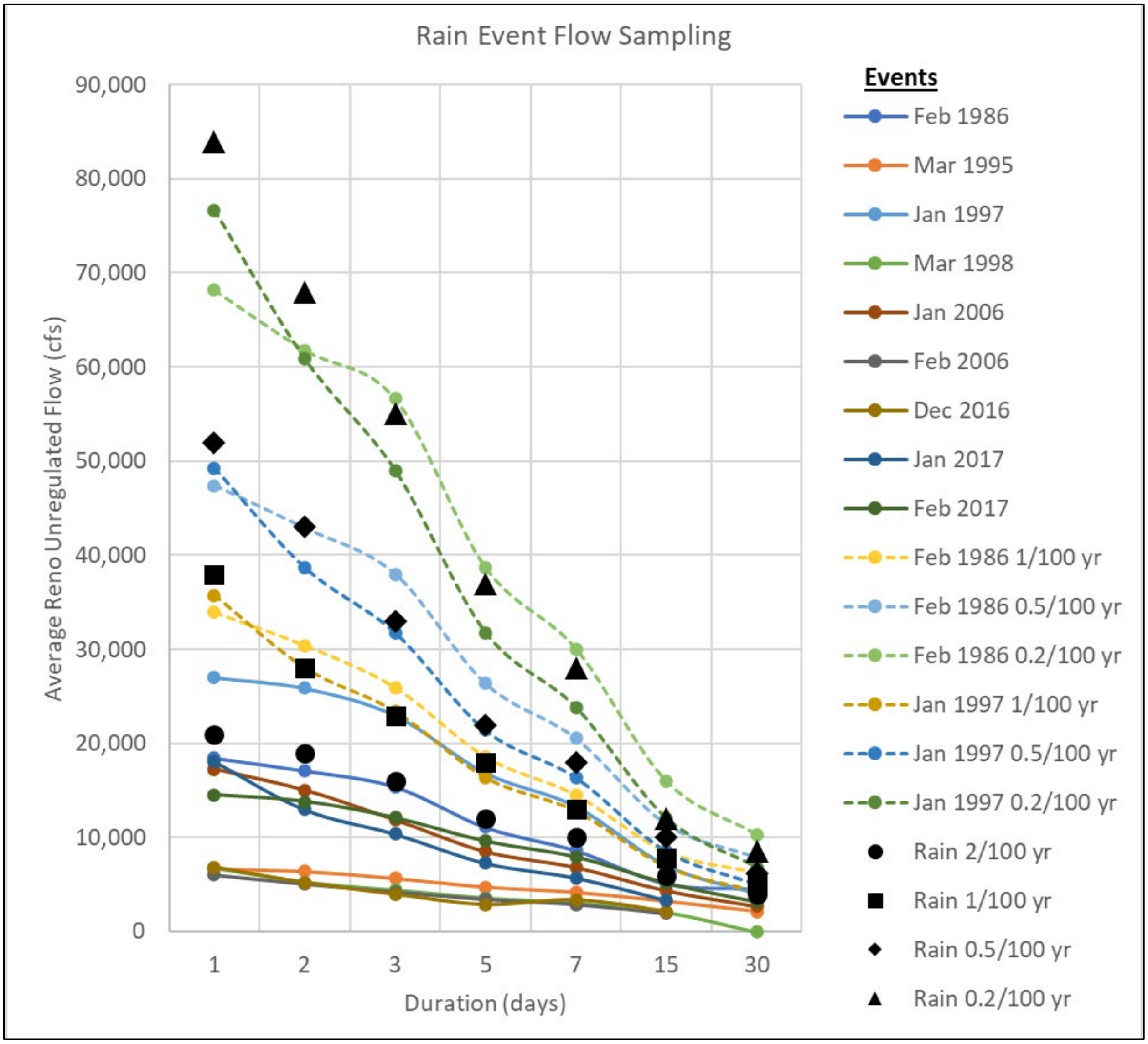


Figure 30.—Truckee River at Reno unregulated average flow for the rainy season (October through March) flood events. Solid lines denote historical flows (Lawler, 2022), dashed lines denote scaled hindcasts (Imgarten, 2022), and the black shapes denote the respective recurrence intervals (Lahde et al., 2022).

Hindcast Uncertainty Analysis

As part of the WMOP, PWRE assessed the uncertainty of the hindcasts at Farad Gage and documented the results in the report, "Inflow Uncertainty Analysis" (Appendix L). Below is an abridgment of the analysis, results, and conclusions.

Understanding and accounting for the skill of the hindcasts in the BAM method ensure that resulting flood space requirements reflect the skill of hindcasts/forecasts in the present and future. Skill is the ability of hindcasts to produce predicted flows that accurately and precisely characterize historical flows. Particularly, the WMOP assessed skill in terms of outlook and seasonality. An outlook is the number of days between the date a forecast is produced and a forecasted date. For example, a forecasted date of January 1st re-forecasting January 3rd of the same year represents the 3-day outlook. Seasonality refers to how well hindcasts predict flow volumes during some seasons relative to others. This analysis sought to answer the following questions:

1. How far in advance of an event can hindcasts accurately predict historical flow volumes?
2. How reliable are hindcasts at predicting flow volumes within certain percent exceedance ranges?
3. Are hindcasts able to predict historical volumes in certain seasons better than others?

The WMOP used five metrics to evaluate the skill of hindcasts in terms of both seasonality and outlook:

- **Ratio of Median Hindcasted to Historical Cumulative Volumes** denotes the average ratio of the median hindcasted cumulative volume and the historical cumulative volume at a specified outlook.
- **R-Squared** represents a linear regression coefficient that describes how much variability within the historical cumulative volumes is explained by the median hindcasted cumulative volumes.
- **Average Difference** denotes the difference between average historical cumulative volumes and average hindcasted cumulative volumes at the selected outlook, percent exceedance, and forecast produced dates.
- **Mean Absolute Error (MAE)** denotes the absolute value of the difference between hindcasted and historical cumulative volumes at the selected outlook, percent exceedance, and forecast produced dates.
- **Average Percent Error** denotes the difference between average historical and hindcasted cumulative volumes divided by average historical cumulative volume at the selected outlook, percent exceedance, and forecast produced dates.

An important visual, independent from the aforementioned metrics, is the Reliability Histogram. This plot helps to answer the question of how precisely hindcasts predict flow volumes within certain percent exceedance ranges. This visual describes the frequency by which hindcasted flow volumes fall within a given percent exceedance range relative to historical data, depending on the outlook, confidence interval, and forecasted dates selected. This metric evaluates how well statistics derived from the hindcast ensembles compare to observations.

The hindcast uncertainty analysis demonstrated that hindcast skill is dependent on both seasonality and outlook. In terms of seasonality, hindcasts skill is best during the runoff (spring-summer) season, in comparison to other seasons (Figure 31). This is evident by R-squared values closest to 1 in April through July. Correlation values during the run-off season generally increase over longer outlooks, likely due the increasing domination of the analysis by many days with no rain and stable inflows. Alternatively, R-squared values from October through February, during the wetter season, decrease during the short-term outlook before leveling off or increasing throughout longer-term outlooks (Figure 31).

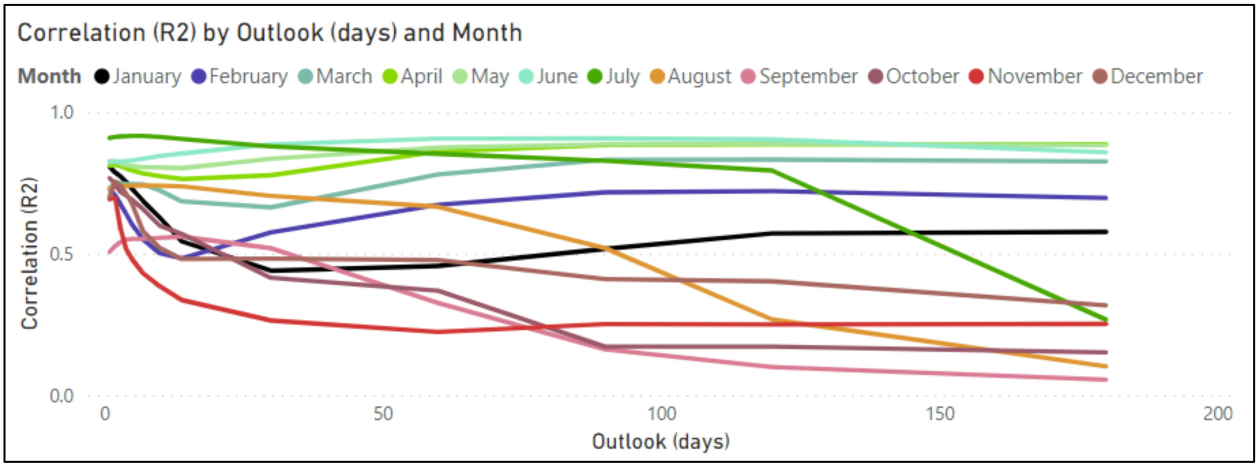


Figure 31.—Measure of accuracy of hindcasts. R-squared (R^2) coefficient of determination of median hindcast cumulative n-day outlook volumes compared to historical cumulative n-day volume (Appendix L).

Furthermore, results indicate that hindcasts are not always indicative of actual probabilities at all outlooks. In other words, results suggest that the range of forecasted volumes was outside the 10%-90% exceedance range more frequently than expected and therefore inside the 10-90% exceedance range less frequently than expected. For example, the historical 5-day cumulative Farad natural flow volume was less than the 90% exceedance volume of a hindcast 45% of the time, which is much greater than the expected 10%. Furthermore, the percentage of time the historical 5-day cumulative Farad volume was greater than the 10% exceedance was 38%, which again is much greater than the expected value of 10%. This is an expected result when compiling statistics for all events of a hindcast. During dry periods, the ensembles will have little to no spread. This will often lead to the observed flow/volume falling outside the range of ensembles as the model is not adjusted to observations during the hindcast process. The results above indicate that the bias is somewhat balanced, as opposed to systemic bias of the hindcasts to over or under forecast conditions. For more detailed information on analysis of hindcast uncertainty at different outlooks, percent exceedance, and forecast produced dates, refer to the report, *Inflow Uncertainty Analysis* (Appendix L).

Other FIRO studies found similar levels of uncertainty in hindcasts, although the use of different metrics makes direct comparison difficult (Yuba-Feather FIRO Steering Committee, 2022) (Jasperse et al., 2020; Ralph et al., 2021). For example, in the Lake Mendocino watershed, R^2 values fall off quickly for longer outlooks during the cool season (October to April) (Figure 32) (Jasperse et al., 2020), similar to the results of the hindcast uncertainty analysis performed in the Truckee Basin. In addition, the Prado Dam Preliminary Viability Assessment noted that operational HEFS forecasts are likely to be more skillful than the HEFS hindcasts (Ralph et al., 2021), as is also the case for the Truckee hindcasts. This results from the opportunity to tune model states and data before a forecast is generated, whereas hindcasts process the hydrology models without the benefit of review and tuning. In addition, the operational HEFS ensembles use the Hydrometeorological Analysis and Support quantitative precipitation forecasts that are more skillful than the GEFS forecasts (Ralph et al., 2021). As a result, real-time operational forecasts are likely to perform better than hindcasts due to this improved forecast skill and the ability to adjust the hydrologic models to observations in real-time.

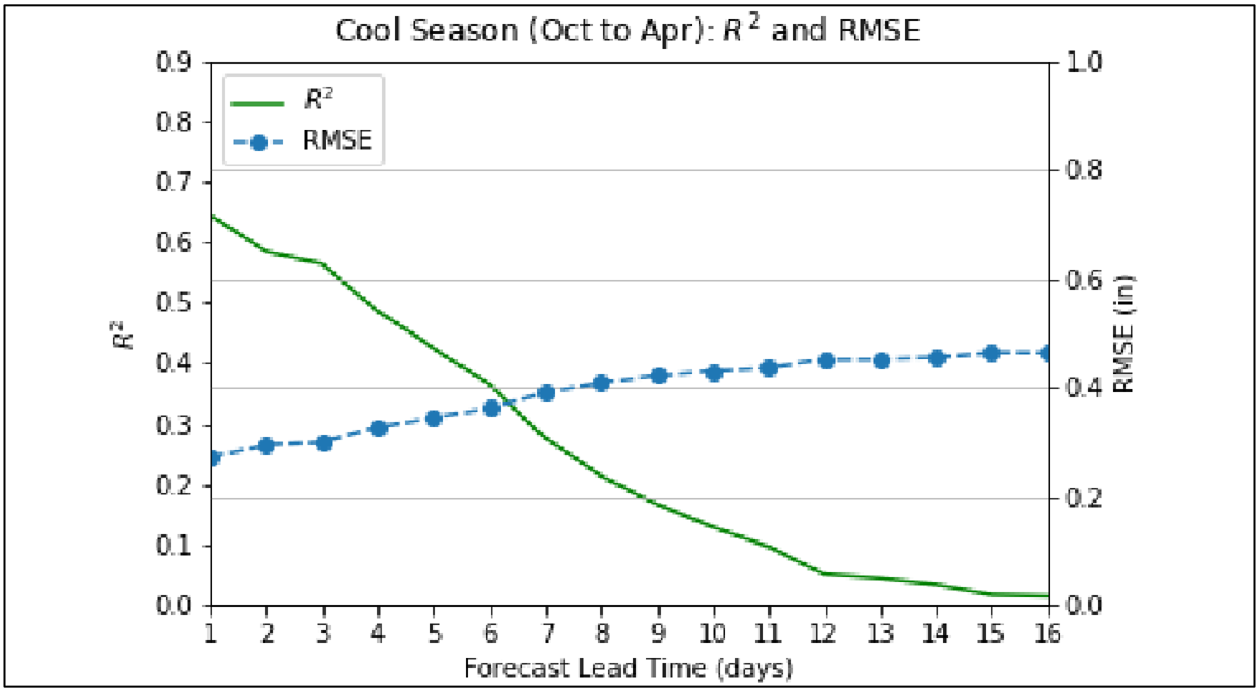


Figure 32.—1985–2010 GEFSv10 6-hour ensemble mean precipitation R^2 and root mean squared error (RMSE) in inches for the Lake Mendocino watershed (Jasperse et al., 2020).

To better account for hindcast skill within the BAM method, the Technical Team bias-corrected the hindcasts using the range adjustment method, similar to the method used regularly by the USWM in Reno, Nevada to adjust CNRFC forecasts to match the NRCS runoff volume forecasts. The bias correction method compares observed values to the ranges of CNRFC hindcast traces and identifies the frequencies that the observed is with the 10%-90% exceedance interval. The range of traces is then expanded and/or shifted so that the observed values land between 10–90% exceedance range, the expected frequency of the time (i.e., 80% of the time). For example, in Figure 33 the Unscaled Volume line represents the unscaled exceedance distribution for the 14-day Farad natural flow volume seen in the ensemble traces for the hindcast produced for March 24, 1986, and the Scaled Volumes line represents the bias-corrected distribution for the same day (refer to Appendix M for a more detailed explanation of the bias correction methodology).

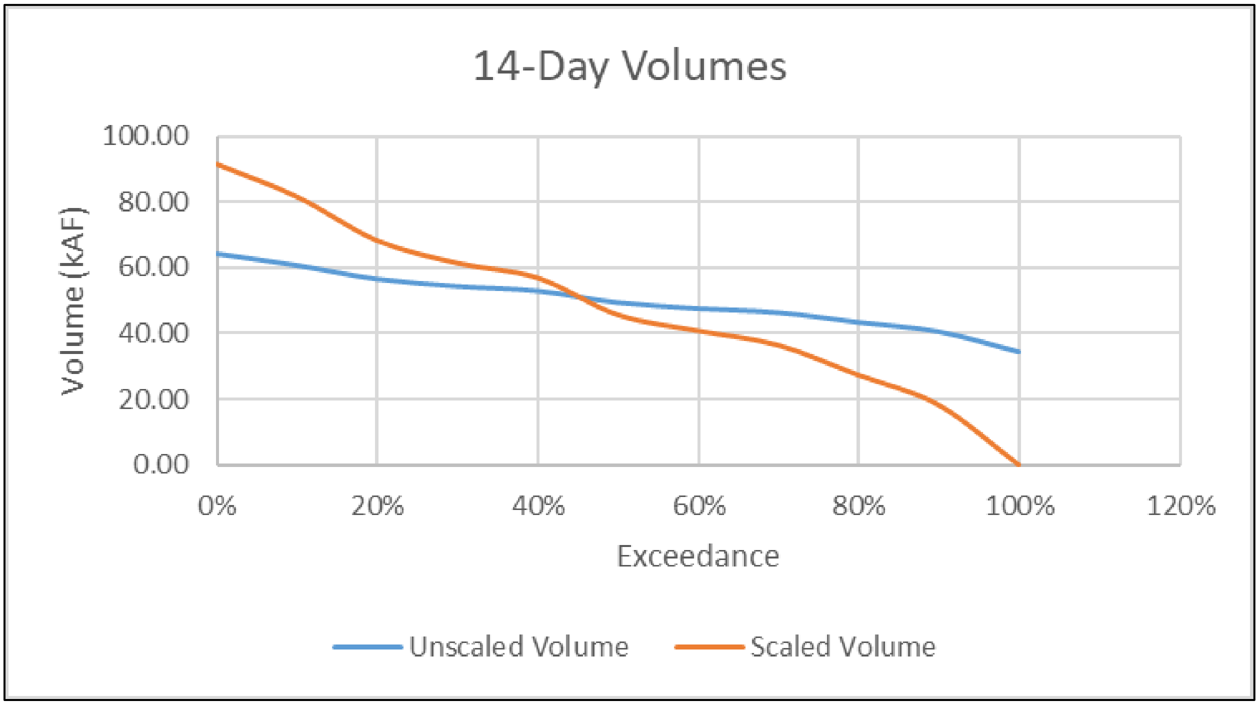


Figure 33.—Bias-correction example of 14-day Farad natural flow volume (Appendix M).

A major benefit of employing the bias correction is that it introduces flexibility to the BAM method to adapt to future improvements in forecasting technology to either better represent the range of possibilities or improve the accuracy. More specifically, improvements made to forecasting technology could be incorporated into the BAM method after completing an updated hindcasting effort and revising the *Inflow Uncertainty Analysis* (Appendix L) using the updated hindcasts. The BAM method balances the relationship between forecasting skill and acceptable flood risk in determining flood space requirements in the Truckee Basin, as described in the following section.

Forecast-Informed Flood Space Requirements: By-a-Model Method

As part of the WMOP, PWRE documented the methods employed to model the alternatives to the WCM in the reports, "Multi-Objective Evolutionary Algorithm (MOEA) Tool Utilization and Development" (Appendix N) and "Action and Alternative Operational Scenario Modelling in the WMOP" (Appendix M). Below is an abridgment of the analysis, results, and conclusions.

Four of the Action Alternatives use the BAM method to determine flood space requirements during reservoir refill and/or fall drawdown. The WMOP employed an MOEA and runoff hindcasts to develop the BAM method. The results of the MOEA helped inform decisions related to:

- How can forecasts be leveraged to ensure sufficient flood space is reserved?
- What percent of the flood space should be determined based on forecasts? (Conversely, what percent of the guide curve's flood space should be exclusively reserved?)
- What portion of the flood space in the Little Truckee River should be maintained in Boca Reservoir?
- What are the tradeoffs between the objectives to maximize water supply, flood risk management, and environmental flows?

This section provides background on MOEAs more generally and details the one that was employed in the WMOP to build out the Action Alternatives.

MOEAs form an innovative decision-making framework that can identify the best compromise solutions given a set of multiple, often competing, objectives. Instead of just seeking a single best solution, these algorithms aim to identify a set of solutions that represent different trade-offs between the objectives. MOEAs can help balance and explore various possible solutions to find the best compromise among multiple criteria. The WMOP employed an MOEA to develop and evaluate tradeoffs between alternatives to the 1985 WCM guide curves—the MOEA adjusts the alternatives' parameters to meet the study objectives while staying within the study constraints.

A few pieces of terminology are key to understanding how the MOEA works (Figure 34). Central to the MOEA is the **function**, or equation/model that is undergoing optimization. **Decision variables** are input to the function by the MOEA—these represent the parameters that the MOEA will optimize. **Objectives** are output from the function and represent the performance of the function given an input set of decision variables.

The BAM method uses CNRFC forecasts to determine the amount of flood space needed to store the forecasted flows without exceeding the downstream flood target(s), building off equation 4 used to determine the required flood space in the dSRDs. The key difference is that the I_t variable in the equation takes on values for *forecasted* unregulated flow in Reno, rather than the observations used to develop the dSRDs (equation 4, Figure 24). The BAM method calculates equation 4 for each of the traces in the CNRFC ensemble forecasts, rather than just using one observed flow value per day. Further, equation 4 is summed over an outlook period, t_f, from the day of interest to ensure that sufficient flood space is reserved to store the forecasted flow above the target, some number of days in advance (outlook).

1. Decision Variables:	**2. Function:**	**3. Objectives to maximize:**
• Shape of exceedance-outlook curve • % of Flood Space in Boca • % of Revised Guide Curve to Reserve	Run the Planning Model Dataset through the operational scenario characterized by the decision variables, where: $RFS = \sum_{t=0}^{t_f} \max(I_t - T_{Reno}, 0)$	• Water supply • Flood risk management • Environmental flows

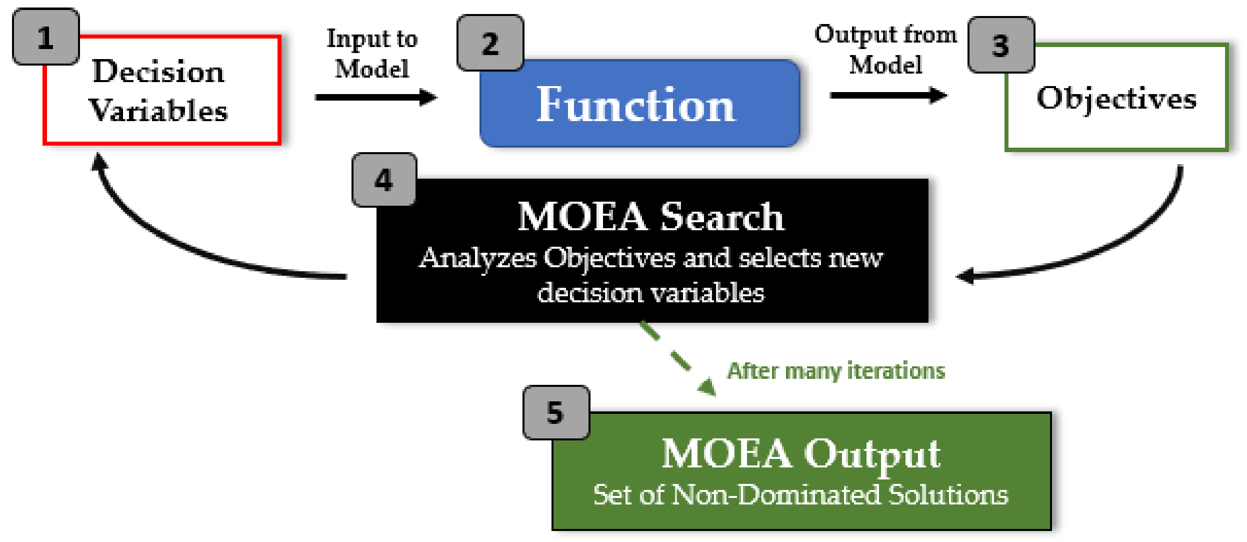


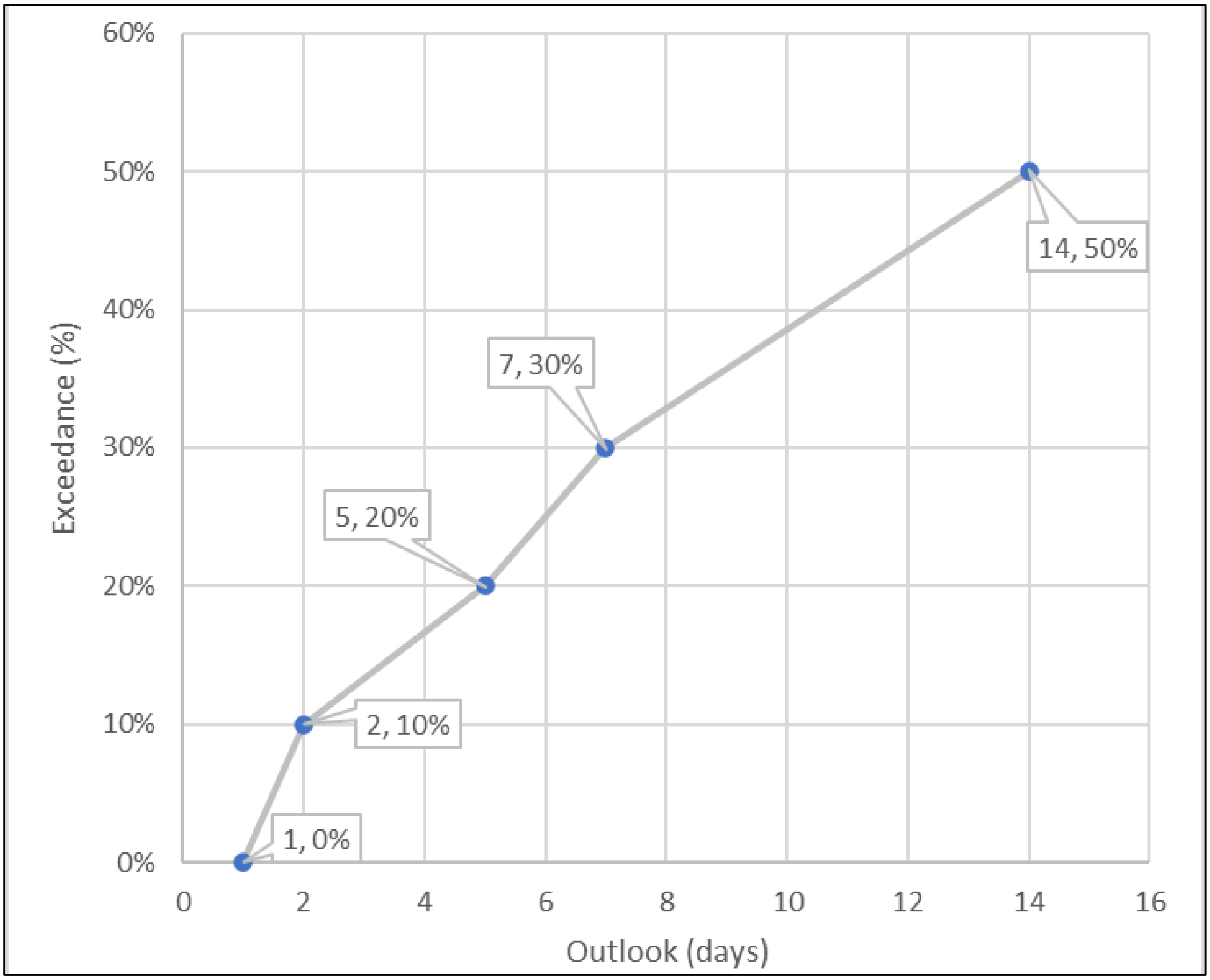
Figure 34.—Interactions between the five main components of the MOEA (Noe and Erkman, In review).

To provide a simplified example, assume a hindcast for a given day is composed of 10 traces. Equation 4 is applied to each trace of this hindcast at outlooks of 1, 2, 5, 7, and 14 days resulting in the cumulative storage over the flood flow target summarized in Table 14. Note implementation of the BAM method in the WMOP Study included outlooks up to 365 days to incorporate runoff information contained in forecasting into the methodology.

Table 14.—Example of Applying the Cumulative Storage Over Flood Flow Target Calculation to a Hindcast Ensemble and BAM Calculation of Required Flood Space Based on the Exceedance-Outlook Curve in Figure 35 (Noe and Erkman, In review)

		Outlook 1-day	Outlook 2-day	Outlook 5-day	Outlook 7-day	Outlook 14-day
Cumulative storage over flood flow target (acre-feet)	**Trace 1**	0	0	5,000	15,000	15,000
	Trace 2	0	1,000	4,000	10,000	11,000
	Trace 3	100	1,500	3,000	12,000	12,000
	Trace 4	0	0	2,000	12,500	12,700
	Trace 5	0	0	2,000	12,500	12,500
	Trace 6	0	200	3,000	11,500	11,500
	Trace 7	50	100	1,000	10,000	10,000
	Trace 8	500	2,000	5,000	6,000	7,000
	Trace 9	0	500	1,500	11,500	11,500
	Trace 10	0	0	0	10,000	11,000
Exceedance from exceedance-outlook curve		0%	10%	20%	30%	50%
Required flood space at exceedance (acre-feet)		500	1,550	4,200	12,150	11,500
					BAM required flood space	

The exceedance probability for a particular outlook and forecast can be computed by determining the volume that is exceeded by the desired percentage of traces. For example, in Table 14, for the 2-day outlook, 2 of the 10 traces exceed 1,000 acre-feet so there is a 20% chance that the required flood space will exceed 1,000 acre-feet in the next 2 days. For the 14-day outlook, 9 of 10 traces exceed 8,000 acre-feet so there is a 90% chance that the required flood space will exceed 8,000 acre-feet in the next 14 days. The BAM method uses an exceedance-outlook curve to select what hindcasted cumulative storage over flood flow target should be considered at every outlook period to determine the flood space requirement (Figure 35). For example, based on Figure 35, at the 1-day outlook, the most conservative (i.e., largest) forecasted volume for flood space requirements should be considered, i.e., 500 acre-feet; at the 7-day outlook, the 30% exceedance of the 7-day cumulative storage over flood flow target should be considered in the determination of the flood space requirement (Figure 35 and Table 14). The model takes a more conservative approach with shorter outlooks because there is more skill in a forecast and less time to react. As such, higher exceedance probabilities are used further out in the forecast (Figure 35). In other words, more forecast traces need to agree to require the reservation of more flood space for longer outlook forecasts. The risk assessment portion of the BAM method boils down the results of the cumulative storage over flood flow target to a single, refined flood space requirement by selecting the maximum required flood space by outlook (Table 14). In Table 14, this is associated with the required flood space calculated for the 7-day outlook of 12,150 acre-feet.



$$Exceedance = C + A(Outlook)^B$$

Figure 35.—Example exceedance-outlook curve characterize by coefficients A, B, and C. By constraining the B coefficient to values greater than 0, the resulting exceedance percentage will increase as a function of outlook. Thus, for smaller outlooks, more conservative flood space requirements should be implemented (Noe and Erkman, In review).

MOEAs vary the **decision variables** to optimize multiple **objectives**. The BAM method attempts to maximize **objectives** for water supply, flood risk management, and environmental flows. It does this by varying the following five parameters, or **decision variables**:

- Shape of the exceedance-outlook curve (Exceedance Coefficients A, B, and C): Three of the decision variables define the shape of the exceedance-outlook curve (Figure 35).

- Portion of Flood Space in Boca: The MOEA allows for re-proportioning the 30,000 acre-feet of joint flood allocation between Boca and Stampede Reservoirs, whereas the WCM currently requires Boca to reserve at least 8,000 acre-feet. This decision variable determines the portion of Little Truckee flood space allocated to Boca versus Stampede Reservoir.

- Percentage of Revised Guide Curve to Reserve: This variable adds a safety factor to the BAM method. The BAM method applies a minimum value to the required flood space calculation (equation 4). That is, the required flood space, will always be at least as large as a percentage of the flood space reserved in the Revised Guide Curve, as described in the following section. Thus, a larger Percentage of the Revised Guide Curve to Reserve represents a more conservative approach to incorporating forecasts into the required flood space calculation.

As the MOEA runs, the MOEA Search Algorithm intelligently selects new values of decision variables (Step 4, Figure 34) to evaluate in the function (Step 2, Figure 34) by learning the relationship between decision variables and objective performances (Step 3, Figure 34).

In other words, the MOEA uses a set of decision variables (Step 1, Figure 34) to determine flood space requirements that characterize an operational scenario. It then uses the Planning Model to assess the performance of that operational scenario over the 37-year model run (Step 2, Figure 34) in terms of a set of objectives (Step 3, Figure 34). Last, the MOEA varies the decision variable in a way it believes will increase the performance in one or more objectives, without decreasing the performance in another objective (Step 4, Figure 34) and repeats the process. The MOEA used in the WMOP developed roughly 2,000 iterations of decision variables and evaluated their performance relative to the objectives for water supply, flood risk management, and environmental flows.

The result of the MOEA is a set of **non-dominated solutions**. In a non-dominated solution, no objective can be further improved without a cost, or tradeoff, to another objective, e.g., it is not possible to increase water supply or environmental flows without increasing flood risk. In contrast, a dominant solution is one in which an objective can be improved without a cost to the performance of other objectives, i.e., a win-win situation. The collection of non-dominated solutions that result from the MOEA is referred to as a **Pareto-front**. These concepts are illustrated in Figure 36, where the objectives are to minimize both x and y values.

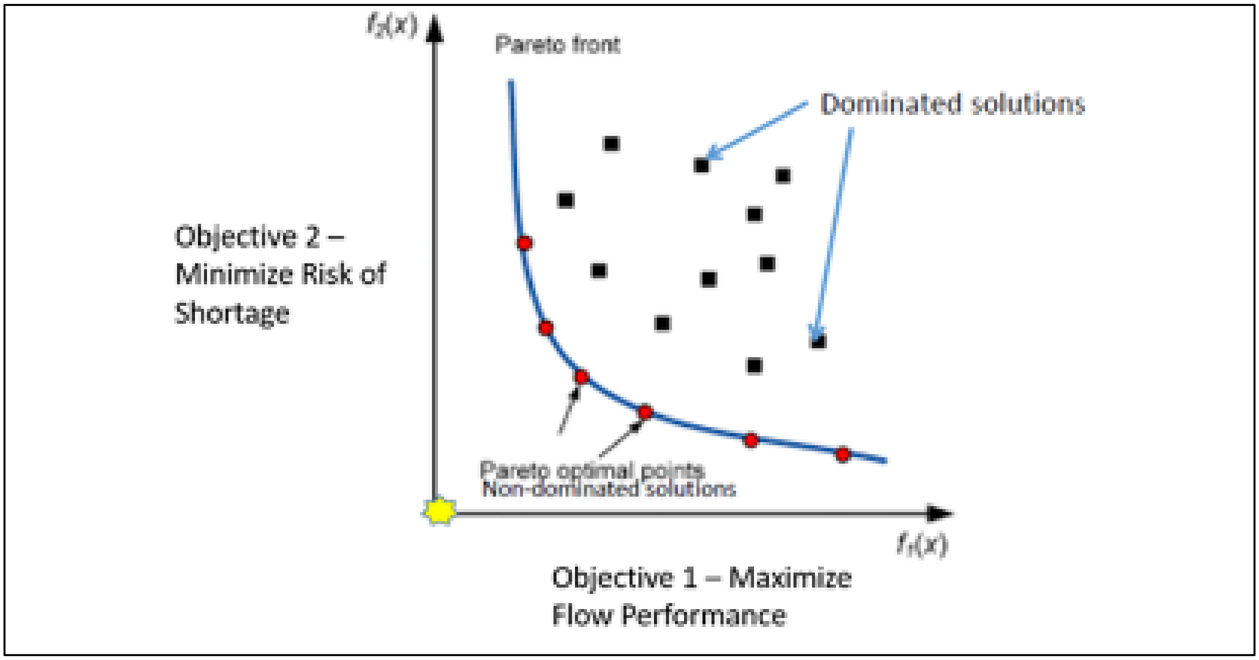


Figure 36.—Illustration of 2D Pareto-front and non-dominated versus dominated solutions (Noe and Erkman, In review) adapted from the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES, 2019). Note all objectives were coded so that lower numbers, or the bottom left corner of the graph, represent more optimal solutions.

The MOEA in the WMOP Study used the NSGA-II evolutionary algorithm. This algorithm was selected for the study because it is well-established and successful in civil engineering applications, it does not require additional complicating input to the analysis required for other algorithms, and it allows for parallel function evaluations (i.e., efficiency in run time).

The MOEA provided a holistic technical framework to thoroughly explore a set of alternatives to the 1985 WCM that determine flood space based on forecasted stream flow ensembles. The MOEA solutions vary in the Portion of Flood Space in Boca, the Percentage of Revised Guide Curve to Reserve, and the shape of the exceedance-outlook curve, i.e., what exceedance forecasted flow to consider when determining flood space a certain number of days in advance. Quantifying the tradeoffs of the study objectives allowed the Key Stakeholders to compare forecast-informed alternatives to the WCM. Ultimately, the MOEA analysis facilitated a discussion amongst the Key Stakeholders on the best-performing, or optimal, forecast-informed alternative.

Four Action Alternatives use the selected BAM method. BAM:All and BAM:All $^{+}$Flood (Alternatives 2 and 3) use the BAM method to determine flood space during fall drawdown, normal winter operations, and spring refill. BAM:Spring (Alternative 5) only uses the BAM method during spring refill, and BAM:Var (Alternative 6) limits use of the BAM method to a certain portion of flood space, dependent on the water year Farad natural flow.

Importantly, this method was also designed so that any future advances in forecasting technology would seamlessly integrate into the determination of flood space requirements.

Evaluation of Alternative Operational Scenarios

As part of the WMOP, PWRE documented the process by which the Technical Team evaluated and compared alternative regulation criteria to determine a Preferred Operational Scenario in the report, "Preferred Operational Scenario Selection Process" (Appendix O). Below is an abridgment of the analysis, results, and conclusions.

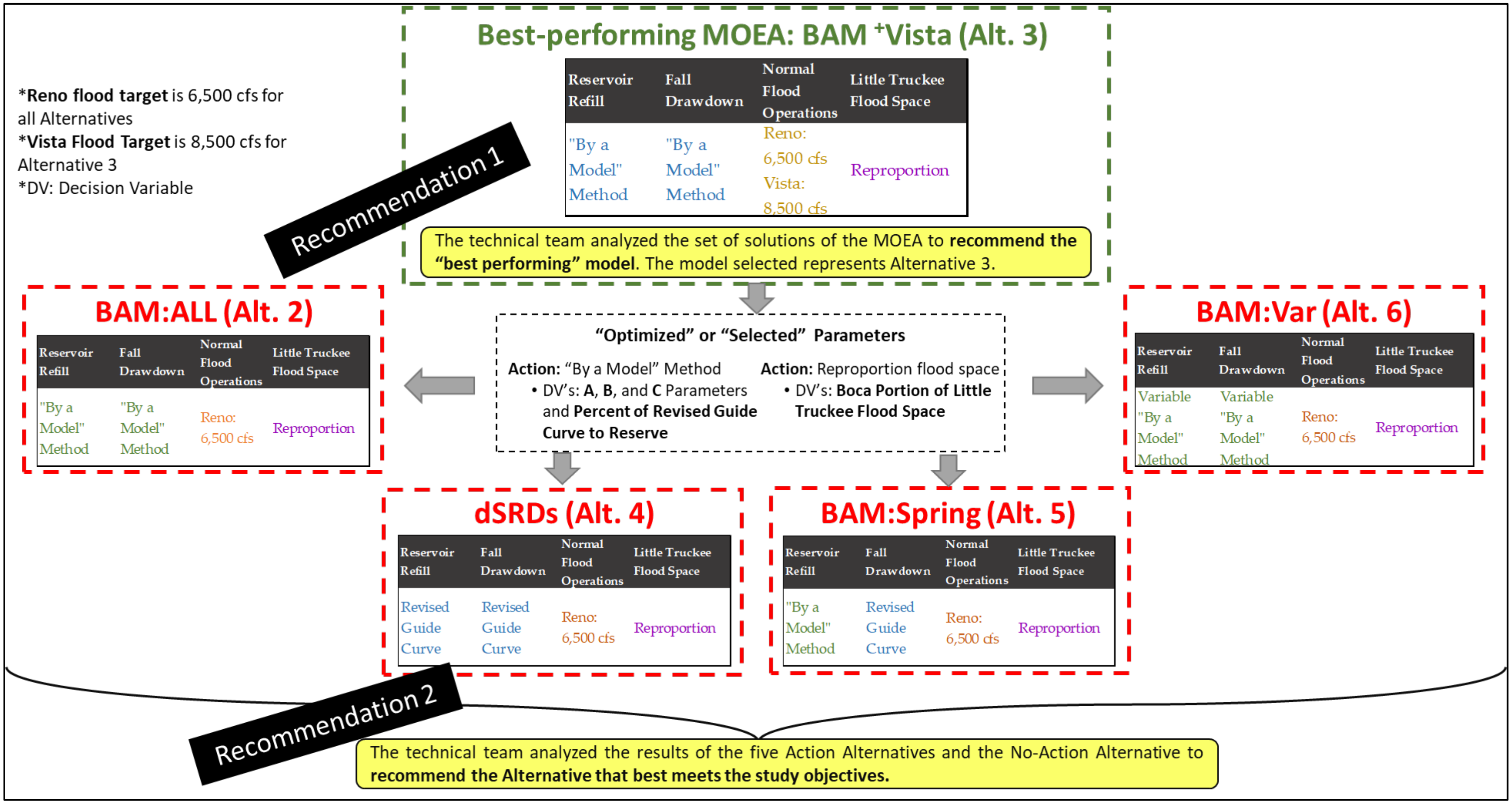
The process to evaluate the Alternative Operational Scenarios and select a Preferred Operational Scenario tied together all of the pieces of the WMOP up to that point. The Alternative Selection Process entailed multiple remote sessions with the Technical Team, some of which also included the larger group of Key Stakeholders, as well as two in-person, multi-day workshops.

In the two-part decision process, the Key Stakeholders first decided upon the Best-Performing MOEA Scenario and secondly, selected the Preferred Operational Scenario (Figure 37). The MOEA Scenarios represent Alternative 3 (BAM $^{+}$Vista), which incorporates the BAM method throughout the flood season and includes additional flood criteria at Vista. In the first decision, the Technical Team evaluated the non-dominated MOEA solutions to determine the Best-Performing MOEA Scenario to represent Alternative 3. In doing so, the Technical Team also "optimized" parameters used in some of the other Action Alternatives, including the Boca Portion of Little Truckee Flood Space, the Percentage of Revised Guide Curve to Reserve, and the shape of the exceedance-outlook curve.

Once all the alternatives were modeled with the best-performing set of decision variables, the Key Stakeholders evaluated the quantifiable and non-quantifiable objectives to select a Preferred Operational Scenario. The Technical Team developed a set of evaluation criteria at the outset of the project, making slight modifications along the way. This section describes the evaluation criteria, the results of applying those criteria to evaluate the performance of the MOEA Scenarios and Alternative Operational Scenarios, and how the Key Stakeholders interpreted those results to select the Preferred Operational Scenario for the WMOP.

Given the large volume of data output by the technical analysis, it was essential to develop a decision-making framework to decide (1) the Best-Performing MOEA Scenario and (2) the Preferred Operational Scenario (Figure 37), as documented in the following section.

Of note, the Key Stakeholders undertook the Preferred Operational Scenario selection process twice, due to an error in the MOEA code detected during a technical review after the first workshop to select a Preferred Operational Scenario (March 2023). After correcting the error and conducting additional quality control, PWRE re-ran the MOEA, and the Preferred Operational Scenario selection process was undertaken again with the updated results (June 2023). The same selection process (Figure 38) was undertaken on both occasions, with only slight modifications to avoid repetition. Further, due to the similarity in results and objectives scores before and after the coding error was remedied, the Key Stakeholders reached the same decision on the Preferred Operational Scenario. Due to these similarities, this section focuses on the second selection process, with the corrected MOEA code.



***Reno flood target** is 6,500 cfs for all Alternatives
***Vista Flood Target** is 8,500 cfs for Alternative 3
*DV: Decision Variable

Best-performing MOEA: BAM $^{+}$Vista (Alt. 3)

Reservoir Refill	Fall Drawdown	Normal Flood Operations	Little Truckee Flood Space
"By a Model" Method	"By a Model" Method	Reno: 6,500 cfs Vista: 8,500 cfs	Reproportion

The technical team analyzed the set of solutions of the MOEA to **recommend the "best performing" model**. The model selected represents Alternative 3.

BAM:ALL (Alt. 2)

Reservoir Refill	Fall Drawdown	Normal Flood Operations	Little Truckee Flood Space
"By a Model" Method	"By a Model" Method	Reno: 6,500 cfs	Reproportion

"Optimized" or "Selected" Parameters

Action: "By a Model" Method
- DV's: **A**, **B**, and **C** Parameters and **Percent of Revised Guide Curve to Reserve**

Action: Reproportion flood space
- DV's: **Boca Portion of Little Truckee Flood Space**

BAM:Var (Alt. 6)

Reservoir Refill	Fall Drawdown	Normal Flood Operations	Little Truckee Flood Space
Variable "By a Model" Method	Variable "By a Model" Method	Reno: 6,500 cfs	Reproportion

dSRDs (Alt. 4)

Reservoir Refill	Fall Drawdown	Normal Flood Operations	Little Truckee Flood Space
Revised Guide Curve	Revised Guide Curve	Reno: 6,500 cfs	Reproportion

BAM:Spring (Alt. 5)

Reservoir Refill	Fall Drawdown	Normal Flood Operations	Little Truckee Flood Space
"By a Model" Method	Revised Guide Curve	Reno: 6,500 cfs	Reproportion

The technical team analyzed the results of the five Action Alternatives and the No-Action Alternative to **recommend the Alternative that best meets the study objectives.**

Figure 37.—Summary of the Alternative Operational Scenarios modeling. Parameters of Alternative 3 (BAM $^{+}$Vista) were optimized using an MOEA and then utilized to model Alternatives 2, 4, 5, and 6 (Appendix O).

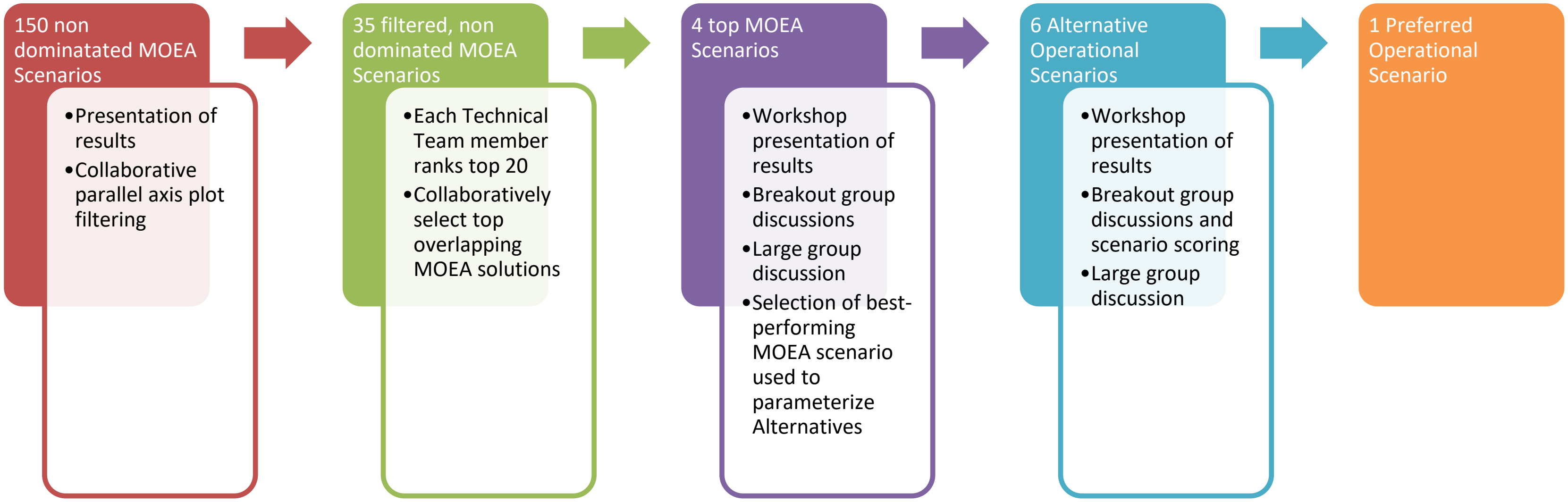


Figure 38.—Preferred Operational Scenario selection process.

Evaluation Criteria

As mentioned previously, during the plan formulation the Key Stakeholders defined a set of quantifiable and non-quantifiable project objectives through which to evaluate the alternatives' performance relative to the WMOP's goals (Table 6). Developing calculations for the quantifiable objectives allowed for:

- Optimizing the decision variables in the BAM method,
- Evaluating the performance of alternatives, and
- Making comparisons between alternatives.

Calculations were designed to accurately quantify the alternative's performance in the objectives using a single number for each objective. This set of quantifiable objectives along with the non-quantifiable objectives, described subsequently, played a significant role in selecting the Preferred Operational Scenario.

Quantifiable Objectives and Metrics

To reduce the complexity of comparing the alternatives, the Key Stakeholders narrowed the list of objectives in Table 6 down to five quantifiable objectives that still capture the goals of the original objectives conceived during the WMOP plan formulation:

- **Average Annual Volume for Floriston Rate**.—A measure of ability to meet demands for municipal, agricultural, industrial, ecological, and hydropower uses.

- **Average Annual Prosser, Boca, and Stampede Storage**.—A measure of ability to meet water demands and of flexibility in meeting those demands.

- **Average Annual Volume for Flow Regime**.—A measure of ability to meet environmental flow demands in the lower basin.

- **Root Mean Squared (RMS) Flow Over Flood Target**.—A measure of ability to mitigate flood risk.

- **Average Daily Increase in Flood Space Requirement**.—A measure of operational challenges due to large daily increases in flood space requirements and potentially abrupt increases in downstream flows (flashiness).

To balance the desire for a manageable set of objectives, as well as the need to comprehensively understand the performance of each alternative, the Technical Team also developed a set of Supplemental Metrics. The following subsections describe each of the quantifiable objectives, their respective calculations, and their relationship to the objectives from the plan formulation.

Average Annual Volume for Floriston Rate

The Annual Average Volume for Floriston Rate objective computes the average annual volume of water used to meet the Floriston Rate Target plus the change in storage that occurred over the 37-year model run. The Floriston Rate is the required average daily flow rate at the Farad Gage near the California-Nevada border, intended to ensure secure water to serve hydroelectric power generation, municipal and industrial use in Truckee Meadows, environmental flows, and numerous agricultural water rights. This objective is designed to quantify how well an alternative maximizes the Floriston Rate in the system (Objective 1, Table 6).

Average Annual Prosser, Boca, and Stampede Storage

The Average Annual Prosser, Boca, and Stampede Storage objective calculates the average combined daily storage in the three active flood control reservoirs during a model run. This objective indirectly characterizes an alternative's performance at maximizing the flexibility of timing of reservoir drawdown and the ability to refill reservoirs (Objectives 2 and 3, Table 6). Conceptually, more storage in reservoirs provides the TROA parties and water managers more flexibility to better meet their objectives. Secondarily, this objective helps to quantify how well an alternative optimizes storage to satisfy water demands throughout the year (Objective 10, Table 6). Importantly, alternatives will perform better in this objective if the reservoirs refill earlier; conversely, alternatives that fill the reservoirs, but later, will perform worse in the objective score. However, a later refill is not necessarily indicative of a lower ability to meet summer water demands.

Average Annual Volume for Flow Regime

The Average Annual Volume for Flow Regime objective computes the average annual volume at the Nixon Gage limited to the Flow Regime Target plus the change in PLPT storage over the model run. This objective is designed to quantify how well an alternative improves environmental flows downstream of reservoirs (Objective 4, Table 6). Alternatives can achieve higher scores in this objective when (1) the alternative met higher Flow Regime Targets, (2) the Flow Regime Targets were met more often, or (3) PLPT ended the alternative run with more water in storage. Each of these cases benefit downstream environmental flows.

Root Mean Squared Flow Over Flood Target

The RMS Flow Over Flood Target objective quantifies how well an alternative reduces the risk of flooding downstream of the flood control reservoirs (Objective 5, Table 6). This objective is calculated using the equation:

Calculation for Root Mean Squared Flow Over Flood Target: Equation 5

$$RMS\ Flow\ Over\ Target = \sqrt{\sum(Reno\ Flow_t - Flood\ Target\ Flow)^2, 0)}$$

The calculation occurs at an hourly timestep throughout an entire model run and assesses the magnitude of flows at the Reno Gage above the flood flow target, set to 6,500 cfs for evaluating alternatives. This objective captures the effects of flood damages associated with the following:

- **Peak Flows**.—Peak flow is the primary indicator of flood damage, and in the calculation, higher flows penalize this objective more due to the squared term in equation 5.
- **Duration of Inundation**.—Sustained flood flows over the target can also contribute to damage as sustained high flows deplete floodplain storage, resulting in decreased infiltration rates and increased runoff as the ground becomes saturated. Inundation for longer periods can also increase damage and flood-fighting expenses.
- **Surcharge**.—This objective also indirectly quantifies an alternative's ability to reduce surcharge in the reservoirs (storage exceeding the reservoirs designed full storage) (Objective 5, Table 6). The modeling assumes that when a reservoir is in surcharge, the outlet works would be operated to evacuate the surcharge from reservoirs as quickly as possible even if this causes downstream flows to exceed or further exceed the flow target. Therefore, alternatives that result in more surcharge may have lower performance in the RMS Flow Over Flood Target objective because the reservoirs will often make releases above the downstream flow target when in surcharge.

Average Daily Increase in Flood Space Requirement

The Average Daily Increase in Flood Space Requirement objective calculates the daily average increase in the flood space requirement in active flood control reservoirs for any day a storm was forecasted. This objective was added at the June 2022 Workshop to address undesirable outcomes of utilizing FIRO to calculate flood space requirements. For example, if ensemble forecasts leading up to an event required the immediate evacuation of flood space and the event did not occur, storage would needlessly have been evacuated downstream and negatively impact water supply. Furthermore, large day-to-day fluctuations in flood space could result in large day-to-day fluctuations in downstream flows, i.e., flashiness, in the Truckee River, which could have negative environmental impacts and present operational challenges. Abrupt flow reductions can contribute to stranding aquatic biota as stage drops. On the other hand, abrupt flow increases can flush fish eggs and fry downstream, possibly into less optimal habitats, and escalate macroinvertebrate drift, potentially creating a gap at the base of the aquatic food web (California Department of Water Resources and California Department of Fish and Wildlife, 2018). The Average Daily Increase in Flood Space Requirement objective helps to quantify how well an alternative avoids the above situations (Objectives 10 and 4, Table 6). Furthermore, this objective also supports the non-quantifiable objective in the study to develop methodologies that are feasible to implement (Objective 11, Table 6).

Supplemental Metrics

The modeling effort also calculated a set of 34 Supplemental Metrics that provide more details on the performance of the alternatives. Some of these metrics calculate a different or more detailed measurement of an objective. For example, the Floriston Rate objective calculates the

Average Annual Floriston Rate flow in cfs over the 37-year model run; this objective is complemented with a Supplemental Metric that calculates the Average *Days* Missing Floriston Rate Annually. Further, this metric is broken down by how many days the Floriston Rate is missed each season. The Supplemental Metrics include similar seasonal break downs for Average Nixon Flow. Other metrics provide information of importance to specific stakeholders. For example, the metrics provide information on individual TROA parties' water storage and establishment, and the Pyramid Lake Pool Elevation is an important metric for the PLPT. Stakeholders used the metrics to help inform their selection of the Best-Performing MOEA and Preferred Operational Scenario, as described in subsequent sections.

Non-Quantifiable Objectives

The non-quantifiable objectives are more subjective and cannot be calculated from the model results:

- Maximize the flexibility for timing for drawdown under flood control measures.
- Maximize the flexibility for refill in reservoirs up to the maximum conservation elevations.
- Bring the WCM up to date with current technologies and capabilities and allow for flexibility for future improvements in data availability/forecasting of future climate conditions.
- Allow flexibility for varying future operating conditions of Martis Creek Dam.
- Allow flexibility for future increases in flood thresholds because of flood improvements downstream.
- Develop methodologies that are implementable in operational mode.

The Key Stakeholders discussed the non-quantifiable objectives in workshop break-out groups and used these in their rankings of the alternatives. The *Action and Alternative Operational Scenario Modelling in the WMOP* report (Appendix M), contains more detailed information about the development of the non-quantifiable objectives and how they were considered and met through the design of the WMOP.

Evaluation and Selection of Best-Performing MOEA Scenario

The Technical Team took three distinct steps to arrive at a Best-Performing MOEA Scenario from the 150 non-dominated solutions (Figure 39). These steps allowed for the efficient elimination of several less desirable MOEA Scenarios so that the stakeholders could focus their analysis and discussion on a curated, short list of "best" MOEA Scenarios.

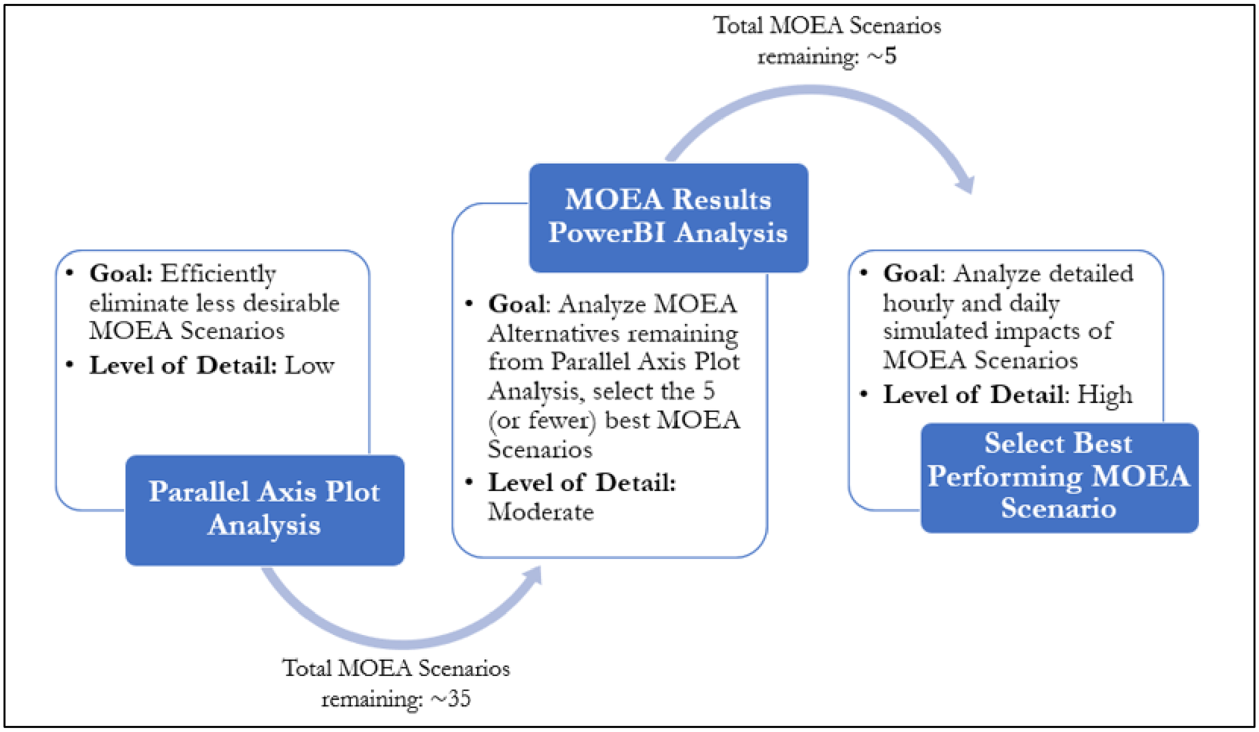


Figure 39.—The three steps used by the Technical Team to select the Best-Performing MOEA Scenario (Appendix O).

Parallel Axis Plots Analysis

Parallel Axis Plots are visualizations used to compare many variables together and illustrate the relationships between them (The Data Visualisation Catalogue, No date). These plots feature one axis for each quantifiable objective oriented from bottom to top from smallest (best) to largest (worst) values. In Figure 40, each of the 150 non-dominated MOEA Scenarios is illustrated as a continuous line connecting its objective scores across each vertical axis. The objective scores of the Baseline are indicated by the green line in this figure—its location on the top of the plot for the four leftmost objectives indicates that it scored the worst in all objectives besides Average Daily Increase in Flood Space. These plots allow for high-level evaluation of the:

1. MOEA Scenarios' performance in terms of objective scores relative to each other (smaller scores are better).
2. Tradeoffs between the objectives (i.e., flood risk management benefits at the expense of water supply benefits).

The purpose of this analysis was to efficiently eliminate less desirable MOEA Scenarios by broadly comparing all scenarios in terms of their relative objective scores. An ideal MOEA Scenario would populate the minimum (best) score for every objective along the bottom of Figure 40; however, this scenario does not exist due to tradeoffs between the objectives. For example, many MOEA Scenarios with the best (smallest) scores for Average Annual Prosser, Boca, and Stampede Storage also have some of the best scores for Average Annual Volume for

Flow Regime and Average Daily increase in Flood Space Requirement; however, they also tend to have the largest (worst) scores for the RMS Flow Over Flood Target objective. This demonstrates the tradeoff between benefits to water supply and environmental flows and benefits to flood risk management.

The Technical Team used the Parallel Axis Plot to filter the MOEA Scenarios from 150 non-dominated solutions to approximately 35 options by removing as many of the worst-performing scores for each objective as possible while keeping some of the best-performing scenarios for each objective (shown in blue in Figure 40).

Figure 40.—Parallel Axis Plot of the Baseline (green line) and the 150 non-dominated MOEA Scenarios (blue, grey, and orange lines). The approximately 35 remaining MOEA Scenarios after the initial filtering process are shown in blue, and the MOEA Scenarios removed in this process are shown in grey. The orange line designates the identified Best-Performing MOEA Scenario (Appendix O).

MOEA Results PowerBI Analysis

The second phase of the Best-Performing MOEA Selection Process involved a more detailed review of the approximately 35 remaining MOEA Scenarios to determine the top four scenarios. The MOEA evaluation results were configured into a Microsoft PowerBI viewer to provide a user-friendly interface to explore the objective scores and the parameters associated with each of the remaining MOEA Scenarios. This MOEA results viewer facilitated a more in-depth comparison of each MOEA Scenario performance in terms of any two user-selected objectives. For example, Figure 41 from the PowerBI viewer compares the Annual Average Volume for Flow Regime and RMS Flow Over Flood Target objectives on the x- and y-axis, respectively. The triangle data points in Figure 41 represent the best (lowest scoring) MOEA Scenario in each individual objective—in each case, the MOEA Scenario with the best performance in one objective (lowest score) represents the worst performance in the other objective (highest score), demonstrating the tradeoffs between objectives. The solutions closest to the bottom left of Figure 41 represent the best-compromised performance in terms of the objectives, whereas the Baseline's location in the upper right corner indicates the worst scores in both objectives. The tradeoffs associated with objectives required a subjective valuation to determine what MOEA Scenario the stakeholders identified as "best."

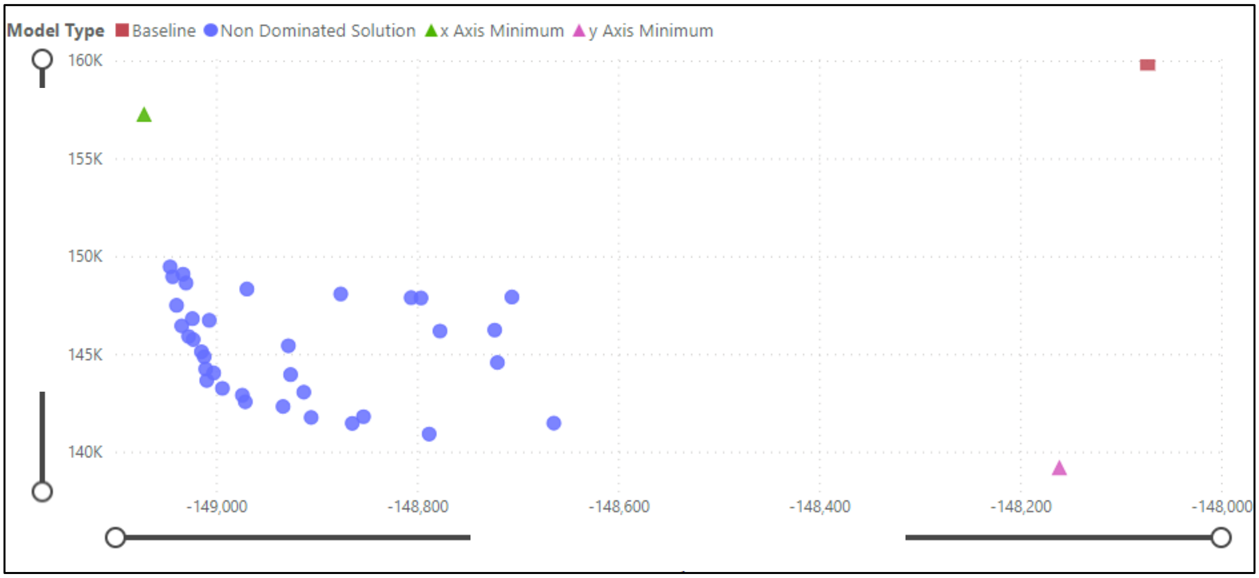


Figure 41.—Two objective comparison of the non-dominated MOEA Scenarios and Baseline (Appendix O).

Each agency represented in the Technical Team determined their top 20 MOEA Scenarios by using the PowerBI Viewer and applying their subjective values of what represented the best MOEA Scenarios. The criteria each agency used for determining the best MOEA Scenarios are summarized in Table 15.

Table 15.—Main Goals of the Technical Team Members' Top 20 MOEA Selections (Appendix O)

Cost-Share Partner	Main Goals of Top 20 MOEA Selections
PLPT	Maximize Average Annual Volume for Flow Regime Maximize Average Annual Prosser, Boca, and Stampede Storage Minimize Average Daily Increase in Flood Space Requirement Maximize Annual Average Volume for Floriston Rate
CA DWR	Maximize Average Annual Prosser, Boca, and Stampede Storage Minimize RMS Flow Over Flood Target Maximize Average Annual Volume for Flow Regime
TMWA	Maximize Annual Average Volume for Floriston Rate No adverse effects to RMS Flow Over Flood Target Objective
Reclamation	Prioritized scenarios with Percent of Revised Guide Curve to Reserve of 40% and higher Maximize Average Annual Volume for Flow Regime Maximize Average Annual Prosser, Boca, and Stampede Storage Minimize Average Daily Increase in Flood Space Requirement
USWM	Eliminate worst scenarios for Average Annual Volume for Flow Regime Objective and Boca portion of Flood Space Decision Variable greater than 50% Minimize Average Daily Increase in Flood Space Requirement

Once completed, a small committee consisting of at least one representative from each agency on the Technical Team met to determine the top four best MOEA Scenarios. To do this, any MOEA Scenario not within any of the agencies' top 20 was eliminated. Secondly, the three MOEA Scenarios that ranked within the top 20 scenarios for all parties were accepted for consideration by the larger Technical Team. Another scenario was added to this short list that it was within the top 20 rankings of all agencies but one, performed reasonably well in all objectives, and importantly, maintained one of the largest percentages of the Revised Guide Curve of the remaining MOEA Scenarios, at 60%.

Selection of the Best-Performing MOEA Scenario

After agreeing upon the top four MOEA Scenarios, stakeholders met at the WMOP Select Preferred Operational Scenario Workshop (June 2023) to look more in-depth at the performance of each of the remaining MOEA Scenarios and collaboratively determine the Best-Performing MOEA Scenario. A summary of the MOEAs Scenario's performance related to the objectives was presented to the workshop participants who then discussed the results in break-out groups before reporting back to the full group for discussion and an interactive examination of specific hydrologic events and water years of interest.

This section summarizes the performance of the top four MOEA Scenarios in terms of the WMOP objectives and the subjective stakeholder valuation of those objectives to arrive at the Best-Performing MOEA Scenario. The stakeholder evaluation focused primarily on 1) differences in the decision variables in each MOEA Scenario (Table 16 and Figure 42) and their implications for operations, 2) the quantifiable objective scores (Table 17), and 3) the time-series examination of hydrologic events. Like the larger set of MOEA Scenarios, the top four MOEA Scenarios present tradeoffs between the WMOP objectives.

Initial discussions and comparisons of the MOEA Scenarios focused on the benefits and challenges of different values of the Boca Portion of Flood Space and the Percent of Revised Guide Curve to Reserve decision variables (Table 16). For example,

Scenarios with a **higher Boca Portion of Scenario Flood Space** (Table 16) have both expected benefits and associated challenges, that again present as tradeoffs:

- Increasing the required flood space in Boca (acre-feet) increases the flood protection provided by Boca but leads to reduced operational flexibility of Boca by decreasing the conservation pool.
- Decreasing the required flood space in Stampede (acre-feet) allows for more carry-over storage further upstream but leads to increased Stampede surcharge risk during extreme flood events.

Similarly, Scenarios with a **higher Percent of Revised Guide Curve to Reserve** also have expected benefits and associated challenges:

- Reserving more of the revised guide curve required flood space allows for more preparedness for an under-forecasted or short lead time storm but leads to less benefits to water supply.

The interactions between these two decision variables determine the minimum and maximum required flood space from November 1 – April 10. With a large flood in the forecast, 100% of the revised dSRDs' flood space is reserved, and the volume of flood space in Boca equals the total Little Truckee flood space (30,000 acre-feet) multiplied by the Boca Portion of Flood Space decision variable (Table 16). If the forecast contains no floods, the minimum flood space is required, calculated in the MOEA scenarios by multiplying the maximum required flood space by the Percentage of Revised Guide Curve to Reserve Decision Variable (Table 16). As such, when there is no flood in the forecast the MOEA scenarios require less flood space in both Boca and Stampede than required in the Baseline. When there is a flood in the forecast the MOEA scenarios can require almost double the required flood space in Boca (up to 15,000 acre-feet) than under the Baseline (8,000 acre-feet). As such, the combined effect of these two decision variables allows for potential benefits to the water supply objective during dry years when the minimum flood space is required and more water can be stored, as well as flood risk management benefits during wet years when the maximum Little Truckee flood space is required, but more evenly split between Boca and Stampede than under the Baseline.

Table 16.—Top Four MOEA Scenarios' Decision Variables and Maximum and Minimum Required Flood Space

		MOEA Scenario			
	Baseline	A	B	C	D
Exceedance Coefficient A	N/A	12	24	24	18
Exceedance Coefficient B	N/A	0.6	0.7	0.7	0.6
Exceedance Coefficient C	N/A	-10	-60	-60	-40
Boca Portion of Flood Space	27%	50%	45%	50%	40%
Percentage of Revised Guide Curve Flood Space to Reserve	N/A	30%	30%	30%	60%
	Maximum Required Flood Space November 1 – April 10 100% Revised Guide Curve Flood Space Reserved Boca Portion of Flood Space Decision Variable				
Boca (acre-feet)	8,000	15,000	13,500	15,000	12,000
Stampede (acre-feet)	22,000	15,000	16,500	15,000	18,000
Total (acre-feet)	30,000	30,000	30,000	30,000	30,000
	Minimum Required Flood Space November 1 – April 10 Percentage of Revised Guide Curve to Reserve Decision Variable Boca Portion of Flood Space Decision Variable				
Boca (acre-feet)	8,000	4,500	4,050	4,500	7,200
Stampede (acre-feet)	22,000	4,500	4,950	4,500	10,800
Total (acre-feet)	30,000	9,000	9,000	9,000	18,000

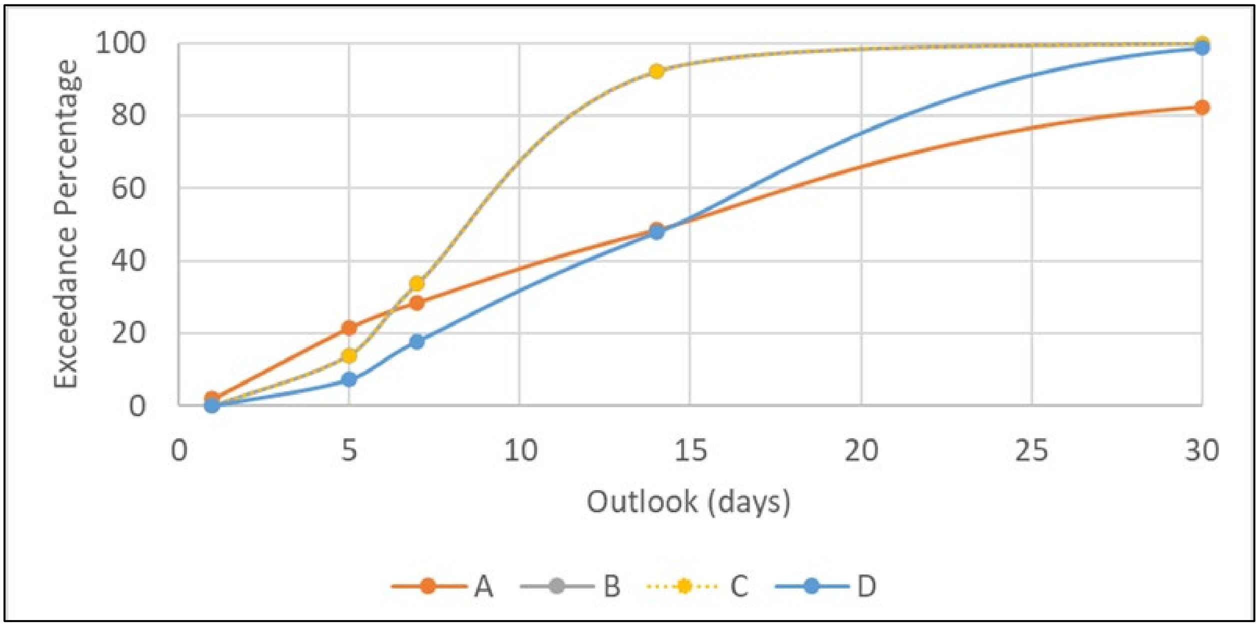


Figure 42.—Exceedance vs. Outlook Relationship for the Top 4 MOEA Scenarios, where Scenarios B and C Overlap (Appendix O).

These operational changes significantly influence several of the quantifiable and non-quantifiable objectives. To explore this interaction, the results of the MOEA scenarios with all decision variables equal to those in Scenario A, except the Boca Portion, were compiled. This allows for a simple sensitivity analysis showing how different Boca Portions of Flood Space decision variable values impact the study objectives. RMS Flow Over Flood Target is closely correlated to this decision variable, with larger Boca Portion of Flood Space resulting in better performance for the objective (Figure 43). This simple sensitivity analysis also revealed that the other quantifiable objectives were nearly independent of the Boca Portion of Flood Space. Of note, the MOEA non-dominated solutions only contained one scenario with 50% Boca Portion of Flood Space and an exceedance-outlook curve that matched Scenario A. This indicates the interconnection between decision variables in determining scenario performance; if a different Percentage of Revised Guide Curve to Reserve was selected, all the decision variables would require adjustment to avoid selecting a dominated, less optimal solution.

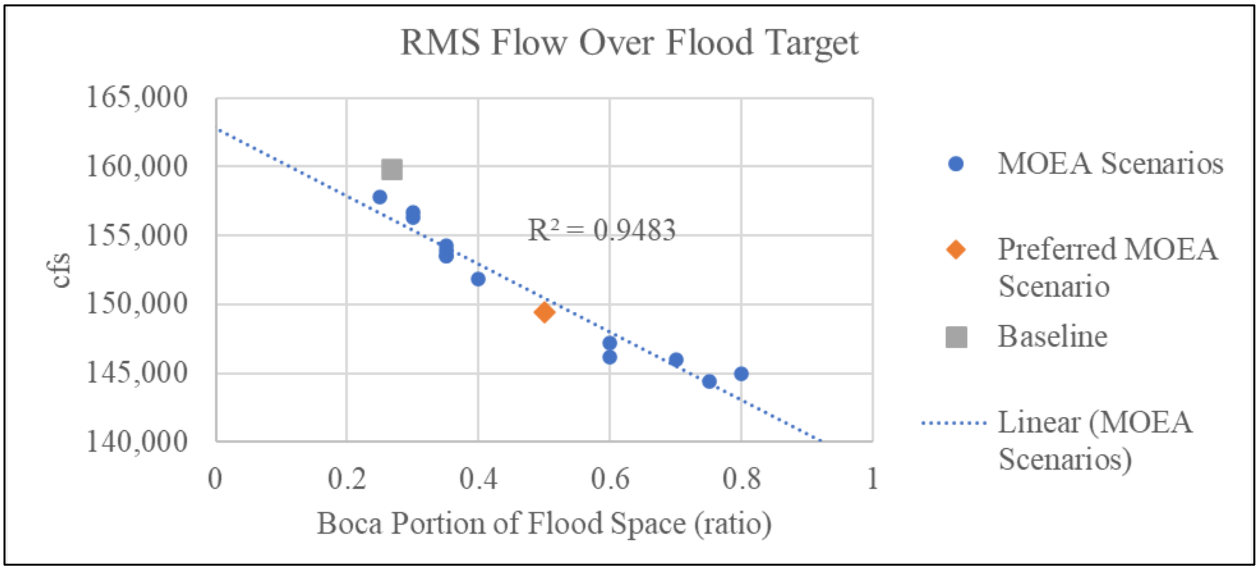


Figure 43.—Sensitivity analysis of root mean squared (RMS) Flow Over Flood Target objective to the Boca Portion of Flood Space decision variable.

After examining the objectives' scores and the Portion of Boca Flood Space and the Percentage of Revised Guide Curve to Reserve decision variables, the workshop participants first eliminated MOEA Scenario D. Scenario D generally shows poorer objective score performance than the other Scenarios with the worst objective score for three out of five objectives:

- Average Annual Volume for Flow Regime;
- Average Daily Increase in Flood Space Requirement; and
- Average Annual Prosser, Boca, and Stampede Storage (Table 17).

While Scenario D does achieve the highest score in Average Annual Volume for Floriston Rate, the extremely small range of this objective makes differences between the MOEA Scenario rankings less significant than other objectives.

Table 17.—Top Four MOEA Scenarios' Objectives' Scores

	MOEA Scenario				
Objective	**Baseline**	**A**	**B**	**C**	**D**
Annual Average Volume for Floriston Rate (acre-feet)	-263,079	-263,281	-263,279	-263,278	-263,303
Average Annual Volume for Flow Regime (acre-feet)	-148,067	-149,046	-149,039	-149,027	-148,706
Average Annual Prosser, Boca, and Stampede Storage (acre-feet)	-175,026	-184,088	-183,926	-183,867	-181,210
Average Daily Increase in Flood Space Requirement (acre-feet)	187	179	268	268	379
RMS Flow Over Flood Target (cfs)	159,960	149,457	147,487	145,897	147,915

Note: The scores are ranked by color where green represents the best scoring alternatives and blue represents the worst scoring alternatives.

The poorer performance of Scenario D is likely related to its high Percentage of Revised Guide Curve to Reserve and high Boca Portion of Flood Space, which is also associated with reduced operational flexibility in Boca and perceived increased risk of Stampede Surcharge during extreme flood events. For these reasons, Scenario D was eliminated from further consideration for the Preferred Operational Scenario.

In looking at the remaining MOEA Scenarios, each of the break-out groups noted that MOEA Scenario A outperforms the other Scenarios in three out of five objectives:

- Average Annual Volume for Flow Regime,
- Average Annual Prosser, Boca, and Stampede Storage; and
- Average Daily Increase in Flood Space Requirement (Table 17).

MOEA Scenario A was also the only MOEA Scenario that produced a better score than the Baseline for the Average Daily Increase in Flood Space Requirement, which attempts to minimize operational challenges and downstream flow fluctuations associated with large daily increases in the flood space requirement.

While MOEA Scenario A performed slightly worse than some other MOEA Scenarios in the Floriston Rate and RMS Over Flood Target objectives, it still performed better than the Baseline and the stakeholders generally put less weight towards differences in the ranking of these two objectives. The differences in the Floriston Rate objective amongst MOEA Scenarios are rather insignificant, and the interpretation of the RMS Over Flood Target objective score must consider that the stakeholders recommend increasing the Reno flood flow target to better reflect downstream flood management efforts. Recalculating this objective with a recommended higher Reno flood flow target would improve MOEA Scenario A's score in this objective.

With all of this under consideration, the Key Stakeholders unanimously selected MOEA Scenario A as the Best-Performing MOEA.

Key Recommendation: Use the decision variable values in MOEA Scenario A, the identified Best-Performing MOEA, as the parameters associated with the BAM method and Reproportion of Little Truckee Flood Space actions in the Alternative Operational Scenarios.

Lastly, Scenario B and C were compared, and the workshop participants identified Scenario C as the "second-best" performing MOEA Scenario (refer to Appendix O for a more detailed discussion of the MOEA ranking and selection process).

Out of the 150 non-dominated MOEA Scenarios, the Best-Performing MOEA identified by the Key Stakeholders was one of the best MOEAs overall for maximizing Average Annual Prosser, Boca, and Stampede Storage and Average Annual Volume for Flow Regime and minimizing Average Daily Increase in Flood Space Requirement (Table 18).

Table 18.—Best-Performing MOEA Scenario Ranking

Preferred MOEA Scenario Ranking Within All 150 Non-Dominated Solutions	
Objective	**Top N% of MOEA Solutions**
Average Annual Volume for Floriston Rate	33%
Average Annual Prosser, Boca, and Stampede Storage	3%
Average Annual Volume for Flow Regime	2%
RMS Flow Over Flood Target	51%
Average Daily Increase in Flood Space Requirement	2%
Cumulative Storage Over Dam Failure Elevations	0%

Note: All 150 non-dominated solutions perform better than the Baseline for all objectives except for the Average Daily Increase in Flood Space Requirement (Appendix O).

Evaluation and Selection of Preferred Operational Scenario

In selecting the Best-Performing MOEA Scenario, stakeholders essentially "optimized" Alternative 3 and selected the best-performing set of parameters associated with the BAM method and Reproportion of Little Truckee Flood Space actions. As illustrated in Figure 37, these parameters were then utilized to model the other alternatives and stakeholders were tasked with selecting the Preferred Operational Scenario for the WMOP Study.

Similar to the process used to determine the Best-Performing MOEA Scenario, the Key Stakeholders met at the June 2023 workshop to look more in-depth at the performance of each of the alternatives and collaboratively determine the Preferred Operational Scenario. A summary of the alternatives' performance related to the objectives was presented to the workshop participants, who then discussed the results and ranked the alternatives in break-out groups, before reporting back to the full group for discussion. This section summarizes the performance of the alternatives in terms of the WMOP objectives and the subjective stakeholder evaluation of the alternatives to arrive at the Preferred Operational Scenario.

Summary of Quantifiable Objective Scores

Assessing the performance of the alternatives in terms of the WMOP objectives entailed an examination of the quantifiable objective scores in Table 19 as well as a more in-depth, interactive exploration of performance during historic and simulated hydrologic events, described in this section.

Table 19.—Summary of the Quantifiable Objective Scores for the Alternatives

		Alternative Operational Scenarios					
		1	2	3	4	5	6
Objectives	**Units**	**Baseline**	**BAM:All**	**BAM +Vista**	**dSRDs**	**BAM:Spring**	**BAM:Var**
Average Annual Volume for Floriston Rate	acre-feet	-263,079	-263,281	-263,281	-263,210	-263,222	-263,281
Average Annual Volume for Flow Regime	acre-feet	-148,067	-149,046	-149,046	-148,553	-148,404	-149,015
Average Annual Prosser, Boca, and Stampede Storage	acre-feet	-175,026	-184,089	-184,088	-178,002	-180,047	-181,804
Average Daily Increase in Flood Space Requirement	acre-feet	187	179	179	276	349	220
RMS Flow Over Flood Target	cfs	159,960	149,387	149,457	146,189	146,587	146,029

Note: The scores are ranked by color where green represents the best scoring alternatives and blue represents the worst scoring alternatives.

Average Annual Volume for Floriston Rate

The Average Annual Volume for Floriston Rate objective assesses the system's ability to meet the Floriston Rate targets, the primary indicator of the water management system's ability to meet water demands.

Similar to the MOEA Scenarios, the Action Alternatives exhibit a relatively small range in Average Annual Volume for the Floriston Rates; the best and worst Action Alternative only differ by 72 acre-feet per year (Table 19). That said, the alternatives that use the BAM method for fall drawdown (Alternatives 2, 3, and 6) provide the most overall benefit for the Floriston Rate water supply objective, offering roughly 202 acre-feet per year of additional benefit to meeting the Floriston Rates over the Baseline, on average. This is equivalent to about 7,500 acre-feet of additional water over the Baseline available to meet the Floriston Rates across the entire 37-year model run.

One reason for the relatively small differences in the Floriston Rate objective between the Baseline and Action Alternatives results from the fact that the Floriston Rate benefits are concentrated in a few select years in the 37-year model run (Figure 44). The greatest benefits accrue after wet years and in the alternatives whose guidelines allow for carrying over more water from wet years to dry years.

All of the alternatives store more Floriston Rate water in Prosser Reservoir in spring 2011 than in the Baseline because of the earlier refill guidelines in the revised dSRDs (Figure 44). The year 2011 recorded a large snowpack, resulting in a large runoff that filled the reservoirs in the basin. BAM:All, BAM +Vista, and BAM:Var represent the largest improvements over Baseline, storing roughly 9,000 acre-feet more Floriston Rate Storage in 2011. These alternatives require less drawdown in fall 2011 than the Baseline and the scenarios that use the revised dSRDs for drawdown and winter operations. As a result, BAM:All, BAM +Vista, and BAM:Var can store and retain the runoff for use in the ensuing years (Figure 44). In this case, the water stored in 2011 is used to meet higher Floriston Rates in spring 2013, providing water to meet higher targets than the Baseline for 27 more days (Figure 45).

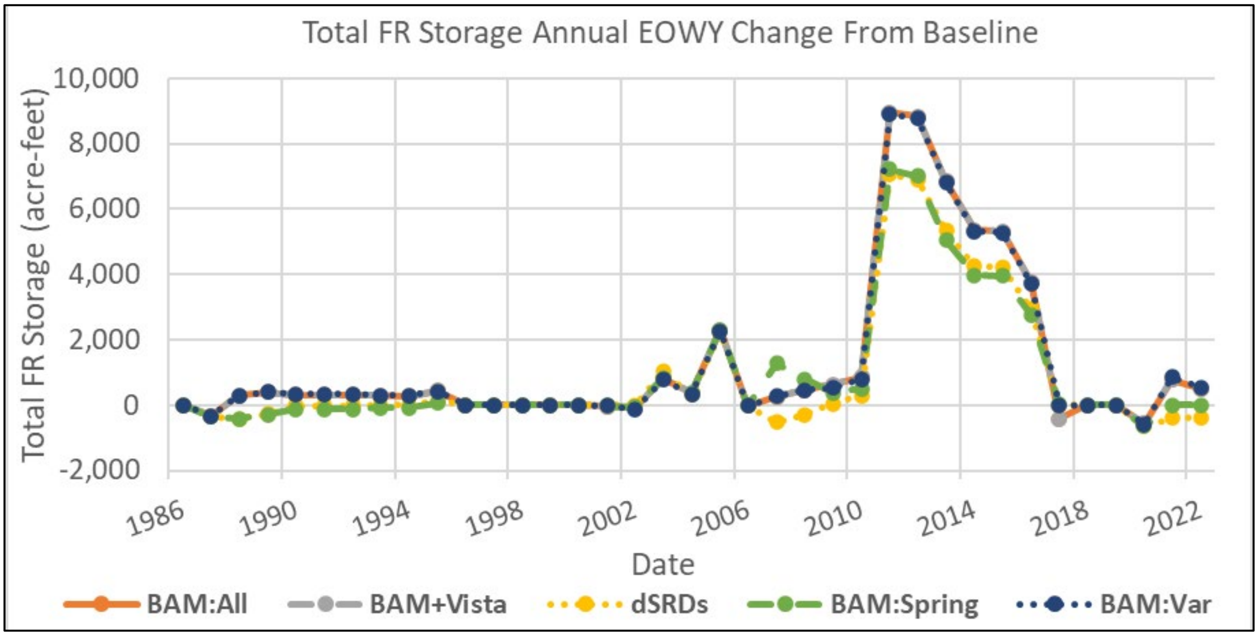


Figure 44.—Change in end of water year (EOWY) Floriston Rate (FR) storage from Baseline. BAM:All, BAM +Vista, and BAM:Var overlap throughout the period (Appendix O).

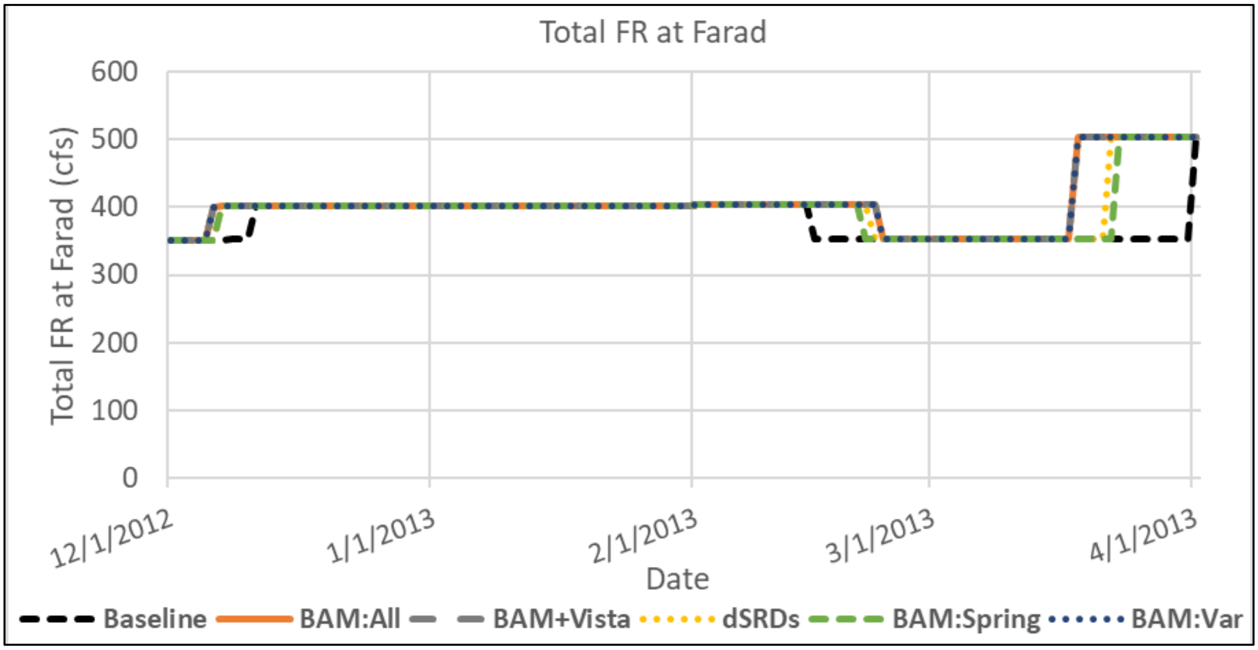


Figure 45.—Floriston Rate at Farad from December 2012 to March 2013. BAM:All, BAM $^+$Vista, and BAM:Var meet a higher Floriston Rate target for 27 more days in the spring of 2013 than the Baseline due to their ability to carryover water from water year 2011 to use during drier periods (Appendix O).

Average Annual Volume for Flow Regime

The Average Annual Volume for Flow Regime objective quantifies how well an alternative improves environmental flows downstream of the active flood control reservoirs.

The BAM:All and BAM $^+$Vista Alternatives provide the largest overall benefits for the flow regime objective. On average, these alternatives result in an additional 980 acre-feet per year of storage available to meet flow regime targets over the Baseline, equivalent to about 36,300 acre-feet of benefit across the 37-year model run (Table 19). Similar to the Floriston Rate objective, the benefits to flow regime are concentrated in a couple of periods, primarily 1990 and 2015, and relate to the ability of some of the alternatives to carryover more water during wet periods for use during dry periods. The flow regime benefits in the fall of 1990 originate from additional storage accumulated in 1986. BAM:All and BAM $^+$Vista store and retain 9,000 acre-feet more water in 1986 for PLPT to meet flow regime targets than the Baseline (Figure 46). When this water is called on during the drought year of 1990, BAM:All and BAM $^+$Vista can meet fall flow regime targets for 8 weeks longer than the Baseline, and BAM:Var provides almost as significant benefits (Figure 47).

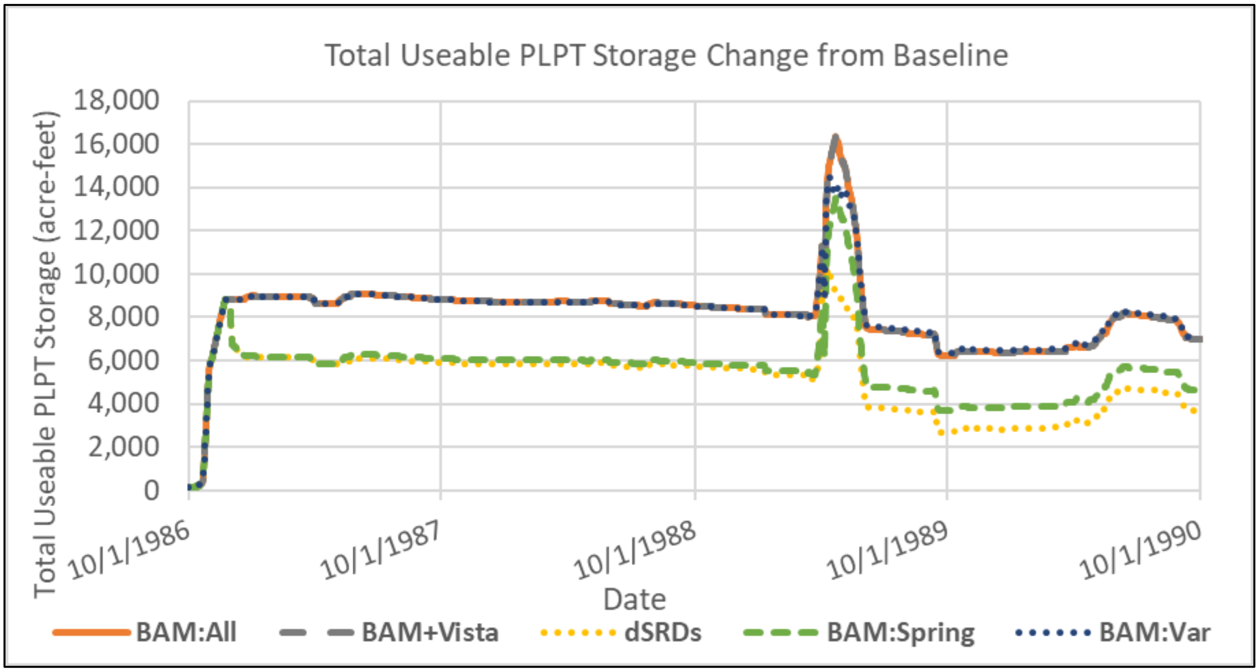


Figure 46.—Simulated PLPT storage in the late 1980s. BAM:All and BAM $^+$Vista overlap throughout the period (Appendix O).

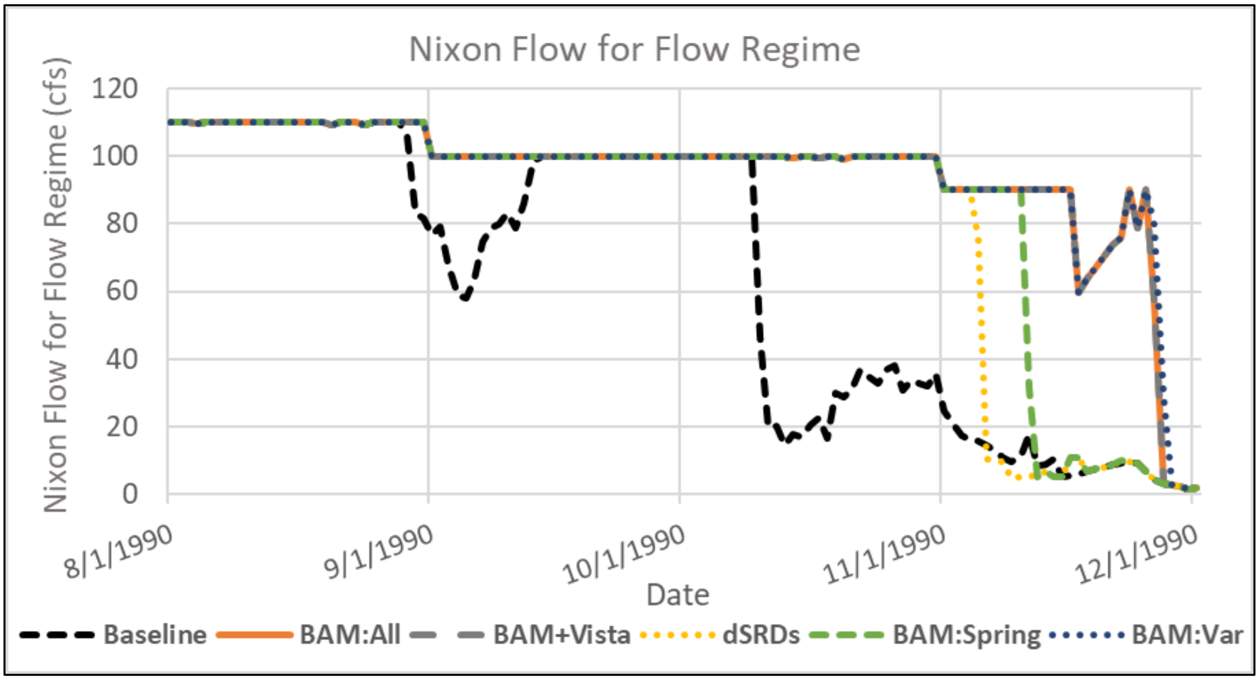


Figure 47.—Nixon Flow for Flow Regime from August 1990 through December 1990. All Action Alternatives overlap until early November 1990, after which time, BAM:All, BAM $^+$Vista, and BAM:Var overlap (Appendix O).

The modeling demonstrates similar benefits to the flow regime objective in 2015 resulting from storage accumulated over the Baseline during 2011 (Figure 48). (As discussed previously, water was also stored to meet the Floriston Rate during this time). However, in this case, the additional stored water is used to meet flow regime targets in the spring, rather than the fall. Approximately 15,000 acre-feet of additional storage accumulated in BAM:All, BAM $^{+}$Vista, and BAM:Var in 2011 is carried over until spring 2015 when it is used to meet flow regime targets for as much as 2 months longer than the Baseline (Figure 49). Meeting environmental flow targets at the Nixon Gage for an extended period in the spring represents a significant improvement over the Baseline, particularly since this coincides with the LCT and Cui-ui spawning season.

Similar to the Floriston Rate objective, the ability of BAM:All, BAM $^{+}$Vista, and BAM:Var to better meet the flow regime objective traces back to the flexibility of the BAM method used to guide fall drawdown operations. The dSRDs and BAM:Spring Alternatives which operate drawdown based on the revised dSRDs, show less pronounced improvement over the Baseline (Figure 48 and Figure 49).

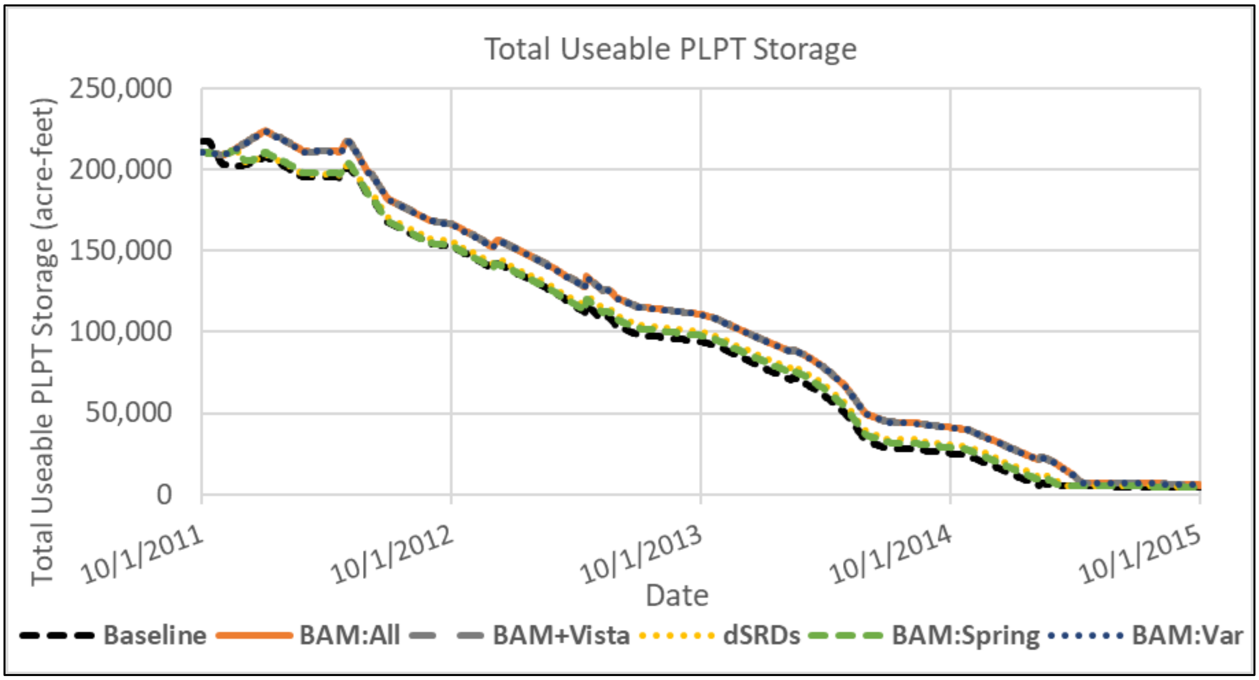


Figure 48.—Total useable PLPT storage from October 2011 through October 2015. BAM:All, BAM $^{+}$Vista, and BAM:Var overlap throughout the demonstrated period, as do the revised dSRDs and BAM:Spring (Appendix O).

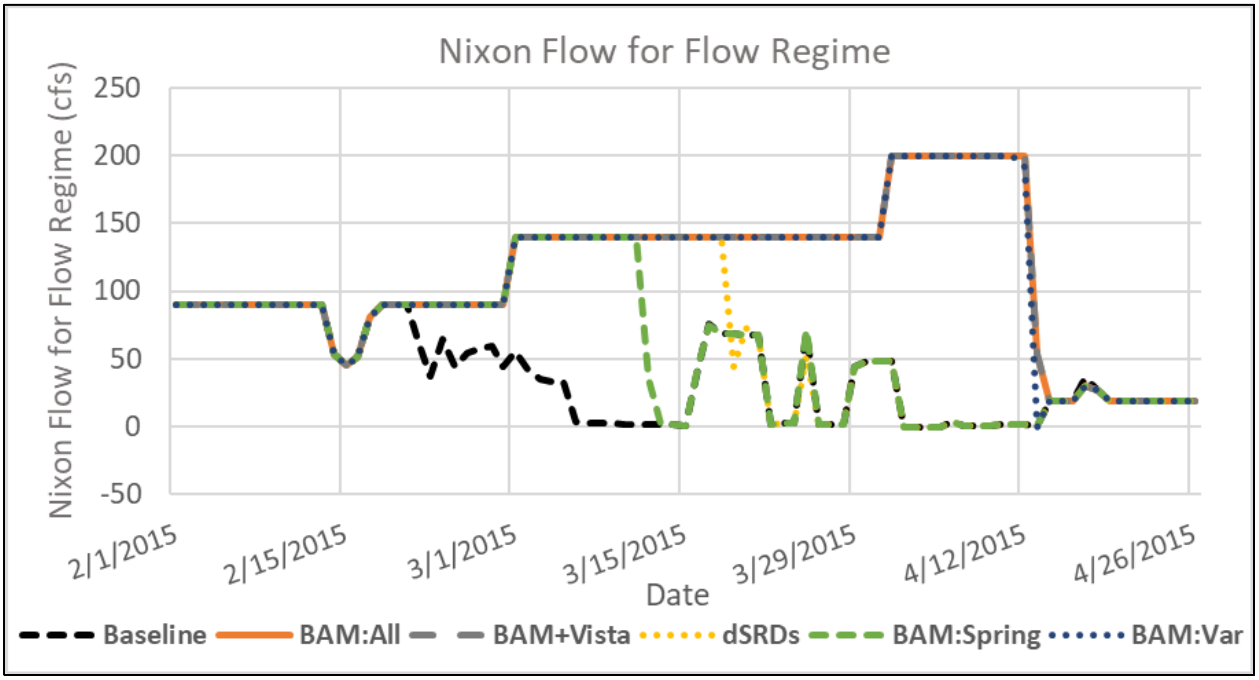


Figure 49.—Nixon Flow for Flow Regime from February 2015 through April 2015. BAM:All, BAM $^+$Vista, and BAM:Var overlap throughout the demonstrated period, whereas the revised dSRDs and BAM:Spring overlap after mid-March 2015 (Appendix O).

Average Daily Increase in Flood Space Requirement

The Average Daily Increase in Flood Space Requirement objective aims to minimize large day-to-day fluctuations in the required flood space and thus downstream flows, i.e., flashiness, which can have negative environmental impacts and potentially present operational challenges.

BAM:All and BAM $^+$Vista are the only alternatives that score better than the Baseline for this objective. On the other hand, BAM:Spring scores the worst of all alternatives, exhibiting an average daily increase in the flood space requirement of about 350 acre-feet (Table 19). Understanding the meaning of these scores in operational terms requires further examination of the time-series data. The Technical Team specifically examined the Daily Increase in Flood Space Requirement objective for 3 distinct years:

1. 2011 – a wet year that was cold and recorded no floods.
2. 2015 – an extremely dry year.
3. 2017 – a wet year that recorded floods.

Plots of flood control capacity are provided for each year for Prosser Creek Reservoir (Figure 50, Figure 51, and Figure 52), and the other flood control reservoirs behave similarly. In these plots, the Daily Increase in Flood Space Requirement is characterized by the downward slope and absolute change in flood capacity (y-axis) in each of the alternatives. Steeper, downward-sloping lines in Figure 50, Figure 51, and Figure 52 indicate larger, poorer scores in the Daily Increase in Flood Space Requirement objectives, as do larger absolute increases in the flood space requirement and a larger number of downward lines. Constant values for the flood space requirement (zero slope lines in Figure 50, Figure 51, and Figure 52) and decreases in the flood space requirement (upward slope lines in Figure 50, Figure 51, and Figure 52) yield values of zero in the Daily Increase in Flood Space Requirement objective.

In 2011, BAM:All and BAM $^{+}$Vista score better, lower values in the Daily Increase in Flood Space Requirement objective, because they require less drawdown and flood space than the other alternatives and also maintain a constant flood space requirement until the spring refill (Figure 50). Although 2011 was a wet year, the lack of actual or forecasted floods allows BAM:All and BAM $^{+}$Vista to maintain the minimum required flood space at 30% of the revised guide curve, maintaining 24,000 acre-feet of conservation storage throughout the winter. BAM:Var exhibits more conservative operations than BAM:All and BAM $^{+}$Vista because it requires more flood space during wet years, such as 2011. The dSRDs and BAM:Spring require all of Prosser's flood space by December 1st resulting in a higher, worse Daily Increase in Flood Space Requirement objective during drawdown than the other scenarios (steeper, downward sloping green line in Figure 50).

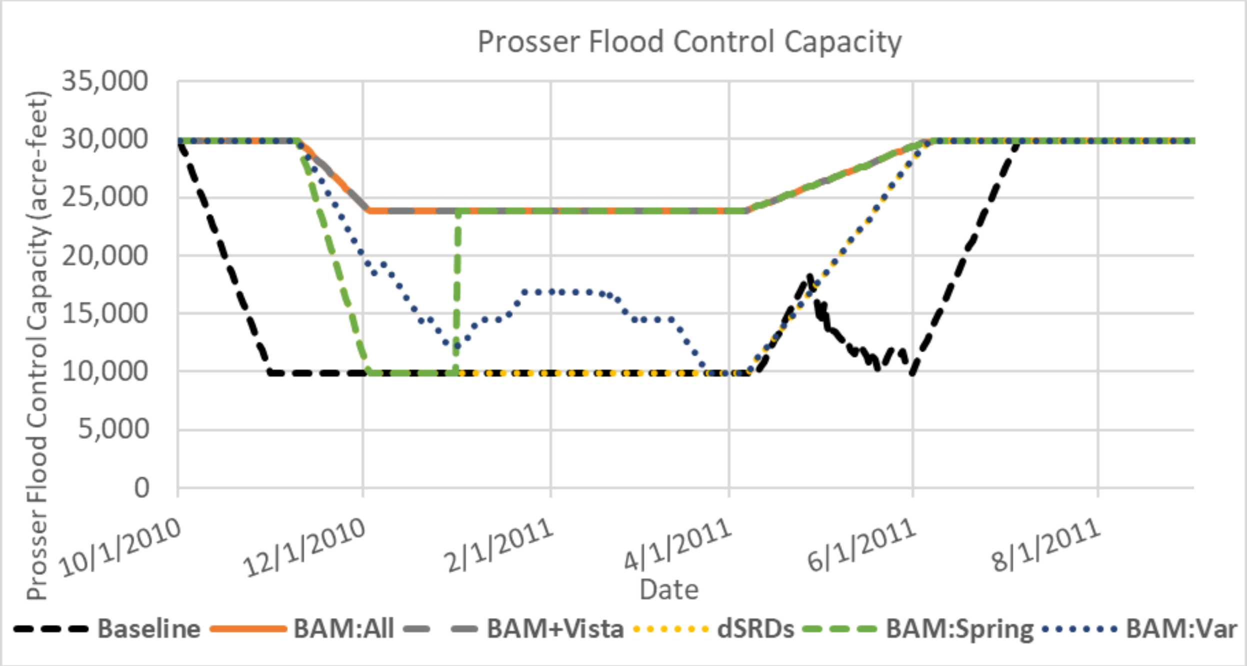


Figure 50.—Prosser flood control capacity during water year 2011. BAM:All and BAM $^{+}$Vista overlap throughout the demonstrated period.

Note: The vertical dashed line green line on January 1st indicates the point when Alternative 5 (BAM:Spring) transitions from determining required flood space using the revised dSRDs to the BAM method (Appendix O).

Water year 2015 represents an extremely dry year when the operations in BAM:All, BAM $^{+}$Vista, and BAM:Var only necessitate drawing down to the minimum required flood space at 30% of the revised guide curve on December 1st (Figure 51). However, a forecasted flood in February requires evacuation of flood space, contributing negatively to the Average Daily Increase in the Flood Space Requirement objective for these alternatives.

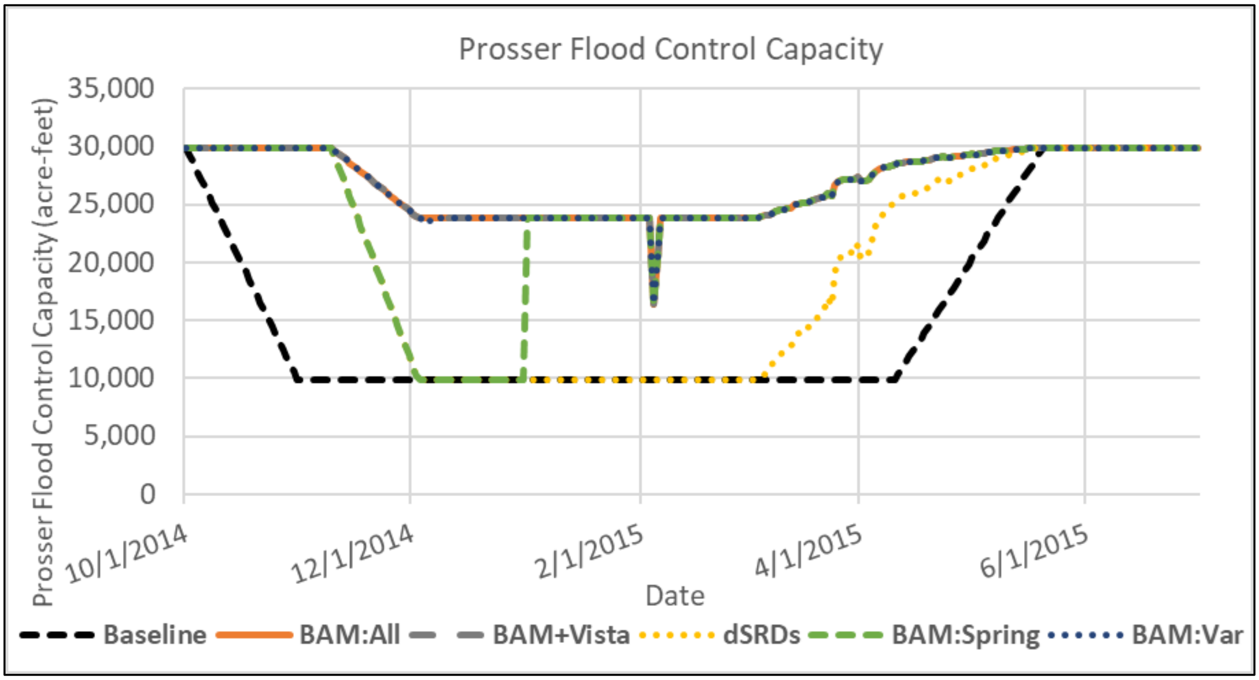


Figure 51.—Prosser flood control capacity from October 2014 through July 2015. BAM:All, BAM $^{+}$Vista, and BAM:Var overlap throughout the period (Appendix O).

In 2017, a large precipitation year where flooding did occur, the BAM:All, BAM $^{+}$Vista, and BAM:Spring Alternatives exhibit large fluctuations in flood control capacity from January through July (Figure 52). During this timeframe, the BAM method specifies as much as a 14,000-acre-foot change in flood space in 1 day. These fluctuations in flood space requirements exhibited by the BAM method result in large fluctuations in reservoir outflows to maintain the flood control capacity, and this type of operation was undesirable by the Technical Team. In contrast, the BAM:Var Alternative offers a relatively steady drawdown and refill of Prosser Reservoir with the largest daily change in flood space of about 9,000 acre-feet occurring in May (Figure 52).

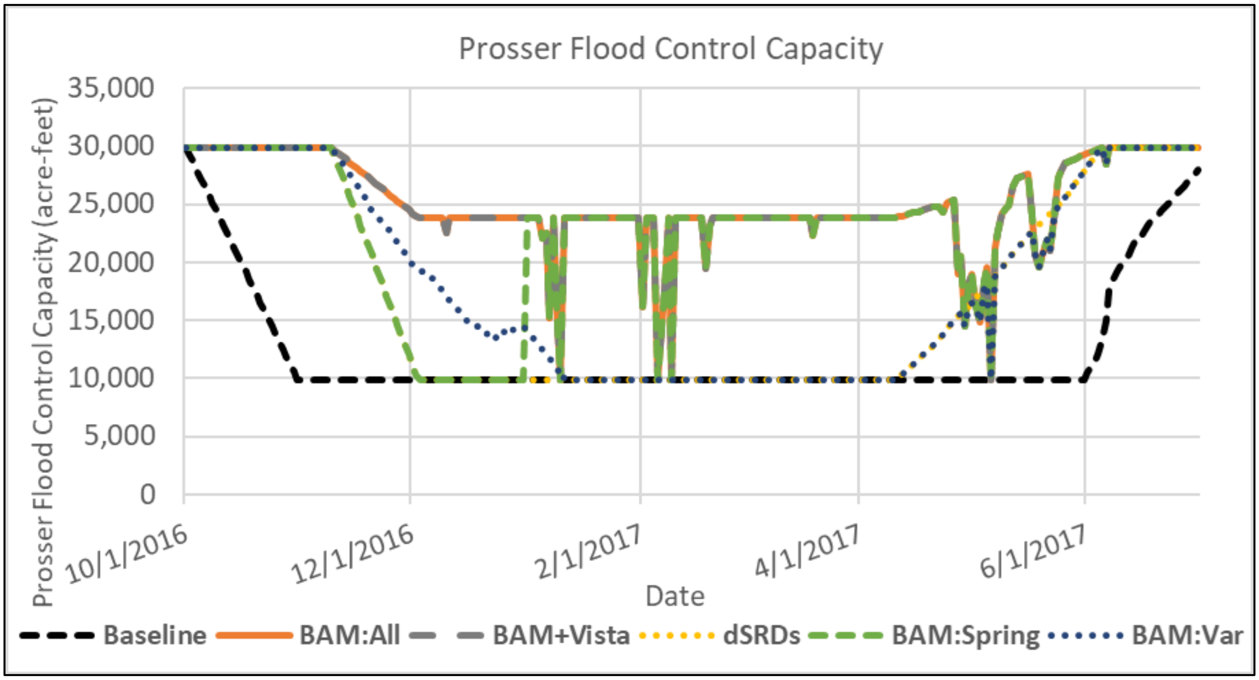


Figure 52.—Prosser flood control capacity from October 2016 through July 2017. BAM:All, BAM $^{+}$Vista, and BAM:Var overlap from January 2017 through July 2017. Fluctuations in flood control capacity in BAM:All, BAM $^{+}$Vista, and BAM:Var relate to the BAM method of flood space determination's fluctuating flood space requirements (Appendix O).

Average Annual Prosser, Boca, and Stampede Storage

The Average Annual Prosser, Boca, and Stampede Storage objective evaluates the ability of the alternatives to optimize water storage and increase flexibility to satisfy water demands throughout the year. BAM:All and BAM $^{+}$Vista offer the largest benefit of about 9,000 acre-feet of additional reservoir storage over the Baseline (Table 19). BAM:Var exhibits a lower average annual reservoir storage volume than BAM:All and BAM $^{+}$Vista due to operations that maintain lower reservoirs levels, later in the runoff season during wet years. Nonetheless, the reservoirs fill almost as often in the BAM:Var Alternative. As such, BAM:Var exhibits a similar probability of reservoir refill and similar water supply benefits as BAM:All and BAM $^{+}$Vista, despite having a slightly lower quantifiable score in this objective. The dSRD Action Alternative scored the worst for this objective, offering one-third (3,000 acre-feet) of BAM:All and BAM $^{+}$Vista's storage benefits over the Baseline.

In line with the Floriston Rate and flow regime objectives, better scores for the reservoir storage objective relate to the extent to which the alternatives can carry over excess water during wet periods for use during dry periods. Better scores in this objective also relate to the extent to which the alternatives maximize spring runoff capture. Water years 1986 and 2006, described below, demonstrate these differences.

As mentioned earlier, the large water year of 1986 provides an opportunity to store surplus water after the end of the summer to carry over until needed in a drier year. The alternatives that employ the BAM method for fall drawdown (Alternatives 2, 3, and 6) maintain higher reservoir levels from fall 1986 to 1991 than the other alternatives. In addition, the ability to refill earlier in the BAM and revised dSRDs, allows all of the Action Alternatives to capture significantly more runoff in the spring of 1989 than under the Baseline (Figure 53). This allows the BAM:All, BAM $^+$Vista, and BAM:Var Alternatives to meet flow regime targets longer in 1991, than other alternatives.

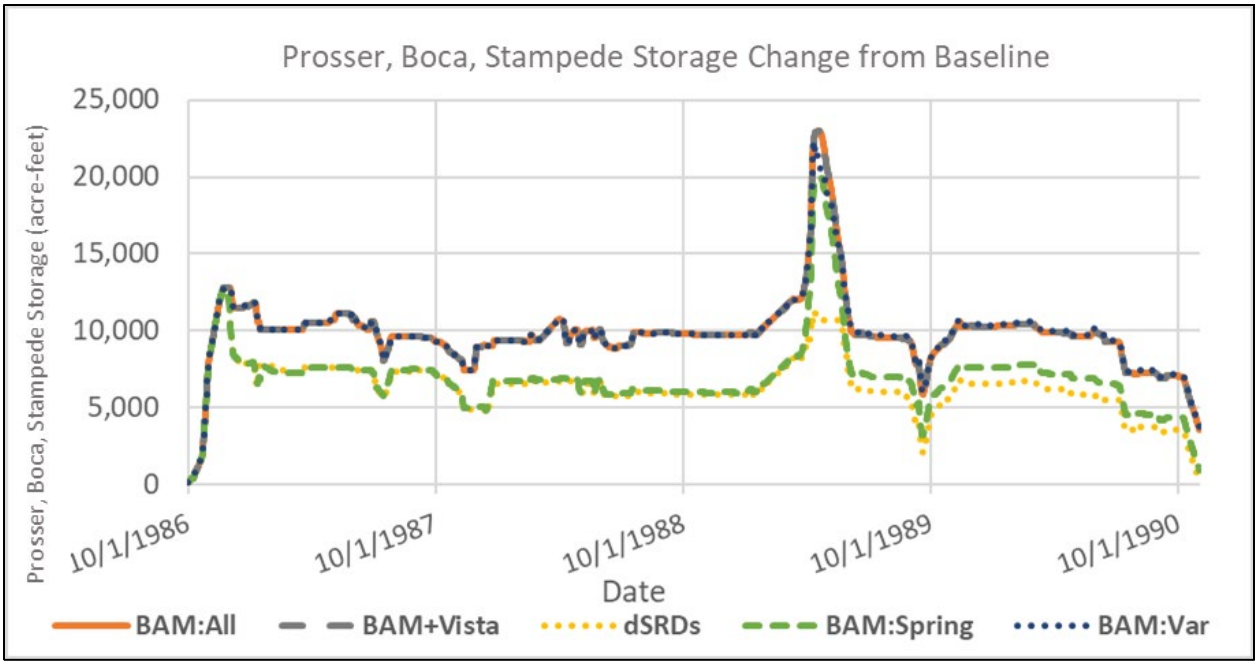


Figure 53.—Prosser, Boca, and Stampede storage from fall 1986 to summer 1991. BAM:All, BAM $^+$Vista, and BAM:Var overlap throughout the demonstrated period, whereas the revised dSRDs and BAM:Spring overlap prior to mid-1989 (Appendix O).

Similarly, in 2006, BAM:All and BAM $^+$Vista store and carryover more water than the other alternatives, maintaining higher reservoir levels until all the alternatives fill the reservoirs in the spring of 2011 (Figure 54). While this additional storage eventually spilled in 2011 and was not put to beneficial use, it does represent a benefit if a dry year had occurred during this timeframe. Further, in the fall of 2011, the alternatives that include the BAM method for fall drawdown, again carryover more additional storage than the alternatives that follow the revised dSRDs or 1985 WCM guide curves (Figure 54).

Overall, the better performance exhibited by the BAM:All, BAM $^+$Vista, and BAM:Var Alternatives in the reservoir storage objective, again, traces back to the additional flexibility provided by using the BAM method for fall drawdown and benefits in the objective also result from the earlier spring refill provided by both the revised dSRDs and BAM method.

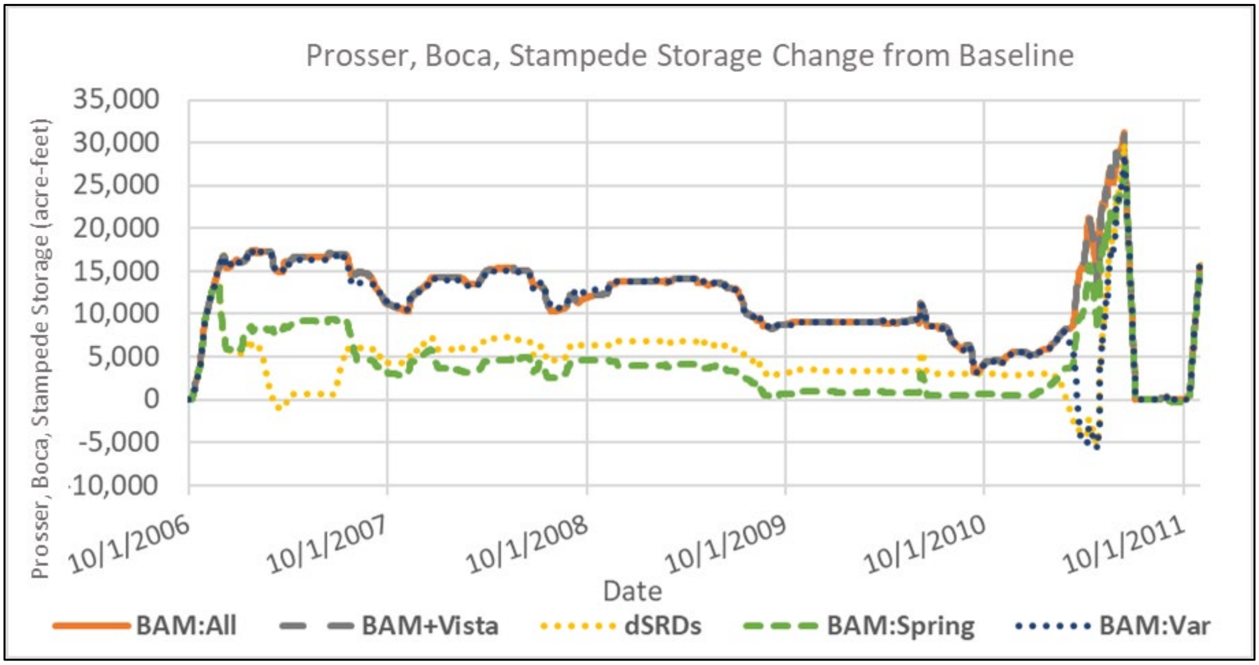


Figure 54.—Prosser, Boca, and Stampede Storage from water years 2007–2011. BAM:All, BAM $^+$Vista, and BAM:Var overlap throughout the period (Appendix O).

Root Mean Squared Flow Over Flood Target

The RMS Flow Over Flood Target objective quantifies how well an alternative reduces the risk of flooding downstream of the flood control reservoirs.

The BAM:Var Alternative offers the greatest benefit to the RMS Flow Over Flood Target objective of approximately 14,000 cfs less than the Baseline (Table 19). BAM:All and BAM $^+$Vista offer the least benefit of approximately 10,500 cfs reduction in the RMS Flow Over Flood Target from the Baseline.

Deeper analysis of the flood risk objective focused on the 10 largest historic and simulated flood events (Table 20). Of note, all the alternatives that incorporate the BAM method (2, 3, 5, and 6) have virtually identical peak flows for most events. During several events, one or more Action Alternatives substantially changed the Baseline's peak flow. The February 1986 500-year scaled event demonstrates the largest reduction of peak flow for all Action Alternatives, reducing the peak flow in the Baseline from approximately 57,247 to 50,385 cfs, or 6,863 cfs less. The following examination of hourly times series during the 1986 100-year simulated event and the May 1996 historic event further demonstrates the impact of the alternatives on flood flows.

Table 20.—Flood Event Change in Maximum Hourly Flow (cfs) From the Baseline at the Reno Gage

Peak Flow		Change in Peak From Baseline (cfs)				
		2	3	4	5	6
Event	**Baseline**	**BAM:All**	**BAM $^{+}$Vista**	**dSRDs**	**BAM:Spring**	**BAM:Var**
Dec–May, WY 2017: 500-year	63,604	0	0	0	0	0
Feb 1986: 500-year	57,247	-6,862	-6,844	-6,862	-6,862	-6,862
Dec–Jan, WY 1997: 500-year	41,609	-1,525	-1,525	-1,525	-1,525	-1,525
Feb 1986: 100-year	26,409	-1,298	-1,297	-1,298	-1,298	-1,298
Dec–Jan, WY 1997	18,010	0	0	-12	-12	0
May 1996: 500-year	15,657	41	40	49	41	32
Jan 2017	12,275	9	9	6	6	10
May 1996: 100-year	11,479	5	5	0	5	-98
Feb 2017	10,305	-11	-11	13	-15	13
May 1996	7,793	284	284	-1,251	340	-1,272

Note: The events with the recurrence interval listed represent simulations of scaled historical events. Reductions in peak flows greater than 100 cfs from baseline are colored green and blue represents peak flows more than 100 cfs above baseline.

During the 1986 flood event scaled to the 100-year volume, all Action Alternatives lessen the time that flows are over the 6,500 cfs Reno flood flow target (Figure 55). All Action Alternatives also reduce the second peak flow on February 19th from approximately 26,000 to 22,500 cfs (Figure 55). The similar flood risk reduction improvements experienced under all Action Alternatives appears related to the high Boca Portion of Flood Space and its correlation with lower RMS Flow Over Flood Target (Figure 43). Additionally, the 6,500 cfs Reno flood flow target allows for swifter evacuation of reservoir flood space over the course of the event, resulting in a lower peak flow at the time of the second event that occurred on March 8th (Figure 55).

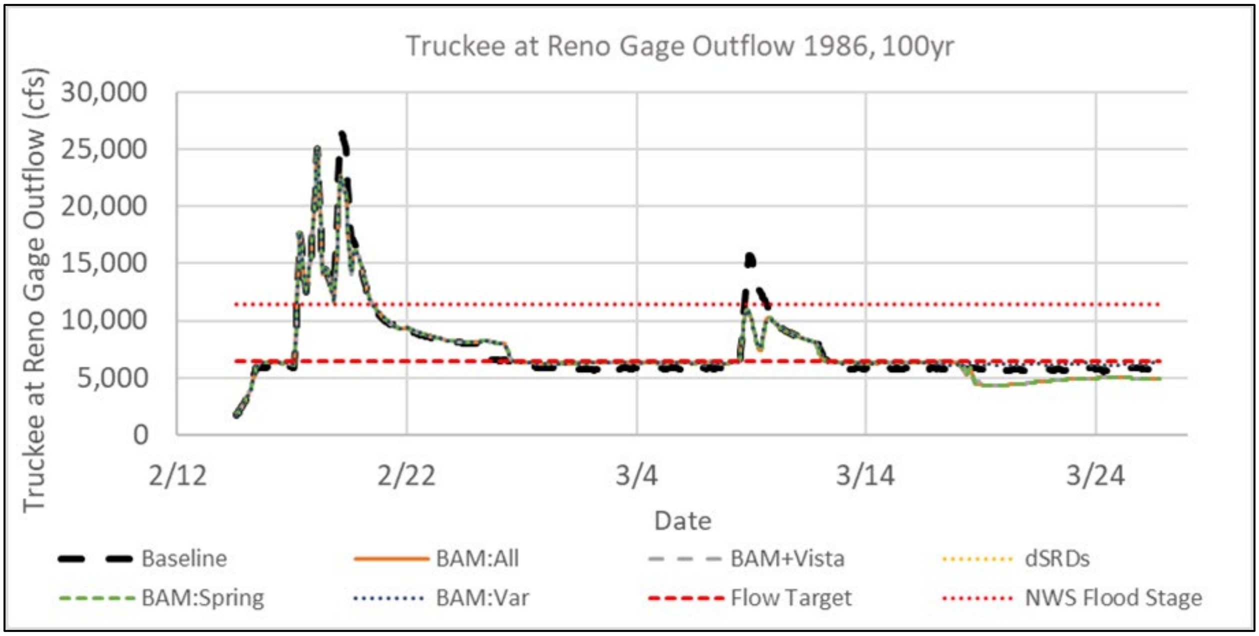


Figure 55.—February 1986 100-year flows over the flood flow target of 6,500 cfs. All alternatives overlap throughout most of the period (Appendix O).

In the May 1996 flood event, BAM:All, BAM $^{+}$Vista, and BAM:Var have 300 cfs higher peak flow than the Baseline, all of which exceed the Reno flood flow target. On the other hand, the dSRD and BAM:Var Alternatives maintain the flood flow target of 6,500 cfs, lowering the peak flow by about 1,200 cfs (Figure 56).

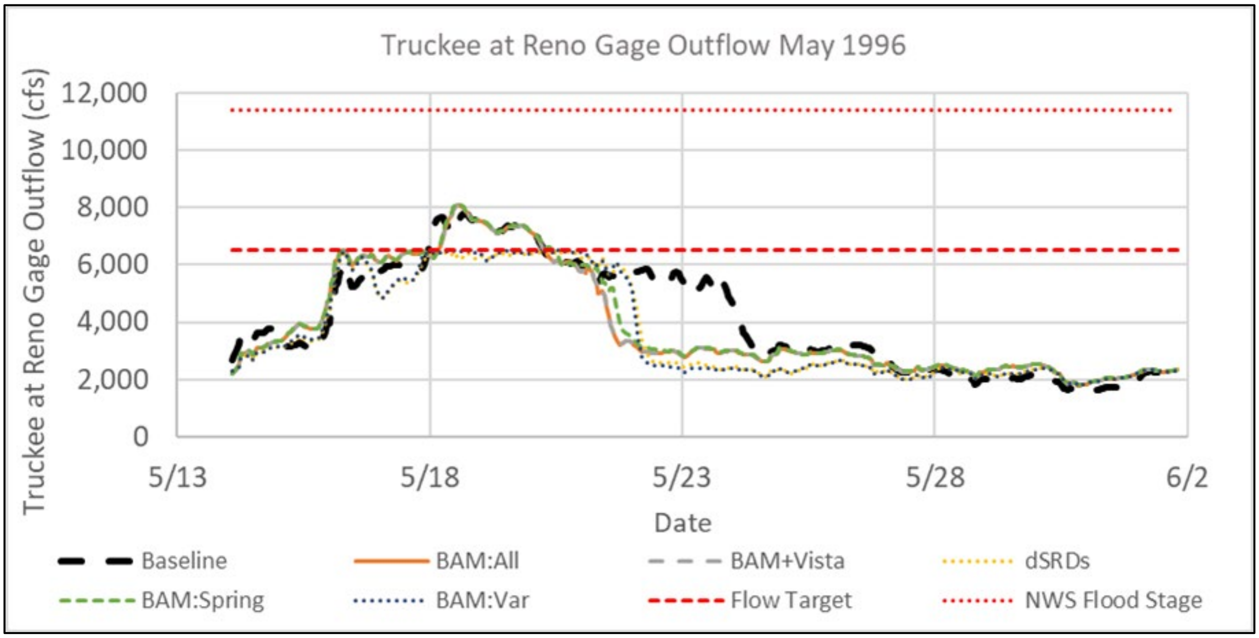


Figure 56.—Truckee at Reno Gage flow during the May 1996 flood event, with a 6,500 cfs flood flow target (Appendix O).

Supplemental Metrics

Results for the supplemental metrics are included for reference (Table 21).

Table 21.—Alternative Operational Scenarios Supplemental Metric Calculations

Objectives	Supplemental Metrics	Alternative Operational Scenarios					
		Baseline	BAM: ALL	BAM +Vista	dSRDs	BAM: Spring	BAM:Var
Water Supply	Average Days Missing Floriston Rate at Farad: Annual	73.70	73.68	73.68	73.68	73.68	73.68
	Average Days Missing Floriston Rate at Farad: Apr to Oct	32.51	33.00	33.00	32.62	32.59	32.68
	Average Days Missing Floriston Rate at Farad: Nov to Mar	40.70	40.68	40.68	40.78	40.84	40.73
	Average Floriston Rate Flow at Farad: Annual (cfs)	379.2	379.5	379.5	379.4	379.4	379.4
	Average Floriston Rate Flow at Farad: Apr to Oct (cfs)	431.7	431.7	431.6	431.7	431.8	431.7
	Average Floriston Rate Flow at Farad: Nov to Mar (cfs)	307.6	308.2	308.2	308.0	307.9	308.0
Environmental Flows	Average Nixon Flow for Flow Regime: Annual (cfs)	208.2	209.0	209.0	208.5	208.5	208.5
	Average Nixon Flow for Flow Regime: Aug to Feb (cfs)	117.6	118.2	118.2	117.9	118.0	117.9
	Average Nixon Flow for Flow Regime: Mar to Jul (cfs)	334.0	335.0	335.0	334.4	334.3	334.2
	End Pyramid Lake Pool Elevation (feet)	3,807.57	3,807.39	3,807.39	3,807.44	3,807.46	3,807.38
	Average Pyramid Lake Pool Elevation (feet)	3,811.55	3,811.46	3,811.46	3,811.50	3,811.49	3,811.47
	Average California Preferred Objective Score: Annual	5.47	5.63	5.63	5.52	5.52	5.55
	Average California Preferred Objective Score: Mar to Aug	5.31	5.44	5.44	5.33	5.35	5.35
	Average California Preferred Objective Score: Oct to Feb	5.79	6.02	6.02	5.88	5.87	5.94
Flood Risk Management	100-Year Regulated Daily Flood Flow: Reno (cfs)*	38,665	39,662	39,665	38,653	40,267	38,744
	100-Year Regulated Daily Flood Flow: Vista (cfs)	42,352	43,644	43,649	42,890	44,238	43,025
	100 Year Regulated Daily Flood Flow: Wadsworth (cfs)	46,188	49,106	49,123	48,792	50,003	48,833
	Average Annual Maximum Surcharge (acre-feet)	922	1,108	1,106	799	1,057	799
	Average Annual Maximum Surcharge: Boca (acre-feet)	14	22	22	8	22	16

Objectives	Supplemental Metrics	Alternative Operational Scenarios					
		Baseline	BAM: ALL	BAM +Vista	dSRDs	BAM: Spring	BAM:Var
	Average Annual Maximum Surcharge: Prosser (acre-feet)	182	195	193	94	152	96
	Average Annual Maximum Surcharge: Stampede (acre-feet)	726	896	896	704	887	694
	Average Annual Volume Over Flood Ops Target (acre-feet)	5,746	5,964	5,967	5,683	5,859	5,708
	Average Fall-Winter Flood Space Requirement (acre-feet)	41,576	6,600	6,600	21,696	21,696	8,141
TROA Parties Objectives	Average Annual Establishment: Total (acre-feet)	13,377	17,039	17,039	14,045	15,704	16,614
	Average Annual Establishment: CA-DWR (acre-feet)	629	1,326	1,326	916	1,123	1,280
	Average Annual Establishment: PLPT (acre-feet)	864	2,225	2,225	1,088	1,460	2,141
	Average Annual Establishment: TMWA (acre-feet)	1,208	1,256	1,256	1,195	1,193	1,241
	Average Annual Establishment: WQ (acre-feet)	3,103	3,519	3,519	2,992	3,378	3,345
	Average Annual Establishment: Newlands (acre-feet)	5,741	6,095	6,095	5,698	6,145	6,075
	Average Annual Establishment: Fernley (acre-feet)	1,202	1,291	1,291	1,240	1,282	1,251
	Average Annual New Project Water Storage: Total (acre-feet)	100,964	101,380	101,384	102,201	102,044	101,208
	Average Annual New Project Water Storage: Boca (acre-feet)	33,497	33,556	33,538	33,530	33,854	33,940
	Average Annual New Project Water Storage: Prosser (acre-feet)	12,988	13,904	13,903	13,818	13,986	13,910
	Average Annual New Project Water Storage: Stampede (acre-feet)	54,480	53,920	53,942	54,853	54,204	53,358

Note: The scores are ranked by color where green represents the best scoring alternatives and blue represents the worst scoring alternatives.

*The 100-year flood flows included in the Supplementary Metrics were calculated in the daily RiverWare Planning Model based on the *regulated* annual peak daily average flow. RiverWare automates the general flood frequency guidance in Bulletin 17B (USGS, 1982) for comparison purposes between scenarios. The method used here contains a few simplifying assumptions, including but not limited to the: use of regulated and not unregulated flow, omission of a manual review of data and calculations, use of a truncated period of record, and lack of distinction between rain-on-snow and no-snow floods. Use of this method was approved by the Key Stakeholders for comparison purposes only. The timeseries results from the Hourly Model provide a richer and more accurate picture of how well the alternatives manage floods.

Interpretation of Quantifiable and Non-Quantifiable Objectives

The individual quantifiable objective scores formed one piece of the alternatives' evaluation, and it was followed by a more subjective, discussion-based evaluation of the non-quantifiable objectives, the weight stakeholders placed on each objective, and comparative tradeoffs between different objectives and alternatives.

A few select objectives and interactions between objectives formed the main discussion topics and decision factors of the Preferred Operational Scenario, as discussed subsequently:

- Bring WCM up to date with current technologies and capabilities and allow flexibility for future improvements in data availability and forecasting of future climate conditions.
- Ease of implementation in an operational mode.
- Flood risk, water supply, and environmental flows tradeoffs.

Through this process, workshop participants eliminated some alternatives from further discussion, allowing for more focus on the pros and cons of the remaining alternatives.

Bring WCM Up to Date With Current Technologies

One of the main impetuses for the WMOP was to bring the WCM up to date with current technologies and capabilities. FIRO sits at the global forefront of operational guidelines for reservoirs, and the workshop participants agreed that the alternatives that incorporate BAM components (Alternatives 2, 3, 5, and 6) bring the WCM more up to date with current technologies than the revised dSRDs (Alternative 4). Further, all of the Action Alternatives represent substantial improvements over the 1985 WCM in this regard. Crucially, the evaluation of the quantifiable objectives demonstrated the potential of the BAM method to improve water supply reliability and environmental conditions in the basin, without increasing flood risk. As streamflow forecast ensembles improve in accuracy, their improved predictive performance will automatically be integrated into calculations of flood space requirements, meeting the objective of allowing flexibility for future improvements in data availability and forecasting.

Ease of Implementation in an Operational Mode

Bringing the WCM up to date with current technologies produces trade-offs with the objective of Ease of Implementation in an Operational Mode. Workshop participants noted that the novel, untested, and more complex BAM method would introduce new operational requirements and challenges. The BAM method introduces a more complex calculation of flood space; however, the calculation will be automated, resulting in a minimal increase in effort. Thus, once the BAM method is in place, it should not be substantially more difficult to determine the daily required flood control space than the current WCM. The BAM and dSRD Alternatives will both increase the part of the year when these considerations are necessary.

The primary challenge comes from the operational release changes and coordination required to operate to variable flood space. These changes are likely to raise questions from a wide variety of basin stakeholders and the public, increasing the coordination necessary for the USWM. However, these challenges would only be necessary when there is a storm in the forecast that would require more than 30% of the revised guide curve, something that only happened on 41 days over the 37-year dataset. While these periods have always required very intense operational coordination, the BAM method adds complications to these high-flow periods.

On the other hand, workshop participants deemed the revised dSRDs, the easiest of the Action Alternatives to implement, due to its similarity with the flood space determination method in the current WCM.

Workshop participants also noted that operating to flood flow targets in Reno and Vista in BAM $^+$Vista adds complications for operators involving travel time adjustments and additional forecasting requirements in the lower Truckee River.

Flood Risk, Water Supply, and Environmental Flow Tradeoffs

As expected, and known from the outset of the WMOP, the alternatives represent tradeoffs in the operational objectives. Assessing these tradeoffs, with consideration of the values that stakeholders place on different objectives, occupied the majority of the more subjective evaluation of the alternatives.

In general, the alternatives that performed best in objectives related to water supply and environmental flows (BAM:All and BAM $^+$Vista), performed worst in the objective related to flood risk management and vice versa (dSRDs and BAM:Spring), whereas BAM:Var performed somewhere in the middle (Table 19). In looking at the actions contained within these alternatives (Table 9), along with the time-series data of when benefits accrue, the additional water supply and environmental flow benefits in BAM:All and BAM $^+$Vista are primarily attributed to the use of the BAM method for fall drawdown. On the other hand, the additional reduced flood risk benefits in the dSRDs and BAM:Spring Alternatives relate to the use of the revised dSRDs to determine the required flood space in the spring in high runoff years which reduced the peak flow in some of the runoff minor flood events (Table 19).

The workshop participants examined the similarities and differences within alternative pairs (Alternatives 2 and 3, and Alternatives 4 and 5) to help narrow the Preferred Operational Scenario selection process. BAM:All and BAM $^+$Vista (Alternatives 2 and 3) offer the same water supply benefits, but BAM:All does not contain the Vista flood flow target. Due to increased implementation challenges without additional benefits, workshop participants eliminated BAM $^+$Vista for further discussion. Similarly, BAM:Spring (Alternative 5) was eliminated since it performs the overall worst in the Average Daily Increase in Flood Space Requirement objective and did not produce additional significant benefits in comparison to the alternative that used the revised dSRDs year-round (Alternative 4). This left three alternatives for consideration as the Preferred Operational Scenario: BAM:All, dSRDs, and BAM:Var.

Although BAM:All outperformed the other alternatives in all quantifiable objectives, except the RMS Flow Over Flood Target (cfs), digging into the time-series data exposed some concerns with using the BAM method exclusively. Despite achieving the best (lowest) value in the Average Daily Increase in Flood Space Requirement objective, workshop participants were concerned that the BAM method requires operators to quickly, evacuate flood space at times, as seen in the 2017 time series (Figure 57). Under BAM:All, from January to June 2017, Prosser Reservoir releases eight short pulses of outflow, whereas the dSRD Alternative only releases a couple pulses of outflow and these are spread out over more days (Figure 57). These quick releases create operational challenges, can illicit concerns from the public and basin stakeholder, and negatively impact fish species.

Relatedly, the BAM method allows 22,000 acre-feet of storage until April 1, 2017, except for a few days when storms were forecasted, whereas the revised dSRDs only allow 10,000 acre-feet of storage through April 10th (Figure 57 and Figure 58). While a key benefit of using the BAM method is the ability to maintain higher winter reservoir levels and more carryover water from one year to another, workshop participants pointed out that 2017 was a wet year with a historic runoff. As such, there was not any need to carry over water since all the reservoirs would fill during spring runoff—the Baseline started the refill season at 10,000 acre-feet and steadily refilled by early June (Figure 58). Further, in addition to the flashy winter flows in BAM:All, the higher reservoir levels during spring refill also result in flashy flood storage requirements and outflows in the spring (Figure 57). Workshop participants questioned the benefit of allowing encroachment into flood space and filling early in a wet year when a lot of snow remains on the ground. The Technical Team saw this as an unnecessary risk and expressed a preference for regulation criteria that would give operators justification for delaying refill and keeping reservoirs lower in wet years.

BAM:Var offers an elegant solution that leverages both the water supply benefits of BAM:All and the benefits of reduced flood risk and flashiness in the revised dSRDs. BAM:Var accomplishes this by incorporating a variable percentage of the required flood space in the revised dSRDs to operate BAM. Ultimately, this alternative is very similar to BAM:All except that its regulation criteria prevent reservoirs from filling early in wet years. As a result, during wet years, BAM:Var mitigates risky and unnecessary encroachment into the flood space, while still providing the water supply benefits associated with BAM:All in drier years, with a lower probability of floods. As shown in Figure 59, BAM:Var offers a compromise between BAM:All and the revised dSRDs—it is less flashy and refills more smoothly than BAM:All, but slightly flashier, with less smooth refill than the revised dSRDs.

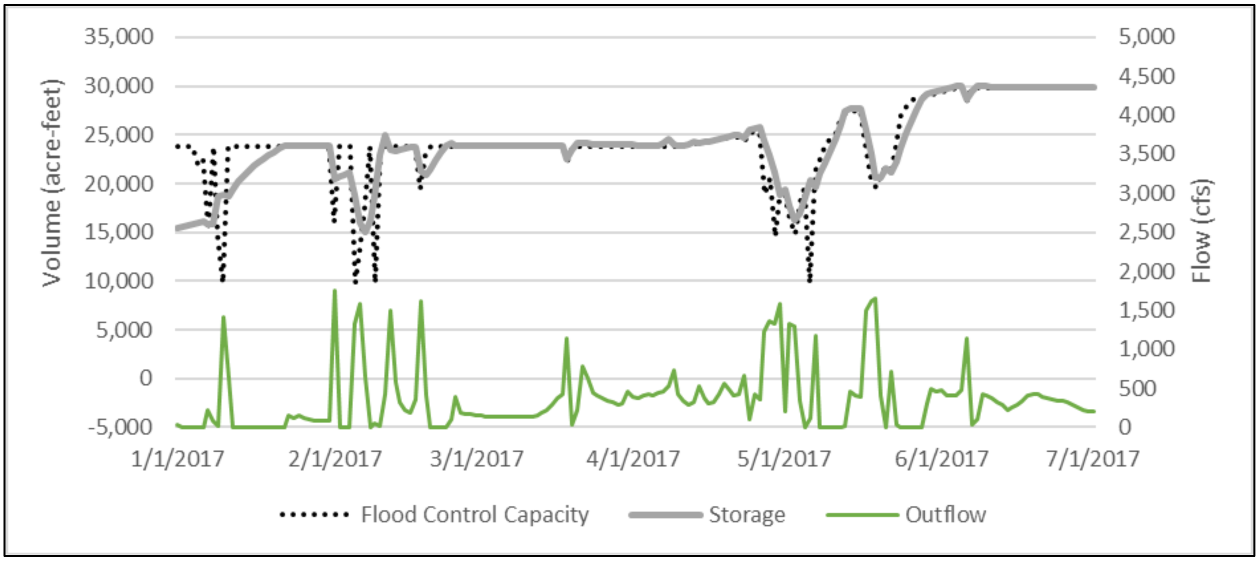


Figure 57.—Prosser required flood space, storage, and outflow in 2017 under BAM:All (Appendix O).

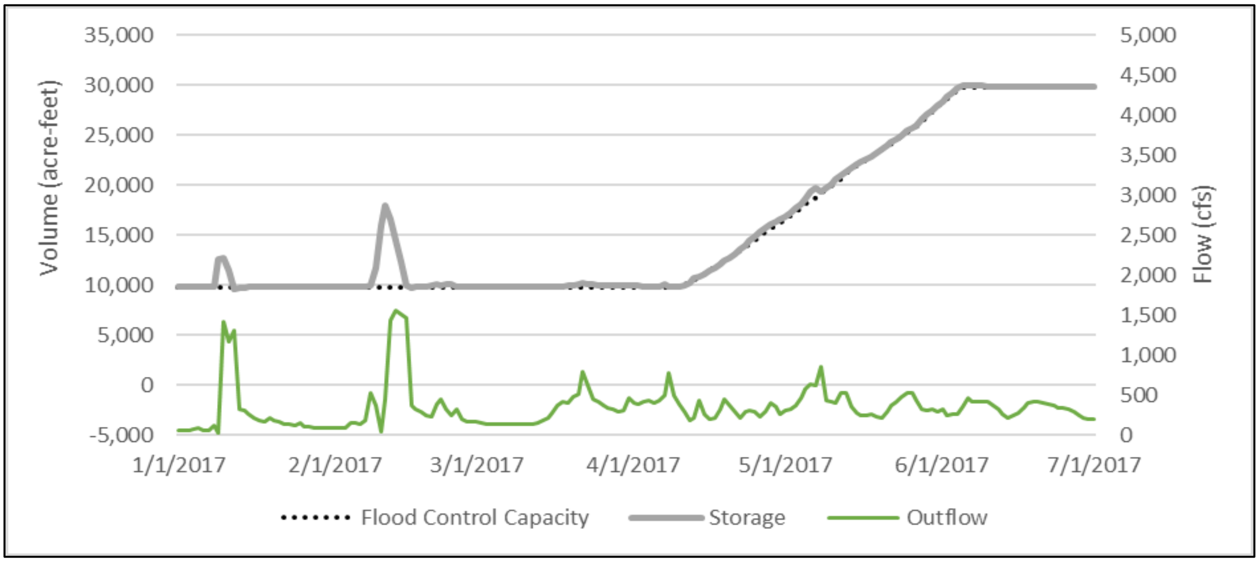


Figure 58.—Prosser required flood space, storage, and outflow in 2017 under revised dSRDs (Appendix O).

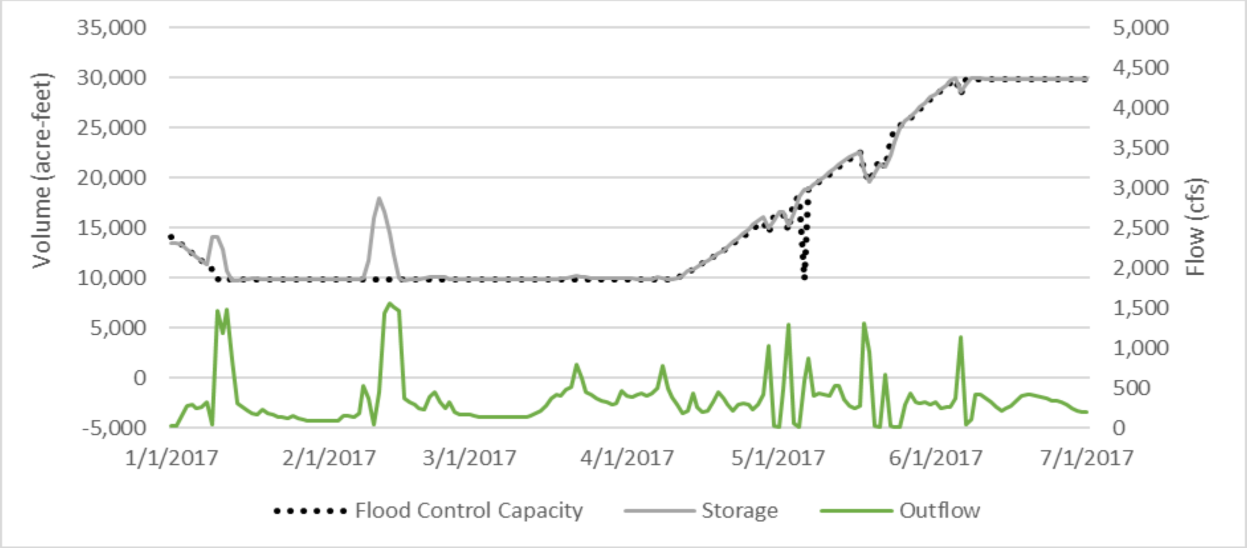


Figure 59.—Prosser required flood space, storage, and outflow in 2017 under BAM:Var (Appendix O).

Alternative Operational Scenario Scoring and Ranking

In recognition of the need for a methodological decision-making framework to evaluate and select a Preferred Operational Scenario, before the March 2023 workshop, the Technical Team developed a set of evaluation criteria (Table 22) along with an associated Likert rating system (Table 23) that attempts to encapsulate the quantifiable and non-quantifiable objectives used in the selection process. Workshop participants were split into three groups to fill out the evaluation criterion for the six alternatives.

Table 22.—Alternative Operational Scenario Evaluation Criteria (Appendix O)

Evaluation Criterion	Possible Values
Maximize Benefit to Floriston Rate (e.g., amount of Floriston Rate water in storage, timing storage available)	Score of -3 to 3 <0 is Excluded from Further Consideration
Maximize Benefit to Threatened and Endangered Fish Species (e.g., VIFR, storage available)	Score of 0-5 <0 is Excluded from Further Consideration
Improve Environmental Instream Flows Downstream of Reservoirs	Score of -3 to 3
Optimize Storage to Satisfy Water Demands Through the Year (e.g., improve refill probability, flexibility of drawdown timing)	Score of -3 to 3
Reduce Risk of Damage from Flooding Downstream	Score of -3 to 3 <0 is Excluded from Further Consideration
Minimize Use of Surcharge Space Above the Spillway	Score of -3 to 3
Do not Increase Probability of Dam Failure	Score of -3 to 3 <0 is Excluded from Further Consideration

Evaluation Criterion	Possible Values
Bring WCM up to date with current technologies and capabilities and allow flexibility for future improvements in data availability and forecasting of future climate conditions	Score of -3 to 3
Implementable in an Operational Mode (i.e., Feasible to Implement).	Score of -3 to 3

Table 23.—Evaluation Criteria Likert Scoring System (Appendix O)

Possible Rating	Meaning
-3	Significantly worse than baseline
-2	Moderately worse than baseline
-1	Slightly worse than baseline
0	No change from baseline
1	Minor improvement over baseline
2	Moderate improvement over baseline
3	Significant improvement over baseline

Each of the three groups provided similar scores for the six alternatives and identical overall rankings; BAM:Var, Alternative 6, ranked as every group's highest-scoring alternative (Table 24).

Table 24.—Ranking of the Six Alternative Operational Scenarios (Appendix O)

	Alternative Operational Scenarios					
	Baseline	BAM:All	BAM $^{+}$Vista	dSRDs	BAM:Spring	BAM:Var
Group 1	0	9	8	6	3.5	9
Group 2	0	11	10	8	7	12
Group 3	0	12	11.75	7.5	5.5	16.25
Average	**0**	**10.7**	**9.9**	**7.2**	**5.3**	**12.4**

Preferred Operational Scenario Selection

Based on the valuation and scoring of the quantifiable and non-quantifiable objectives, the workshop participants, representing all the Technical Team members and many of the other Key Stakeholders, unanimously **recommend the Variable By-a-Model Space (BAM:Var, Alternative 6) as the Preferred Operational Scenario.**

BAM:Var elegantly maintains the majority of benefits related to the:

- Higher water supply and environmental flow volumes observed in BAM:All by using the BAM method to determine flood space requirements.
- Lower flood flows observed in revised dSRDs by constraining the flexibility of normal flood and spring refill operations in wet years.
- Less significant fluctuations in reservoir storage and downstream flow by constraining the flexibility of normal flood and spring refill operations in wet years.

Thus, BAM:Var represents the "best" alternative for leveraging the water supply and environmental benefits associated with the BAM method, while mitigating the unnecessary risk associated with high storage during wet hydrologic years.

In the case of the inaccessibility of CNRFC forecasts or any unforeseen operational roadblock, **the Technical Team recommends using the Revised Guide Curves (dSRDs, Alternative 4) as the backstop operational plan**. The dSRDs ranked highest in terms of the objective related to ease of operation and do not rely on daily CNRFC forecasts, while still offering significant benefits over the No Action Baseline.

Key Recommendation: The Technical Team recommends use of the Variable By-a-Model Space Alternative (BAM:Var) as the Preferred Operational Scenario with the Revised Guide Curves (dSRDs) selected as the backstop operative criteria to the Preferred Operational Scenario.

Reno Flood Flow Target Update

The Key Stakeholders also decided at the March 2023 workshop (re-confirmed at the June 2023 workshop) to recommend updating and increasing the instantaneous Reno flood flow target from 6,000 to 7,000 cfs. In making this recommendation, the Key Stakeholders considered all of the information present in the "Channel Capacity Analysis" section of this VA, along with the source documentation in Appendix I and Appendix J. The three major reasons for this recommendation included:

1. Although the *Channel Capacity Analysis* report suggests that significant flooding near the Truckee River occurs at 7,000 cfs flow, some key modeling assumptions and simplifications indicate the potential for the modeling to suggest higher out-of-bank flows than observed on the ground (Appendix I).
2. On-the-ground survey evidence presented by Dr. George Robison (TRFMA Executive Director) showed that observed flood flows around and above 7,000 cfs flows did not jeopardize any structures in the WMOP's geographical areas of interest (Appendix J).

3. In 2018, the NWS, in coordination with the City of Reno, the City of Sparks, TRFMA, and others, raised the flood stage levels in all locations on the Truckee River due to both natural and manmade changes over the watershed, raising the flood stage at Reno to 12 feet to 11,403 cfs (National Weather Service, National Oceanic and Atmospheric Administration, 2018). Raising the operational target for the flood control reservoirs brings the regulation criteria more in line, though still significantly below, the NWS flood stages.

Key Recommendation: The Technical Team recommends increasing the Reno flood flow target from 6,000 to 7,000 cfs.

Follow-Up Analysis of Preferred Operational Scenario

After the Technical Team selected BAM:Var as the Preferred Operational Scenario and recommended an updated Reno flood flow target, several follow-up analyses were conducted. This includes analyses of the performance of the BAM:Var with the recommended Reno flood flow target, under Probable Maximum Floods (PMFs), and with Martis Dam Operational.

Updated Flood Flow Target

Each Action Alternative was simulated with a Reno flood flow target of 6,500 cfs; however, the Technical Team later recommended increasing the flood flow target to 7,000 cfs. This section compares the quantifiable objective performance of BAM:Var with a Reno flood flow target of 7,000 cfs (BAM:Var 7000) to BAM:Var with a Reno flood flow target of 6,500 cfs (BAM:Var 6500) and to the Baseline that uses a 6,000-cfs target.

BAM:Var 7000 improves upon the performance of the BAM:Var 6500 for all quantifiable objectives, except for a slight decrease in Average Annual Prosser, Boca, and Stampede Storage of 35 acre-feet (Table 25). Of note, the magnitude of most of these objective score differences is relatively small. BAM:Var 7000 also improves upon the performance of the Baseline for all objectives except one. The Baseline outperformed the BAM:Var 7000 cfs in the Average Daily Increase in Flood Space Requirement objective by just 16 acre-feet per day (Table 25).

Table 25.—Comparison Between the Preferred Operational Scenario With a 7,000-cfs Reno Flood Flow Target, the Preferred Operational Scenario With a 6,500 cfs Reno Flood Flow Target, and the Baseline (Appendix O)

	Annual Average Volume for Floriston Rate (acre-feet)	**Average Annual Volume for Flow Regime (acre-feet)**	**Average Annual Prosser, Boca, and Stampede Storage (acre-feet)**	**Average Daily Increase in Flood Space Requirement (acre-feet)**	**RMS Flow Over Flood Target (cfs)**
Baseline	-263,079	-148,067	-175,024	187	159,960
BAM:Var 6500	-263,281	-149,015	-181,804	220	146,029
BAM:Var 7000	-263,284	-149,018	-181,769	203	145,587
BAM:Var 7000 – Baseline	**-205**	**-951**	**-6,745**	**16**	**-14,373**
BAM:Var 7000 – BAM:Var 6500	**-3**	**-3**	**35**	**-17**	**-442**

Note: The scores are ranked by color where green represents the best scoring alternatives and blue represents the worst scoring alternatives.

The most significant benefits of BAM:Var 7000 over BAM:Var 6500 occur in the RMS Flow Over the Flood Target objective, as shown in the time series data for the 1997 historic flood (Figure 60) and the 1986 February through March scaled 100-year flood event (Figure 61).

In the 1997 flood simulation, BAM:Var 7000 and BAM:Var 6500 reduce the period over which the Reno flow was close to or above the flood flow target. On January 4th, 1997, BAM:Var 7000 and BAM:Var 6500 reduce the flow of the Baseline by about 4,000 cfs. When compared to the BAM:Var 6500, BAM:Var 7000 reduces the period in which the reservoirs are under flood operations by 2 days (i.e., operating to the 7,000-cfs flood flow target at the Reno Gage).

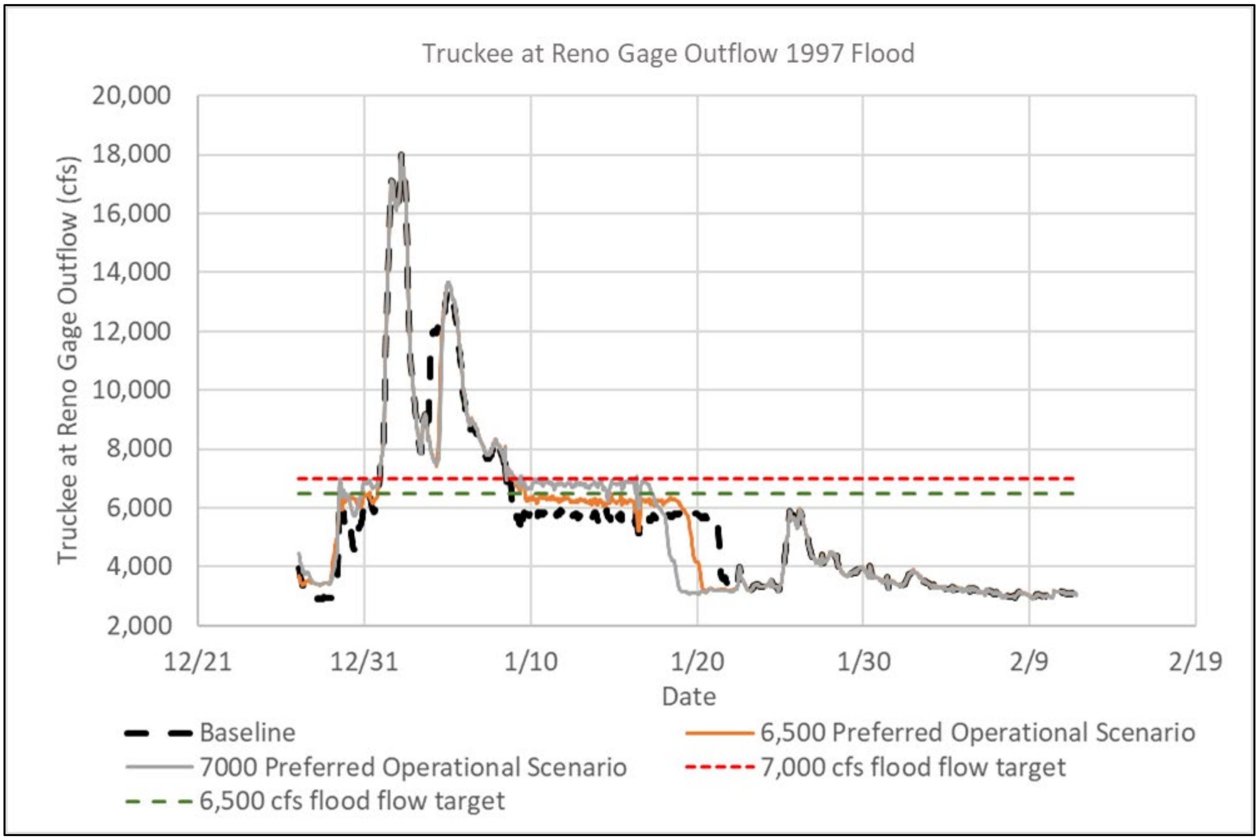


Figure 60.—Truckee at Reno Gage flow during the 1997 flood (Appendix O).

The scaled 1986 100-year flood represents another period of significant differences between the Reno Gage flows in the Baseline and BAM:Var 7000 and BAM:Var 6500. When compared to the Baseline, BAM:Var 7000 reduces the March 9th peak flow from about 15,500 to 10,000 cfs. BAM:Var 7000 also reduces the period during which the March 9th flows were over the flood flow target by a few days, compared to BAM:Var 6500 (Figure 61).

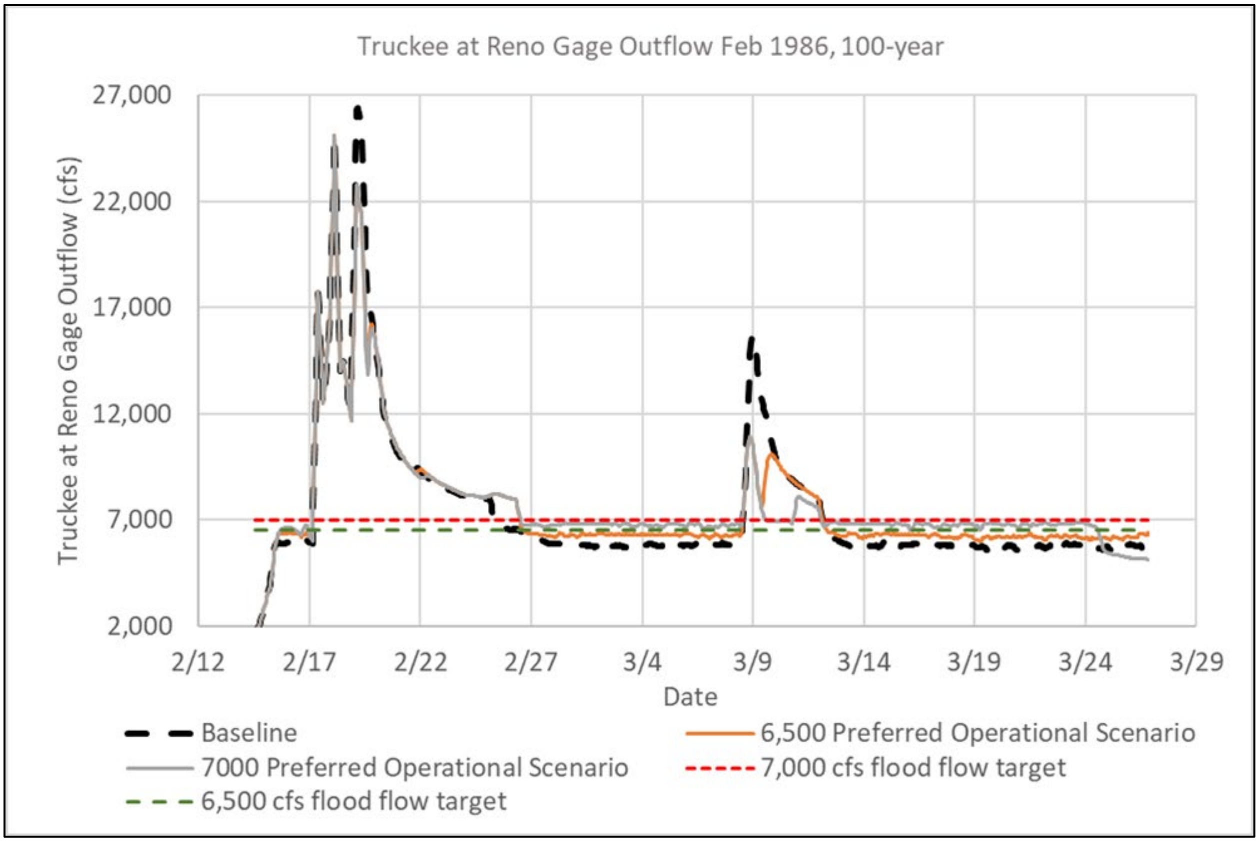


Figure 61.—Truckee at Reno Gage outflow during the Feb-Mar 1986 100-year scaled flood (Appendix O).

In these two simulated events, raising the flood flow target to 7,000 cfs reduces the duration of Reno Gage flows at, or above, the Reno flood flow target. The increased flood flow target allows for more efficient evacuation of reservoir encroachment, particularly important in years when multiple events occur. Reducing periods near or above the target may reduce flood damage.

Probable Maximum Flood

As part of the WMOP, the USWM assessed the performance of the Preferred Operational Scenario under PMF routings and documented the methodology and results in the report, "Truckee Basin Water Management Options Pilot (TBWMOP) Probable Maximum Flood Routings" (Appendix P). Below is an abridgment of the analysis, results, and conclusions.

The 37-year historical dataset (1986–2022) and scaled historic events representing the 100-, 200-, and 500-year Reno floods used to evaluate the alternatives did not contain any floods of significant magnitude to pose a risk of dam failure by overtopping or internal failure. As such, to assess the risk of the dams overtopping and/or internal failure, the USWM routed the latest PMF hydrographs for Prosser and the Little Truckee River (Boca and Stampede) through their respective flood reservoirs for the Baseline, Preferred Operational Scenario (BAM:All), and Backstop Operational Scenario (dSRDs).

Probable Maximum Floods

Reclamation's Technical Service Center (TSC) developed the PMF routings for the Little Truckee River and Prosser Creek within a few months of each other, using similar methods and assumptions (Bullard, 2002a; Bullard, 2002b). In both sub-basins, the PMF events include a rain-on-snow event with a heavy antecedent snowpack (termed rain-on-snow PMF) and a local summer thunderstorm with no snow on the ground (termed no-snow PMF).[10] Due to the placement of Boca and Stampede Dams in a series seven miles apart on the Little Truckee River, TSC developed PMF hydrographs for both rain-on-snow and no-snow events centered over each reservoir. Further, the 2006 routings developed for Prosser also introduced 10,000-year (10kyr) versions of the rain-on-snow and no snow events (Kamstra, 2001).

The rain-on-snow and rain PMFs yield significantly different hydrographs in terms of peak flow and volume, and these also differ significantly from the Spillway Design Flood referenced in the 1985 Water Control Manual in terms of both peak flows and flood flow volumes (Table 26 and Figure 62). The peak flows in all the most recent PMFs are more than double the Spillway Design Flood referenced in the 1985 WCM. On Prosser Creek, rain-on-snow events also yield larger flood volumes than the 1985 Spillway Design Flood, whereas the no-snow events are concentrated over a shorter time, yielding smaller flood volumes than the 1985 Spillway Design Flood. Flood volumes were not available for the Little Truckee 1985 Spillway Design Flood.

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[10] TSC refers to the events in this Viability Assessment termed "snowmelt PMFs" as "General PMFs" and "no-snow PMFs" as "Local PMFs." The terminology was altered for clarity and non-subject matter experts.

Table 26.—Summary of Prosser and Stampede PMF Events

Event	Peak Flow (cfs)	Volume (acre-feet)	Duration (hours)	Assumed Initial State
Prosser PMFs				
1985 WCM Spillway Design Flood*	13,900	41,200	96	20,000 acre-feet of flood space (9,840 acre-feet storage)
Prosser rain-on-snow** PMF	30,200	59,000	96	Storage after antecedent event
Prosser rain-on-snow 10kyr	30,100	59,000	96	Storage after antecedent event
Prosser no-snow PMF	48,200	16,800	24	Max Capacity
Prosser no-snow 10kyr	28,700	9,400	24	Max Capacity
Stampede PMFs				
1985 WCM Spillway Design Flood	29,900	95,900	156	22,000 acre-feet flood space (204,500 acre-feet storage)
Rain-on-snow abv Stampede	80,400	158,900	96	Storage after antecedent event
Rain-on-snow abv Boca	79,100	156,000	96	Storage after antecedent event
No-snow abv Stampede	97,700	34,000	20	Max Capacity
No-snow abv Boca	90,300	33,800	20	Max Capacity
Boca PMFs* **				
1985 WCM Spillway Design Flood**	5,170	10,400	144	Max Capacity
Rain-on-snow abv Stampede	14,900	25,300	96	Storage after antecedent event
Rain-on-snow abv Boca	16,300	28,100	96	Storage after antecedent event
No-snow abv Stampede	72,500	13,600	20	Max Capacity
No-snow abv Boca	72,500	13,600	20	Max Capacity

*The 1985 Spillway Design Flood was not routed as part of this analysis and is included in Table 26 for reference only.

**TSC refers to the events this Viability Assessment termed "rain-on-snow PMFs" as "General PMFs" and the events this Viability Assessment termed "no-snow PMFs" as "Local PMFs". The terminology was altered for clarity and non-expert readers.

***The Boca PMF flows and volumes are based on the intervening flow between Stampede and Boca. For the PMF routings the resultant discharge from Stampede for each event was added to these intervening flows to determine the total inflow to Boca.

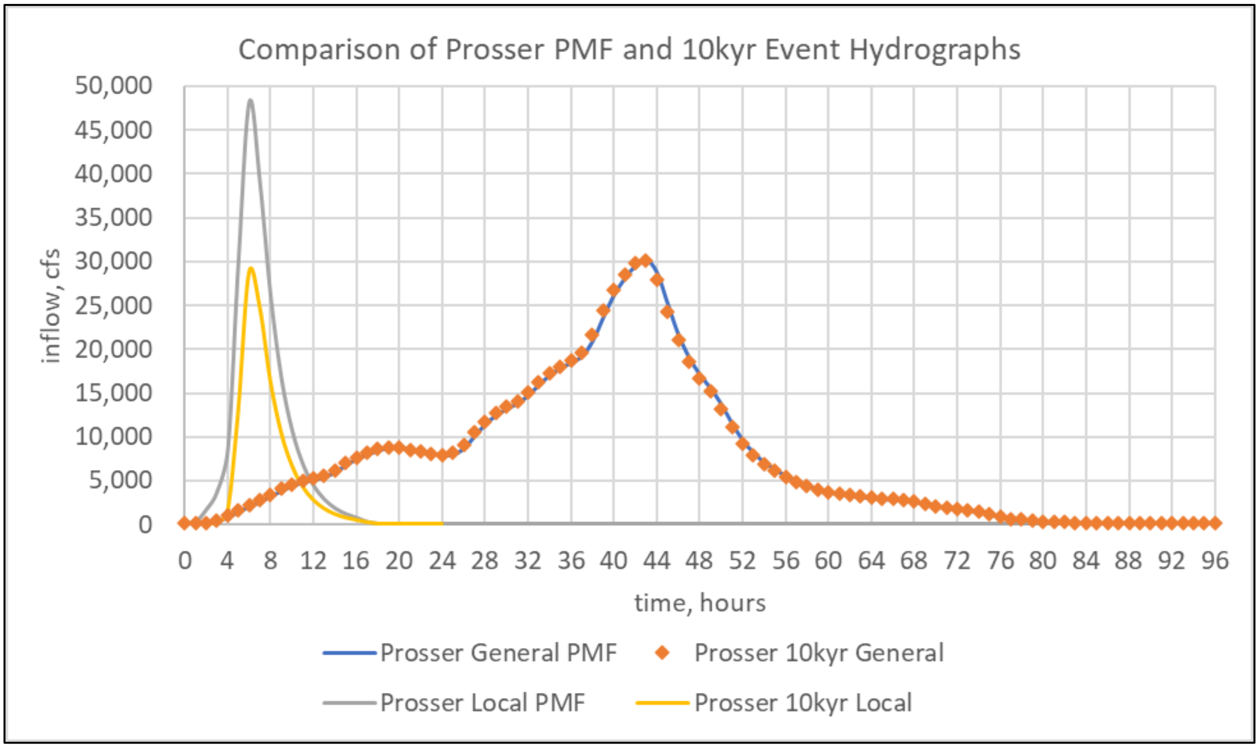

Figure 62.—Comparison of Prosser rain-on-snow (general) and no-snow (local) PMF and 10kyr event hydrographs.

Antecedent Events for Initial States

For the WMOP, the initial states of the reservoirs before the PMFs were determined per ER 1110-8-2 (U.S. Army Corps of Engineers, 1991), which states:

> "The minimum starting elevation for routing the [Inflow Design Flood] IDF[11] will be assumed as the full flood control pool level or the elevation prevailing five days after the last significant rainfall of a storm that produces one-half the IDF, whichever is most appropriate."

To represent summer thunderstorms on saturated soils, all the no-snow PMFs were assumed to occur in mid-July during the record-setting 2017 runoff when the reservoir would be at the full flood control pool in all scenarios (Table 26). For the rain-on-snow events, the initial states were assumed as the elevation 5 days after the end of the flood event in the WMOP dataset most closely matching the 50% PMF volume. For example, the Prosser rain-on-snow PMF was initialized to occur 5 days after the 1997 flood, representing 44% of the PMF volume, 26,100 acre-feet and 59,000 acre-feet, respectively (Figure 63).

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[11] ER 1110-8-2 (U.S. Army Corps of Engineers, 1991) uses the term Inflow Design Flood (IDF) instead of PMF. This report and analysis use the PMFs developed by Reclamation and the terms IDF and PMF are assumed to be interchangeable for the sake of this study.

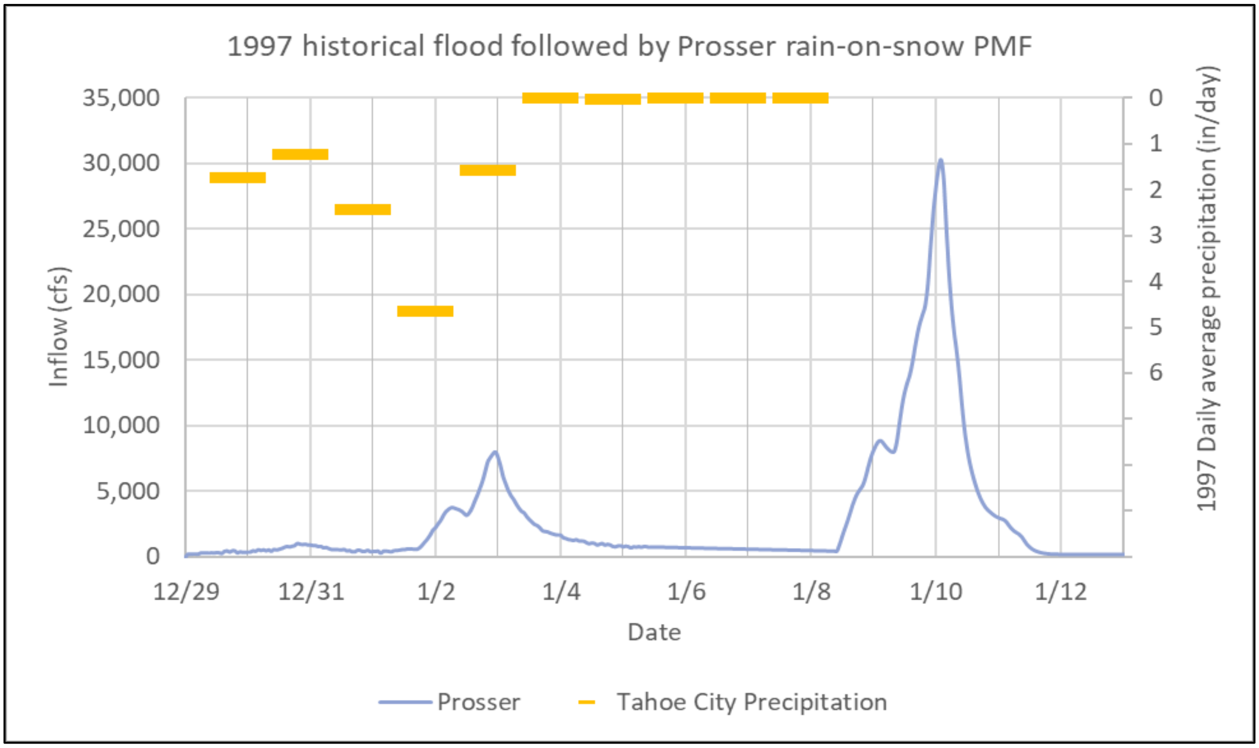

Figure 63.—Prosser rain-on-snow PMF with the historic 1997 flood as the antecedent event occurring 5 days prior, with 44% of the PMF volume (Appendix P).

The initial state assumptions determine the extent to which the different alternatives impact dams' safety. For all alternatives, when the reservoir pool elevation reaches the full flood control pool, outlet works' releases are increased to the maximum extent necessary to return the reservoir to the full flood control pool. As such, the Max Capacity initial state assumption results in almost identical operations for all alternatives during Rain PMFs. Conversely, the alternatives operate differently below the full flood control pool based on the required flood space and downstream Reno flood flow target. These differences in the alternatives could lead to different end storage levels after the antecedent event to the rain-on-snow PMFs, potentially impacting the PMF routings.

The PMF analysis conducted for the WMOP examined whether the dams overtop under the different PMF events and alternatives, finding that:

- None of the rain PMF events result in overtopping.
- Boca does not overtop under the Baseline, BAM:All, or dSRDs Alternatives.
- Prosser is overtopped for all alternatives in the rain-on-snow PMF and the rain-on-snow 10kyr storm.
- Stampede is overtopped for all alternatives in the rain-on-snow PMFs, including those centered over Stampede and those over Boca.

To better assess the impact on dam safety of BAM:All and the dSRDs compared to the Baseline, the USWM compared the maximum pool elevations and freeboard. The freeboard is the vertical distance between the maximum normal water elevation and the crest of the dam, where the dam will start overtopping. In this analysis, if the reservoir elevation reached the crest of the dam, flow over the dam was estimated. In all cases the dams were assumed to not fail, yielding the following results (Table 27):

- The BAM:All, dSRDs, and the Baseline Alternatives result in essentially identical maximum pool elevations for all PMF events at Prosser Reservoir (Table 27).
- Under BAM:All and the dSRDs, the rain-on-snow PMF events result in slightly higher maximum pool elevations in Boca than under Baseline (0.08 foot higher), but the dam maintains over a 1-foot freeboard during all PMF events (Table 27).
- Under the BAM:All and the dSRDs, the rain-on-snow PMF events exceed the crest of Stampede Dam by more than the Baseline (0.24–0.28 foot higher) (Table 27).

Table 27.—Freeboard (feet) During PMF Events at Prosser, Stampede, and Boca Dams

Dam	Event	Baseline	BAM:Var	Revised dSRDs
Prosser	Rain-on-snow PMF	-2.54	-2.53	-2.53
	Rain PMF	7.28	7.27	7.27
	Rain-on-snow 10kyr	-2.53	-2.53	-2.53
	Rain 10kyr	13.72	13.69	13.69
Stampede	Rain-on-snow PMF abv Stampede	-0.45	-0.66	-0.66
	Rain PMF abv Stampede	24.47	24.47	24.47
	Rain-on-snow PMF abv Boca	-0.26	-0.49	-0.49
	Rain PMF abv Boca	24.54	24.54	24.54
Boca	Rain-on-snow PMF abv Stampede	4.05	3.97	3.97
	Rain PMF abv Stampede	3.20	3.12	3.12
	Rain-on-snow PMF abv Boca	1.16	1.16	1.16
	Rain PMF abv Boca	1.13	1.13	1.13

Note: Negative values indicate overtopping (highlighted in blue).

The USWM also looked at the mechanisms and conditions that result in overtopping, which is confined to the rain-on-snow PMFs. The antecedent events in the rain-on-snow driven PMFs fill all the flood space in Prosser and Stampede. At Prosser, under BAM:All and the dSRDs, the 5-day spacing between the end of precipitation in the antecedent event and the PMF is sufficient to evacuate the surcharge but, it is insufficient to evacuate any additional flood space. At Stampede, leading into the PMF, the 5-day spacing is insufficient to draw the reservoir below the spillway under BAM:All and the dSRDs, resulting in 3,500 acre-feet more water stored in the reservoir (1 foot of elevation) than in the Baseline (Figure 64). Despite starting the PMF routing 1 foot higher, the Stampede Dam crest was only exceeded by 0.28 foot more in BAM:All and the dSRDs, than in the Baseline.

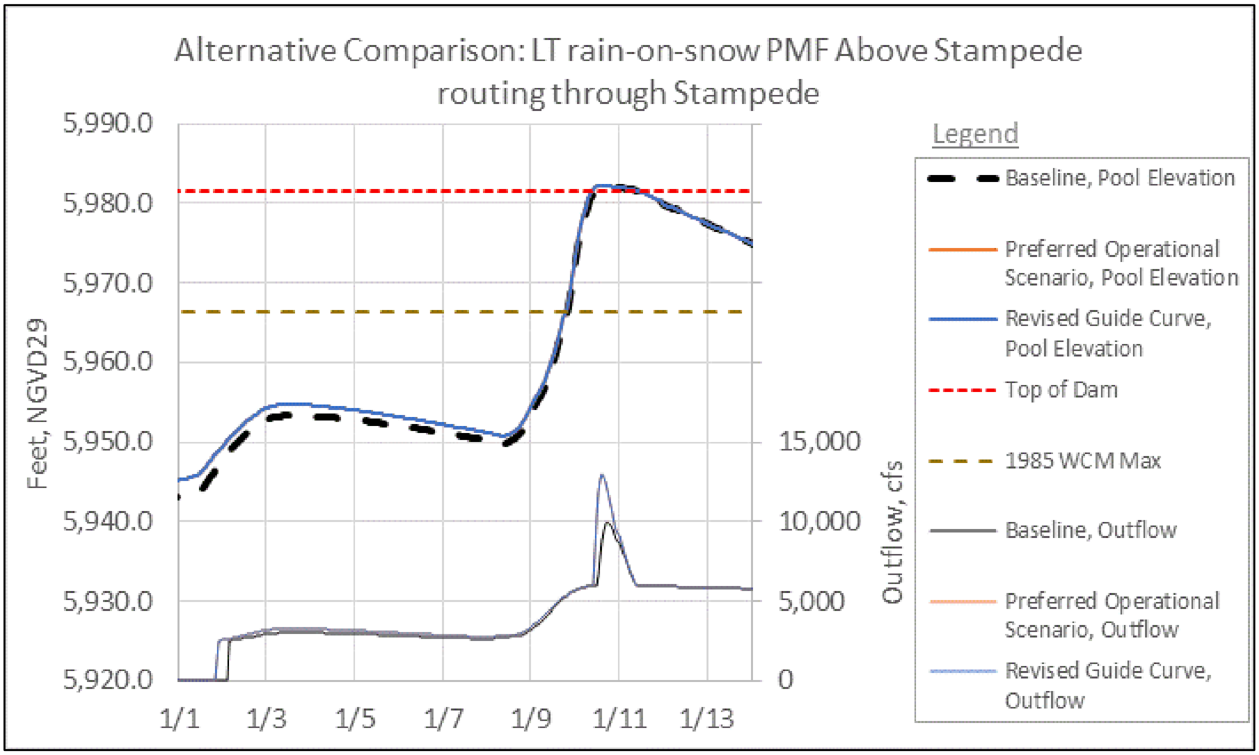

Figure 64.—Comparison of the alternatives' Stampede pool elevation (feet) and outflow (cfs) during the rain-on-snow PMF in the Little Truckee (LT) Basin centered on Stampede. The Preferred Operational Scenario and Revised Guide Curves' pool elevation and outflow overlap throughout the period (Appendix P).

Overall, routing the most recent PMFs through the reservoirs on Prosser Creek and the Little Truckee River under the BAM:All, dSRDs, and the Baseline produces very similar results in terms of maximum pool elevation and outflow hydrographs. One of the only noticeable differences between the alternatives occurs at Stampede during rain-on-snow PMF events when the BAM:All and dSRDs overtop the crest by 0.66 foot and the Baseline only overtops the crest by 0.45 foot. These differences result from operations during the antecedent event and the subsequent reservoir elevation at which the PMF routing begins. Future studies should investigate how different initialization states and antecedent conditions affect the rain-on-snow PMF routings under the alternatives.

Martis Creek Dam Operational

As part of the WMOP, the USWM assessed the performance of the revised dSRDs and the Preferred Operational Scenario, BAM-Var, with Martis Dam operational and documented the methodology and results in the report, "Truckee Basin Preferred Operational Scenario with Martis Creek Reservoir Operational" (Appendix Q). Below is an abridgment of the analysis, results, and conclusions.

The 1985 WCM authorizes the use of Martis Creek Reservoir to store water for flood control when flows at the Reno Gage are forecast to reach or exceed 14,000 cfs; however, the USACE designated Martis Creek Dam (Martis) as having moderate risk. As such, it is operated to keep the gates open until the USACE can complete a test fill and not as intended in the WCM. The operational capacity of Martis was one the primary themes during early discussion of problems and opportunities with flood management operations in the Truckee Basin. As a result, the stakeholders adopted an objective for the WMOP to "allow flexibility for varying future operating conditions of Martis Dam." This section provides an initial analysis of the performance of the revised dSRDs and the Preferred Operational Scenario, BAM-Var, with and without Martis operational.

Changes to Operational Scenarios With Martis Operational

The revised dSRDs with Martis operational extend the period when other basin reservoirs can encroach into flood space for both the fall drawdown period and the spring fill period, adding more operational flexibility. Without Martis in operation, the dSRDs require reservation of all the Truckee Basin flood space on December 6th, 36 days later than the 1985 WCM requires reservation of all the flood space (November 1st) (Figure 65). With Martis operational, the full amount of flood space is not required until December 16th (Figure 65). The dSRDs also allow encroachment into the flood space earlier with Martis' operational. For example, in water year 2000, which was near median runoff, encroachment into Prosser flood space is permitted as early as March 24th without Martis operational and March 3rd with Martis operational, compared to April 10th in the 1985 WCM (Figure 65).

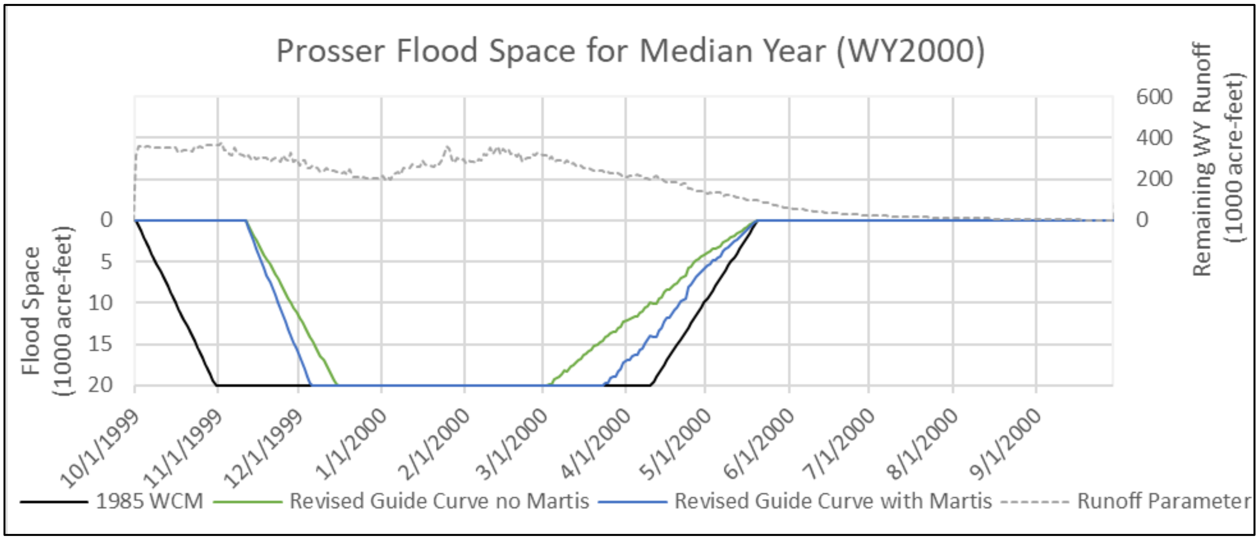

Figure 65.—Prosser required flood space for a median water year, 2000.

Inclusion of the Martis flood space in the total Truckee Basin flood space more evenly distributes the proportion of basin flood space in each reservoir, without changing the absolute volume of flood space (Table 28). Of note, BAM-Var also reproportions the flood space between Boca and Stampede in the Little Truckee Basin. As a result, BAM-Var with Martis operational spreads out the flood space between the basin reservoirs most evenly, with each reservoir maintaining 23–31% of the basin's flood space; versus reservoirs maintaining 30–40% of the flood space under BAM-Var without Martis. Under the 1985 WCM and revised dSRDs without Martis, 44% of the basin's flood space is concentrated in Stampede with only 16% allocated to Boca.

Table 28.—Summary of Truckee Basin Reservoirs Flood Space Reservations for Each Scenario

	dSRDs (WCM and revised)		BAM:Var			
	without Martis		without Martis		with Martis	
Reservoir	Flood Space (acre-feet)	Percent of Total	Flood Space (acre-feet)	Percent of Total	Flood Space (acre-feet)	Percent of Total
Prosser	20,000	40%	20,000	40%	20,000	31%
Martis	0	0%	0	0%	15,000	23%
Boca	8,000	16%	15,000	30%	15,000	23%
Stampede	22,000	44%	15,000	30%	15,000	23%
Little Truckee Total	**30,000**	**60%**	**30,000**	**60%**	**30,000**	**46%**
Basin Total	50,000	100%	50,000	100%	65,000	100%

BAM-Var also changes the criteria in the 1985 WCM for how Martis should be operated during a flood (assuming that Martis is operational). During the Plan Formulation phase of the WMOP the Technical Team expressed that if Martis is operational for flood control it should be operated to meet the same downstream target flow rather than operating to meet a different downstream Reno flow target of 14,000 cfs, as currently specified in the WCM. As such, during a flood event, Martis releases would be operated conjunctively with the releases of other reservoirs to maintain the Reno flood target of 7,000 cfs.

Scenario Performance With Martis Operational

Operationalizing Martis for flood control in BAM-Var yields improvements or no significant change in the five quantifiable objectives (Table 29).

Table 29.—Comparison of Quantifiable Objective Performance With and Without Martis Operational

Objective	Units	Baseline	BAM-Var		
		without Martis	without Martis	with Martis	difference with Martis
Average Annual Volume for Floriston Rate	acre-feet	263,079	263,277	263,282	5
Average Annual Prosser, Boca, and Stampede Storage	acre-feet	175,024	181,559	182,252	693
Average Annual Volume for Flow Regime	acre-feet	148,067	149,023	149,022	-1
RMS Flow Over Flood Target	cfs	159,960	144,811	135,442	9,369
Average Daily Increase in Flood Space Requirement	acre-feet	187	204	196	9

The largest benefits with Martis operational in BAM-Var accrue in the flood management objective, with a 9,369 cfs or 5.9% decrease in RMS Flow Over Flood Target compared to the BAM-Var without Martis scenario (Table 29). As such, operationalizing Martis in BAM-Var decreases RMS Flow Over Flood Target nearly as significantly as BAM-Var decreases RMS Flow Over Flood Target compared to the baseline 1985 WCM (15,150 cfs reduction).

Operationalizing Martis also results in 693 acre-feet more Average Annual Prosser, Boca, and Stampede Storage, even if Martis were only operational for flood control and not water supply storage (Table 29). The water supply benefits accrue in the late spring and early fall when only smaller historical flood events have occurred. In the spring, utilizing Martis for flood control allows the other flood control reservoirs—Prosser, Boca, and Stampede—to begin filling earlier and fill at a slower rate. In the fall, Martis would allow slower drawdown of the flood space and allows for drawdown releases more conducive for native fish spawning as prescribed in the California Guidelines (California Department of Water Resources and California Department of Fish and Wildlife, 2018).

Recommendations

Key Recommendation: The Key Stakeholders in the WMOP recommend the use of the Variable By-a-Model Space Alternative with a 7,000 cfs Reno flood flow target as the new WCM guidance, with the Revised Guide Curves used as the backstop operational plan, in the case of the inaccessibility of CNRFC forecasts or any other seen or unforeseen operational roadblock.

The process of formally updating the WCM will take some time. This closing section outlines recommendations the Key Stakeholders can take to best position the basin for a WCM update, which includes:

- An **Implementation Plan** for sequentially and strategically updating dam operations during the WCM update processes,
- **Flexibility and Adaptive Management** to refine BAM:Var and the dSRDs as new information accrues, and
- **Additional Studies and Future Work** to fill data and information gaps identified in the WMOP as well as those uncovered while enacting the Implementation Plan.

Implementation Plan

The WMOP produced encouraging results regarding the potential benefits of updating the 1985 WCM. However, uncertainty remains in implementing and operationalizing the BAM:Var Alternative presented on paper and in models. Planned deviations from the 1985 WCM and parallel virtual simulations will allow for real-world testing of the proposed operational changes from which to gain insight and experience with forecast-informed tools and approaches, as described below.

Deviation Request Water Year 2023 (Spring and Fall 2023)

The WMOP coincided with one of the largest snowpacks on record in the Sierra Nevada Mountains (water year 2023), conditions for which the WMOP was designed to address. This led the Technical Team to submit a formal request to the USACE in March 2023 for a planned deviation from the 1985 WCM operations (Worsley, 2023). Under the requested deviation, the three Reclamation reservoirs would have been operated in spring 2023 and fall 2023 to the revised dSRDs developed as part of the WMOP. Whereas the dSRD Action Alternative included a Reno flood flow target of 6,500 cfs, the deviation operations maintain the 6,000-cfs target (Worsley, 2023). The revised dSRDs represent a step between the guide curves in the

1985 WCM and the BAM method. This deviation would also provide an opportunity to test, in real-time, the use of the revised dSRDs as the backstop for BAM:Var, the Preferred Operational Scenario.

During years with significant snowpack, the 1985 WCM requires operators to reserve flood space late into the spring and can prohibit reservoir refill from starting until June 1st. Under the revised dSRDs and using the March 15, 2023, CNRFC forecast volumes, the reservoirs would have begun filling in the first half of April, and steadily refilled, reaching full capacity at the beginning of June. (Figure 66 shows the Prosser Reservoir storage under the Baseline and deviation operations). Alternatively, under the Baseline, the reservoirs would not begin filling until June 1st and would refill more rapidly, reaching capacity in early July (Figure 66). Downstream hydrographs under the dSRDs would've better resembled the reservoirs' inflow hydrograph, allowing for a more natural flow regime downstream during refill (Figure 67). Although all the Truckee reservoirs did fill in 2023, some of the CNRFC ensemble forecasts during the spring suggested that Boca and Prosser might not completely fill under the 1985 WCM, whereas all reservoirs refilled, in all traces under the deviation.

Unfortunately, the deviation request was not approved in time for implementation in spring 2023.

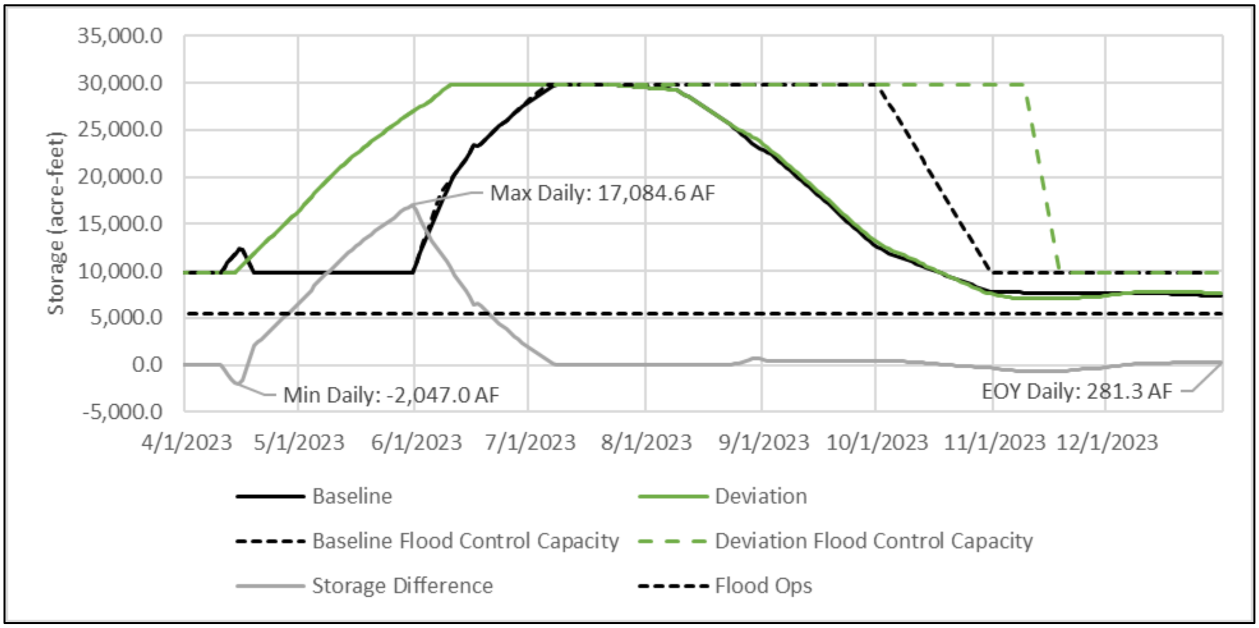

Figure 66.—Projected Prosser storage (acre-feet) under Baseline operations (WCM 1985) and under the requested deviation to use the revised dSRDs, based on the median CNRFC forecast on March 15, 2023 (Worsley, 2023).

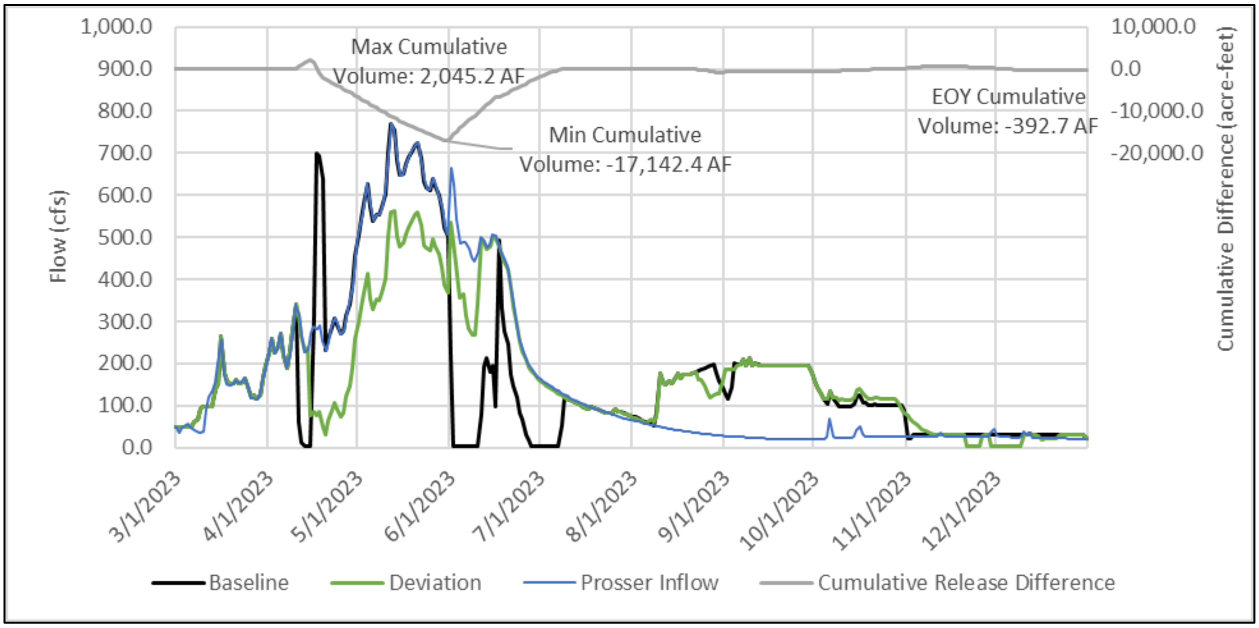

Figure 67.—Projected Prosser releases (cfs) under the Baseline Alternative and under the requested deviation to use the revised dSRDs, based on the median CNRFC forecast on March 15, 2023 (Worsley, 2023).

Deviation Request Water Year 2024 (Fall 2023 and Spring 2024)

To provide more time for the USACE to assess the requested operational changes, the Technical Team, in collaboration with the USACE, shifted the deviation to request to use the revised dSRDs for the full 2024 water year, October 1, 2023, to September 30, 2024. The Technical Team continues to collaborate with the USACE to integrate the dSRDs into the USACE's systems, as well as provide the USACE access to the TROA RiverWare models so that the USACE can perform their own analysis with the deviation in place.

To evaluate performance under the deviation compared to the Baseline, the USWM ran a 42-year historical ensemble (using historical hydrology from 1980–2021) through the end of the 2024 water year (September 2024) under both operational scenarios, yielding the following results:

- The **revised dSRDs allow later drawdown** in fall 2023. For example, Prosser draws down to the flood conservation pool on November 1st under the Baseline 1985 WCM Scenario (Figure 68) and December 1st under the deviation with the revised dSRDs (Figure 69).
- The **revised dSRDs allow for earlier reservoir refill** in spring 2024, allowing for more consistent April and May releases from all reservoirs, and higher carryover of water in Boca and Stampede going into water year 2025.
- The **revised dSRDs and Baseline yield the same magnitude peak flow in the largest winter floods**; however, under the dSRDs, the Reno peak flow is 800 cfs higher in the WY 1983 trace and 800 cfs lower in the WY 1996 trace. The revised dSRDs also result in slightly less time spent in flood operations.

If approved, the Technical Team will track the performance of the revised dSRDs and the Baseline throughout the deviation (water year 2024). This will include, but not be limited to, the quantifiable objectives used to assess the alternatives (Table 19).

The deviation modeling during water year 2024 also provides an opportunity to potentially assess the sensitivity of operations under the dSRDs to different Reno flood flow targets. The dSRDs in the deviation request maintain the 6,000-cfs instantaneous flood flow target at Reno, however, the Technical Team recommended increasing this target to 7,000 cfs in the Preferred Operational Scenario. As such, during water year 2024, the Technical Team may want to examine model runs with dSRDs that operate to different Reno flood flow targets, e.g., 6,500; 7,000; and 7,500 cfs.

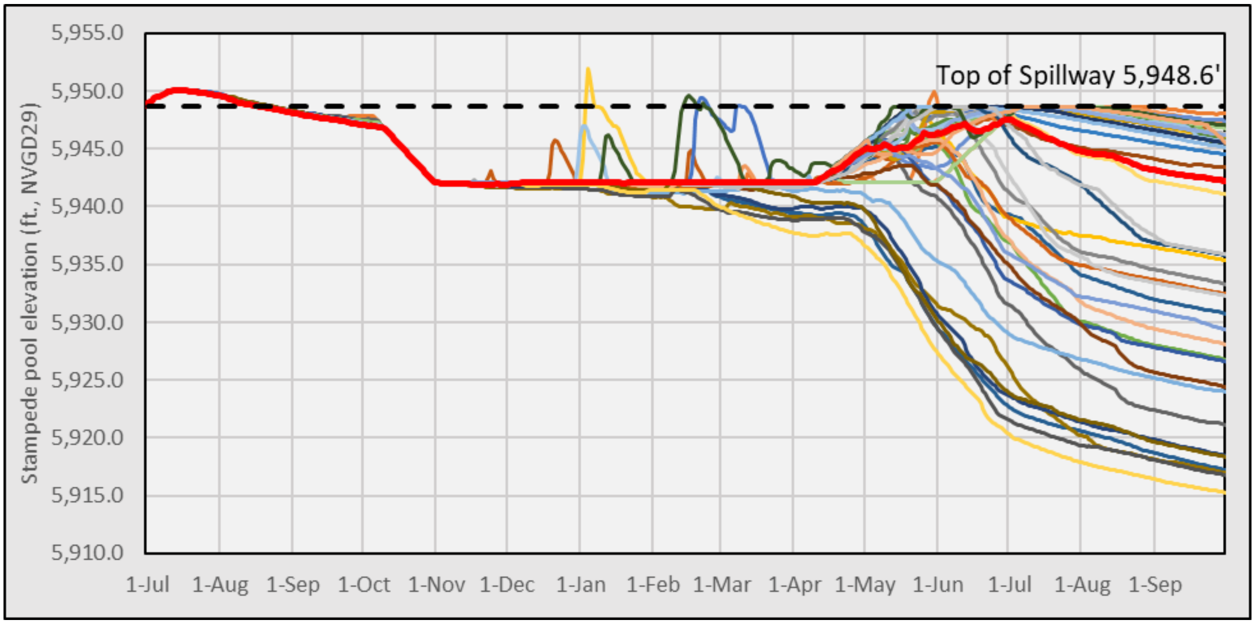

Figure 68.—Stampede pool elevation (in feet; NVGD29) operated under the Baseline for the July 13th, 2023, CNRFC ensemble traces through September 2024. The thicker red line represents the median ensemble forecast.

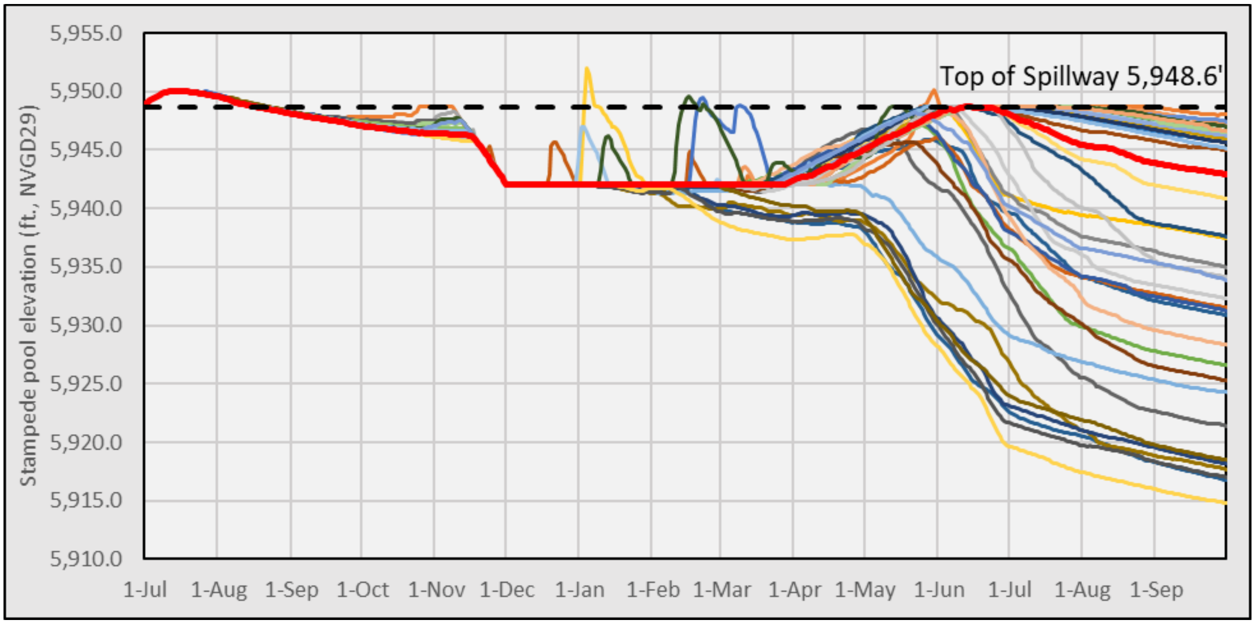

Figure 69.—Stampede pool elevation (in feet; NVGD29) operated under the deviation with revised dSRDs for the July 13th, 2023, CNRFC ensemble traces through September 2024. The thicker red line represents the median ensemble forecast.

Virtual Simulation of Preferred Operational Scenario, BAM:Var

The dSRDs represent the first step towards updating the data sources and more effectively using forecasts to inform reservoir operations in the Truckee Basin, but the Technical Team's goal is to implement the BAM:Var Alternative that incorporates FIRO. During water year 2024, the Technical Team in collaboration with the USACE, plans to simulate the recommended BAM:Var Alternative in RiverWare, using the CNRFC ensemble forecasts. This will allow for examining real-time operations of BAM:Var in a virtual setting and provide an opportunity to identify and address any issues, concerns, or challenges with operationalizing the alternative.

The Technical Team will track the performance of the BAM:Var alongside that of the dSRDs throughout water year 2024 using the quantifiable objectives, and potentially other metrics.

Deviation Request Water Year 2025 and Beyond

The Technical Team plans to submit a deviation request for water year 2025, and potentially additional years, that incorporates the BAM:Var Alternative. This would allow the benefits of BAM:Var to accrue while the WCM is updated, as well as provide an opportunity to refine the method before it is codified. Data and information gathered during the proposed water year 2024 deviation and simulation of BAM:Var will help inform the water year 2025 request. Further, the knowledge gained from these deviations could then be leveraged to refine the WCM update.

The WCM update began in the summer of 2023. The USACE will undertake technical tasks that include, but are not limited to, reviewing existing conditions, hydrologic analysis, hydraulic analysis, reservoir simulation analysis, environmental effects analyses, and public outreach. Research and development associated with this VA will inform the Water Control Plan that is formulated during the WCM update. Anything associated with the WCM update is subject to USACE District and Division approval along with Headquarters and public review. It is currently estimated that the overall update may be completed in September 2028 and operational for water year 2029.

Flexibility and Adaptive Management

The WMOP used an MOEA along with multiple selection rounds by the Technical Team to select Pareto-optimal values for the decision variables that strategically balance water supply and environmental benefits with flood risk. The MOEA identified a set of non-dominated solutions based on a quantifiable, objective assessment of metrics and tradeoffs. The subsequent selection process by the Technical Team layered on a subjective assessment that allowed participants to insert their values related to the objectives and trade-offs, including their risk-tolerance level. That said, the Technical Team recognizes that FIRO represents a significant divergence from more traditional and well-tested guide curves and a major policy change for the USACE. Insights gained from new information, improved forecasts, and experience implementing FIRO-based approaches, may reveal advantages to refining the recommended BAM:Var Alternative, and/or revised dSRDs used as a backstop.

Flexible and adaptive management creates a pathway for continued improvement over time as science, technology, and experience advance. In addition to the proposed stepwise update to the WCM through strategic and sequential deviations, the Technical Team intentionally built flexibility into the recommended operational changes to allow for adaptively managing the system. Adaptive Management is defined as,

> "[a decision process that] promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process. Adaptive management also recognizes the importance of natural variability in contributing to ecological resilience and productivity. It is not a 'trial and error' process, but rather emphasizes learning while doing" (Williams, 2009).

In line with this definition and as described above, the Technical Team recommends monitoring the performance of the dSRDs and BAM:Var in real time, to advance our understanding of these alternatives. This includes tracking their performance related to the quantifiable and non-quantifiable objectives and tradeoffs between the alternatives, as well as other monitoring deemed important. Regularly scheduled meetings between the Technical Team and USACE will allow for:

- Evaluating the monitoring results,
- Collaboratively assessing any potential need to modify the operating scenarios, and
- Identifying and addressing any issues or challenges before they become a problem.

Potential modifications to the operating scenarios primarily take the form of adjustments to the parameters used to define the dSRDs and BAM:Var, including the:

- Flood Flow Target at Reno
- MOEA Decision Variables:
  - Percentage of Revised Guide Curve to Reserve
  - Boca Portion of Flood Space
  - Shape of outlook-exceedance curve
- Variable By-a-Model Space Parameters

The Technical Team identified these parameter values through a systematic decision-making process, and any recommended changes should go through a similarly rigorous review process. While the revised dSRDs and BAM:Var parameters represent the “best” combination of parameters, as viewed by the Technical Team with current information and conditions, we acknowledge that uncertainty and data gaps exist that may reveal advantages to altering these parameter values. Importantly, the MOEA takes into consideration the relationship between the decision variables as well as the flood flow target; as such, varying one parameter independently is likely to result in a non-optimal solution and meticulous care must be given to the inter-relationships between these variables, as described below.

Flood Flow Target at Reno

In designing the alternatives, the Technical Team specifically identified the objective to, “Allow flexibility for future increases in flood thresholds because of flood improvements downstream” (Table 6). This objective was included with consideration of the ongoing, large-scale Truckee River Flood Management Project managed by TRFMA. To meet this objective, the flood flow target used in the dSRDs, BAM:Var, and the Hourly River Model was designed to maintain flexibility, i.e., if the flood flow target changes in the future, the modeling could adapt to the new target with a simple change in input to each of these modeling components.

As mentioned previously, the deviation modeling during water year 2024 provides an opportunity to assess operations using the dSRDs and BAM:Var with different Reno flood flow targets. At the end of the water year 2024 deviation and possibly before submitting a water year 2025 deviation request, the Technical Team should assess the alternatives’ real-time performance using different flood flow targets and any other new information to assess whether any adjustments should be made to the recommended flood flow target at Reno in the dSRDs and BAM:Var Alternatives. Any changes made to the flood flow target may warrant re-evaluating the other parameters, due to the parameter interactions mentioned previously.

Further, the Technical Team recommends including additional language in the updated WCM to allow for flexibility. This could come in the form of language added after the numeric threshold such as "7,000 cfs or flooding impacts felt" or "7,000 cfs or non-damaging flows." Alternatively, or in addition, the threshold could include a provision for periodic assessments to evaluate the target, or it could be tied to information that is already periodically updated, such as NWS action stages.

The updated WCM should also allow flexibility in flood flow target locations. Currently planned flood control projects near Reno and Vista will increase flood flows in the Lower Truckee River compared with current conditions, which may lead to advantages in adding a downstream flood flow target.

MOEA Decision Variables

The MOEA intelligently identifies Pareto-optimal values for the decision variables based on inputted data and user defined objectives and constraints. Changes in any of these inputs, may warrant a re-evaluation of the values of the MOEA decision variables.

In particular, forecast skill is anticipated to improve over time with effort and investments in science and observation systems (Bureau of Reclamation, 2021b; Lahmers et al., 2022). If an updated hindcast analysis demonstrates greater forecast skill, this can be incorporated into the MOEA results by updating the bias correction parameters which will increase confidence in the flood volumes at various outlooks. Should basin stakeholders feel that adjusting the bias-correction parameters is insufficient to adapt to improvements in forecast skill, then an updated MOEA could be completed and re-evaluated by the stakeholders to potentially revise the Decision Variables based on updated hindcasts and available data.

Percentage of Revised Guide Curve to Reserve

The Percentage of Revised Guide Curve flood space to maintain adds a safety factor to the BAM method, following the approach taken in the Lake Mendocino Hybrid and Modified Hybrid Ensemble Forecast Operations (Jasperse et al., 2020). Within the MOEA's non-dominated solutions, the Percentage of Revised Guide Curve to Reserve ranged from 30 to 70%. Through a collaborative process, the Key Stakeholders selected a non-dominated MOEA solution that reserves 30% of the dSRD flood space in the BAM method, the minimum allowable with the MOEA constraints. MOEA solutions that reserved a smaller percentage of the dSRD flood space and allowed more space to be operated with the BAM method, generally yielded greater benefits across all objectives (Appendix O).

The Technical Team set a constraint prohibiting determination of more than 70% of the revised dSRD flood space using the BAM method, based on the Technical Team's risk tolerance at the outset of the WMOP (conversely, at least 30% of the revised dSRD flood space must be reserved). Greater forecast skill will allow for safely operating at higher storage levels under the BAM method and potentially provide supporting evidence to decrease the Percentage of Revised Guide Curve to Reserve (i.e., increasing the ability to store water). Further, the sliding scale of the Percentage of Revised Guide Curve used in the recommended BAM:Var Alternative, was developed after the Technical Team set the 30% constraint and after the MOEA was developed. The added safety provided by BAM:Var may allow for loosening the constraint on the Percentage of the Revised Guide Curve to Reserve to allow for operating at higher storage levels during dry years, without increasing flood risk.

Boca Portion of Flood Space

The MOEA evaluated the benefits to stakeholder objectives associated with adjusting the flood space allocated between Boca and Stampede Reservoirs. Within the MOEA non-dominated solutions, the Boca Portion of Flood Space ranged from 10 to 80%, whereas the 1985 WCM allocates approximately 27% of the flood space in the Little Truckee River to Boca Reservoir and the rest to Stampede Reservoir. The USWM expressed operational concerns about making large increases to the Boca Portion of Flood Space and recommended constraining the selection of the Best-Performing MOEA to those with 50% or less Boca Portion of Flood Space. Through a collaborative process, the Key Stakeholders selected a non-dominated MOEA solution that reserves 50% Boca Portion of Flood Space, the maximum allowable with the previous constraint. This MOEA solution performs well across all stakeholder objectives, despite the significant increase in the Boca Portion of Flood Space from the 1985 WCM. This increase in the Boca Portion of Flood space only maintains its water supply benefits because of its interplay with the 30% of the Revised Guide Curve decision variable.

Similar to the constraints placed on the Percentage of the Revised Guide Curve to Reserve, loosening the constraint on the Boca Portion of Flood Space may result in benefits to the objective scores, without significant negative tradeoffs. Importantly, any adjustments to the Boca Portion of Flood Space must consider the relationship with the Percentage of the Revised Guide Curve to Reserve and vice versa.

Shape of the Exceedance-Outlook Curve

Like the other decision variables, the Key Stakeholders used the MOEA to select an exceedance-outlook curve that is part of a Pareto-optimal solution set. This aspect of the BAM method was designed so that any future advances in forecasting technology would seamlessly integrate into the determination of flood space requirements. However, if the proposed adaptive management leads to changes in other decision variables, it may warrant an examination of tradeoffs between the cost and benefits of different exceedance-outlook curves.

Variable Guide Curve Parameters

The recommended BAM:Var Alternative is defined by the range of Percentage of Revised Guide Curve to Reserve (30 to 100%), maximum ramping of the revised guide curve (2% a day), and a rounding factor for the forecasted water year Farad natural flow (closest 50 kAF). The Technical Team based the minimum range of the Percentage of Revised Guide Curve to Reserve on the selected MOEA and the maximum based on maintaining the full Revised Guide Curve, while the other parameters were based on a simple analysis of modeled data and trial and error. The impetus for developing the BAM:Var Alternative came from the desire to mitigate the flashiness in results from the first set of alternatives developed using the BAM method (BAM:All, BAM $^+$Vista, and BAM:Spring). While BAM:Var achieves this goal, some Technical Team members maintain concerns with the flashiness demonstrated in the time-series analysis and potential impacts on fish species. The simulation of BAM:Var operations proposed during water year 2024 will allow for testing and refining the BAM:Var parameters to explore the potential to reduce flashiness further. In addition, it may be warranted to apply a more sophisticated method to determine parameter values.

In addition to the work described above to fine-tune the parameters in the BAM:Var and revised dSRDs before the WCM update, the Technical Team recommends including dynamic thresholds and/or a method to periodically review and update these parameters. This would provide the flexibility to make strategic adjustments to operations without the need to update the WCM for every new piece of information and incremental forecast skill improvement.

Additional Studies and Future Work

The WMOP gathered and produced a wealth of information to assess the proposed, as well as future, enhancements to flood risk management in the Truckee Basin through operational changes. However, uncertainty and data gaps remain. Through the WMOP process, the Key Stakeholders identified the flowing areas for follow-up studies or additional data gathering, some of which have already begun. Some of these can, and are, being filled by the Technical Team, while others will require new efforts by other stakeholders, and some of these improvements will simply require time and technological advances.

Address Discrepancies in the TROA Planning Model and Accounting Model

The *TROA Planning Model Verification* report (Appendix B) identified several areas of the Planning Model in need of future development. A challenge with making improvements to the Planning Model is that operations within it are interdependent, and this process requires a holistic approach to making incremental advancements in the model's ability to replicate operations in the basin effectively. As such, PWRE noted the importance of identifying the root cause of the verification issues and not spending time "fixing" issues that are symptoms and not causes. In line with these recommendations, PWRE is merging the Planning Model and the Accounting Model to address the discrepancies and challenges in using the two RiverWare models for water management in the Truckee Basin. The new model will be capable of operating in both a forward- and backward-looking mode that can guide short-term operations to schedule reservoir releases and diversions and account for TROA Party requests and schedules, as well as help guide longer-term planning studies. When implemented, the new model is expected to provide an enhanced water resources management planning tool in the Truckee Basin.

Regularly Update the Daily and Hourly Planning Model Datasets

Projects completed outside of, but relevant to, the WMOP, established a process to compute the hydrologic inflows to the Truckee and Carson Rivers that are needed to run the daily and hourly RiverWare models. The daily dataset currently covers the period from water year 1986 through water year 2021. The Technical Team recommends updating the daily dataset at the end of each water year to efficiently and consistently make the most current observed hydrology available for analysis in the next water year.

Inclusion of Martis Creek Dam and Reservoir

From the outset of the WMOP, the Key Stakeholders noted problems and opportunities associated with Martis Creek Dam and the need for safety improvements to fulfill the dam's role in Truckee Basin flood risk management as outlined in the WCM. Currently, Martis cannot be operated to store water and limit downstream flows due to dam safety concerns. While the studies needed to fully operationalize Martis were out of the scope of the WMOP, the project did model the Preferred Operational Scenario, BAM-Var, under the current restrictions on Martis operations, as well as with Martis operated to maintain flows in Reno below the recommended 7,000-cfs flow target.

Operationalizing Martis for flood management in BAM-Var would yield benefits or no change to the WMOP's quantifiable objectives. This includes a significant reduction in the RMS Flow Over Flood Target objective, as well as an increase in Average Annual Prosser, Boca, and Stampede Storage, even if Martis was not operated for water supply storage. If the dam was fully operational and water supply storage was allowed, it could further improve water managers' ability to satisfy existing or future downstream water demands. However, this change requires more than simply updating the WCM.

Based on these projected benefits, the Key Stakeholders recommend the USACE conduct the necessary studies and potential dam safety improvements to operate Martis Creek Dam and Reservoir for flood management and/or water supply at safe storage levels. This includes:

1. Evaluation of the potential water supply benefits of authorizing Martis reservoir conservation storage and/or Credit Water Operations in BAM-Var, as allowed by TROA (TROA - Truckee River Operating Agreement, 2008);
2. Identification of one or more potential users of water supply stored in Martis; and
3. Evaluation of the necessary actions to authorize Martis to operate in any capacity up to its initial maximum design storage of 20,391 acre-feet.

Improving Forecast Skill and Accuracy

The Key Stakeholders identified a problem centering on the fact that, even with improvements over time, forecasts still do not have all the information about on-the-ground conditions. To address this, partners recommend adding more SNOTEL stations (e.g., located at existing precipitation gages) to better represent the basin at lower elevations, on south-facing slopes, and other aspects. Additional data could also be collected by measuring soil moisture and better tracking and understanding the year's snowpack conditions to improve forecasts or through incorporating vertically pointed radar. However, these actions should be pursued through efforts separate from updating the WCM. At the same time, the WCM updates should include the flexibility to incorporate these types of improvements in forecasting skills and allowing for improvements in flood risk management and water management as better information becomes available.

Future studies of forecasting should also be expanded to the Lower Truckee River. Ongoing and planned flood control projects near Reno and Vista will increase flood flows in the Lower Truckee River compared with current conditions. One of the limitations of including flood flow targets in the Lower Truckee River was lack of information in the lower river, so future studies should be sure to include points of interest in the Lower Truckee River, such as Wadsworth and Nixon.

The recommended planned deviations and subsequent analysis may also reveal additional data and knowledge gaps that can inform the need for future studies.

Conclusions

Forecast-informed reservoir operations represent a new and exciting opportunity to improve water management and adapt to changing conditions. Over the course of the WMOP, the Technical Team learned lessons in developing and evaluating Alternative Operational Scenarios related to both revising dSRDs and incorporating FIRO in flood risk management, uncovered key finding regarding the performance of different alternatives, and developed recommendations for updating the WCM, summarized below.

Lessons Learned in Developing and Evaluating Alternatives

The process undertaken for the WMOP and the development and evaluation of the Alternative Operational Scenarios, yielded the following lessons learned:

- The MOEA offers a viable method to optimize the decision variables used to characterize the FIRO BAM method of determining required flood space.
- Each of the proposed actions – implementing revised dSRDs and/or FIRO, increasing the Reno flood flow target, and re-proportioning of Little Truckee River flood space – has the potential to improve performance over the Baseline.
- Open, collaborative decision-making and interactive opportunities for stakeholder participation provided a space to select a Preferred Operational Scenario that meets the interests of the diverse Technical Team that funded the WMOP, along with other Key Stakeholders.

Key Findings on Alternatives' Performance

All five Action Alternatives produce encouraging results regarding the potential for the proposed actions to better achieve the water management objects than the Baseline, 1985 WCM, as summarized in the following Key Findings.

- Tradeoffs between different actions, alternatives, and objectives required significant stakeholder participation to holistically and effectively evaluate the extent to which the actions and alternatives address the goals of the WMOP.
- All five Action Alternatives result in improvements over the Baseline regarding the goals to:
    - Maximize water supply,
    - Enhance environmental flows, and
    - Reduce flood risk in the Truckee River.

- The alternatives that include the BAM method for fall drawdown (BAM:All, BAM $^+$Vista, and BAM:Var) outperform the alternatives that use the revised dSRDs for fall drawdown (dSRDs and BAM:Spring) regarding the objectives related to water supply and environmental flow, however, these benefits come with a tradeoff in terms of less benefit for the flood risk reduction objective.

- Most of the water supply benefits of the BAM method are achieved by limiting the fall drawdown in the last fill year before a drought and then maintaining this additional storage for multiple years.

- The Action Alternatives maintain or reduce the peak flows and/or the time in flood operations in a wide range of flood events from flows around the current Reno flood flow target to the 500-year recurrence interval floods.

- BAM:Var ranks favorably across all objectives by leveraging the water supply benefits associated with the BAM method and mitigating flood risk during wet years by reserving a larger portion of the flood storage requirements in the Revised dSRDs.

- Increasing the Reno flood flow target from 6,500 cfs in the BAM:Var Alternative to 7,000 cfs improves upon the performance for all quantifiable objectives, except a slight decrease in Average Annual Prosser, Boca, and Stampede Storage.

- Operationalizing Martis in BAM-Var decreases RMS Flow Over Flood Target nearly as significantly as BAM-Var decreases RMS Flow Over Flood Target compared to the baseline 1985 WCM (15,150 cfs reduction), as well as provides water supply benefits.

Recommendations for Updating the WCM

The process of formally updating the WCM will take some time and the Technical Team recommends the following, on the path to the WCM update:

- The Technical Team recommends consideration of a Preferred Operational Scenario that includes the Variable BAM Space as an alternative to the 1985 WCM and the revised dSRDs as a backstop operation, in the case of the inaccessibility of CNRFC forecasts or other technical, or other unforeseen operational challenges.

- The Technical Team should continue to formally request deviations to Truckee Basin dam operations aimed to implement the recommended operational changes sequentially and strategically during the WCM update processes.

- The Technical Team and other Key Stakeholders should implement the identified additional studies and data gathering to help inform the WCM update process.

- Based on the information gathered through the deviated operations and additional analysis and studies, the Technical Team and other Key Stakeholders should adaptively adjust BAM:Var and plans toward a WCM update.

- The updated WCM should provide a pathway for updating the Preferred Operational Scenario with advances in science and technology and experience gained from operationalizing FIRO, if supported by studies of similar technical rigor and stakeholder coordination as the WMOP.

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Appendices

Note: The following appendices are available as separate documents.

Appendix A - Alternative Operational Scenarios Development Report

Appendix B - TROA Planning Model Verification

Appendix C - Truckee River Basin Historical Data Development Methodologies: Water Years 2001-2021

Appendix D - Truckee River Basin Historical Data Development Methodologies: Water Years 1986-2000

Appendix E - Truckee River Basin Historical Hourly Data Development Methodologies: Water Years 1986-2021

Appendix F - WMOP Truckee River Hourly River Model Time Lag Routing

Appendix G - Truckee River Hourly Model Verification for WMOP

Appendix H - Truckee Basin Water Management Options Pilot Study—Rain Flood and Snowmelt Flood Frequency Curve Update

Appendix I - Truckee Basin Water Management Options Pilot Study—Channel Capacity Analysis

Appendix J - Truckee River Flood Management Authority and National Weather Service Memorandums and Presentation

Appendix K - Revised Guide Curve Modeling, Improving Current Guide Curves with dSRD Approach

Appendix L - Inflow Uncertainty Analysis

Appendix M - Action and Alternative Operational Scenario Modelling in the WMOP

Appendix N - Multi-Objective Evolutionary Algorithm (MOEA) Tool Utilization and Development

Appendix O - Preferred Operational Scenario Selection Process

Appendix P - Preferred Operational Scenario Probable Maximum Flood Routings Analysis

Appendix Q - Preferred Operational Scenario with Martis Creek Reservoir Operational Analysis