Structured Decision-Making for Folsom Dam Power Bypass Operations

Central Valley Project, California

California-Great Basin Region

Cover Photo: Folsom Dam during November 2025 (Brian Mahardja)

U.S. Department of the Interior 2/10/2026

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Executive Summary

The U.S. Bureau of Reclamation (Reclamation) must balance competing objectives in its operation of Folsom Dam on the Lower American River. Accessing the reservoir's coldest water to protect threatened fall-run Chinook salmon and steelhead during their critical fall life stages often requires a "power bypass." This action, however, forgoes significant hydropower revenue and risks depleting the finite cold-water pool, potentially worsening conditions later in the season. Historically, decisions on whether to implement a bypass lacked quantitative transparency. In 2025, requests for a bypass consideration from the National Marine Fisheries Service (NMFS) and the California Department of Fish and Wildlife (CDFW), coupled with federal directives to both use "best available science" and "produce additional hydropower," prompted Reclamation to initiate a formal Structured Decision Making (SDM) process.

In collaboration with the American River Group (ARG), Reclamation applied the SDM framework to evaluate nine alternatives: "No Bypass" (NB) and eight different bypass scenarios (PBs) with varying volumes and timings. The process identified three fundamental objectives:

1. Maximize fall-run Chinook salmon abundance (Metric: Adult population index)
2. Minimize forgone hydropower revenue (Metric: Cost in U.S. dollars)
3. Maximize steelhead rearing conditions (Metric: Number of days < 18.3 °C/ 65°F)

To evaluate the alternatives, a new fall-run Chinook salmon life-cycle model was developed. This model integrated key biological mechanisms, including temperature-driven pre-spawn mortality, spawn timing, and egg-to-fry survival. To address scientific uncertainty, the model incorporated a weighted average of three different temperature-dependent mortality models, with weights derived from a formal expert elicitation. A temperature model (CE-QUAL-W2) projected downstream conditions, and a hydropower model calculated the replacement cost of lost energy. Consequences were analyzed across four historical meteorological scenarios (2011, 2014, 2017, 2020) to capture environmental uncertainty.

The analysis successfully quantified the central trade-offs. The “No Bypass” alternative had $0 cost but produced the lowest salmon abundance (population index of 17,833). The most biologically effective alternatives, PB2b and PB2c, produced the highest salmon abundance (index ~20,700-20,900) but also incurred the highest costs ($430,000-$470,000). The steelhead objective showed little meaningful variation between alternatives, making it a low-priority driver for this decision.

Reclamation management weighted the objectives as follows: 50% for hydropower, 40% for fall-run Chinook salmon, and 10% for steelhead. While a purely linear analysis favored low-cost options, managers indicated some non-linearity in their value/utility function for cost, and a desire to balance the contributions of fish and hydropower objectives toward the final utility score. Based on this, Reclamation selected Alternative PB4 as the final operational plan, consisting of the following schedule: 250 cfs bypass starting October 21, 500 cfs bypass on October 28, 250 cfs bypass on November 7, and end bypass on November 21. This alternative was identified as the most-balanced choice, providing significant biological benefits (salmon index of 19,253) at a moderate loss of hydropower generation (estimated value of approximately $240,000). Overall, this SDM, and new associated tools, represent a foundational step towards a more structured and transparent management process for managing seasonal temperature and flow in the Lower American River.

Introduction

The management of water temperature in regulated river systems is one of the main conservation tools for cold-water species such as anadromous salmonids. In California's Central Valley, nearly every major river has been dammed, fundamentally altering the thermal regimes that native fish evolved with (Williams 2006). The American River in California, a highly regulated snow- and rain-fed system that drains from the Sierra Nevada, exemplifies the challenge of balancing economic demands and the thermal requirements of key fish species.

The current state of the American River is the result of over a century of profound anthropogenic modifications. Following the impacts of large-scale gold mining in the 1800s, the river was further re-engineered in the 1890s with the development of old Folsom Dam, which provided hydropower to the city of Folsom and the nearby State Prison (Williams 2001). In the 1950s, Folsom and Nimbus dams were completed as part of the Central Valley Project (Moyle 2002). This infrastructure provided critical water storage and flood control but further blocked anadromous fishes from most of their historical spawning and rearing habitat (Yoshiyama et al. 1998). Below Folsom and Nimbus dams (area referred to as the "Lower American River"), the American River today still supports populations of fall-run Chinook Salmon (*Oncorhynchus tshawytscha*) and steelhead/rainbow trout (*Oncorhynchus mykiss*), whose survivals are intrinsically linked to the maintenance of suitable thermal regimes for spawning, egg incubation, and juvenile rearing.

Paradoxically, the same dams that caused the decline for these species are also now one of the primary tools used to support them. Thermal stratification in Folsom Reservoir during the hot and dry summer-fall months of California creates a finite cold-water pool in the lower depths. The selective withdrawal of coldwater through the Folsom dam's temperature control shutters allows operators to modulate release temperatures to minimize negative impacts for both fall-run Chinook Salmon and steelhead. However, to access the coldest water, especially during the tail end of the summer-fall period and prior to the wet season (i.e., October-November), operators must at times use a series of low-level outlets in a power bypass operation. Releasing water this way forgoes hydropower electric generation, making it a useful but economically costly tool for providing suitable thermal regime for salmonids. In addition to the challenge of trade-offs, this decision is also difficult because of uncertainty surrounding meteorology. Conducting a power bypass also depletes cold-water pool in the reservoir more quickly, increasing the risk for loss of temperature control in the Lower American River should air temperatures become exceedingly warm for an extended period of time.

Folsom and Nimbus Dams are operated by the U.S. Bureau of Reclamation (Reclamation) as part of the Central Valley Project. Historically, the Reclamation's decisions on power bypass operations were guided by informal negotiations among stakeholders and regulatory agencies rather than a reproducible, transparent process. Navigating complex trade-offs and uncertainties requires an effective framework that technical experts and stakeholders can use to examine areas of agreement or disagreement about the anticipated effects of management actions (Gregory et al. 2012). Towards this goal, the Reclamation implemented a Structured Decision Making (SDM) process to formally guide Folsom Dam operations, specifically on the potential use of power bypass action for fall of 2025. SDM provides a structured method to disentangle the scientific and policy elements of a decision, as well as to systematically evaluate the consequences of each potential action and transparently weight competing objectives. This document summarizes the SDM process that took place in fall of 2025 and describes how Reclamation arrived at the decision.

Background

In Water Year 2025, Reclamation initially operated the Lower American River according to a Temperature Management Plan (TMP) circulated on June 30th, 2025 based on the Automated Temperature Selection Procedure (ATSP) Schedule 33 (Table 1). However, on August 5, 2025, Reclamation convened a meeting with the American River Group (ARG), a multi-agency and stakeholder technical team that coordinates fishery science and water operations for the Lower American River, to address a forecasted loss of downstream temperature control later in the fall. At this meeting, the group agreed to request a modification from the National Marine Fisheries Service (NMFS), which was subsequently approved via email, amending the operational plan to ATSP Schedule 36.

Following this revision, Reclamation received requests from NMFS and the California Department of Fish and Wildlife (CDFW) to consider a Folsom Dam power bypass in the fall of 2025 to benefit salmonids. This request prompted the need for a formal and transparent evaluation, especially in light of several key directives. A 2019 Reclamation Commissioner Memorandum (“*Directives Resulting from the Central Valley Project Power Initiative*”) mandates that Reclamation “*use best available science when evaluating power plant bypass operations*” and engage the Western Area Power Administration in the process (Reclamation 2019). Concurrently, Executive Order 14181 (January 24, 2025) instructed the Central Valley Project “*to deliver more water and produce additional hydropower*.” It was in response to these agency requests, and the clear need to rigorously evaluate the biological merits of a bypass against its explicit impact on hydropower generation, that Reclamation initiated this Structured Decision Making (SDM) process.

Table 1. Temperature targets associated with the ATSP schedules originally chosen in the June 30th Temperature Management Plan (Schedule 33) and the modification approved by National Marine Fisheries Service on August 8th (Schedule 36). Shaded cells indicate the temperature target that was operated to for the respective months

Month	Schedule 33	Schedule 36
May	66° F	67° F
June	67° F	67° F

Month	**Schedule 33**	**Schedule 36**
July	67° F	68° F
August	67° F	68° F
September	67° F	68° F
October	65° F	65° F
November	59° F	59° F

Methods

We followed the PrOACT model of decision analysis to guide the decision surrounding Folsom Dam power bypass, which includes developing the problem statement (Pr) to ensure a common understanding of the decision at hand, establishing objectives (O), developing alternative management strategies (A) designed to meet the objectives, predicting the consequences (C) of the alternatives to the objectives, and identifying the tradeoffs (T) between them (Hammond et al. 1999).

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Decision Framework

The decision framework for temperature management on the Lower American River was first initiated within the ARG. During initial deliberations, the scope of potential management actions was formally constrained to focus exclusively on the implementation of a power bypass at Folsom Dam (i.e., setting aside other alternatives beyond power bypass at Folsom Dam). Therefore, given its authority and discretion over dam operations, Reclamation was identified as the lead decision-making agency. The formal problem statement for this SDM effort was then developed by Reclamation's management team. This statement was then refined further based on input from the broader membership of the ARG (see Box 1 for the final problem statement). While the comprehensive management of the Lower American River involves numerous objectives (including water delivery, downstream water quality, and recreation), the scope of this analysis is intentionally focused on the primary trade-offs inherent in Folsom Dam power bypass operations. Although Reclamation was the primary decision maker, the intent was to elicit input and feedback from stakeholders through the ARG that includes representation from California Department of Fish and Wildlife, National Marine Fisheries Service, Sacramento Bratovich et al., and Western Area Power Administration.

Box 1

Problem Statement

The U.S. Bureau of Reclamation (Reclamation), under its authorities to operate the Central Valley Project (CVP), is considering strategies to manage water and hydropower operations to meet numerous and often competing needs, requirements and objectives. On the American River, Reclamation has discretion to implement a power bypass operation at the Folsom Dam, typically in late summer-fall, when water temperatures are higher and may negatively impact Chinook salmon and steelhead. Power bypass operations draw colder water from below the power plant intake at Folsom dam and can provide cooler water to the lower American River for more suitable rearing and spawning conditions, but at the cost of lost hydropower generation. Power Bypass is also intended to improve the quality of water supplied to the Nimbus Fish Hatchery supporting spawning operations, juvenile rearing, and egg incubation to support the objectives of Reclamation's mitigation requirement for fish production. The decision to implement a power bypass operation and how a power bypass is implemented involves trade-offs between CVP goals of hydropower generation and fisheries benefits, including those to minimize impacts to holding adult Chinook salmon, early-spawning Chinook salmon, summer and fall rearing steelhead and coldwater availability for late-spawning Chinook salmon. Further, risks of exhausting the limited coldwater pool resource in Folsom Reservoir and loss of temperature control in the lower American River and to the Nimbus Fish Hatchery need to be balanced. Reclamation's decision cannot be arbitrary, capricious, nor unreasonable. Reclamation seeks input from cooperating agencies and interest holders to help inform the decision concerning power bypass operations in a given year.

Objectives

The “objectives” for the decision problem describe the desired future conditions the decision maker is trying to achieve (Runge and Bean 2020). They are ultimately the direct expression of the values of the decision maker (Keeney 1992). An important consideration in this step is to distinguish “fundamental” objectives from “means” objectives. Fundamental objectives in decision analysis represent desired outcomes that are pursued for themselves (i.e., what decision makers and interest holders ultimately care about), which differ from means objectives, which are pursued only in that they lead towards a fundamental objective (Runge and Walshe 2014). Focusing on means objectives may unnecessarily narrow ideas/options and distract from what the decision maker is attempting to achieve, and therefore, we encouraged the group to identify fundamental objectives rather than means. Two additional types of objectives can also come up in the elicitation of objectives. The first is a process objective, which is an objective around how the decision gets made (Gregory et al. 2012). The second is a strategic objective, which is an objective related to an individual or organization’s strategic priorities or goal. Once fundamental objectives for the decision context have been described, performance metric for each fundamental objective then have to be identified. Performance metrics are the measures of the consequences of the alternative management strategies (i.e, actions) with respect to the fundamental objective.

The preliminary list of objectives and performance metrics were first elicited from Reclamation managers that have authority (or delegated authority) over the decision. Over a number of meetings open to ARG members, we focused on soliciting their objectives and openly discussing their values. Some objectives were classified as means, process, or strategic, and these were set aside (Table 2). Reclamation and ARG members agreed that a population abundance for fall-run Chinook Salmon and steelhead, as well as hydropower generation represented fundamental objectives (Table 3). Nimbus Hatchery, a mitigation facility funded by Reclamation and operated by CDFW, is a critical component in the consideration of Folsom Dam power bypass (Box 1). During the fall months, operations at Nimbus Hatchery are frequently hampered by elevated temperatures and low dissolved oxygen levels, and a power bypass at Folsom Dam can typically help mitigate these adverse conditions. However, evaluation of the potential impacts of various bypass alternatives on hatchery operations require involvement from CDFW hatchery staff, and they were unable to participate in fall of 2025. As a result, an objective related to hatchery operations was excluded from the SDM process.

Table 2. List of objectives that were brought up by Reclamation management and ARG participants and their designations. Fundamental objectives are marked in bold.

Objective Description	Objective Type	Reasoning
Maximize the abundance and resilience of naturally spawning fall-run Chinook Salmon in the American River	**Fundamental**	Fall-run Chinook Salmon is a species of interest in the Lower American River.
Minimize the risk of a loss of temperature control on the lower American River in October-November (measured in exceedance of 'extreme' temperature conditions)	Means	"Loss of temperature control" is a concern over negative impacts to fall-run Chinook Salmon that spawn in October-November.
Support greater life history diversity by moving towards the historic spawn timing of the American River	Means	Life history diversity contributes to the resilience of the fall-run Chinook Salmon and steelhead populations.
Minimize exceedances of temperature targets on the Lower American River (measured in exceedance of 'extreme' temperature conditions).	Means	Exceedance in "extreme temperature conditions" is a concern in that they can cause harm to the salmonid species.
Minimize pre-spawn mortality of fall-run Chinook Salmon	Means	Pre-spawn mortality affects one life stage of the fall-run Chinook Salmon.

Objective Description	Objective Type	Reasoning
Maximize egg-to-fry survival of fall-run Chinook Salmon	Means	Egg-to-fry survival is one component of the fall-run Chinook Salmon life cycle.
Maximize rearing and outmigration survival and life history diversity of fall-run Chinook Salmon	Means	Rearing and outmigration of juveniles are aspects of the fall-run Chinook Salmon life cycle. Life history diversity contributes to the abundance and resilience of the fall-run Chinook Salmon population.
Maximize the abundance and expression of anadromy in the American River's natural steelhead population.	**Fundamental**	***O.mykiss*** **(steelhead) is a species of interest in the Lower American River.**
Maximize steelhead rearing	Means	Rearing habitat suitability and number of rearing steelhead are components that determine the abundance and overall population trajectory of steelhead in the system.
Maximize juvenile rearing growth and survival of Central Valley steelhead	Means	Rearing and outmigration of juveniles are aspects of the Central Valley steelhead life cycle.
Maximize expression of migratory Central Valley steelhead life histories.	Means	Life history diversity contributes to the abundance and resilience of the Central Valley steelhead (*O. mykiss*) population

Objective Description	Objective Type	Reasoning
Maximize successful Central Valley steelhead spawning by minimizing overlap of fall-run Chinook Salmon and Central Valley steelhead spawning in the American River	Means	Competition for spawning habitat is a concern over reduced spawning capability for both salmonid species.
Minimize forgone hydroelectric power generation	**Fundamental**	**Hydropower generation is one of the primary purposes of Reclamation as an agency and serve the local power customers in the region.**
Maximize water supply storage	Unclear (removed)	There is interest in ensuring water storage is sufficient to hedge against dry year. However, SDM participants agreed that there is no plan to alter or impact flow or water supply objectives through this SDM process.
Minimize impacts to hatchery operations; Maximize probability of successful hatchery production	Fundamental (removed)	Nimbus hatchery can experience difficulties with maintaining suitable temperature and dissolved oxygen level for fish in the fall months. Power bypass at Folsom Dam can typically alleviate these issues. Hatchery staff were unable to participate in the SDM process and thus, this objective was removed.
Maximize likelihood of supporting system demands (measured in exceedance of these flow conditions)	Strategic	A statement to highlight the competing demands inherent in the decision and downstream flow or water quality requirements that Reclamation has to meet.

Objective Description	Objective Type	Reasoning
Maximize the ability to objectively predict the outcomes of different scenarios and reduce reliance on individual opinions.	Process	A process objective noting the desire to rely more on quantitative tools rather than expert opinions for decision-making.
Maximize use of the ARG for the SDM process	Process	Interest in engaging with interest holders and receiving feedback.
Minimize the annual staff resources expended on power bypass decision making	Strategic	Interest from Reclamation that is not a shared objective in a multi-interest holder process.

Table 3. The fundamental objectives considered in the SDM effort along with their performance metrics

Topic	Fundamental Objective	Performance Metric
Fall-run Chinook Salmon	Maximize the abundance and resilience of naturally spawning fall-run Chinook salmon in the American River	Adult population index. The estimated adult return numbers based on a life cycle model that focus on river temperature effects and calibrated to historical adult escapement numbers from the American River.

Topic	Fundamental Objective	Performance Metric
American River steelhead	Maximize the abundance and expression of anadromy in the American River's natural steelhead population.	Number of days within the months of October and November where rearing conditions are "ideal" (<18.3 °C/65 °F). This metric also serves to track adherence to Reclamation's operational commitments (Reclamation 2024).
Hydropower generation	Maximize the reliability and value of Central Valley Project hydropower generation	Estimated financial impact cost from forgone hydropower generation in dollars.

Influence Diagram

We collaborated with the ARG to develop an influence diagram depicting the linkages between the power bypass action, the fundamental objectives, and key external uncertainties (Figure 1). This diagram formed the conceptual basis for the Chinook salmon life-cycle model used in the SDM process. The diagram illustrates the central hypothesis: a power bypass is expected to reduce hydropower revenue and improve juvenile production for fall-run Chinook salmon and enhance rearing conditions for steelhead.

The analysis focused primarily on the mechanisms benefiting fall-run Chinook salmon, the target species for the action. Cooler fall temperatures are expected to reduce pre-spawn mortality of holding adults (Colvin et al. 2018), thereby increasing total egg deposition. Furthermore, eggs deposited in cooler water are expected to have higher survival rates (Martin et al. 2017), leading to more juvenile outmigrants and, ultimately, higher adult returns. A third component, spawn timing, was identified as a critical feedback mechanism. As spawn timing is influenced by temperature (Dusek Jennings and Hendrix 2020), a power bypass could induce earlier spawning. This shift in spawn timing is noteworthy because it could potentially offset the risk of late-season cold-water pool depletion by ensuring the majority of incubation occurs earlier, when cold water is still available.

Two critical uncertainties were identified, which were highlighted in the influence diagram: external meteorological conditions (represented by air temperature) and structural uncertainty in the salmon mortality model. Fall air temperatures directly influence river temperatures and the rate of cold-water pool depletion. High air temperatures would increase the biological need for a bypass while simultaneously increasing the risk of exhausting the cold-water pool. Conversely, low air temperatures might render a bypass unnecessary if water temperatures are sufficiently cool. The second key uncertainty is the temperature-dependent mortality mechanism for salmon early life stages. Several alternative models exist (e.g., Bartholow and Heasley 2006, Martin et al. 2017, Bratovich et al. 2020) that posit different relationships between temperature and egg-to-fry survival. Because these models vary in their sensitivity to temperature, they produce different estimates of the biological benefit (or harm) of a power bypass, directly influencing the optimal management decision.

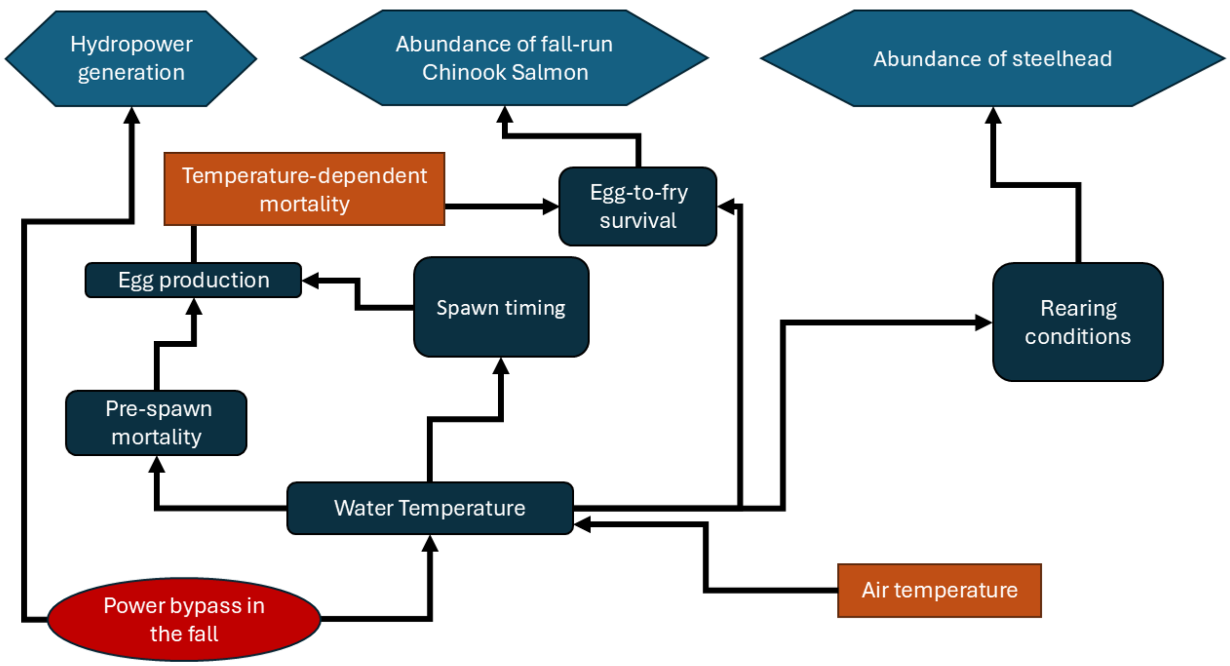

Figure 1. Influence diagram for the Folsom Dam power bypass decision in the lower American River developed based on input from the ARG. The diagram depicts the hypothesized relationships between management action (red circle), ecological variables (dark blue rounded rectangle), uncertainties or chance events (orange rectangles), and the fundamental management objectives (blue hexagon).

Objective 1: Maximize the abundance and resilience of naturally spawning fall-run Chinook salmon in the American River

Fall-run Chinook Salmon is the most abundant run of Chinook Salmon in the Central Valley and occur in almost all major tributaries within the system, including the Lower American River (Moyle 2002). Today, the population of fall-run Chinook Salmon is heavily supplemented by large hatcheries (Sturrock et al. 2019), including the Nimbus hatchery on the American River. Within the American River, naturally spawning of fall-run Chinook Salmon occur in the Lower American River downstream of Nimbus Dam. Folsom and Nimbus dams are operated by Reclamation to maintain suitable habitat, particularly cold-water temperatures, for holding, spawning, and egg incubation. Elevated water temperatures during the fall spawning and incubation period (October-December) may increase pre-spawn mortality in holding adult salmon in the river and cause mortality to eggs and pre-emergent fry. As such, the viability of each year's cohort can be tied to Reclamation's ability to manage Folsom Reservoir's limited cold-water pool. The challenge surrounding the rate of cold-water pool releases varies from year to year, as releasing too much cold-water early may lead to a loss of temperature control in the Lower American River (especially in years with exceedingly warm air temperatures) and releasing not enough may not maximize use of the releases by the end of the season.

The performance metric for the fall-run Chinook Salmon objective was the estimated number of adult returns based on a simplified life cycle model that focuses on riverine water temperature effects. Because of the simplified and deterministic nature of the fall-run Chinook Salmon model, we referred to the performance metric to as “adult population index” when discussing our results to the SDM participants.

Objective 2: Minimize forgone hydroelectric power generation

Hydroelectric power generation is one of the primary purposes of Reclamation’s Central Valley Project (CVP). Operational decisions that prioritize other objectives, such as fisheries protection, can potentially be in conflict with power generation. Releasing water through the low-level power bypass outlets to achieve cooler temperatures prevents that same water from passing through the hydroelectric turbines, resulting in a quantifiable loss of potential energy production and revenue.

The performance metric for the hydropower objective is the forgone hydropower revenue, in which we are aiming to minimize. While this loss can be calculated in megawatt-hours (MWh), this SDM process uses the more direct metric of the total dollar value ($) of lost revenue to quantify the trade-off because it is easier to grasp for most decision-makers and interest holders.

Objective 3: Maximize the abundance and expression of anadromy in the American River's natural steelhead population.

Another species of interest in the American River with regards to temperature management is steelhead (*Oncorhynchus mykiss*). Temperature management is a key conservation strategy for California’s Central Valley anadromous salmonids in general, and steelhead is no exception as this region represents one of the southernmost extent of their range. The California Central Valley steelhead distinct population segment (DPS) was listed as “threatened” under the Endangered Species Act in 1998 and the status was reaffirmed in 2006 (NMFS 2006). Although it was found that most *O. mykiss* in the Lower American River today are derived mostly from out-of-basin stocks (Pearse and Garza 2015), SDM participants and Reclamation remain interested in ensuring the viability of the steelhead population within this stretch of the river. Adult steelhead enter the lower American River from roughly November through April with a peak occurring from December through March.

No abundance estimates or life cycle model for *O. mykiss* in the American River was available at the time of the decision, and for that reason, the group resorted to a proxy measure. The performance metric for the steelhead objective is the number of days within the months of October and November when rearing conditions are “ideal”. This is defined as the number of days in these two months below a certain temperature threshold. There was large support from the group to use 18.3 °C (65 °F) as the threshold to use, given that this was the temperature target for American River steelhead described in 2024 regulatory documents (NMFS 2024, Reclamation 2024).

The threshold of 18.3 °C (65 °F) appeared to have originated from an unpublished report cited in the National Marine Fisheries Service Biological Opinion on CVP operations, which indicated that “visibly symptoms of thermal stress in juvenile steelhead are associated with exposure to daily mean water temperatures above 65 °F” (Sacramento Water Forum [2005] in NMFS [2009]). This runs counter to another report where American River steelhead demonstrated peak growth at 19°C and consistently selected temperatures of 18-19 °C (Myrick and Cech 2001). A more recent study also demonstrated that wild *O. mykiss* from the Tuolumne River nearby can maintain high aerobic performance from 17.8 °C to 24.6 °C, with a peak at around 21.2 °C (Verhille et al. 2016). Verhille et al. (2016) also argued against the use of a universal thermal criterion of 18 °C as recommended by U.S. Environmental Protection Agency (USEPA 2003), as *O. mykiss* in the warmer southern range may be adapted to higher temperatures. Given the conflicting evidence for this thermal threshold of 18.3 °C (65 °F), we proposed that the metric served a dual purpose: to approximate ideal rearing conditions and to track adherence to Reclamation's operational commitments (Reclamation 2024).

Alternatives

Given the decision framework, participants of the SDM effort focused on alternatives involving power bypass operations. Based on temperature profile at Folsom reservoir on September 18th 2025, temperature forecast assuming no power bypass was conducted. Based on this information, ARG members proposed six alternative power bypass actions (PB1-6) for consideration in the SDM process (Table 4). Two additional alternatives (PB2b, PB2c) were brought in after the first set of temperature models for the initial six power bypass alternatives were completed. Including the “no power bypass” alternative, a total of nine alternatives were considered in this SDM process.

Table 4. Description of alternatives considered in the SDM effort.

Alternative	Volume required for power bypass (in acre feet)	Description
NB	0	No power bypass
PB1	10,163	125 cfs starting October 15, 250 cfs on October 28, 125 cfs on November 7, end bypass on November 14
PB2	32,224	250 cfs starting October 15, 500 cfs on October 28, 250 cfs on November 14, end bypass on November 30
PB2b	40,156	250 cfs starting October 15, 500 cfs on October 28, end bypass on November 30
PB2c	37,181	250 cfs starting October 21, 500 cfs on October 28, end bypass on November 30
PB3	17,351	250 cfs starting October 21, 500 cfs on October 28, 250 cfs on November 7, end bypass on November 14

Alternative	Volume required for power bypass (in acre feet)	Description
PB4	20,822	250 cfs starting October 21, 500 cfs on October 28, 250 cfs on November 7, end bypass on November 21
PB5	17,351	500 cfs bypass starting October 28, reduce to 250 on November 7, end bypass on November 21
PB6	30,141	100 cfs October 1, 200 cfs October 8, 300 cfs October 15, 400 cfs October 22, 500 cfs November 1, ending November 14

Consequences

In a SDM process, the consequence analysis stage is where we predict the outcome and compare the relative performance of the alternatives. The consequences or results from the analyses then serve as the basis for the subsequent trade-off analysis.

Temperature Model

The temperature impacts on Folsom Reservoir for each alternative were modeled using a customized CE-QUAL-W2 model of Folsom Reservoir (Cardno 2021). This modeling package was originally developed for Placer County Water Agency (PCWA) and was subsequently updated in 2023 as part of Reclamation's Water Temperature Modeling Platform Project (WTMP) by Kleinschmidt Group. Inflow temperatures from the North and South Forks of the American River and downstream temperatures at Watt Avenue (Figure 2) were modeled using regression relationships developed from 22 years of empirical data (2000–2021). These models allow for automated management of Folsom Dam's water temperature control shutters, similar to current operations, to optimize use of the cold-water pool to meet downstream temperature targets for fish in the Lower American River. For additional information on the development, calibration and validation of these models, please see Reclamation's Water Temperature Modeling Platform Report.

Initial Conditions

Initial conditions in Folsom Reservoir were set using a temperature profile collected on September 18th, 2025 near Folsom Dam. This profile was used to set the starting temperature throughout the CE-QUAL-W2 model domain.

Boundary Conditions

Meteorological Conditions

A meteorological dataset was compiled for Folsom Reservoir using data from nearby stations, including air temperature, dew point temperature, wind speed, wind direction, and cloud cover. The dataset includes four historical years (2011, 2014, 2017, and 2020) to capture a range of potential meteorological conditions. Among these, 2011 represents the coolest fall period on record, while 2014 represents the warmest.

Inflows to Folsom Reservoir

Total inflow to Folsom reservoir was based on the Reclamation's September 90% CVP Outlook. The total reservoir inflow was then divided between the North Fork American River and the South Fork American River by using historical averages.

Inflow Temperatures

Average daily air temperature for each meteorological scenario, along with daily average flows for the North Fork and South Fork of the American River, served as inputs to the previously described water temperature regression models. These inputs were used to estimate the daily average inflow temperature for each fork.

Outflows from Folsom Reservoir

Folsom Dam releases, evaporation from Folsom Reservoir, and municipal pumping were based on Reclamation's September 90% CVP Outlook.

Modeled Operations

Using the initial condition and boundary conditions described above, water temperature in the Lower American River at Watt and Hazel Avenues (Figure 2) was forecasted for each of the alternative actions/operations (Table 4) and meteorological scenarios. The model was configured to operate the Folsom shutters in accordance with ATSP schedule #36, targeting temperatures of 68 °F in September, 65 °F in October, and 59 °F in November.

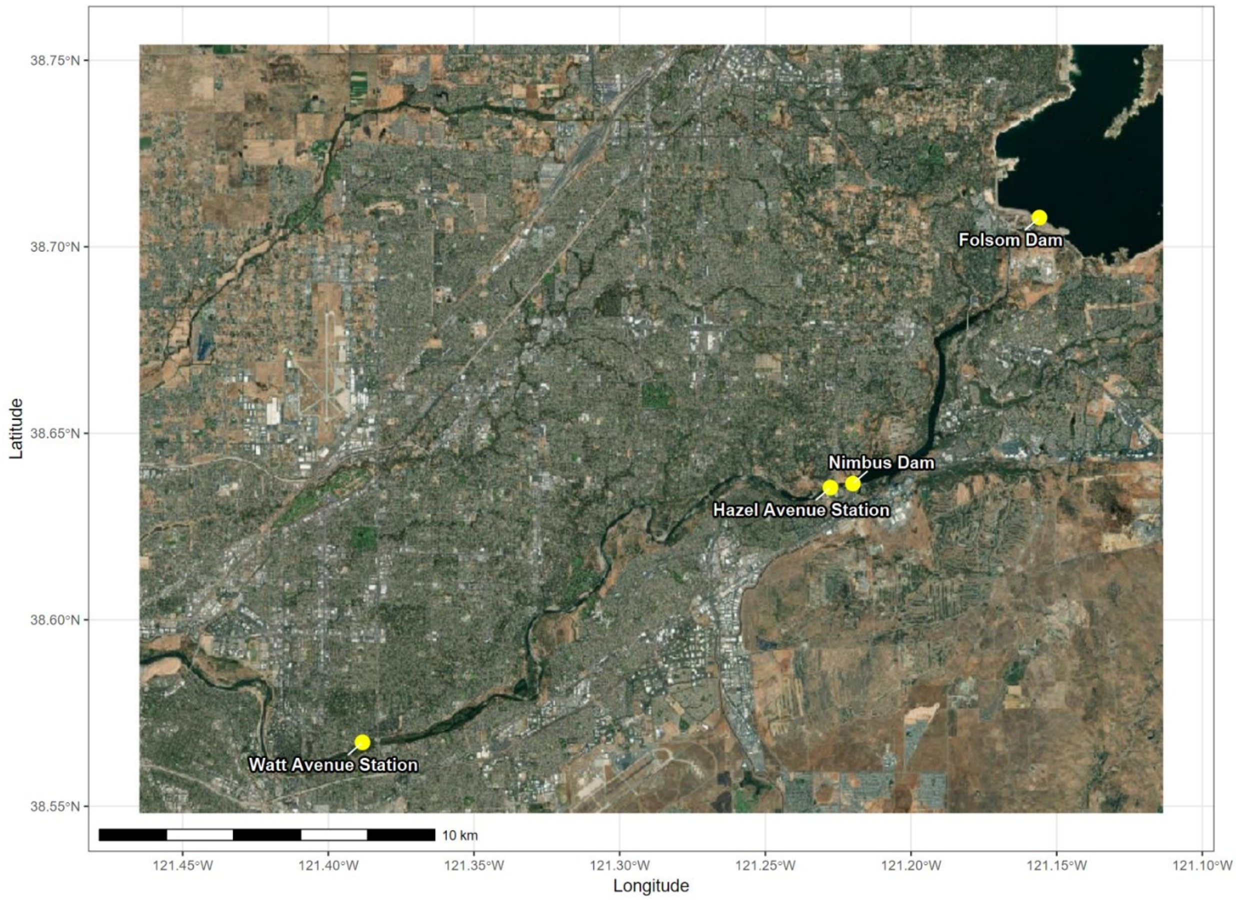

Figure 2. Map of the Lower American River and stations used in the temperature and Chinook Salmon models.

Chinook Salmon Model

Model Overview

We developed an integrated life-cycle simulation model for lower American River fall-run Chinook salmon to evaluate population responses to alternative water management scenarios over multi-decadal time horizons. The modeling framework linked environmental conditions resulting from different Folsom Dam power bypass operational alternatives to population-level outcomes through mechanistic relationships calibrated to empirical data from 2011 to 2024. The model synthesized spawn timing dynamics, temperature and density-dependent early life stage mortality, juvenile rearing survival, and smolt-to-adult return ratios (SAR) to project spawner abundance under alternative management scenarios.

Data Sources

We compiled daily water temperature measurements from monitoring stations at Hazel Avenue (river sections NB, W, 1a, 1b, and 2; USGS gauging station 11446500) and Watt Avenue (section 3; USGS gauging station 11446980) for the period 2011-2024. Each management alternative generated distinct downstream temperature regimes based on different operational scenarios for Folsom Dam power bypass flows. These temperature time series drove spawn timing, pre-spawn survival, egg and alevin development rates, and temperature-dependent mortality calculations.

We obtained redd data from annual carcass surveys conducted throughout the spawning season from 2011 to 2024 from the California Department of Fish and Wildlife (CDFW) CalFish database (Azat and Killam 2025). We estimated spawn dates by backdating fresh female carcass recovery dates by seven days. These empirical observations of spawn phenology provided the basis for calibrating the spawn timing model. We obtained annual escapement estimates from the CDFW GrandTab database for model calibration, including total in-river spawners (Azat and Killam 2025).

We derived age-at-return distributions from coded-wire tag (CWT) recoveries for American River fall-run Chinook salmon from 2011-2024 obtained from the Regional Mark Information System (RMIS) database (RMIS Database 2025). We parameterized fecundity from the Central Valley Project Improvement Act (CVPIA) Science Integration Team (SIT) fall-run decision support model (Peterson and Duarte 2020).

We derived weighted usable area (WUA) relationships for spawning habitat as a function of flow from Physical Habitat Simulation (PHABSIM) modeling for the American River (Chris Hammersmark, unpublished data). SAR was obtained from American River coded wire tag returns using fish released from the American River and returning to the American River, where the SAR was number of fish that returned divided by the number of fish released (RMIS Database 2025).

Spawn Timing Model

We modeled the temporal distribution of spawning activity in response to thermal conditions using a cumulative link model (CLM) for ordinal regression, following approaches similar to those used for winter-run Chinook salmon on the Sacramento River (Dusek Jennings and Hendrix 2020). This approach modeled the probability of spawning within sequential 10-day bins spanning the October through January spawning season as a function of antecedent temperature conditions. We specified the model as:

$$\log i\, t[P(Y \leq j)] = \zeta_{\mathrm{j}} - (\beta^1 \times Oct_{std} + \beta^2 \times Nov_{std})$$

where Y represents the ordinal spawn bin, ζ_j are threshold parameters defining transitions between bins, and Oct_{std} and Nov_{std} are standardized mean temperatures for October and November, respectively. We standardized temperatures using the calibration period (2011-2024) mean and standard deviation.

We implemented maximum likelihood estimation through the ordinal package in R (Christensen 2023), fitting the CLM to observed spawn timing data across 14 years. We defined 12 distinct 10-day spawn timing bins, with the earliest beginning October 5th based on the minimum observed spawn date in the empirical dataset. For forecast simulations, spawn timing emerged from a two-step stochastic process: we computed spawn bin probabilities for each year based on that year's standardized temperatures, then sampled individual redd dates by drawing spawn bins proportionally to their predicted probabilities and assigning specific dates uniformly within selected bins. This approach preserved both central tendency and variability of spawn timing while allowing spawn phenology to shift in response to altered thermal regimes.

Temperature-Dependent Mortality Models

We captured early life stage survival from egg deposition through fry emergence using three alternative temperature-dependent mortality (TDM) formulations representing different formulations of egg-to-fry temperature sensitivity (Figure 3).

The exponential models assumed mortality risk increased exponentially with temperature, with daily hazard rates calculated as:

$$h(T) = \alpha \times \exp(\beta T)$$

where parameters α and β differ between developmental stages. The Bratovich et al. (2020) calibration specifies egg stage parameters $\alpha = 3.408 \times 10^{-11}$ and $\beta = 1.211$, shifting to alevin parameters $\alpha = 1.018 \times 10^{-10}$ and $\beta = 1.241$ after hatching. The Bartholow and Heasley (2006) calibration uses egg parameters $\alpha = 1.475 \times 10^{-11}$ and $\beta = 1.392$, with alevin parameters $\alpha = 2.521 \times 10^{-12}$ and $\beta = 1.461$. Under both exponential formulations, cumulative survival is:

$$S = \exp\left(-\Sigma h(T)\right)$$

where the summation extends across all days of the incubation period.

The linear-threshold model (Martin et al. 2017) represents an alternative hypothesis where mortality only occurs above a threshold temperature, with cumulative survival:

$$S = \exp(-\alpha \times \Sigma \max(T - \beta, 0))$$

where parameters α = 0.026 and β = 12.14°C. This formulation assumes temperatures below the threshold impose no mortality, with risk increasing linearly above the threshold.

We based developmental timing for stage transitions on accumulated thermal units (ATU) derived from temperature-controlled incubation studies of fall-run Chinook salmon (Zeug et al. 2012), with hatching occurring at 958 degree-days and emergence at 1,375 degree-days total. The model tracked daily temperatures from each redd's spawn date, accumulating ATUs to determine when stage transitions occurred and applying stage-specific mortality parameters accordingly.

We conducted an expert elicitation process to account for scientific uncertainty surrounding these competing models. A panel of five biologists and scientists with Chinook salmon expertise assigned weights following the modified Delphi method (Clark et al. 2006). The final weights assigned 0.25 to the Martin et al. (2017) model, 0.51 to the Bratovich et al. (2020) model, and 0.24 to the Bartholow and Heasley (2006) model. These weights reflected collective professional judgment on how well each model represented mortality dynamics in the Lower American River.

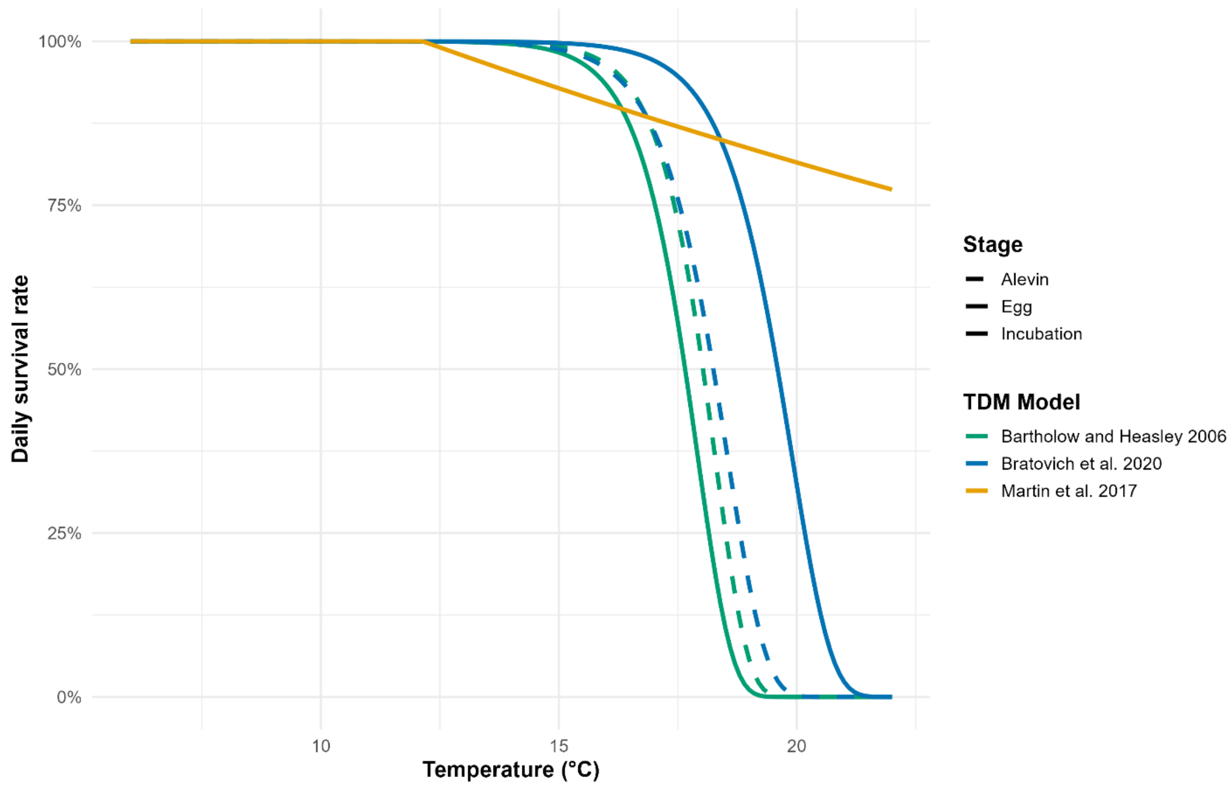

Figure 3. Comparison of temperature-dependent mortality (TDM) models for egg and alevin survival. Daily survival rates for three TDM formulations: Martin et al. (2017) linear-threshold model (orange), Bartholow and Heasley 2006 exponential model (green), and Bratovich et al. 2020 exponential model (blue). Dashed lines indicate alevin stage parameters.

Adult Pre-spawn Survival

We modeled adult salmon cumulative thermal stress during upstream migration and pre-spawn holding as a function of accumulated temperature exposure. Following Colvin et al. (2018), pre-spawn survival follows a logistic relationship with cumulative degree-days:

$$S_{pre} = 1/\left(1 + \exp\left(-(3.0 - 0.00067 \times DD)\right)\right)$$

where *DD* represents degree-days accumulated from October 1st through the spawn date. Degree-days accumulated as Σmax(T - 0, 0), capturing the cumulative thermal burden experienced by adults.

Population Dynamics and Life-Cycle Integration

We tracked cohorts through sequential life stages using coupled difference equations that incorporated stage-specific survival and capacity constraints. We calculated initial egg production for each cohort as:

$$Eggs = S \times f \times S_{pre} \times F$$

where S represents spawner abundance, f is the female fraction (0.5), S_pre is temperature-dependent pre-spawn survival, and F is mean fecundity (5,522 eggs per female) (Zeug et al. 2012). Eggs developed through the incubation period experiencing temperature-dependent mortality according to the selected TDM variant, with survival tracked daily based on actual temperature exposure from spawn date through emergence.

We modeled density-dependent regulation at the fry stage through a Beverton-Holt relationship:

$$dd\ = \frac{S_0}{\left(1\ + \frac{R}{K}\right)}$$

where S_0 represents maximum survival in the absence of competition (0.347), R is the number of redds, and K is habitat capacity. We varied habitat capacity with flow according to weighted usable area (WUA) relationships (Chris Hammersmark, unpublished data). We calculated the relationship between flow and spawner carrying capacity as:

$$K_{spawners} = \frac{WUA(Q)}{9.29\ m^2 per\ redd}$$

where Q represents flow in cubic feet per second. We used linear interpolation to calculate $K_{spawners}$ for any flow value within the observed range (500-5000 cfs), with values held constant at boundaries for flows outside this range.

We calculated fry production after incorporating both temperature-dependent mortality and density dependence as:

$$Fry_{dd} = \ Eggs\ \times\ S_{egg} \times\ dd$$

where S_egg represents cumulative survival through the egg-to-fry period from the TDM model. The transition from fry to smolt incorporated a fixed rearing survival parameter:

$$Smolts\ =\ Fry_{dd} \times\ rear_{surv}$$

where rear_surv = 0.5419 (54.19%; Erica Meyers, unpublished data). We modeled ocean survival and adult returns using age-structured dynamics with smolt-to-adult return ratios (SAR) applied to each cohort. The fixed SAR value of 0.0025 (0.25%) represented combined survival from smolt outmigration through ocean residence and return migration for portions of the life cycle.

We based age at return on a fixed distribution from coded-wire tag recoveries from 2011-2024 RMIS data: 82.9% at age-3, 16.9% at age-4, and 0.2% at age-5 (RMIS Database 2025). We updated spawner abundance through the population recursion:

$$S[y+a] = S[y+a] + Smolts[y] \times SAR[y] \times P(age = a)$$

where y indexed brood year, a represented age at return, and P(age=a) gave the probability of returning at age a.

Model Calibration and Validation

We calibrated life-cycle parameters to minimize combined error across all three TDM variants simultaneously. This approach ensured consistency in representing life-cycle processes while allowing each TDM variant to express its inherent differences in temperature-dependent egg-to-fry survival. We optimized two parameters, SAR (smolt-to-adult return ratio) and rearing survival (freshwater survival from fry to outmigration), to minimize the total sum of squared errors between predicted and observed spawner abundance across all TDM variants for the period 2011-2024.

We used the L-BFGS-B algorithm (Limited-memory Broyden-Fletcher-Goldfarb-Shanno with box constraints; Byrd et al. 1995), a quasi-Newton optimization method that efficiently estimates parameters by approximating the curvature of the objective function using recent gradient information rather than storing the complete Hessian matrix. This approach is particularly advantageous for salmon life-cycle models because it handles the complex, non-linear relationships between survival parameters and escapement outcomes while allowing biologically realistic parameter bounds (e.g., constraining SAR between 0 and 1).

We initialized the algorithm with SAR = 0.0025 and rear_surv = 0.5419. We seeded the first three years (2011-2013) from CDFW GrandTab observed escapement to provide initial conditions, while years 2014-2024 served as the fitting period. The objective function minimized the sum of squared differences between model-predicted and observed escapement. This combined calibration approach yielded final parameter estimates of SAR = 0.0025 (0.25%) and rearing survival = 0.5419 (54.19%), which we then applied uniformly across all TDM variants. We use 2022-2024 observed escapement as initial values for projections beyond 2025.

The primary difference between model variants lay in temperature-dependent egg-to-fry survival calculations. Each TDM variant produced different survival rates for identical temperature conditions, creating a range of population forecasts that reflected scientific uncertainty in the mortality-temperature relationship. We assessed model performance by comparing modeled versus observed spawner abundance across the full calibration period (2014-2024), evaluating both magnitude and temporal dynamics of the population trajectory (Figure 4).

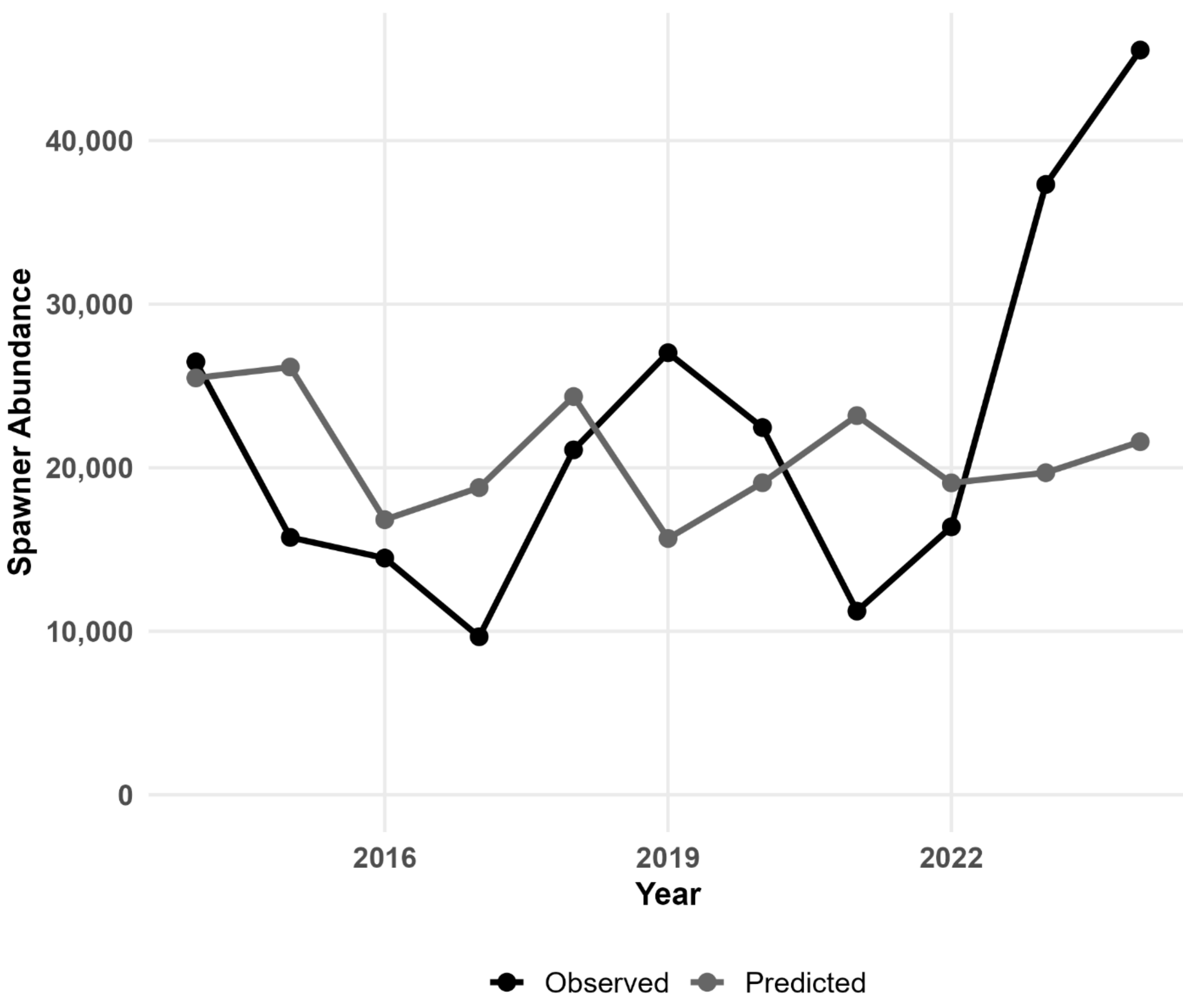

Figure 4. Observed versus predicted spawner abundance for American River fall-run Chinook salmon, 2014-2024. Predictions use weighted ensemble of three TDM models (51% Bratovich et al. 2020, 24% Bartholow and Heasley 2006, 25% Martin et al. 2017) with fixed population parameters.

Forecasting

We project populations for up to 100 years using environmental conditions specified by management alternatives, with spawn timing and temperature-dependent processes responding to alternative-specific thermal regimes. We applied calibrated life-cycle parameters with environmental conditions cycling through observed temperature patterns under specific operational scenarios. We initialized forecasts using the final three years of observed escapement (2022-2024) as seed spawners, then deterministically projected population dynamics forward based on the temperature-survival relationships and density-dependent processes described above.

Our forecast framework allows weighted combinations of management alternatives based on climatology weights across four climate year types (cool years [2011, 2020], and warm years [2014, 2017]) representing different hydrological and thermal conditions, TDM model weights across three mortality model variants with expert-elicited weights, and flow scenarios with user-specified downstream flow levels that dynamically adjusted carrying capacity. We implemented all simulations in R version 4.5.1 (R Core Team 2025).

Hydropower Generation Cost Calculation

The economic impact of a power bypass was quantified as the forgone hydropower revenue, calculated as the replacement value of the lost generation. The analysis compares each proposed bypass alternative against a baseline 'No Power Bypass' scenario, with all other operational parameters held constant. The model was driven by Folsom Reservoir storage and total release volumes derived from the Reclamation Central Valley Operations Office's September 50% exceedance forecast for water year 2025, assuming a linear daily release. Daily powerhouse efficiency, measured in megawatt-hours per acre foot (MWh/AF), was modeled as a function of the daily reservoir storage elevation. The total daily generation (MWh) was then calculated based on this efficiency and the daily generation release volume (AF), which is defined as the total daily release minus any bypass volume.

The valuation assumes an optimal power peaking operation, wherein generation is dispatched during the most economically valuable hours of the day (Table 5). Daily powerhouse capacity was determined based on reservoir elevation and the number of available generating units, accounting for scheduled outages. For each day, the minimum number of hours required to produce the total daily generation was calculated, and that energy was distributed across the hours with the highest market prices to determine its maximum potential value.

Because both the baseline and the bypass scenarios are modeled with this optimal peaking strategy, the resulting difference in revenue represents the value lost in the "shoulder hours." These are the moderately high-value periods that can no longer be served by generation when the total energy volume is reduced by a bypass operation. The total forgone revenue is the sum of these differences over the entire analysis period.

Table 5. Monthly average hourly prices ($/MWh) used for hydropower valuation. Values were derived from 2024 day-ahead locational marginal prices at the Western Area Power Administration (WAPA) trading node (WAPAMEEA3_ACT_ASR_APND), which represents the cost of replacement power. The profiles were calculated by averaging the price for each specific hour across all days of a given month to smooth daily volatility. Color is scaled according to values where green color indicates high value hours.

Hour Ending	September	October	November	December
1	37.06	46.19	43.09	44.2
2	36.08	44.33	42.36	43.01
3	35.29	43.57	41.49	42.04
4	34.78	43.15	41.26	41.85
5	35.28	43.71	43.23	43.49
6	37.77	46.43	47.52	48.41
7	39.51	50.32	49.29	50.65
8	34.93	52.28	45.04	49.46
9	25.88	45.63	42.06	44.39
10	24.53	42.58	39.42	43.53
11	24.71	42.1	37.2	41.58
12	24.44	39.93	34.79	39.13
13	24.57	40.03	33.41	36.48
14	26.08	40.76	34.19	36.73
15	27.94	42.5	36.01	40.45
16	32.6	48.03	42.9	45.61
17	36.39	53.91	51.26	52.64
18	47.69	64.39	53.31	53.45
19	72.5	77.69	51.22	52.46
20	76.03	62.82	50.56	51.8
21	50.72	56.38	50.18	51.55
22	43.09	53.59	49.75	51.09
23	40.6	49.73	48.15	49.75

Hour Ending	September	October	November	December
24	38.16	46.67	45.56	47.86

Trade-offs

Upon the completion of all model runs, we populated the final consequence table (table that displays the anticipated outcome for each objective across all alternative actions) assuming equal probability for all four different meteorological conditions (i.e., 0.25 probability for 2011 cooler meteorological conditions in the fall, 0.25 probability for 2014, etc.). We then used swing weighting to elicit the decision-makers' objective weights prior to calculating composite utility scores. Swing weighting is a method used to determine the relative importance of different objectives in a decision by asking decision-makers to evaluate the "swing" in preference from the worst possible outcome to the best possible outcome for each objective and then ranking these hypothetical scenarios (Gregory et al. 2012). For swing weighting, we opted to use local scale (range, or swing in the outcomes) observed in the final consequence table.

To assess trade-offs in this decision context, we used the objective weights gathered from the swing weighting exercise in combination with multi-criteria decision analysis (MCDA), a set of methods that can be used to address problems involving multiple competing objectives (Converse 2020). We used a linear value MCDA model and normalized the performance metric scores for the 3 fundamental objectives on a 0-1 scale (where 1 is the desired outcome). We then calculated the composite utility score using the objective weights as follows:

$$V_{j,k} = \sum_{i=1}^{3} w_i x_{i,j,k,g}$$

where $x_{i,j,k}$ is the normalized performance measure score on objective *i* for alternative *j* under meteorological condition *k* (represented by the years 2011, 2014, 2017, and 2020), TDM model *g* and w_i is the weight placed on objective *i* (where the sum of the objective weights = 1).

Value of Information

Value of information (VoI) is an analytical method used to quantify the potential benefits of resolving uncertainty associated with a well-defined decision problem. One of the most commonly used VoI calculation is the expected value of perfect information (EVPI), a quantification of the maximum expected improvement in management performance after obtaining perfect information and resolving all uncertainties (Raiffa and Schlaifer 1961). In the decision problem over Folsom Dam power bypass operations, the various TDM models represent a key uncertainty that may be reducible through studies, whereas meteorological conditions spanning months into the future would represent irreducible uncertainty. In order to estimate the value of conducting future studies to resolve uncertainty surrounding TDM, we conducted a VoI analysis upon the completion of the SDM effort (i.e., after the decision has been made).

As noted above, we used the narrow, local scale observed in the final consequence table after the integration of TDM model expert-elicited weights and multiple meteorological scenarios. The use of this narrow local scale was preferred by the decision-makers in our case because it was deemed more intuitive; however, it precluded us from conducting a proper EVPI calculation. As such, for the purpose of EVPI calculation, we recalculated the Chinook Salmon normalized scores for MCDA using the maximum and minimum values observed when we assumed each TDM model can be “true”. Using this new re-scaled normalized score, we then adjusted the objective weights so that the resulting ranking of alternatives matched what was produced for the decision. Subsequently, we calculated EVPI using the new objective weights and the expert-elicited TDM model weights. EVPI is defined as the difference between the expected management performance after uncertainty has been fully resolved and the expected performance under uncertainty:

$$\text{EVPI} = \sum_{g=1}^{3} p_g(max_j(p_k V_{j,g})) - max_j\left(\sum_{g=1}^{3} p_g p_k V_{j,g}\right)$$

where *V* is the composite utility score for alternative *j*, and *p* is the assigned probability (or relative belief) for each competing TDM model *g* and meteorological condition *k*. The first term of the equation represents the maximum performance under perfect information (i.e., if we knew which TDM model was true) and the second term represents the maximum performance score of the alternatives under uncertainty (i.e., maximum of V_j).

Results

Temperature Model

Four historical meteorological scenarios (2011, 2014, 2017, and 2020) were selected to capture a range of potential fall conditions. Among these, 2011 represents the coolest fall period in the historical record, while 2014 represents the warmest (Figure 5). Despite differences in the meteorological inputs, the relative performance and ranking of the alternative actions remained largely consistent across all scenarios.

The 'No Power Bypass' alternative (NB) generally resulted in the warmest downstream thermal regime. All power bypass alternatives lowered river temperatures by drawing from the reservoir's cold-water pool (hypolimnion) accessible only through Folsom Dam's low-level outlets. If the bypass was stopped prematurely while warm temperatures persisted, water temperatures below Folsom and at Watt Avenue in mid- to late-November could be warmer than the 'No Power Bypass' (NB) alternative (e.g., alternative PB1, PB3, and PB6). Overall, alternatives PB2, PB2b, and PB2c were the most effective at maintaining cooler conditions throughout the fall-run Chinook salmon spawning and incubation period across all four meteorological scenarios.

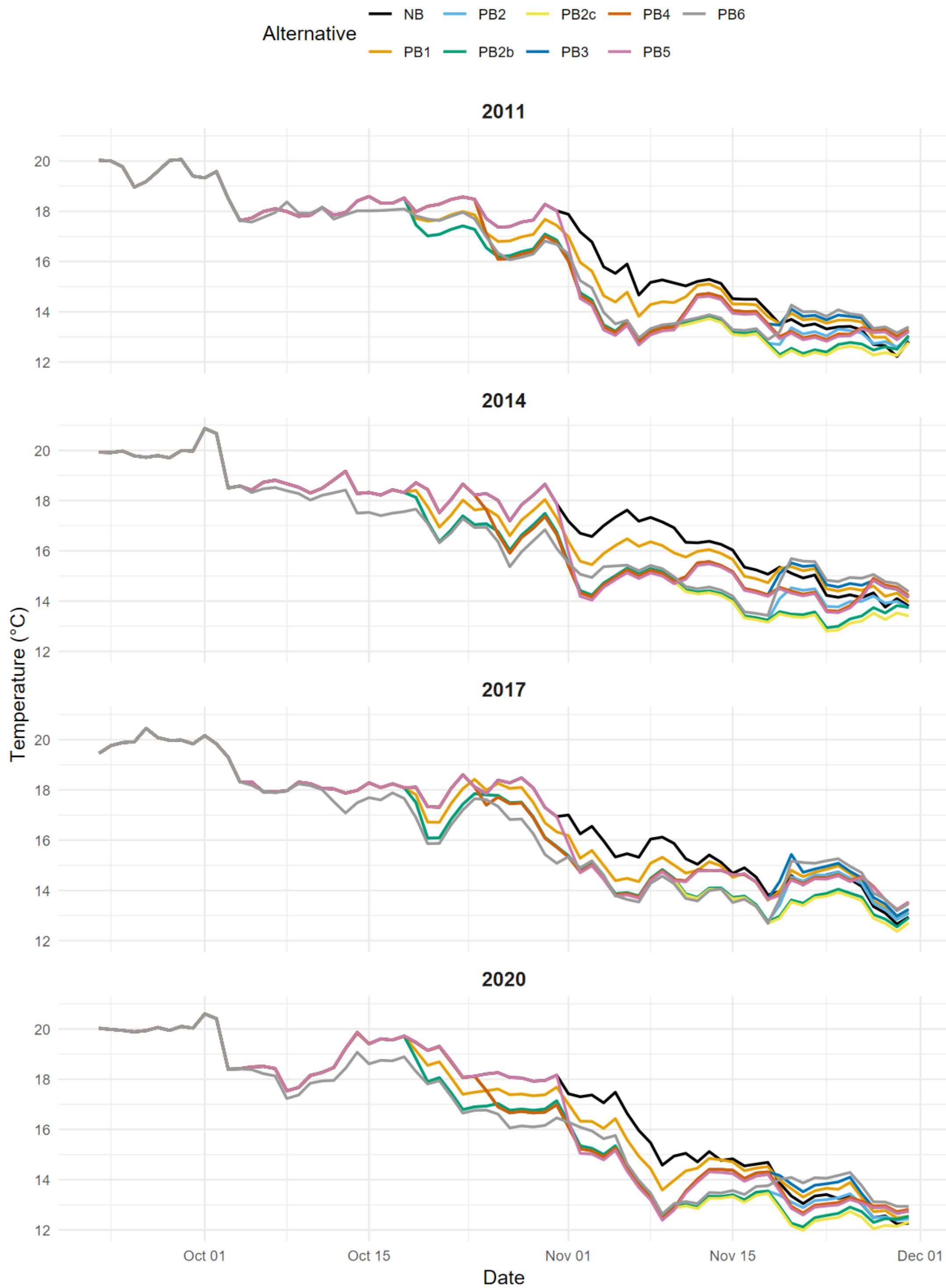

Figure 5. Predicted water temperature at Watt Avenue in the Lower American River by meteorological condition/year and alternative action.

Chinook Salmon Model

The results from the Chinook Salmon population model broadly corresponded with the temperature model outputs, where cooler October-November temperature regimes resulted in higher predicted juvenile production and, consequently, a greater adult population index. Across all meteorological scenarios and TDM models, alternative PB2c consistently produced the highest salmon abundance. In contrast, the worst-performing alternative varied depending on the TDM model used, highlighting a key uncertainty. Under the exponential TDM models (Bartholow and Heasley 2006, Bratovich et al. 2020), the 'No Power Bypass' (NB) alternative always resulted in the lowest predicted salmon abundance. Meanwhile, under the linear Martin et al. (2017) model, several power bypass alternatives were consistently predicted to perform worse than the NB alternative, though the number varied depending on the meteorological scenario. The median estimate of the adult population index across all scenarios ranged widely, from a low of 665 using Martin et al. (2017) model and 2014 scenario, to a high of 27,411 using Bratovich et al. (2020) model and 2011 scenario (Figure 6).

In the integrated analysis, which assumed an equal probability for each meteorological scenario and applied the expert-elicited TDM model weights, fall-run Chinook Salmon population index ranged from 17,833 to 20,925. All power bypass alternatives were predicted to produce a higher salmon abundance than the 'No Power Bypass' option (adult population index of 17,833). Alternative PB2c was projected to yield the highest abundance with an index of 20,925. This was followed closely by alternatives PB2b and PB2, with population indices of 20,702 and 20,146, respectively. The next best-performing alternative was PB4, with a predicted abundance index of 19,253 (Figure).

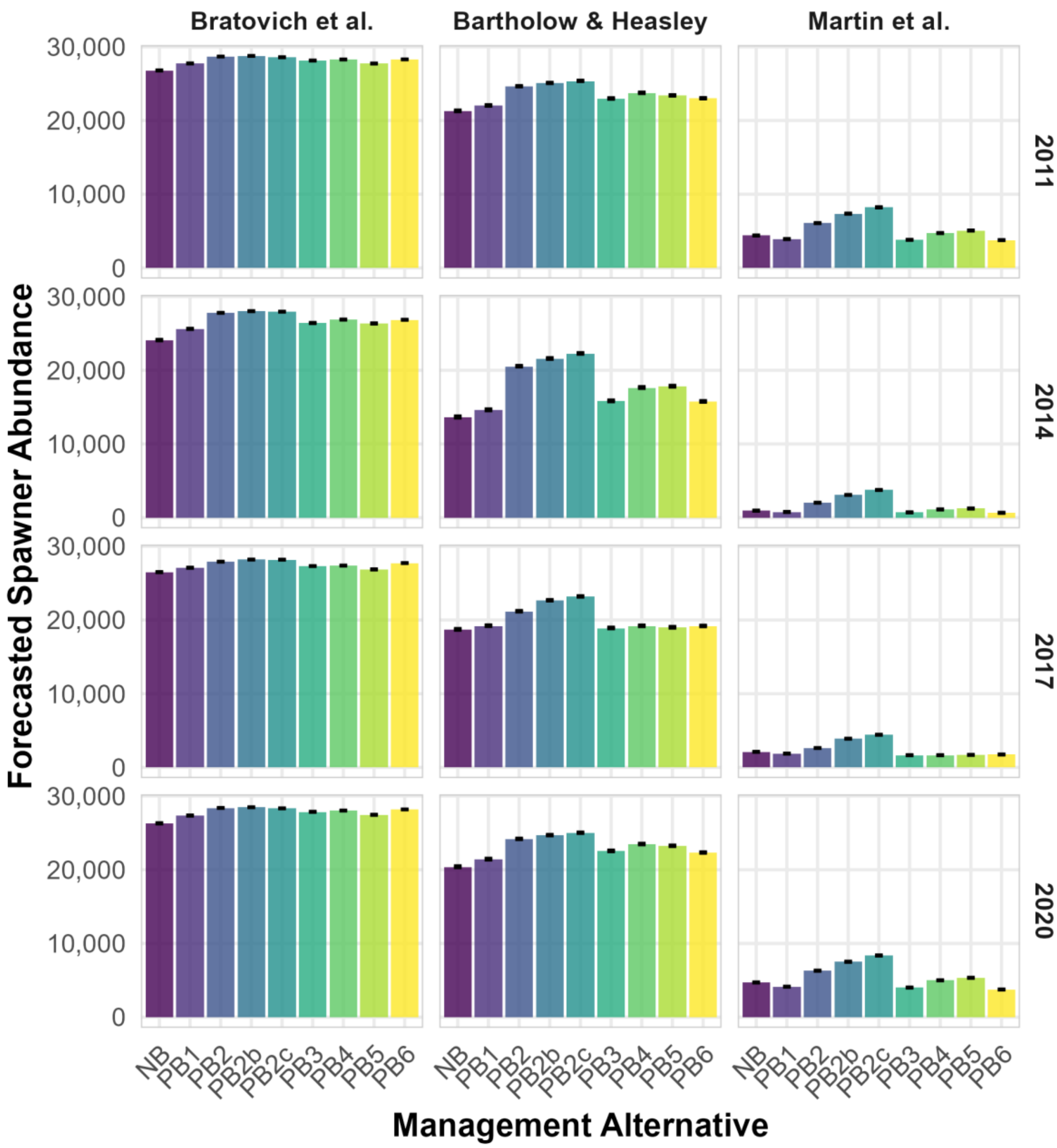

Figure 6. Sensitivity of 20-year spawner abundance forecasts to climate year and temperature-dependent mortality (TDM) model selection across nine management alternatives. Each panel represents a unique combination of one of four representative climate years (2011, 2014, 2017, 2020) and one of three TDM formulations: Bratovich et al. 2020 exponential model, Bartholow and Heasley 2006 exponential model, and Martin et al. 2017 linear-threshold model. Bars show median forecasted spawner abundance for the final 20 years of a 100-year projection period, with error bars indicating the interquartile range (25th to 75th percentile). Management alternatives range from No Bypass (NB) through six pulse barrier configurations (PB1–PB6).

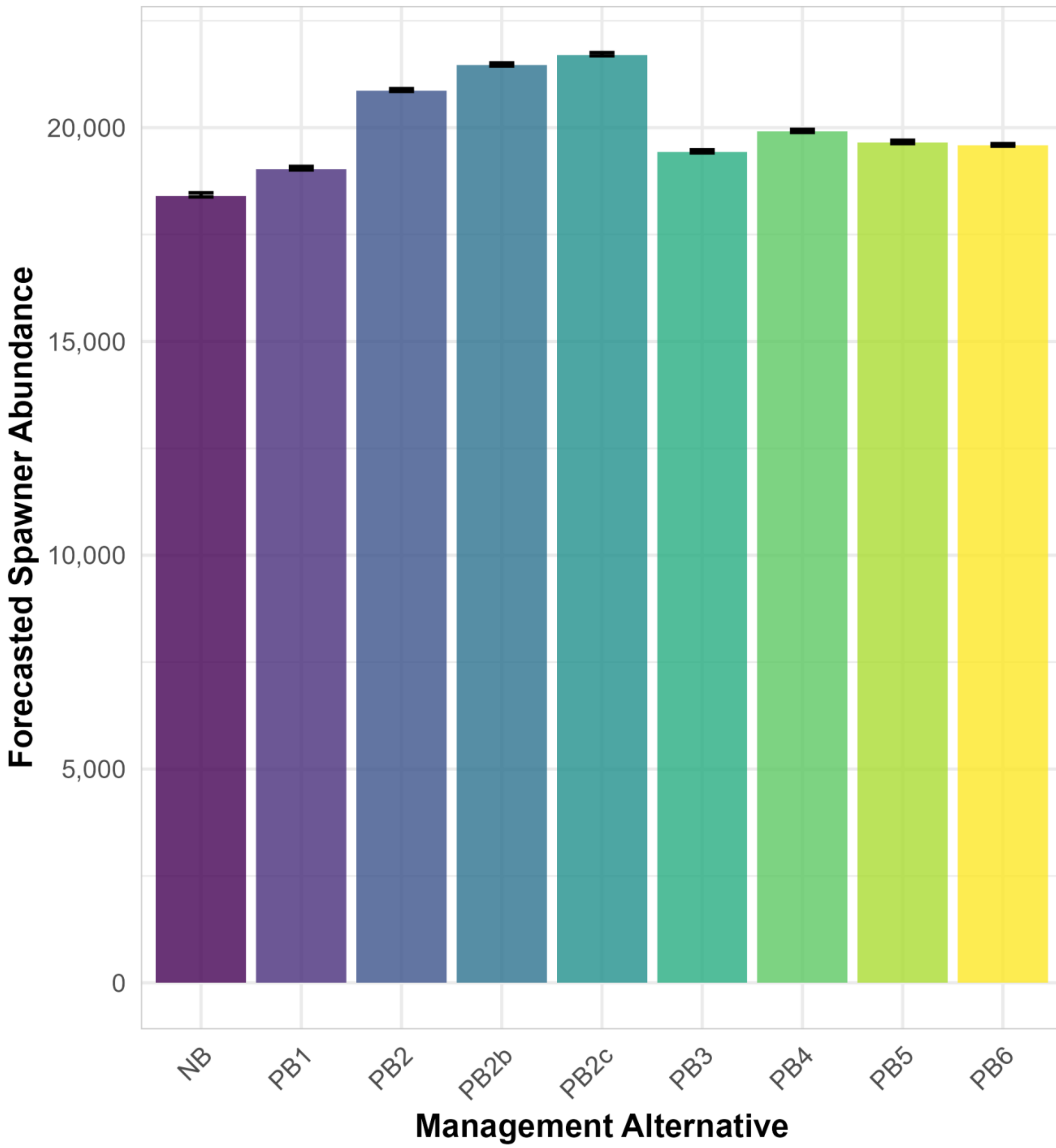

Figure 7. Long-term simulated spawner abundance of fall-run Chinook salmon under nine management alternatives using default model weights. The bar height represents the median abundance from the final 20 years of a 100-year simulation. This forecast assumes an equal likelihood for four future climate conditions (2011, 2014, 2017, 2020) and a blended assumption for three Temperature-Dependent Mortality (TDM) models.

Decision Analysis

Alternative NB (no power bypass) performed the best for the hydropower generation objective, as it does not involve any forgone hydropower generation. Hydropower generation cost for each alternative also remains static across different meteorological scenarios, as the volume of water to be bypassed remain static regardless of scenarios. Alternative PB2c is expected to produce the highest salmon abundance, but it has the second highest associated hydropower generation cost at $433,215. Alternative PB6 performed the best for the steelhead performance metric with a predicted 52.75 days of "ideal" rearing conditions in the months of October and November, with moderate performance on the fall-run Chinook Salmon and hydropower generation objectives (Table 6). However, the number of days under "ideal" rearing conditions for steelhead did not vary considerably in the integrated results, ranging from 48.75 to 52.75 days.

Table 6. Consequence table showing the expected outcome for each alternative across the three objectives assuming equal probability for each meteorological scenario, with green color indicating the more preferred outcome for each objective.

Alternative	Fall-run Chinook Salmon abundance (adult population index)	Hydropower generation cost ($)	American River steelhead (# of days of "optimal" rearing conditions)
NB	17,833	$ -	48.75
PB1	18,428	$ 111,422	52
PB2	20,146	$ 370,826	52.5
PB2b	20,702	$ 470,090	52.5
PB2c	20,925	$ 433,215	51.25
PB3	18,801	$ 201,552	51.25
PB4	19,253	$ 241,590	51.25
PB5	19,011	$ 199,382	49
PB6	18,953	$ 348,806	52.75

All agencies and organizations within the ARG were invited to the swing weighting process; however, only Reclamation shared their objective weights publicly. Reclamation assigned the highest weight to the hydropower generation objective (0.5), followed by the fall-run

Chinook Salmon and steelhead objectives (0.4 and 0.1, respectively). Reclamation managers placed low weight on the steelhead objective because the range of outcomes for steelhead under the various alternatives were deemed less likely to result in a population-level effect. Based on Reclamation's set of objective weights, we calculated composite utility scores for all nine alternatives. Based on the scores, alternative PB1 is the highest ranked alternative (0.537), followed closely by alternative PB2c (0.502), NB (0.5), PB2 (0.499), and PB4 (0.491).

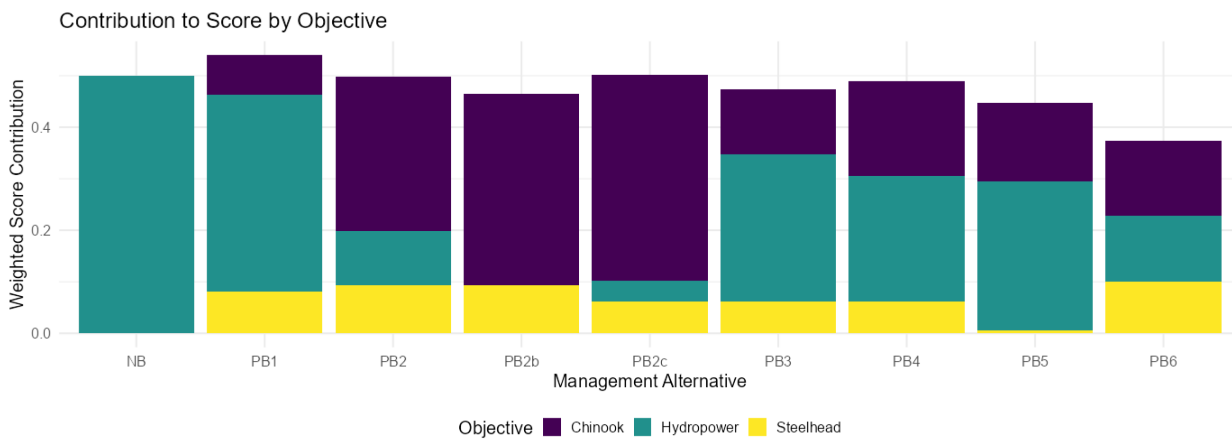

Figure 7. Composite utility scores from the multi-criteria decision analysis across alternatives. Color indicate the relative contribution from each objective towards the total utility score.

Although alternatives NB and PB1 ranked high in overall utility score, it was largely due to the benefits from continuing hydropower generation with little contribution from fish benefits (Table 6, Figure 7). Oppositely, PB2 and PB2c scored high mostly due to the fish benefits at the cost of hydropower generation. Reclamation ultimately selected alternative PB4, as it represented the best balance from the two competing goals (hydropower generation and fish benefit). During discussion with Reclamation managers, it also became apparent that the linear utility/value function did not accurately portray their views. Reclamation managers expressed interest in ensuring that forgone hydropower generation cost does not exceed Folsom Dam power bypass operations from previous years (~$250,000; L. Johnson, personal communication, October 3, 2025).

Value of Information

Normalized scores for the fall-run Chinook Salmon objective were re-scaled using the maximum and minimum values observed when we allowed each TDM model to have 100% weight but continue assuming equal probability of all four meteorological conditions. This resulted in the lowest adult population index of 2,474 for alternative PB6 under the Martin et al. (2017) TDM model, and the highest value of 27,048 for alternative PB2b under the Bratovich et al. (2020) TDM model. We approximated the ranking of alternatives that resulted in the decision using the new scales when we placed 0.8 weight for the fall-run Chinook Salmon objective, 0.05 weight for the steelhead objective, and 0.15 weight for the hydropower generation objective (Figure 8). Based on this set of objective weights, we calculated EVPI of 0.009 in utility score, which is the equivalent of 1.3% increase in performance if we resolve uncertainty surrounding TDM models.

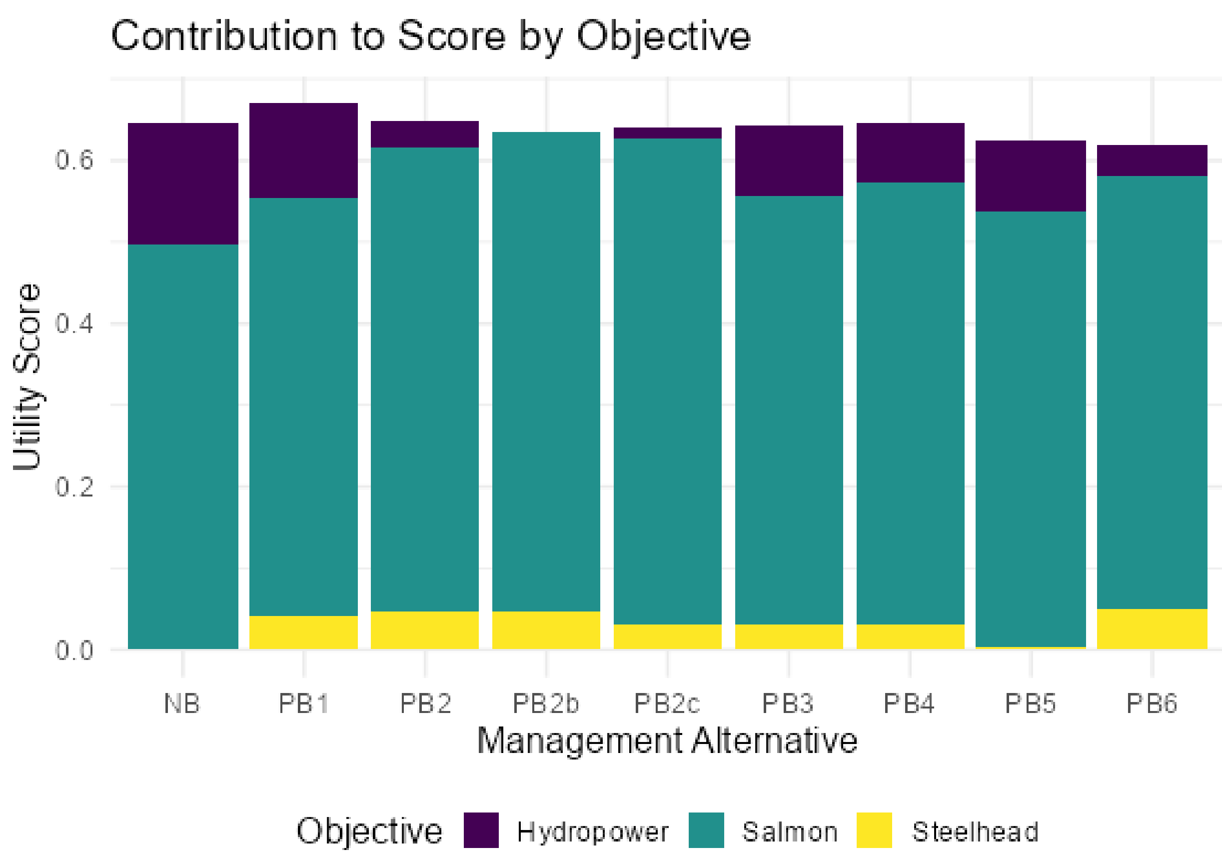

Figure 8. Composite utility scores from the multi-criteria decision analysis using re-scaled normalized scores from each TDM model variant and new set of objective weights intended to match the results in Figure 7. Color indicates the relative contribution from each objective towards the total utility score.

Discussion

Historically, the decision-making process for Folsom Dam power bypass operations has been somewhat informal and lacked quantitative transparency. This created challenges, as exemplified in 2024 when conflicting outputs from alternative TDM models made it unclear whether a bypass would benefit or harm fall-run Chinook salmon production. Furthermore, the selection of a final operational alternative without full deliberation within the ARG led to criticism regarding procedural transparency. The 2025 SDM effort described here was initiated to rectify these issues, providing a defensible framework that incorporates the diverse objectives of participating agencies and interest holders.

The application of a formal decision analysis yielded several key successes. First, it clarified the problem's scope by confirming that the power bypass was the central management action under consideration and thus defining Reclamation as the lead decision-maker, with other ARG members participating as interest holders. Second, the process successfully identified and structured the key objectives, even though one objective (Nimbus Hatchery operations) was ultimately excluded due to the non-participation of key staff members. Third, the analysis revealed that uncertainty in the TDM models was not a critical impediment, as the relative ranking of alternatives remained largely consistent and VoI was estimated to be low. Finally, the use of MCDA and swing weighting provided a transparent mechanism for evaluating trade-offs and communicating the rationale for Reclamation's selection of a preferred alternative to the ARG.

Another significant component of this SDM process was the collaborative development of a fall-run Chinook Salmon life cycle model to quantify the biological benefits of a power bypass. This model integrated key mechanisms identified as critical by interest holders, including temperature-driven pre-spawn mortality, temperature-dependent egg-to-fry survival (i.e., the weighted TDM models), and shifts in spawn timing in response to thermal cues. While this model was developed in a rapid manner, it reflects the best available science on thermal effects on fall-run Chinook salmon in the Lower American River. It also serves as a crucial foundation for future iterative decision cycles, where it can be refined as new information becomes available.

This SDM process represents an important step toward a more robust decision-making framework for the ARG, but there are a few areas for future improvement. First, the 2025 process was unable to formally incorporate objectives related to Nimbus Hatchery operations. Given that high temperatures and low dissolved oxygen levels at the hatchery intake can adversely affect fish production, a key mitigation requirement for Reclamation, integrating this objective in the future seems crucial. Second, the performance metric for steelhead may warrants a re-evaluation. The current metric (days < 18.3 °C) functions as a measure of adherence to established regulatory targets, but its biological justification is unclear (NMFS 2009). Studies from local steelhead populations suggest that this threshold may not confer significant population benefits compared to slightly warmer temperatures (e.g., 19-21 °C) (Myrick and Cech 2001, Verhille et al. 2016). Future efforts may focus on developing a more biologically meaningful metric, or determining if this objective is a relevant factor for power bypass decisions.

Another key concept that could not be quantitatively incorporated was the potential for a power bypass to increase life-history diversity. Some participants hypothesized that providing a wider window of suitable spawning temperatures would diversify spawn and outmigration timing, thereby increasing population resilience (i.e., the "portfolio effect"). While the benefits of portfolio effects are well-documented (Greene et al. 2010, Schindler et al. 2010, Sorel et al. 2024), few studies have quantitatively linked them to migration timing in a predictive manner. Doing so would likely require a complex simulation of trait inheritance and environmental stochasticity, an undertaking beyond the scope of this rapid SDM process. Furthermore, a gap remains between the academic theory of the portfolio effect and its practical application in annual, high-stakes management decisions. In some instances, managing for life-history diversity may present a difficult trade-off, whereby increasing life-history diversity can decrease inter-annual variability in abundance (reducing fishery closure risk), but at the cost of a lower mean population abundance (Carvalho et al. 2023). How to balance the trade-off between stability and mean productivity warrants further research for Central Valley salmon management.

This effort represents a foundational step toward a more structured and transparent management process for seasonal temperature and flow management in the Lower American River. The current decision context is narrow, focusing only on the power bypass. Future iterations would benefit from expanding the suite of alternatives to include other actions that support salmonid populations. The trade-offs identified, particularly the cost of forgone hydropower, can be significant if it was to occur on an annual basis. An ideal next step for the ARG should be to develop creative alternatives that might mitigate these trade-offs. For example, further research into the proper thermal tolerance of steelhead could reveal that allowing warmer late-summer temperatures (e.g., > 18.3 °C) is biologically acceptable. This could conserve the reservoir's cold-water pool for fall-run Chinook salmon, potentially precluding the need for any power bypass and creating a more optimal outcome for both fisheries and hydropower operations.

Ultimately, the Folsom power bypass decision is a microcosm of the complex water management challenges facing the Central Valley of California. This SDM effort serves as a critical case study, demonstrating that even contentious decisions with significant scientific uncertainty can be decomposed and analyzed. By explicitly quantifying trade-offs, such as the dollar cost of forgone hydropower for a modeled increase in salmon survival, this framework moves the interest holder conversation beyond conflicting positions to a shared understanding of values and consequences. This transparent, science-based approach is essential for adaptive management in a future where conflicts between ecological needs and resource demands are likely to intensify.

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Acknowledgments

We thank Reclamation Bay-Delta Office and Central Valley Operations Office management teams for their support for this structured decision-making process: David Mooney, Mario Manzo, Joshua Israel, Randi Field, and Levi Johnson. We also appreciate advice and feedback from Brian Healy and Corey Phillis during the structured decision-making process. We are grateful for the facilitation and logistical support provided by Karis Johnston, Rafael Silberblatt, and Mia Schiappi. The participants also willingly and constructively engaged in the structured decision-making process, which was critical to the success of the effort. Participants included, but not limited to: Erica Meyers, Jason Julienne, Nicholas Bauer, Stephen Maurano, Eric Mork, Ashlee Casey, Mechele Pacheco, Erica Bishop, and Chris Hammersmark.

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