Environmental Flow Study for the Hetch Hetchy Reach of the Upper Tuolumne River

A project of the Upper Tuolumne River Ecosystem Program
Early Draft for the Upper Tuolumne River Workgroup – October 2024

Prepared by

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Cover photograph

Downstream view of a 2009 experimental flood release from O'Shaughnessy Dam.

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List of Abbreviations

°C	degrees Celsius
°F	degrees Fahrenheit
2-D	two-dimensional
ac	acres
ac-ft	acre-feet
ACOE	United States Army Corps of Engineers
ANOVA	Analysis of Variance
BAGS	Bedload Assessment in Gravel-bedded Streams
BMI	benthic macroinvertebrates
CCSF	City and County of San Francisco
CDEC	California Data Exchange Center
CDFW	California Department of Fish and Wildlife
CESA	California Endangered Species Act
cfs	cubic feet per second
DHM	direct habitat mapping
DOI	U.S. Department of the Interior
DPS	Distinct Population Segment
EFS	Environmental Flow Study
EI site	Early Intake 2-D modeling site
ESA	Endangered Species Act
FERC	Federal Energy Regulatory Commission
ft	feet
ft/sec	feet per second
FYFAM	Foothill Yellow-legged Frog Assessment Model
FYLF	Foothill Yellow-legged Frog
Hetch Hetchy Project	Hetch Hetchy Water and Power Project
HSC	habitat suitability criteria
HSD	Honest Significant Difference
HVT	Hoopa Valley Tribe Fisheries Department
IBM	individual based model
inSTREAM	individual-based Stream Trout Research and Assessment Model
LiDAR	Light Detection and Ranging
M&T	McBain & Trush
mi	miles
mi^2	square mile
NGD	Number of Good Days
NHE	Northern Hydrology and Engineering
NPS	National Park Service
OSD site	O'Shaughnessy Dam 2-D modeling site
PG&E	Pacific Gas and Electric Company
PHABSIM	Physical Habitat Simulation
RBT	Rainbow Trout
RHJV	Riparian Habitat Joint Venture
RM	river miles

RMC	RMC Environmental
SD	Standard deviation
SFPUC	San Francisco Public Utilities Commission
Spill-Sim analysis	Spill Simulation spreadsheet analysis
TRPA	Thomas R. Payne & Associates
UCSC	University of California, Santa Cruz
USFS	U.S. Forest Service
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UTREP	Upper Tuolumne River Ecosystem Program
WUA	weighted usable area
WY	Water Year (October 1–September 30)

1 Executive summary

The San Francisco Public Utilities Commission (SFPUC) owns and operates the Hetch Hetchy Water and Power Project on the Upper Tuolumne River located in the Sierra Nevada of California. The SFPUC initiated the Upper Tuolumne River Ecosystem Program (UTREP) to develop recommendations for improving ecosystem conditions within the 13 mile long Hetch Hetchy Reach downstream of the Project while maintaining the water supply reliability and the hydropower capacity of the Project.

To develop flow recommendations, the UTREP and program partners conducted a series of site-specific studies, reviewed relevant scientific literature and previous studies, and defined a set of "focal elements" to focus management recommendations; focal elements included Rainbow Trout, Foothill Yellow-Legged Frog, Poopenaut Valley wetlands, and geomorphic functions. A set of reference conditions representing pre-development conditions were established developed to provide guidance for recommendations and context for evaluating modeled outcomes. The recommendations are described in this document and associated appendices.

The recommendations include updates to baseflow requirements, a new water year classification, snowmelt management objectives, and ramping rate management. Relative to existing baseflow requirements, the recommended baseflows are greater in magnitude in spring, but lower in summer, with the goal of improving ecological habitat and mimicking the reference condition hydrology in spring and summer. These changes are anticipated to provide more Rainbow Trout habitat in the wetter years, while improving Foothill Yellow-legged Frog habitat in drier years.

The spring snowmelt management objectives were developed to mimic natural geomorphic processes and inundate important wetland habitats within the Poopenaut Valley. The achievement of these flow magnitudes and durations is expected to improve spawning habitat, support bed mobility and scour, increase BMI habitat and production, limit riparian encroachment, and improve riparian recruitment. Slower high flow downramping rates were recommended to better mimic the duration of the natural snowmelt hydrograph recession limb, increasing Rainbow Trout spring time growth and reducing Foothill Yellow-legged Frog early life stage desiccation and stranding.

The baseflow, snowmelt management, and downramping recommendations were combined into annual hydrograph and water temperature scenarios to develop a recommended future scenario that could be compared against existing and reference condition scenarios. The scenarios were developed using the Spill-Sim analysis, reservoir release simulation modeling tool, and then evaluated using a series of models to predict the effect of flow recommendations on the focal elements.

Overall, the ecological goals for each focal element were predicted to be achieved under the recommended future scenario. For example, relative to the existing scenario the recommended future scenario modeling predicted higher adult Rainbow Trout growth and inundation of Poopenaut Valley wetlands in wetter years, but did not predict favorable conditions for Foothill Yellow-legged Frog reproduction in those years. In drier years, Foothill Yellow-legged Frogs were predicted to have higher reproductive success, but Rainbow Trout were predicted to exhibit no change from the existing conditions in those years.

Overall, the recommendations and their predicted outcomes represent an approach that seeks to mimic the ecological functions of the natural hydrology of the Upper Tuolumne River, while maintaining the essential functions of the Hetch Hetchy Water and Power Project.

2 Introduction

The San Francisco Public Utilities Commission (SFPUC), a department of the City and County of San Francisco (CCSF), owns and operates the Hetch Hetchy Water and Power Project (the Hetch Hetchy Project), located in the upper Tuolumne River watershed in California's Sierra Nevada (Figure 1). The Hetch Hetchy Project (described in Section 3.1) is a system of major dams, diversion structures, and hydropower facilities on the Tuolumne River; Cherry Creek, a tributary to the Tuolumne River; and Eleanor Creek, a tributary to Cherry Creek. The system supplies water to 2.7 million customers in the San Francisco Bay Area and provides hydropower for San Francisco residents, businesses, and municipal departments. The U.S. Congress authorized the Hetch Hetchy Project via the Raker Act of 1913 (38 Stat. 242), which granted the CCSF rights-of-way to certain public lands within Yosemite National Park and Stanislaus National Forest to develop water and hydropower resources.

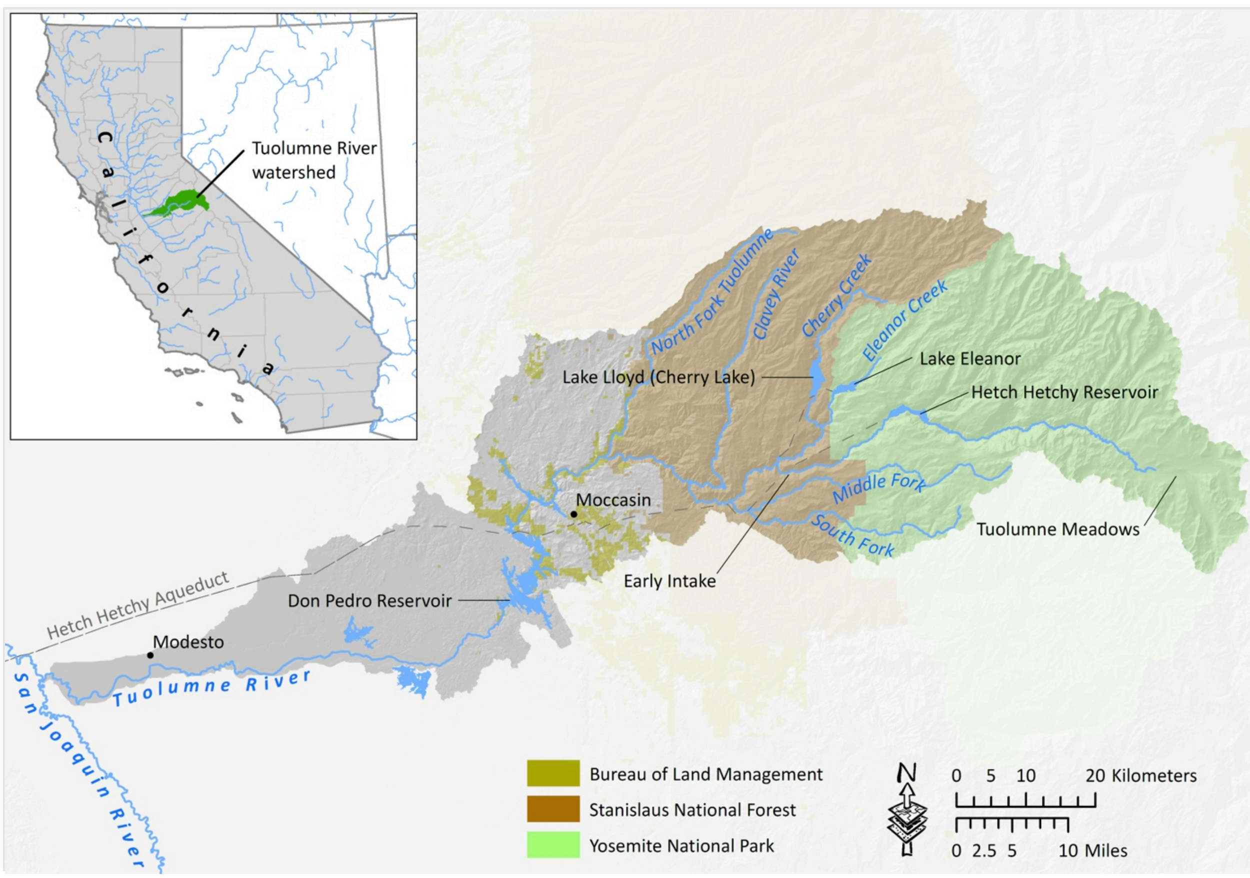

Figure 1. The Tuolumne River watershed and designations of land ownership.

Dams, diversions, and hydropower facilities regulate the passage of water, sediment, and large wood to areas downstream. Because water acts as a "master variable" in river ecosystems (Power et al. 1995, Boltz et al. 2019), the quantity, complexity, and quality of downstream habitats for aquatic and terrestrial species in regulated rivers depend on the timing, frequency, duration, rate of change, and magnitude of water releases from dams, powerhouses, and related facilities. Such water releases tend to vary from the natural flow regime to which native species are adapted and may lead to consequential changes in the riverine environment. To ensure the health of river ecosystems, minimum environmental flow releases from dams and other facilities are often required by regulatory authorities. Through existing agreements with the U.S. Department of the Interior (DOI), the major Hetch Hetchy Project dams are required to provide minimum water releases to downstream areas affected by project operations.

2.1 The Water Enterprise Environmental Stewardship Policy and the Upper Tuolumne River Ecosystem Program

In 2006, the SFPUC adopted the Water Enterprise Environmental Stewardship Policy (Appendix L), which establishes a long-term policy for managing SFPUC-owned lands and natural resources affected by operation of the Hetch Hetchy Project and related components of the SFPUC water system. The policy states that SFPUC environmental flow releases will mimic, to the extent feasible, "…the variation of the seasonal hydrology (e.g., magnitude, timing, duration, and frequency) of their corresponding watersheds in order to sustain the aquatic and riparian ecosystems upon which native fish and wildlife species depend."

After adoption of the Stewardship Policy, the SFPUC initiated the Upper Tuolumne River Ecosystem Program (UTREP) with the goal of conducting long-term, collaborative, science-based investigations designed to (1) describe historical and present-day upper Tuolumne River ecosystem conditions, (2) assess their relationship to Hetch Hetchy Project operations, and (3) develop recommendations for improving river ecosystem conditions. Recommendations developed by UTREP strive to incorporate the concepts described within the Stewardship Policy.

UTREP is led by the SFPUC, in collaboration with the National Park Service (NPS) at Yosemite National Park, the U.S. Fish and Wildlife Service (USFWS), the U.S. Forest Service (USFS) at Stanislaus National Forest, consultants, and academics. Input is provided by the Upper Tuolumne River Workgroup, which is convened twice per year to discuss upper Tuolumne River issues, share information, and provide periodic updates regarding UTREP activities.

The UTREP study area includes portions of the upper Tuolumne River mainstem and major tributaries regulated by the Hetch Hetchy Project. The study area is delineated into seven reaches based on present-day operations and major tributary locations (Figure 2). A more detailed description of the entire UTREP study area is provided in RMC Environmental (RMC) and McBain & Trush (M&T) (2008).

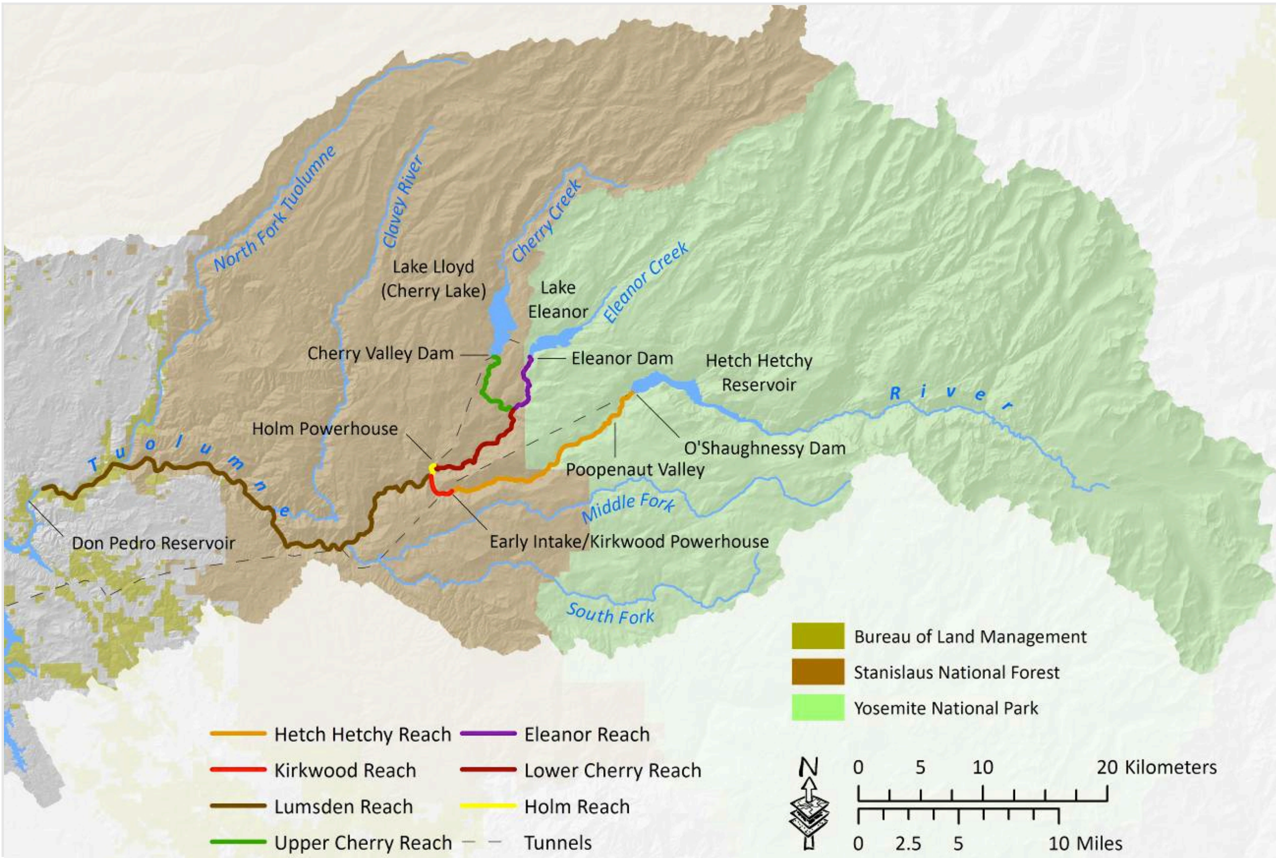

Figure 2. Reaches, land ownership designations, and locations of infrastructure in the UTREP study area.

2.2 The purpose and scope of the Environmental Flow Study

Present-day environmental flow releases from O'Shaughnessy Dam are governed by a series of agreements, known as the 1961, 1985, and 1987 stipulations, between the DOI and the SFPUC under the Raker Act. These agreements specify requirements for baseflow releases, ramping rates, snowmelt spill management, and scientific studies with a focus on maintaining trout fisheries within the Hetch Hetchy Reach. However, unresolved issues remain regarding the implementation of conditions specified in the 1987 Stipulation (see discussion in Section 3.2.3).

The purpose of the Environmental Flow Study (EFS) is to describe environmental flow recommendations and associated analyses developed by the UTREP for the reach of the upper Tuolumne River between O'Shaughnessy Dam (Hetch Hetchy Reservoir) and Kirkwood Powerhouse (near Early Intake), known as the Hetch Hetchy Reach (see Section 3.2). The recommendations are intended to resolve remaining issues associated with implementation of the 1987 Stipulation. The geographic scope of this study (the Hetch Hetchy Reach) was set in reference to the requirements of 1961 and subsequent stipulations (see Section 3.2.3).

Given the geographic focus of existing requirements, this EFS does not examine environmental flow needs downstream of the Hetch Hetchy Reach. In addition, this EFS does not, by itself, assess all potential effects of implementing the recommendations. Such assessments will be the subject of separate environmental reviews. An analysis of anticipated water supply reliability and hydropower effects is provided in Appendix M.

The EFS does not describe the implementation of the recommendations made in this document. Implementation, monitoring and adaptive management will be described in a separate document.

2.3 Overview of approach and goals for the Environmental Flow Study

Previous environmental flow studies for the Hetch Hetchy Reach have focused on (1) productive riffle habitat for Rainbow Trout, Brown Trout (not native to the Hetch Hetchy Reach), and benthic macroinvertebrates (BMI) (USFWS 1976), and (2) Rainbow Trout and Brown Trout physical habitat and suitable water temperatures (USFWS 1992). Given SFPUC policy directives, priorities, and evolving scientific understanding of river ecosystem management, this EFS incorporates a broader view of environmental flow management that includes managing for ecosystem-based objectives, including physical processes (e.g., hydrology and geomorphology), habitats (e.g., aquatic, floodplain, and wetland/wet meadow), native species, and persistence and recovery of state and federally listed species (Foothill Yellow-legged Frogs).

An ecosystem-based approach to dam management balances the allocation of water resources for human needs and ecosystem health (Kennen et al. 2018). Regulated river systems across the globe have benefitted greatly from ecosystem-based management strategies that mimic the natural flow regime (Poff et al. 1997, Palmer and Ruhi 2019). In mimicking key hydrograph components of the natural flow regime, environmental flows can support healthy ecosystems through restoring ecological and geomorphic processes and functions (Yarnell et al. 2020, McBain and Trush, 1997). Some of the benefits arising from ecosystem-based management include the creation of a dynamic habitat that favors native fishes (Radinger et al. 2023), fosters healthy benthic communities, allows bed mobility, and creates floodplain and off-channel connectivity (Bunn and Arthington 2002, Melis et al. 2011, Kiernan et al. 2012).

In support of an ecosystem-based approach, the EFS establishes and evaluates key relationships between geomorphic and ecological processes, habitat, and flow. Estimates of pre-development hydrologic, geomorphic, and biological conditions are used as "reference conditions"[1] to provide guidance in the development of environmental flow recommendations and as context for evaluating estimated outcomes of recommendations (Stoddard et al. 2006). The environmental flow recommendations do not attempt to restore reference conditions, which would imply a return to pre-development conditions, but rather, are intended to mimic the pattern and functionality of selected components of the reference condition under which native species evolved to the greatest extent possible given other constraints (Poff et al. 1997, Ligon et al. 1995, Lytle and Poff 2004). This approach was used within the context of balancing and maintaining values that include supporting water supply reliability, hydropower generation, productive native trout fisheries, and conservation of special status species.

Given the policy priorities described in Sections 2.1 and 2.2 and the general approach described above, the goal of the EFS was to develop recommendations that:

- Mimic the functions of natural year-to-year hydrologic variation, where wetter, normal, and drier water years support a range of physical processes, habitats, and species, recognizing that not all

[1] The watershed above Hetch Hetchy Reservoir remains in a relatively unimpaired state, with no significant diversions, and therefore inflows to Hetch Hetchy Reservoir are referred to as "unimpaired" in this EFS. However, pre-dam or unimpaired conditions (flow, water temperatures, etc.) downstream of Hetch Hetchy Reservoir are referred to as "reference conditions," since these are conditions that no longer exist but provide a useful estimate of pre-dam natural conditions that can be used as context for analyses and outcomes described in this EFS. Importantly, historical reference conditions did not always provide ideal conditions for native species, but provided the conditions that shaped their evolutionary trajectory and are therefore useful benchmarks in the context of future management of altered ecosystems.

years can provide ideal conditions for all species, but that biological diversity and ecosystem function benefit from this variability (Poff et al. 1997, Palmer and Ruhi 2019)

- Mimic the functions of natural hydrologic variation within a single water year, where spring and early summer exhibit high flows and fall and early winter exhibit lower baseflows
- Support productive native species populations and conservation of special status species
- Maintain water supply reliability and existing hydropower generation capacity

The goals above are further described as specific ecological goals and objectives in Section 5.

A reference flow scenario was developed as part of the reference conditions. The reference flow scenario was based on computed inflows to the Hetch Hetchy reservoir and is used throughout the EFS (Appendix J).

2.4 Note for the reader

This EFS assumes familiarity with concepts and terminology in biology, ecology, and physical sciences as they relate to river management. The main body of this EFS is intended to provide background, a summary of analyses, and a description of environmental flow recommendations for the Hetch Hetchy Reach. In-depth, technical descriptions of methods and results are provided in a series of appendices. English units are commonly used for ease of comparison with earlier work and in keeping with units typically used in the field. Metric units are sometimes also presented for metrics or disciplines that predominantly use those units. Locations along the river corridor are given in “river miles” (RM), measured as the distance upstream from the confluence of the Tuolumne River and the San Joaquin River to a point of interest. More fine-scale locations are given in “stationing,” a similar measure to RM, but delineated in foot-long increments from the upstream extent of Don Pedro Reservoir to O’Shaughnessy Dam.

3 Background

The Tuolumne River drains a 1,958-square-mile (mi^2) watershed (Figure 1) on the western slope of the Sierra Nevada range and is the largest of three major tributaries to the San Joaquin River. Originating in headwater streams on the slopes of Mount Lyell and Mount Dana in the high country of Yosemite National Park, the Tuolumne River flows approximately 130 miles (mi) southwest to its confluence with the San Joaquin River, approximately 10 mi west of the city of Modesto. At higher elevations, the watershed is comprised of exposed granitic bedrock scoured by glaciers during the Tioga (ca. 20,000 years ago) and earlier glacial periods, resulting in mountainous terrain, patchy forests, and a variety of steep canyons and mountain meadows (Wahrhaftig et al. 2019). The middle elevations of the watershed from Early Intake to Don Pedro Reservoir are characterized by deep bedrock canyons and forested terrain, while lower elevations downstream of Don Pedro Reservoir have well-developed soils and are primarily developed agricultural lands.

From Tuolumne Meadows (elevation 8,600 feet [ft]), the river descends rapidly through the Grand Canyon of the Tuolumne, a deep canyon in the Yosemite National Park Wilderness, to Hetch Hetchy Reservoir (elevation 3,812 ft). Six mi downstream of O’Shaughnessy Dam, which impounds Hetch Hetchy Reservoir, the Tuolumne River leaves Yosemite National Park and enters the Stanislaus National Forest. Except for a short reach at Early Intake Reservoir (elevation 2,356 ft), the mainstem river flows unimpeded through a deep canyon for approximately 40 mi, from O’Shaughnessy Dam to the upstream end of Don Pedro Reservoir (elevation 500 ft). Several major tributaries, including Cherry Creek, the Clavey River, the North Fork of the Tuolumne, and the South Fork of the Tuolumne, join the mainstem river between Early Intake and Don Pedro Reservoir. Downstream of Don Pedro Reservoir, the river exits the Sierra Nevada foothills into the Central Valley, flowing through a gently sloping alluvial valley incised into Pleistocene alluvial fans.

Runoff in the Tuolumne River watershed is produced by rainfall and snowmelt. Like most west-slope Sierra Nevada rivers, the Tuolumne exhibits significant seasonal snowmelt runoff during the spring and early summer, with occasional rainstorm-generated peak flows and infrequent, larger rain-on-snow floods. Overall, the hydrology of the Tuolumne River watershed is characteristic of a mountainous Mediterranean-type climate, with most precipitation and runoff occurring in the winter and spring months, followed by a dry summer and fall period. The 1924–2021 average annual precipitation at the Hetch Hetchy rain gage at O’Shaughnessy Dam is 35.2 inches (minimum 14.4 inches, maximum 73.2 inches). Annual runoff in the Tuolumne River basin is highly variable; for example, 1924–2021 unimpaired inflows were estimated to yield an average of 763,673 acre-feet (ac-ft) to Hetch Hetchy Reservoir but varied over an order of magnitude from 201,240 ac-ft to 2,050,046 ac-ft (28% to 220% of the average). Approximately 70–80% of annual inflow occurs between April and August during the snowmelt runoff period. Detailed hydrology is available in RMC and M&T (2007).

3.1 The Hetch Hetchy Project

The Hetch Hetchy Project is a complex system of water storage dams and reservoirs, diversion dams, regulating reservoirs, powerhouses, tunnels, and pipelines operated to generate hydropower and deliver water supply to the San Francisco Bay Area. The Hetch Hetchy Project was authorized by the Raker Act, which was passed by the U.S. Congress in 1913 and granted the CCSF rights-of-way to certain public lands within Yosemite National Park and Stanislaus National Forest to develop water and hydropower resources. The Hetch Hetchy Project retains a statutory exemption from the Federal Power Act (16 U.S.C. § 823), and thus hydropower operations, including environmental flow releases, are not subject to Federal Energy Regulatory Commission jurisdiction.

The Hetch Hetchy Project includes three major dams and associated reservoirs: O'Shaughnessy Dam, which impounds Hetch Hetchy Reservoir on the mainstem Tuolumne River; Cherry Valley Dam, forming Cherry Lake on Cherry Creek; and Eleanor Dam, forming Lake Eleanor on Eleanor Creek (Figure 3). Eleanor Dam, completed in 1918, enlarged the natural Lake Eleanor and was the first Hetch Hetchy Project dam constructed. Water from Lake Eleanor was diverted via the Lower Cherry Diversion Dam and Aqueduct to Early Intake Powerhouse, which generated electricity for the construction of O'Shaughnessy Dam. O'Shaughnessy Dam was subsequently completed in 1923 and enlarged in 1938, increasing the storage capacity of Hetch Hetchy Reservoir from 260,000 ac-ft to 360,360 ac-ft. Mountain Tunnel was completed in 1925; the tunnel transfers water from Early Intake to Moccasin.

Cherry Valley Dam was completed in 1955, with the remainder of the Cherry/Eleanor facilities, including Cherry Power Tunnel, Eleanor-Cherry Diversion Tunnel, and Holm Powerhouse, completed by the early 1960s. The Cherry/Eleanor portion of the system was designed to divert water from Cherry Valley Dam via Cherry Power Tunnel to Holm Powerhouse, located near the confluence of Cherry Creek and the Tuolumne River. Cherry Lake and Lake Eleanor are connected via the Cherry-Eleanor Tunnel.

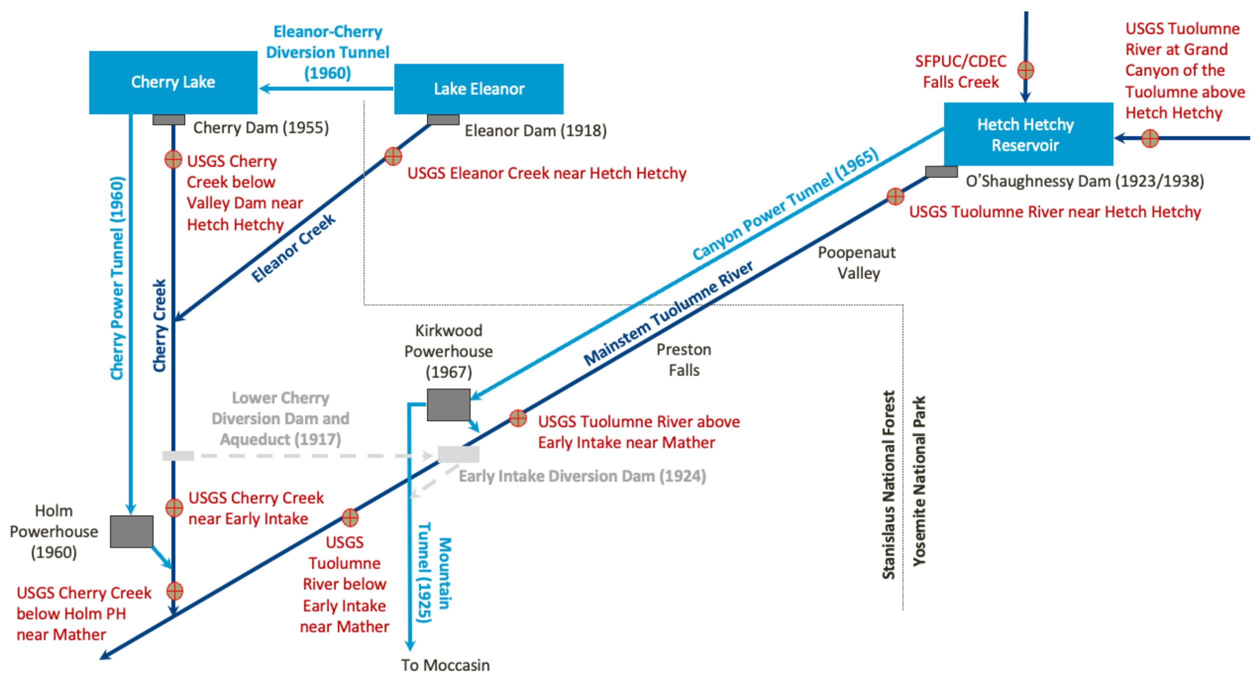

Figure 3. Schematic of major present-day Hetch Hetchy Project infrastructure (completion dates in parentheses). Nearby gaging stations are shown in red and are operated by either the SFPUC or the U.S. Geological Survey (USGS). SFPUC gage data are available from the California Data Exchange Center (CDEC). Existing infrastructure not regularly used in day-to-day water supply and power operations is indicated in light gray.

Prior to completion of Canyon Power Tunnel, water stored at O'Shaughnessy Dam was released into the Hetch Hetchy Reach (approximately 700–800 cubic feet per second [cfs] year-round) and diverted at Early Intake Diversion Dam into Mountain Tunnel. In the mid-1960s, Canyon Power Tunnel and Kirkwood

Powerhouse were completed along the mainstem Tuolumne River, and diversions via Canyon Power Tunnel from O'Shaughnessy Dam to Kirkwood Powerhouse began in 1967. With the construction of Kirkwood Powerhouse, Early Intake Powerhouse was decommissioned. The installation of an additional generator at Kirkwood Powerhouse in 1988 increased the maximum diversion capacity of the powerhouse. With the completion of Canyon Power Tunnel and Kirkwood Powerhouse, direct diversions from the river into Mountain Tunnel at Early Intake ceased, and diversions now flow directly from O'Shaughnessy Dam through Canyon Power Tunnel into Mountain Tunnel, bypassing the Hetch Hetchy Reach. Once in Mountain Tunnel, water continues to Moccasin Powerhouse before it enters the conveyance system to the San Francisco Bay Area.

The Hetch Hetchy Project is part of a broader water system owned and operated by the SFPUC, known as the Regional Water System, that primarily serves water to customers in the San Francisco Bay Area. The Regional Water System is operated under a "Water First Policy"[2] that prioritizes municipal water supply reliability over hydropower generation. Water stored in Hetch Hetchy Reservoir is used for municipal water supply and hydropower generation. Cherry Lake and Lake Eleanor are primarily used for power generation, meeting downstream water rights obligations and summertime recreational releases. If necessary, during emergency or drought conditions, water from Cherry Lake and Lake Eleanor can be released to Cherry Creek, then diverted at the Lower Cherry Diversion Dam to Early Intake and Mountain Tunnel for transport to the Bay Area. Detailed descriptions of the Hetch Hetchy Project and the evolution of project infrastructure can be found in RMC and M&T (2006), SFPUC (2005), and San Francisco Planning Department (2008).

3.2 Hetch Hetchy Reach overview

In the Hetch Hetchy Reach (Figure 4), the Tuolumne River is mostly confined by steep valley walls, flowing for approximately 12 mi through a U-shaped glaciated valley (Huber 2004). The elevation of the reach ranges from 2,350 ft at Early Intake to 3,650 ft at the base of O'Shaughnessy Dam. While the average channel gradient in the Hetch Hetchy Reach is steep (almost 2%), subreach-scale variation in channel gradient and valley confinement results in a diverse set of channel morphologies, ranging from the low-gradient, sand/gravel-bedded channel and broad meadows and wetlands of Poopenaut Valley, to the steep, bedrock-confined Tuolumne River Gorge, to the short, low-gradient confined reaches below Preston Falls (Figure 5 and Figure 6). In most of the Hetch Hetchy Reach, there is extensive bedrock control on the bed and banks, and mobile alluvial deposits (gravels and small boulders) are limited to small or medium-sized patches associated with flow obstructions (such as boulders and bedrock outcrops). While upper valley walls adjacent to the Hetch Hetchy Reach receive some snowfall, precipitation downstream of O'Shaughnessy Dam falls primarily as rain, with a large snowpack forming annually in the Tuolumne River headwaters upstream of the dam.

Five generalized subreaches (Figure 4) within the Hetch Hetchy Reach have been delineated (USFWS 1992). The subreach delineations are based on general stream channel configuration, aquatic habitat types, overall gradient, and fish population assemblage.[3] A longitudinal profile for the Hetch Hetchy Reach with subreach delineations and a set of representative slopes is provided in Figure 6. The five generalized subreaches are as follows:

[2] The "Water First Policy" is codified in California Water Code Section 73504[b], the San Francisco Charter, and the SFPUC's Water Supply Agreement with its wholesale water customers.
[3] Subreach boundaries were standardized for use in UTREP studies of the Hetch Hetchy Reach; however, some previous USFWS studies varied in their delineation of subreach boundaries. See Appendix B for more information on earlier variations in subreach delineations.

- *O'Shaughnessy Subreach* — O'Shaughnessy Dam to the upstream end of Poopenaut Valley (RM 117.5 to 115.3). This subreach is dominated by bedrock pools and relatively coarse bed material. The USGS Tuolumne River near Hetch Hetchy gage (USGS 11-276500) is located in this subreach, approximately 0.9 mi downstream of O'Shaughnessy Dam. Water temperatures are generally cooler in this subreach in the summer due to cold, hypolimnetic releases from O'Shaughnessy Dam.
- *Poopenaut Valley Subreach* — Upstream end of Poopenaut Valley to upstream end of the Tuolumne River Gorge (RM 115.3 to 114.3). Poopenaut Valley (Figure 7) supports a relatively large wetland system that is hydrologically complex. Runs and glides with sand and fine gravel substrates dominate this subreach, which has the lowest gradient within the Hetch Hetchy Reach. The narrow Tuolumne River Gorge just downstream of this reach causes a pronounced "backwater" effect, rapidly increasing stage in the valley with minor increases in release from O'Shaughnessy Dam. A unique off-channel pond in the northern portion of the Poopenaut Valley, hereafter referred to as the "North Pond", is formed by a natural river levee and backfills via a tributary connected to the mainstem Tuolumne River during high flows. The pond also receives water from local slope runoff and direct water from precipitation, although it rarely fills from these sources alone.
- *Gorge Subreach* — Downstream end of Poopenaut Valley to just upstream of the Preston Falls area (RM 114.3 to 110.3). The Gorge Subreach is the steepest section in the Hetch Hetchy Reach, strewn with large boulders of rockfall origin and confined by vertical granite walls for much of its length. Deep pools and boulder gardens dominate the subreach, with coarse cobble, gravel, and boulder substrates. The Gorge Subreach is remote and difficult to survey, with no direct trail or road access.
- *Preston Falls Subreach* — Upstream of Preston Falls to the upstream end of the Early Intake Subreach (RM 110.3 to 108.0). The Preston Falls Subreach is dominated by deep bedrock pools and boulder gardens, with two relatively flat meadow areas. Pools contain fine sandy substrate.
- *Early Intake Subreach* — Lower Preston Falls area to Kirkwood Powerhouse (RM 108.0 to 105.4). The Early Intake Subreach is dominated by deep bedrock pools and boulder gardens with occasional cobble bars and sandy backwater areas. The USGS Tuolumne River above Early Intake gage (USGS 11-276600) is located in this subreach, approximately 0.5 mi upstream of Kirkwood Powerhouse.

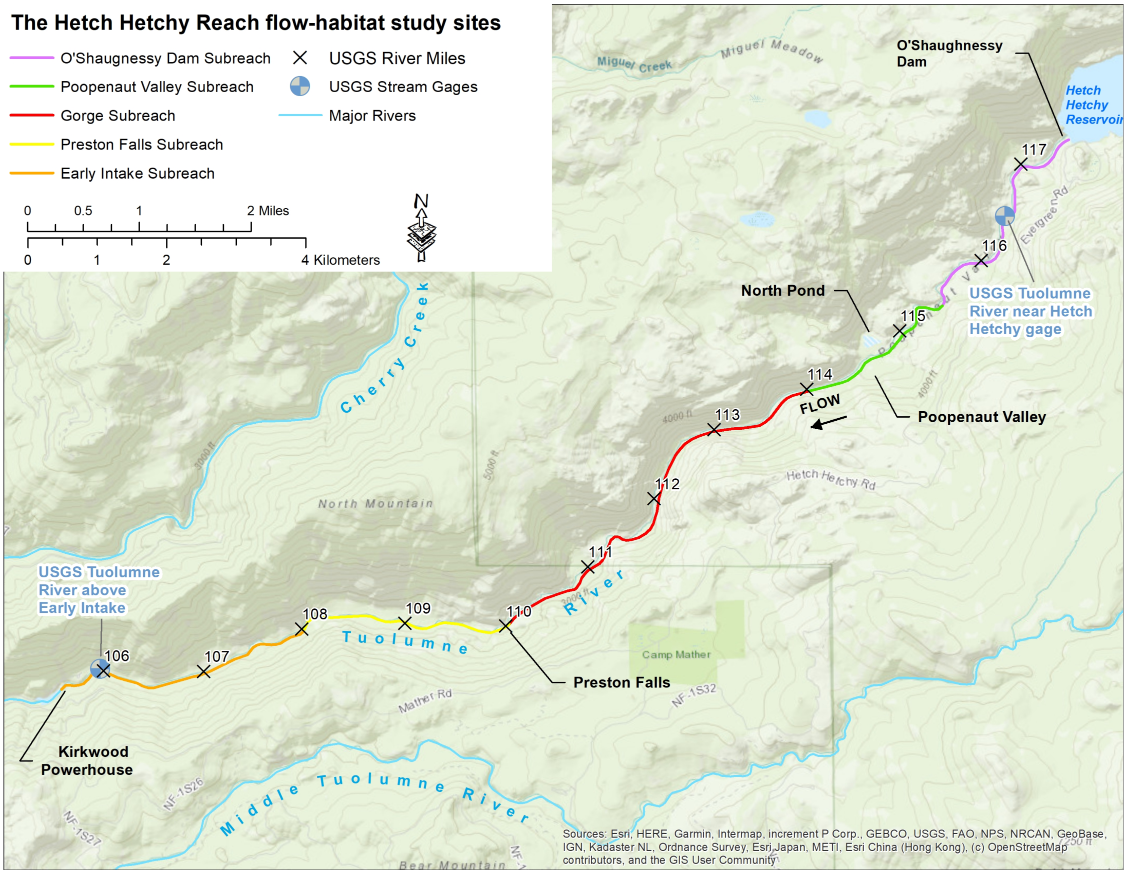

Figure 4. Hetch Hetchy Reach features and subreach boundaries.

Figure 5. Examples of Hetch Hetchy Reach riverine habitats: (A) riffle and pool in the O'Shaughnessy Subreach, (B) sand/gravel-bedded low-gradient run in the Poopenaut Valley Subreach, (C) bedrock-confined high-gradient habitat in the Gorge Subreach, and (D) riffle habitat in the Early Intake Subreach.

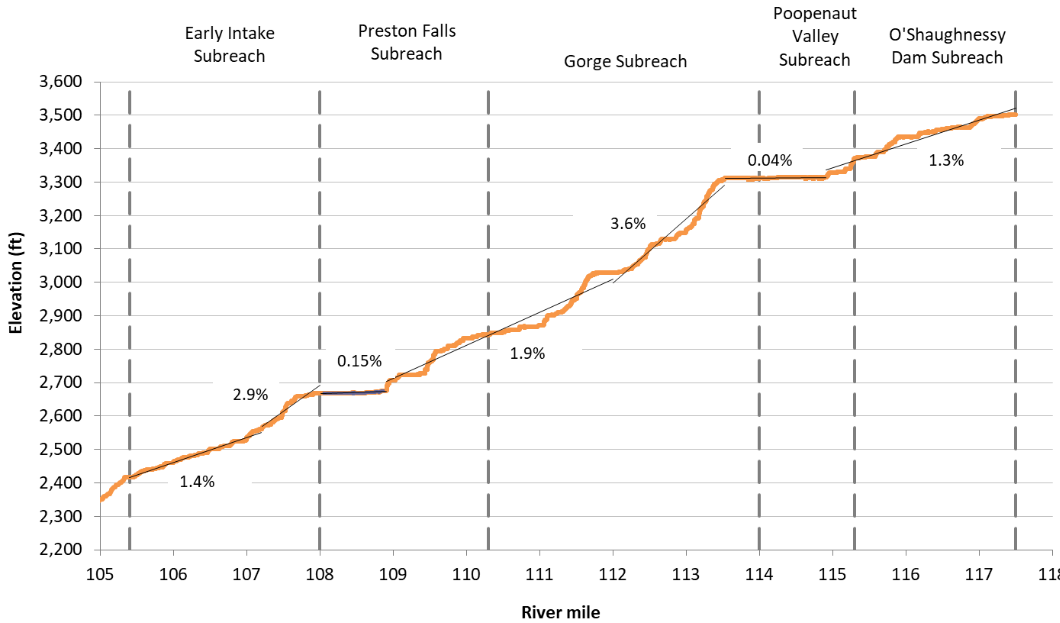

Figure 6. Longitudinal profile of the Hetch Hetchy Reach, illustrating subreach boundaries (dotted vertical lines) and average percent slope for indicated segments.

Figure 7. Oblique photo of Poopenaut Valley looking downstream toward the Gorge Subreach during an experimental release of approximately 7,400 cfs from O'Shaughnessy Dam. The photo shows wetland

areas, the hydrologic connection between the North Pond and the mainstem Tuolumne River, the North Pond, south bank tributaries, and the upstream entrance to the Gorge Subreach.

3.2.1 Present-day O'Shaughnessy Dam and Hetch Hetchy Reservoir operations

In keeping with the Water First Policy, Hetch Hetchy Project operations since 1993 have prioritized water supply reliability over hydropower generation. The primary objective of Hetch Hetchy Reservoir operations is to maximize the volume of water stored in the reservoir by July 1 of every year (referred to as "carryover storage"). The maximum storage capacity of Hetch Hetchy Reservoir is relatively small (360,360 ac-ft) when compared to the 1993–2021 computed average annual unimpaired inflow (762,168 ac-ft) and the average annual Canyon Power Tunnel diversions (467,402 ac-ft). The relatively small reservoir size results in the quantity of inflow exceeding the volume that can be stored or used to generate hydropower during the snowmelt runoff season, producing spring and early summer spills in most years.

Water is diverted or released from Hetch Hetchy Reservoir via the following facilities (Figure 8 and Figure 9):

- *O'Shaughnessy Dam "face valves"* — A series of eight valves (six 60-in and two 72-in valves) are located on the face of O'Shaughnessy Dam. These valves are the mechanism for releasing large volumes of water from Hetch Hetchy Reservoir. The volume of water that can be released increases with reservoir water surface elevation and the maximum flow rating varies for each valve depending on centerline elevation of each valve. Maximum combined face valve releases are approximately 8,000 cfs when reservoir storage is near 286,000 ac-ft (elevation 3,767 ft).
- *O'Shaughnessy Dam "environmental release valves"* — Two additional valves are located immediately downstream of O'Shaughnessy Dam in a separate valve house and draw water from Canyon Power Tunnel. Each valve has a nominal rating of 300 cfs. The valves provide more precise flow release magnitudes than the face valves, and thus are primarily used to maintain required minimum environmental flow releases, particularly during the summer, fall, and winter when spills are less frequent.
- *O'Shaughnessy Dam drum gates and spillway* — Three 65-ft wide drum gates control releases from the reservoir surface into the spillway. The design capacity of the spillway is approximately 45,000 cfs in order to safely pass extreme storm events. Operational releases over the drum gates are typically limited to approximately 2,500 cfs. Drum gate and spillway operations are further described below.
- *Canyon Power Tunnel and Kirkwood Powerhouse* — Water is diverted from Hetch Hetchy Reservoir for water supply and hydropower generation via Canyon Power Tunnel, which bypasses the Hetch Hetchy Reach and terminates at the Canyon Portal Valve House near Kirkwood Powerhouse. The tunnel can be supplied by two outlets (with slide gates) from O'Shaughnessy Dam: the 108-in main outlet and a 60-in auxiliary outlet. Water supply diversions are bypassed through Kirkwood Powerhouse and flow directly into Mountain Tunnel, continuing to Moccasin and the San Francisco Bay Area. Hydropower generation (known operationally as "power draft") at Kirkwood Powerhouse is incidental to water supply diversions during most of the year. During the snowmelt runoff period, however, inflows in excess of water supply needs and storage capacity are diverted for additional hydropower generation, which increases overall generation and reduces spill volumes released via face valves or the drum gates.

Summer, fall, and winter operations typically involve managing releases via the environmental release valves, with larger but infrequent releases from face valves for reservoir management during large winter storms or, in extremely rare cases, rain-on-snow events. In late winter or early spring during wetter years, the SFPUC increases available storage in Hetch Hetchy Reservoir to accommodate and manage snowmelt inflows by (1) increasing power draft, and (2) if needed, making "pre-releases" (spills) to the Tuolumne River via O'Shaughnessy Dam face valves. These operations vary depending on the available storage, real-time inflow pattern, and forecasted snowmelt runoff. As the snowmelt season progresses and inflow forecasts become more certain, power draft and face valve releases are adjusted accordingly to control reservoir elevation and maintain available storage space based on the remaining volume of forecasted inflow.

During peak runoff or shortly thereafter (typically in May or June), power draft and/or spill releases are managed to slowly fill Hetch Hetchy Reservoir. Once Hetch Hetchy Reservoir has filled, peak runoff has passed, and the snowmelt recession has begun, operations since 2009 have used the drum gates and spillway in wetter years to release a maximum of 2,000 to 3,000 cfs of snowmelt spill until the end of the significant inflow. Drum gate operations reduce the need for repeated face valve adjustments during the snowmelt runoff recession. During this period, drum gate releases are maintained by occasionally reducing valve releases, which allows the total release rate to recede in proportion to the snowmelt recession inflow pattern. As inflows recede below spill levels, power draft is gradually reduced to municipal water supply diversion levels, and eventually additional power draft and drum gate releases cease, leaving Hetch Hetchy Reservoir at full storage capacity by the end of snowmelt runoff in most years. The reservoir water surface elevation then declines over summer and fall as diversions and environmetal flow releases exceed unimpaired inflow to the reservoir. See San Francisco Planning Department (2008) for additional details regarding O'Shaughnessy Dam and Hetch Hetchy Reservoir operations.

Figure 8. Aerial view of O'Shaughnessy Dam water diversion and release facilities.

Figure 9. Selected project features in the Hetch Hetchy Reach: O'Shaughnessy Dam face valves (left photo); drum gates (top right photo); looking upstream at Kirkwood Powerhouse with the Tuolumne River to the far right (bottom right photo).

3.2.2 Changes in physical processes

Dams initiate fundamental changes in basic physical processes that govern river ecosystems, including hydrology, sediment transport, water temperature, large wood transport, and other interrelated aspects of the physical riverine environment (Ligon et al. 1995, Poff & Hart 2002). These physical processes directly affect habitat, food, and other resources that biota depend on within a river ecosystem, and thus are important to consider in developing future environmental flow releases. Several UTREP studies (see Section 5.1) focused on estimating changes in physical processes due to flow regulation by O'Shaughnessy Dam.

3.2.2.1 Hydrology

The influence of O'Shaughnessy Dam operations on the Tuolumne River ecosystem is best illustrated by examining changes in hydrology between reference and existing conditions, which drives numerous physical and biological processes. The reference conditions hydrology (developed from pre-dam conditions and computed inflows to Hetch Hetchy Reservoir) of the upper Tuolumne River in the Hetch Hetchy Reach is typical of the spring snowmelt regime of most Sierra Nevada rivers, and is characterized by distinct "hydrograph components" (Figure 10, Table 1). Each of these annual flow patterns has important geomorphic and biological functions (McBain and Trush 2004).

Specifically, the snowmelt runoff period (typically April through August) produces the bulk of inflows (typically 70–75%) to Hetch Hetchy Reservoir. RMC and M&T (2007) provide descriptions of the snowmelt hydrograph components for the Hetch Hetchy Reach. A detailed review of the known linkages between hydrograph components and river ecosystem function is available in recent works, including RMC and M&T (2007), Yarnell et al. (2016), Kupferburg et al. (2012), McBain and Trush (2007), and Yarnell et al. (2020) for more in-depth descriptions.

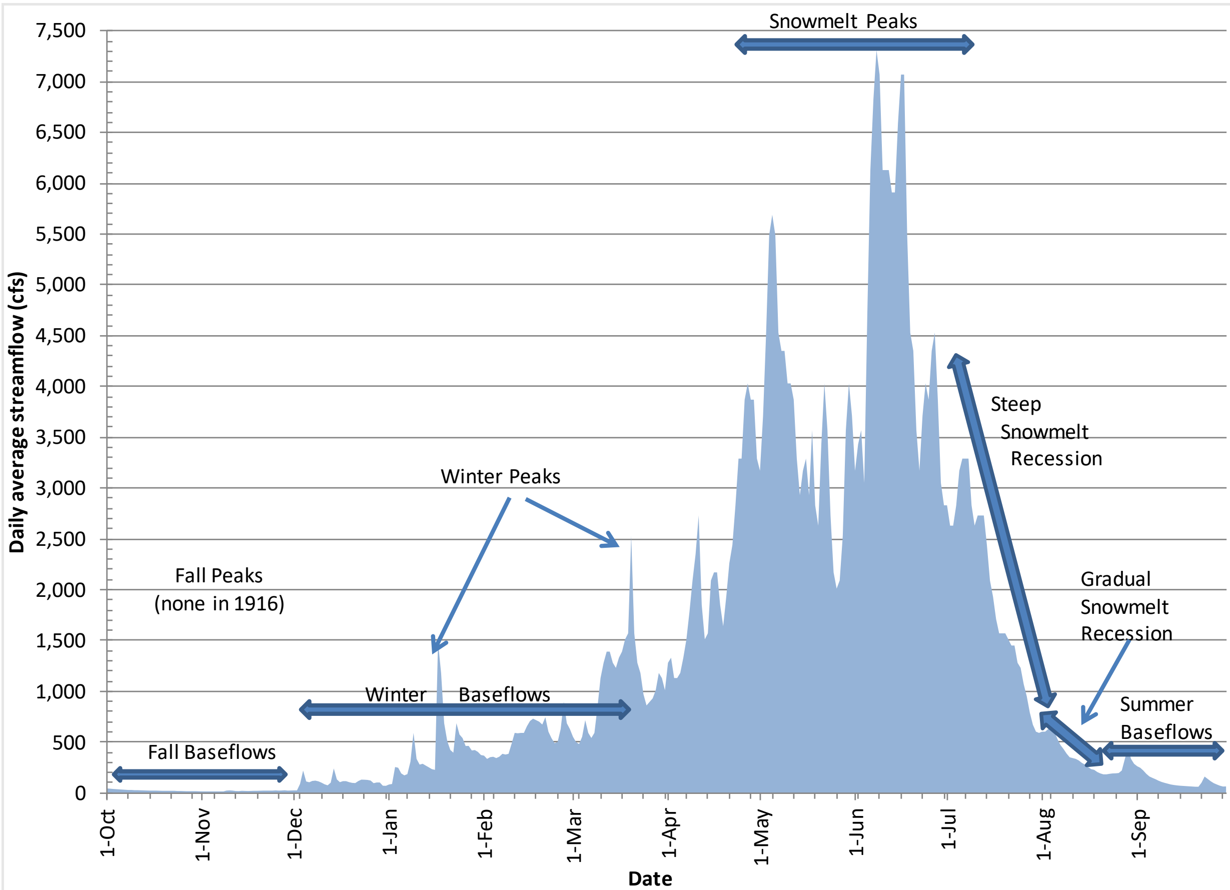

Figure 10. An example of reference condition daily average streamflow hydrograph in the Hetch Hetchy Reach before O'Shaughnessy Dam construction and related hydrograph components at the Tuolumne River near Hetch Hetchy gage (USGS 11-276500) for Water Year (WY) 1916 (an Extremely Wet water year).

Table 1. *Summary of hydrograph components from 1970–2021 reference condition flows. Reference condition flows in Table 1 are computed from Hetch Hetchy inflows (Appendix J)*

	Water year classification and frequency (%)				
	Extremely Wet	Wet	Normal	Dry	Extremely Dry
	15%	20%	30%	20%	15%
Number of Water Years	12	8	15	4	13
Average Daily Flow (cfs)	1,859	1,323	986	697	493
Average Annual Yield (ac-ft)	1,352,775	950,927	700,613	484,305	346,604
Maximum Annual Yield (ac-ft)	1,762,772	1,073,748	828,389	501,039	419,966
Minimum Annual Yield (ac-ft)	1,132,260	842,001	570,234	477,412	209,427
HYDROGRAPH COMPONENT					
Fall Baseflows (October 1 - November 30)					
Median (cfs)	245	118	86	60	78
Minimum (cfs)	25	25	24	25	19
Maximum (cfs)	661	424	303	102	310
Fall Peaks (October 1 - November 30)					
Average Peak Magnitude (cfs)	2681	1851	1304	170	571
Median Peak Magnitude (cfs)	1524	512	1078	134	294
Minimum Peak Flow (cfs)	218	101	108	37	51
Maximum Peak Flow (cfs)	9273	8692	4718	373	3426
Winter Baseflows (December 1 - March 31)					
Median Baseflow (cfs)	651	474	377	190	162
Minimum Baseflow (cfs)	571	377	260	32	37
Maximum Baseflow(cfs)	1013	653	636	367	371
Winter Peaks (December 1 - March 31)					
Average Peak Magnitude (cfs)	8798	2868	2691	2639	993
Median Peak Magnitude (cfs)	6316	2634	2368	2699	783
Minimum Peak (cfs)	1800	1283	701	1025	329
Maximum Peak(cfs)	37685	5541	5630	4133	2498
Snowmelt Peaks (April 1 - July 15)					
Average Peak Magnitude (cfs)	10885	9675	7394	5260	3623
Median Peak Magnitude (cfs)	11071	9172	6401	5314	3602
Minimum Peak (cfs)	7788	7120	4357	4180	1836
Maximum Peak (cfs)	13198	15319	13548	6229	4854
Median Date of Peak	13-Jun	29-May	23-May	6-May	14-May
Earliest Peak	12-Apr	16-May	8-Apr	1-May	25-Apr
Latest Peak	9-Jul	6/137/2022	13-Jun	5-Jun	10-Jun
Summer Baseflows (August 15 - September 30)					
Baseflow Median (cfs)	236	110	65	44	37
Minimum Baseflow (cfs)	93	59	35	38	17
Maximum Baseflow (cfs)	616	170	134	91	112

O'Shaughnessy Dam has altered the natural hydrograph components of the Tuolumne River, as is typical in stream reaches below dams. High-magnitude and long-duration snowmelt season spills still occur during late winter and spring, resembling the shape and timing of reference condition winter peak flood and snowmelt hydrographs, but at a lower duration, frequency, and magnitude (RMC and M&T 2007) and typically only in wetter water year types. Operational releases typically differ from the natural hydrology (Figure 11) and have changed the hydrograph components and associated physical and biological processes in the following ways:

- Winter floods have been eliminated in almost all years (except in some Extremely Wet years), and winter maximum daily average flow values are typically only slightly higher than, or equivalent to, winter baseflows. Winter floods—particularly large "rain-on-snow" events that are infrequent but among the largest floods on record—can perform significant geomorphic work (i.e., sediment transport), effectively scour periphyton, and may play a role in maintaining younger stands of woody riparian vegetation.
- The ascending limb of the snowmelt hydrograph tends to have a faster increase in flow magnitude (upramping rate), increasing from a baseflow release to a much higher release between mid-May and late May.
- Snowmelt peak flow magnitudes have been reduced by 20% to 50% in Extremely Wet to Normal years and have been eliminated in Dry and Extremely Dry years. Under both pre-dam and present-day conditions, the snowmelt runoff season represents the period during which annual peak flows typically occur. Flood frequency has decreased by nearly 50% (Q 1.5) over time as Hetch Hetchy Project infrastructure has developed (Figure 12). Peak flows drive processes important for maintaining habitat, including sediment transport, periphyton scour (Power et al. 2008, Holmquist and Schmidt-Gengenbach 2012), and Poopenaut Valley wetland inundation. Changes in snowmelt peak magnitude and flood frequency directly affect these processes and habitats by reducing sediment transport capacity and wetland inundation frequency, which may lead to the loss of ecologically important wetland area.
- The snowmelt recession limb is typically shorter and reaches the minimum streamflow release earlier. The rate of change in flow magnitude (downramping) during the recession is often faster than reference conditions, particularly under existing downramping rates (Appendix H) (see Section 8.1). The recession limb is significantly shortened in both duration and magnitude in drier years. Combined with the reduced magnitude of snowmelt flows, reduced flow duration shortens the time that wetlands are inundated. The snowmelt recession also plays a well-documented role (see section 3.2.4.6) in the reproductive life cycles of river-dependent species, including Foothill Yellow-legged Frog breeding success and egg mass survival, BMI distribution and drift rates, woody riparian plant species establishment, and native fish rearing.
- Summer and fall baseflows (August 15 to September 30) are typically higher than reference condition flows due to existing environmental flow release requirements under the 1985 Stipulation, which are intended to improve summer and fall thermal conditions for trout. Summer and fall baseflows play an important role in recruitment of native fish, amphibians, turtles, and woody riparian vegetation (described in the following section 3.2.4).

- In some Dry and Extremely Dry years, there are no significant snowmelt spill releases (Figure 11). Since the Water First Policy was implemented in 1993, spills are more frequent than prior to the Water First Policy due to relatively higher carryover storage.

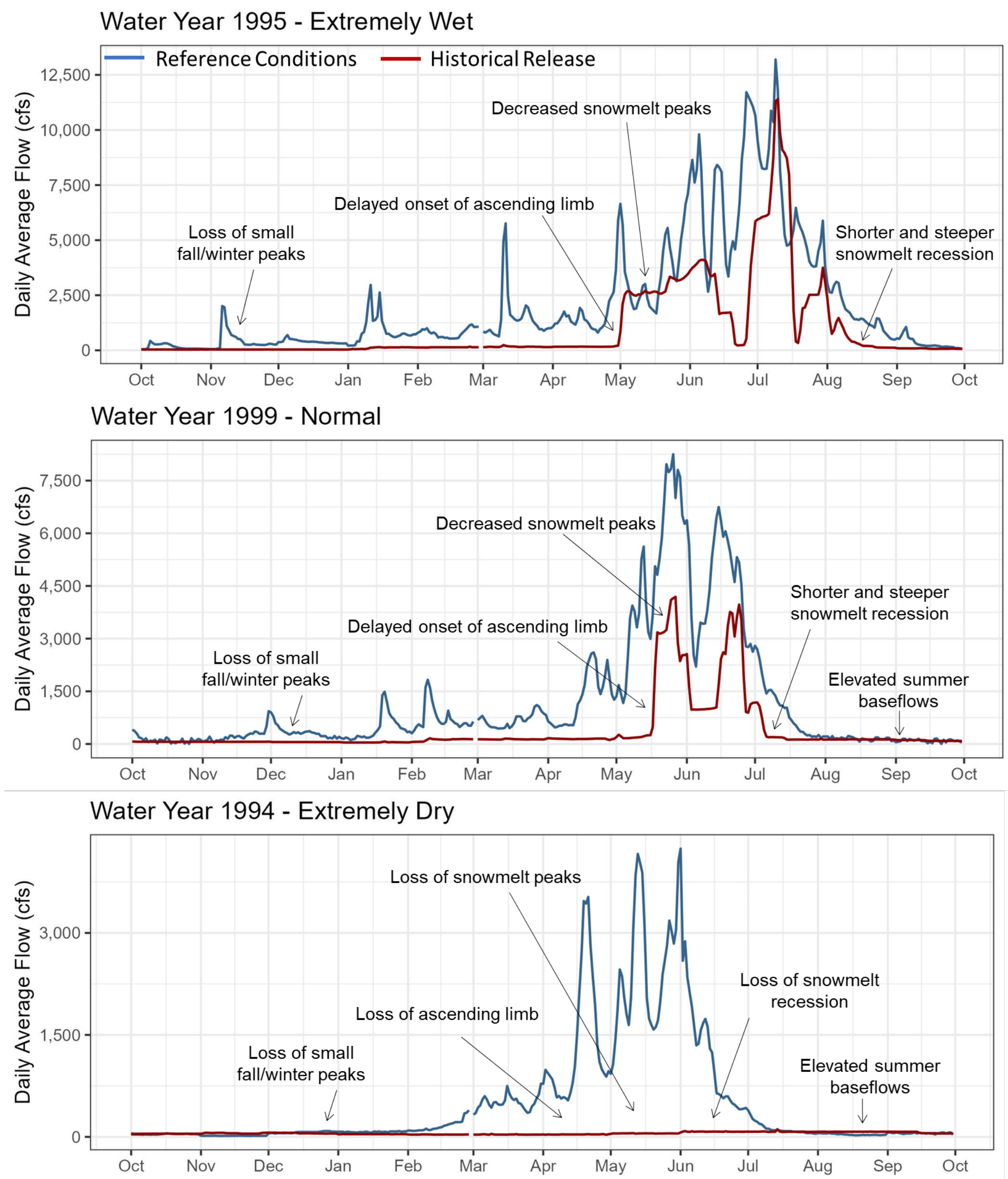

Figure 11. An example of reference conditions flows (developed from computed reservoir inflows) and observed daily average streamflow in the Hetch Hetchy Reach and related changes in hydrograph components at the Tuolumne River near Hetch Hetchy gage (USGS 11-276500) for WY 1995 (Extremely Wet), WY 1999 (Normal), and WY 1994 (Extremely Dry).

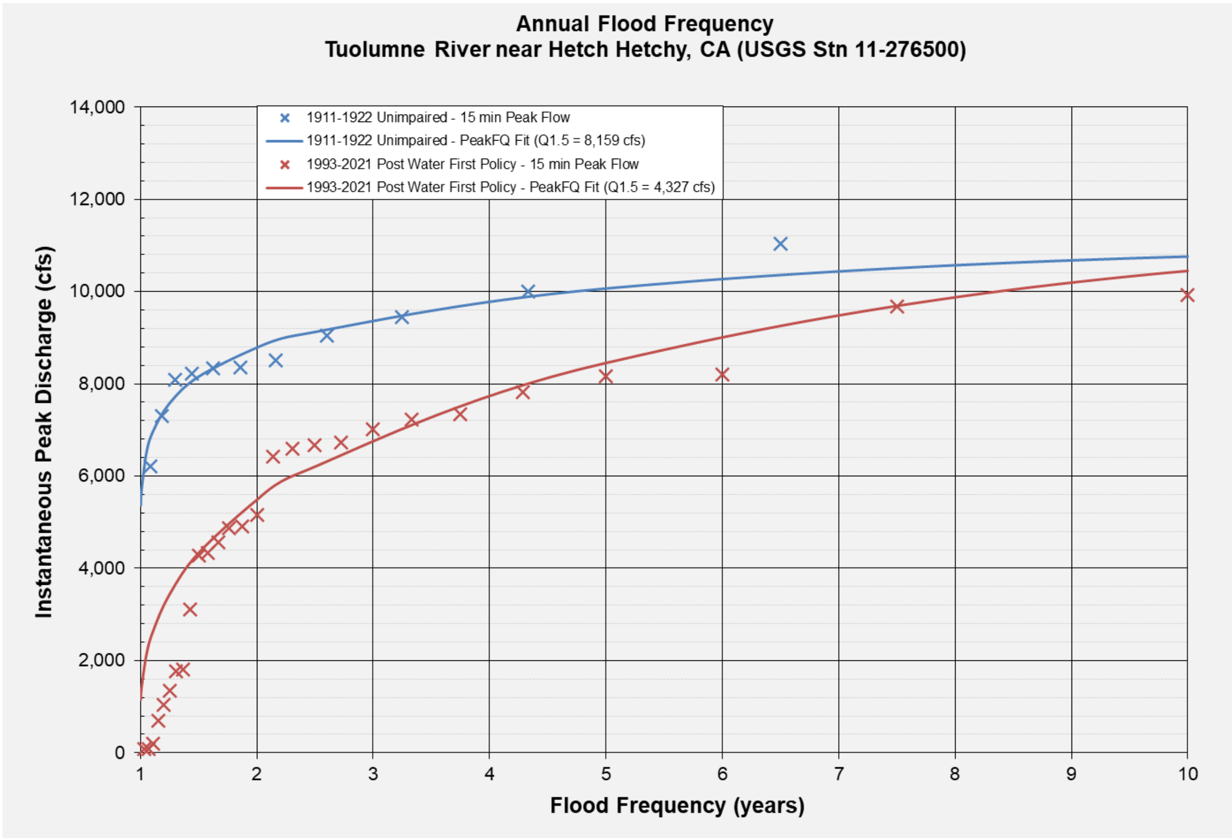

Figure 12. Changes in annual flood frequency (including winter floods and spring snowmelt peak flows) between unimpaired flows (1911–1922) and post-Water First Policy flows (1993–2021), as measured at the Tuolumne River near Hetch Hetchy gage (USGS 11-276500) and analyzed using the PeakFQ Program (England et al. 2018). PeakFQ implements the Bulletin 17C procedures for flood-frequency analysis of streamflow records, providing a fitted frequency curve estimating flood magnitudes and their corresponding variance for a range of annual exceedance probabilities. Unimpaired peak flows for 1911–1922 were estimated at the Tuolumne River near Hetch Hetchy gage by scaling the pre-development gage data using a drainage area mean ratio adjustment.

3.2.2.2 Sediment and large wood supply and transport

Supply and transport of sediment and large woody debris play a crucial role in forming and maintaining habitats within a river ecosystem. Large dams trap most or all the sediment and large wood that are delivered from upstream sources, causing a reduction in these critical habitat elements downstream (e.g., Williams and Wolman 1984). The hillslopes above the Hetch Hetchy Reach are mantled with glacial till, which is likely an important source of sediment to the lower watershed (Dodge & Calk 1987).

An initial evaluation of sediment sources and transport capacity focusing on the O'Shaughnessy Dam and Poopenaut Valley subreaches was completed by the SFPUC in 2008 (M&T and RMC 2008). During reconnaissance surveys, storage of fine sediments (e.g., sand and small gravel) was found to be higher than expected immediately downstream of O'Shaughnessy Dam. Methods for the 2008 study included mapping sediment sources and storage in the reach using aerial photography, field surveys, and sediment transport capacity modeling. Photopoint monitoring was initiated in 2013 and conducted through 2019 to document sediment contribution to the Hetch Hetchy Reach after the Rim Fire (McBain 2021a, McBain Associates 2021b). Lastly, a geomorphic modeling exercise was completed in 2021 to help form and further explore hypotheses surrounding the higher amounts of sediment close to O'Shaughnessy Dam (McBain Associates 2021b). Findings from M&T and RMC (2008) and McBain Associates (2021b) include the following:

- Under pre-dam conditions and the climatic regime of the recent past, most or all coarse sediment (e.g., large gravels, cobbles, and boulders) supplied from the watershed upstream of O'Shaughnessy Dam was likely deposited in Hetch Hetchy Valley (McBain Associates 2021b). As such, the pre-dam supply of coarse sediment passing through Hetch Hetchy Valley to the study reach was probably naturally low. However, O'Shaughnessy Dam likely substantially reduced fine sediment supply to the Hetch Hetchy Reach compared to pre-dam conditions.
- Coarse sediment supply to the Hetch Hetchy Reach is limited to hillslope supply (rockfall, debris flows), minor erosion of coarse sediment stored on bedrock terraces, coarse sediment contributions from tributaries, and limited bank erosion in Poopenaut Valley. Post-dam reductions in flood frequency and magnitude may have a corresponding reduction in coarse sediment recruitment from in-channel sources and adjacent terraces, but would have had little to no effect on supply from hillslope or tributary sources.
- In Poopenaut Valley, the combination of low coarse sediment supply and low channel slope results in the bed surface being composed of sand being deposited at the lower end of Poopenaut Valley with very little sediment larger than 3 inches in diameter.
- Hydraulic conditions that were modeled for the Hetch Hetchy Reach showed that specific areas closer to O'Shaughnessy Dam (from Poopenaut Valley upstream to O'Shaughnessy Dam) have lower shear stress relative to the rest of the Hetch Hetchy Reach and can result in more gravel deposition and less gravel export at high flows. Similarly, smaller areas farther downstream (i.e., Mystery Bar) have low shear stress that can trap sediment (McBain Associates 2021b).
- Field observations prior to the 2013 Rim Fire did not identify any large-scale fine sediment sources except for the remaining fine sediment storage within the pre-dam floodway (e.g., on bars and terraces). It is likely that fine and coarse sediment storage in Poopenaut Valley is a remnant of pre-dam conditions, and that the low slope and backwater conditions caused by the Gorge Subreach limit transport of pre-dam stored sediment out of the valley and downstream.
- Post-Rim Fire, rain and snowmelt delivered fine sediment from newly bare hillslopes into the mainstem channel via overland flow and ephemeral tributaries. Subsequent high flow events near or above 6,500 cfs, coupled with a lack of influx of remnant hillslope sediment, greatly reduced fine sediment storage through the Hetch Hetchy Reach and suggested that short-duration, high-magnitude releases can be effective tools for "resetting" fine sediment deposits within the active channel after a series of drier years.
- Contemporary fine sediment storage in Poopenaut Valley is high and probably remains high because fine sediment transport rates are sufficiently low such that sediments are slowly being removed from pre-dam storage deposits upstream of Poopenaut Valley, and the effects have not fully propagated through the reach. Based on the information available at this time, a small sediment deficit is likely caused by periodic high flows slowly removing the remaining fine sediment stored in the valley, but the rate of removal is very low. Bed scour monitoring during high flows showed very little scour and

redeposition, supporting this hypothesis. Also, historic photographs show that the sand bar on the north riverbank has not changed appreciably over the past century.

Large wood supply to the Hetch Hetchy Reach is reduced by Hetch Hetchy Reservoir (RMC and M&T 2007), due to trapping, as evidenced by large rafts of woody debris at the head of the reservoir (Mazurkiewicz et al. 2011); however, some of the available wood supply may have been trapped by Hetch Hetchy Valley under pre-dam conditions. Altered flows regimes from river impoundments can also cause a lack of large wood recruitment from floodplains and affect longitudinal routing (Ligon et al. 1995, Roni et al. 2015).

Large wood mapping was conducted in the Hetch Hetchy Reach to evaluate the impacts of annual flow conditions on large wood storage and mobilization patterns (McBain Associates 2021). An initial large wood mapping effort was conducted in 2013 in the Hetch Hetchy Reach and subsequent large wood mapping efforts were repeated from 2014 to 2019 to quantify large wood storage downstream of Preston Falls. Monitoring began post-Rim Fire and it was hypothesized that large wood recruitment and storage would increase in the years following due to recruitment of burned trees from the hillslope. In-channel large wood was also expected to mobilize downstream during higher flow years. Findings from McBain Associates (2021) include the following:

- High flow events facilitated local recruitment of large wood from hillslopes into the Hetch Hetchy Reach post-Rim Fire rim, as evidenced by the year-to-year increase in the number of large wood pieces during surveys. However, recruitment from upstream of the Hetch Hetchy Reach was limited and Poopenaut Valley may be acting as a natural large wood trap, similar to Hetch Hetchy Valley.
- Patterns of downstream routing of large wood in the Hetch Hetchy Reach corresponded with high flow events. The Preston Falls Subreach can trap large wood during dry water years but wood from this reach is routed downstream during wetter water years.
- Even after a large fire, densities for the Hetch Hetchy Reach were consistent with densities in other Sierra Nevada rivers with similar watershed areas. Densities of large wood in Sierra Nevada rivers are typically low because the rivers are less forested than most other salmonid-bearing streams; in Sierra Nevada rivers, fish tend to use boulders and deep pools instead of large wood for cover (Berg et al. 1998, Kondolf et al. 1991). Large woody debris can provide important habitat elements for other organisms, particularly the Northwestern Pond Turtles that use it for basking sites and cover (Bury et al. 2012, Reese 1996, Reese & Welsh 1998). The Hetch Hetchy Reach is characterized by large substrate with intermittent deep pools; cover from these habitat types is ubiquitous in the environment. Therefore, the availability of large wood is not believed to be limiting fish populations, but could be limiting suitable in-river habitat for Northwestern Pond Turtles.
- Large wood is most likely not limiting geomorphic function in the Hetch Hetchy Reach. Research on large wood in the Sierra Nevada suggests that large boulders and geologic factors contribute to channel morphology more than large wood features do (Berg et al. 1998). Large granite boulders are more prevalent than large wood in the Hetch Hetchy Reach and likely drive channel morphology.

3.2.2.3 Water temperature regimes

Environmental flow releases from large storage reservoirs that stratify in the summer can cause substantial changes in the downstream thermal regime. The valve intakes for most dams, including O'Shaughnessy Dam, are typically below the thermocline that forms in the spring and dissipates when the reservoir "turns over" in the fall. An overall effect is that reservoir water releases are colder than reference conditions in the summer and warmer in the winter. In many cases, this "reversed" thermal regime greatly benefits trout and other cold-water fish species by creating year-round good conditions for growth (Muth et al. 2000), creating what is commonly referred to as a "tail water" fishery. However, this reversal in thermal regime due to reservoir releases can negatively affect other native species that depend on a natural thermal regime that warms through the spring and summer, such as invertebrates, Foothill Yellow-legged Frogs (Wheeler et al. 2015) and Northwestern Pond Turtles (Brittain and Saltveit 1989, Lind et al. 1996, Olden and Naiman 2010, Ashton et al. 2015). The seasonal warming downstream of dams, especially when combined with lack of flow disturbances, can also influence benthic biofilm communities, favoring cyanobacteria over diatoms (Niedrist et al. 2018) and in some cases causing nuisance blooms of *Didymosphenia geminata* (Didymo) (Kirkwood et al., 2008, Cullis et al. 2015).

O'Shaughnessy Dam causes similar effects on the thermal regime of the Hetch Hetchy Reach (Figure 13). These effects can be seen in comparisons of WY 2008 river temperature data from the USGS gaging stations above Hetch Hetchy Reservoir (representative of the reference conditions thermal regime), near Hetch Hetchy (1 mi downstream of O'Shaughnessy Dam within the O'Shaughnessy Subreach), and above Early Intake (11.5 mi downstream of O'Shaughnessy Dam within the Early Intake Subreach), as follows:

- Winter water temperatures at the near Hetch Hetchy USGS gage are 3°C to 8°C (5°F to 14°F) warmer than water temperature at the above Hetch Hetchy Reservoir USGS gage;
- Spring water temperatures at the near Hetch Hetchy USGS gage are approximately 2°C (4°F) warmer than water temperature at the above Hetch Hetchy Reservoir USGS gage;
- Summer water temperatures at the near Hetch Hetchy USGS gage are up to 10°C (18°F) cooler than water temperature at the above Hetch Hetchy Reservoir USGS gage;
- Average water temperatures in August and September above Early Intake are 2°C to 3°C cooler than water temperature at the above Hetch Hetchy Reservoir USGS gage;
- Average water temperatures in the winter and early spring at the near Hetch Hetchy USGS gage immediately below O'Shaughnessy Dam are up to 7.6°C (13.8°F) warmer than water temperature at the above Hetch Hetchy Reservoir USGS gage due to the reservoir "insulating" water being released from the cold air temperatures in winter and early spring; and
- Average monthly water temperatures in the winter and spring at the above Early Intake gage are still 5.3°C (9.5°F) warmer than water temperature at the above Hetch Hetchy Reservoir USGS gage, due to the insulation effect of the reservoir, but the difference is smaller at Early Intake because cold air temperatures cool the water between O'Shaughnessy Dam and Early Intake in winter and early spring.

3.2.3 Existing environmental flow requirements for O'Shaughnessy Dam

When the U.S. Congress passed the Raker Act in 1913, environmental flow requirements to maintain fisheries and river ecosystems downstream of dams were not commonplace, and thus were not considered in the authorization of the Hetch Hetchy Project. The Raker Act includes provisions for consultation with the DOI if the CCSF proposes changes to the authorized project rights-of-way. In the original rights-of-way approved by the DOI, Canyon Power Tunnel and Kirkwood Powerhouse were to be located on the south side of the Tuolumne River. However, in 1958 the CCSF proposed modifying the original rights-of-way, placing the tunnel and powerhouse on the north side of the Tuolumne River, thereby triggering consultation with the DOI.

In the 1950s and 1960s, the need for minimum flows to maintain fish habitat was becoming more commonly recognized and scientifically understood. Because Canyon Power Tunnel would change the primary diversion point on the Tuolumne River from Early Intake to O'Shaughnessy Dam, the natural river course within the 12-mi-long Hetch Hetchy Reach would be bypassed and could potentially be dewatered at times. The DOI approved the proposed change in the Canyon Power Tunnel right-of-way in 1961, provided that "…the interests of sport fishery and recreation can be protected by requiring continuing releases of water from O'Shaughnessy Dam to maintain the Tuolumne as a live stream between the dam and Early Intake."

This provision identified the need for minimum flow releases from O'Shaughnessy Dam after the development of Canyon Power Tunnel and set the required geographic scope for O'Shaughnessy Dam environmental flow releases as the bypassed Hetch Hetchy Reach. To ensure the provision, the DOI and CCSF signed the 1961 Stipulation, which included interim baseflow requirements, ramping rates, and a required study to inform fisheries and recreational water needs. Over the next two decades, a series of studies and negotiations were undertaken, eventually leading to the development of the 1985 Stipulation and 1987 Stipulation. These two agreements currently direct O'Shaughnessy Dam environmental flow releases (see Appendix L for the full text of the stipulations).

The 1985 Stipulation includes a minimum baseflow schedule (Table 2) that relies on cumulative watershed precipitation or inflows to determine water year class, release schedule, and revised ramping rates. Ramping requirements under the 1985 Stipulation are as follows: (1) for releases less than 200 cfs, ramping cannot exceed 50 cfs every four hours; and (2) for releases greater than 200 cfs, up-ramping may not exceed double the previous release over a four-hour period, and downramping cannot exceed 50% of the existing release every four hours. Compliance with all flow requirements is measured at the Tuolumne River near Hetch Hetchy gage (USGS 11-276500). The 1985 Stipulation also required consultation with the DOI if the CCSF proposed to expand, alter, or modify water or power facilities in the Hetch Hetchy Reach that would affect flows within the reach.

Table 2. *Minimum baseflow release schedules specified in the 1985 Stipulation.*

	Water year classification				
	A (wettest 60% of years)		B (32% of years)		C (driest 8% of years)
Period	**Minimum release[a]**	**Criteria[b,c]**	**Minimum release[a]**	**Criteria[b,c]**	**Minimum release[a]**
January	50 cfs	8.80 inches	40 cfs	6.10 inches	35 cfs
February	60 cfs	14.00 inches	50 cfs	9.50 inches	35 cfs
March	60 cfs	18.60 inches	50 cfs	14.20 inches	35 cfs
April	75 cfs	23.00 inches	65 cfs	18.00 inches	35 cfs
May	100 cfs	26.60 inches	80 cfs	19.50 inches	50 cfs
June	125 cfs	28.45 inches	110 cfs	21.25 inches	75 cfs
July	125 cfs	575,000 ac-ft	110 cfs	390,000 ac-ft	75 cfs
August	125 cfs	640,000 ac-ft	110 cfs	400,000 ac-ft	75 cfs
September 1–14	100 cfs	-	80 cfs	-	75 cfs
September 15–30	80 cfs	-	65 cfs	-	50 cfs
October	60 cfs	-	50 cfs	-	35 cfs
November	60 cfs	-	50 cfs	-	35 cfs
December	50 cfs	-	40 cfs	-	35 cfs

a. Minimum average daily flow as measured at the USGS 11-276500 Tuolumne River near Hetch Hetchy gage.
b. Precipitation criteria in inches are cumulative, measured at Hetch Hetchy Reservoir, starting October 1. For example, if October 1 through December 31 precipitation is greater than or equal to 8.80 inches, refer to year type A schedule for January.
c. Inflow criteria in ac-ft are the cumulative calculated inflow into Hetch Hetchy Reservoir commencing on the previous October 1 of each year.

Shortly after signing the 1985 Stipulation, the CCSF proposed adding an additional generator to Kirkwood Powerhouse. This change triggered consultation with the DOI, leading to the 1987 Stipulation. The 1987 Stipulation amended the 1985 Stipulation to include new release requirements intended to "…provide for additional protection of fishery resources and to provide variability in the water releases resulting from spring runoff to the extent practicable so as to enhance park resources and visitor enjoyment." The additional requirements included new studies by the USFWS to determine what effect, if any, the additional generator would have on habitat for, and populations of, resident fish species between O'Shaughnessy Dam and Early Intake and development by the CCSF of a "framework for the timing and quantity of releases from Hetch Hetchy Reservoir that will enhance the variability of flows and consider other measures to simulate to the extent possible, the natural conditions of the Tuolumne River, and to the extent that such variability and other measures will not affect the City's operating and water requirements."

As part of the fisheries studies required under the 1987 Stipulation, a Physical Habitat Simulation (PHABSIM) model was applied to the Hetch Hetchy Reach by the USFWS, and a draft report was released containing revised minimum baseflow requirements designed for "…optimizing the availability of physical habitat for Rainbow Trout and Brown Trout, and providing suitable water temperatures for growth and development…" (USFWS 1992). The report was not finalized, however, and several of the revised recommendations were not implemented.

3.2.4 Status of vegetation, fisheries, and wildlife

The changes in physical processes due to flow regulation by O'Shaughnessy Dam have altered biotic communities in the Hetch Hetchy Reach. Certain UTREP studies (see Section 5.1) focused on characterizing changes due to flow regulation (where such changes were possible to detect) and/or describing present-day condition of key biotic communities, including vegetation, fisheries, avifauna, herpetofauna, BMI, and bats. The success of the local biota can be strongly influenced by the annual hydrograph, and the life histories have evolved to key into the timing of physical and ecological conditions provided by hydrologic components (e.g. winter freshets, spring recession, summer base flows). Table 3 illustrates the timing of focal element life histories in the Hetch Hetchy Reach.

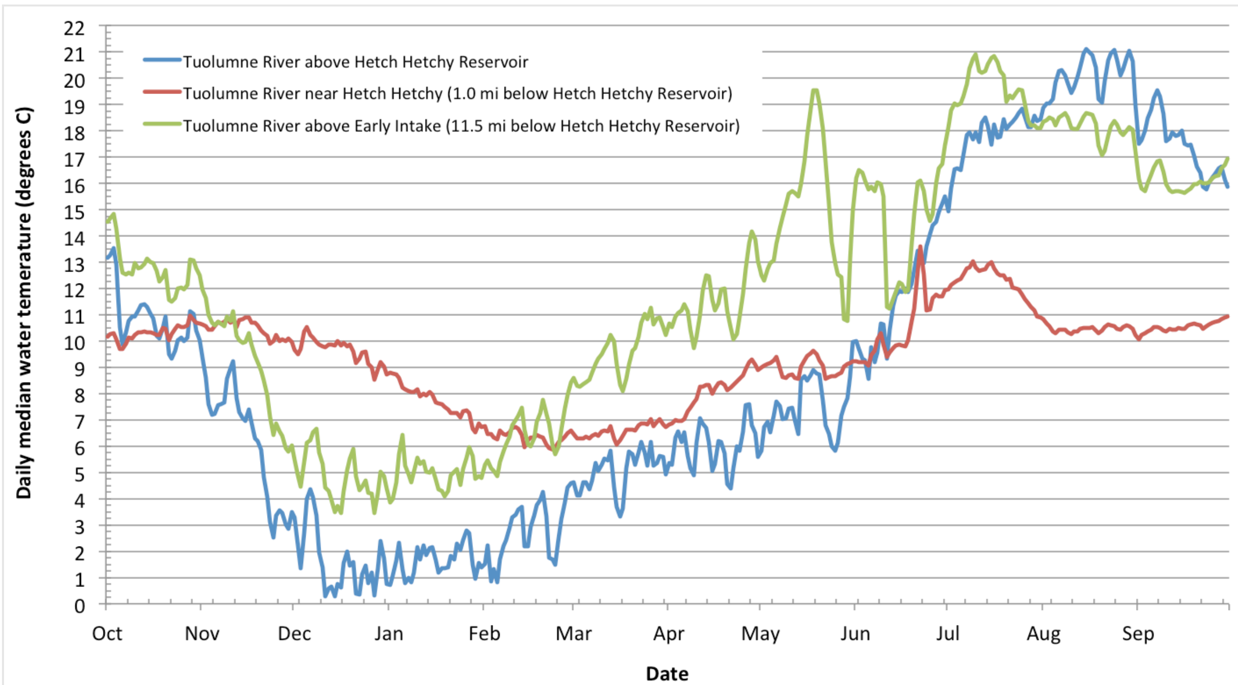

Figure 13. Example of water temperature differences upstream and downstream of Hetch Hetchy Reservoir for WY 2008.

Table 3. Life history periodicity table for Rainbow Trout, Benthic Macroinvertebrates (BMI), and Foothill Yellow-legged Frogs in the upper Tuolumne River. Light grey shading indicates the period when life stage is observed in freshwater and dark grey shading indicates the peak period.

Species	Life Stage	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainbow Trout	Spawning[1,2,3]												
	Fry[1,3]												
	Juvenile[1]												
	Adult[1]												
BMI	All												
Foothill Yellow-legged Frog	Breeding[4]												
	Tadpoles[4]												
	Froglets[4]												
	Frogs[4]												
	Overwintering[4]												

1 = Aceituno 1992, 2 = Raleigh et al. 1984, 3 = Moyle 2002, 4 = Hayes et al. 2016

3.2.4.1 Vegetation

Vegetation in the Hetch Hetchy Reach is typical for the mid-elevations of the west slope Sierra Nevada. Canyon live oak (*Quercus chrysolepis*), ponderosa pine (*Pinus ponderosa*), California black oak (*Quercus kelloggii*), Douglas-fir (*Pseudotsuga menziesii*), and incense cedar (*Calocedrus decurrens*) are common upland woody plants, while white alder (*Alnus rhombifolia*), red willow (*Salix laevigata*), black cottonwood (*Populus balsamifera ssp. trichocarpa*), and dusky willow (*Salix melanopsis*) are common woody riparian plants. The Poopenaut Valley Subreach is unique within the Hetch Hetchy Reach as it supports significant wetland plant communities. Appendix F and the NPS (2009–2013) *Looking Downstream* reports provide detailed descriptions of vegetation in the Hetch Hetchy Reach and Poopenaut Valley Subreach.

Encroachment of woody riparian and upland vegetation into river channels is common where dams modify the frequency and magnitude of floods, reducing high flows that scour and remove seedlings and saplings periodically (Ligon et al. 1995, Power et al. 1996, Poff et al. 1997, Gordon and Meentemeyer 2006, Richter and Thomas 2007, Yarnell et al. 2010a). The existing riparian plant communities along the river margins are also older and more established than they would be under free-flowing conditions with higher occurrence of scouring events. In many locations within the Hetch Hetchy Reach, there is evidence of encroachment of woody riparian plant species, particularly willows and alders, into the low flow channel and gravel bars and along the channel margin (Appendix F). Certain geomorphic settings appear to be more vulnerable to in-channel encroachment, including boulder gardens which are natural sediment receptacles and are prone to sand deposition. Constant flows of 600 to 700 cfs prior to completion of Canyon Power Tunnel created a distinct band of woody riparian vegetation approximately 1 ft above the present-day low flow channel margin. After completion of Canyon Power Tunnel, summer baseflows were reduced to approximately 75 to 200 cfs depending on the water year class, leaving a second band of alder and willow at the present-day low flow channel margin. Both flow regimes appear to have contributed to some channel simplification, at least in Poopenaut Valley, where channel geometry becomes more trapezoidal and less complex due to encroaching vegetation (RMC and M&T 2007).

Vegetation encroachment can alter sediment transport processes and habitat for riverine species. For example, encroachment can reduce the quality of trout spawning gravels, stabilizing them and allowing fine sediment to infiltrate into the pore spaces between the gravels. Modest channel simplification can also degrade Foothill Yellow-legged Frog egg laying habitat by reducing shallow edgewater areas, "fossilizing" cobble bars, and increasing fine sediment deposition (Lind et al. 1996, Yarnell et al. 2010b). Woody vegetation along the shoreline can shade frog egg masses and reduce edgewater warming, slowing developmental rate. Vegetation encroachment into the active channel and along the shoreline can also reduce basking habitat for Northwestern Pond Turtles, which are a California Species of Special Concern and at the time of this writing are proposed for listing under the federal Endangered Species Act.

In addition to causing encroachment of riparian vegetation into the active channel, reduced flows can result in upland vegetation encroaching onto pre-dam floodplain surfaces in some locations in the Hetch Hetchy Reach. Floodplain extent is limited in the Hetch Hetchy Reach due to valley confinement. Before the Rim Fire in 2013, upland vegetation encroachment onto floodplain surfaces was observed in the O'Shaughnessy, Poopenaut Valley, Preston Falls, and Early Intake subreaches. The vegetation in Poopenaut Valley is primarily composed of herbaceous wetlands and upland meadows intermixed with dense riparian trees and shrubs. The initial wetland delineation and description of existing vegetation types in Poopenaut Valley, completed in 2007 (NPS 2009) and refined in 2008 and 2009, provide an inventory of plant communities and wetlands. Vegetation dominance, frequency, abundance, and distribution vary widely among years due to fluctuations in annual temperature and precipitation; ongoing work by the NPS seeks to refine these assessments and detect longer-term trends. Inferences about the conditions of existing plant communities, as related to the existing hydrologic regime in Poopenaut Valley, are limited because of the lack of reference sites and knowledge of the plant communities prior to the construction of O'Shaughnessy Dam, and potentially confounding factors including climate change.

Studies to date (McBain Associates 2021b) suggest that because of several unique factors (e.g., a low overall gradient, a downstream bedrock constriction that promotes floodplain inundation, upslope glacial moraines that contribute sediment to the river), Poopenaut Valley and its ecosystems have likely been spared the typical ecological effects seen downstream of most dams (e.g., channel incision, riparian encroachment, etc.). Given the reduced magnitude of peak runoff, its possible that the wetlands of Poopenaut Valley were much higher historically (Figure 12). There is evidence of conifer encroachment into Poopenaut Valley meadows, a trend observed throughout the Sierra Nevada. Several wetland areas in Poopenaut Valley exhibit an unusual assemblage of plants potentially linked to hydrologic alteration, and certain upland areas exhibit hydric soils and some hydrophytic vegetation despite a lack of regular hydrologic connectivity. These conditions suggest that wetlands were possibly more extensive in the past and may reflect an ongoing transition to upland-type plant communities in response to reduced spring flooding; that these areas are still in transition suggests that they may be tenuously maintained by existing snowmelt season spill releases during wetter water years (NPS 2009).

3.2.4.2 Fisheries

Since 1884, the upstream limit for anadromous fish species (including native salmonids) has been La Grange Dam, approximately 65 RM downstream of O'Shaughnessy Dam. The earlier Wheaton Dam, in approximately the same location as La Grange Dam, may have limited access as early as 1871. The historical post-glacial upstream limit of native fishes may have been Preston Falls (Moyle et al. 1996). While it is possible that salmonids (particularly steelhead) ascended past Preston Falls, no fish were found historically in Hetch Hetchy Valley approximately 8 mi upstream from Preston Falls (Yoshiyama et al. 2001). Non-salmonids are not presently found between Preston Falls and O'Shaughnessy Dam (Moyle et al. 1996, SFPUC unpublished data).

With the exception of the non-native fall-spawning Brown Trout (*Salmo trutta*), fish species observed in the Hetch Hetchy Reach likely represent a native assemblage and include spring-spawning Rainbow Trout

(*Oncorhnychus mykiss*), Riffle Sculpin (*Cottus gulosus*), California Roach (*Lavinia symmetricus*), and Sacramento Sucker (*Catostomus occidentalis*) (RMC and M&T 2007, SFPUC unpublished data). Non-native, hatchery-reared Rainbow Trout have been introduced to the reach, and it is likely that Rainbow Trout occurring upstream of Preston Falls are descendants of this non-native stock. Both Brown Trout and Rainbow Trout were primarily maintained for a recreational fishery and are now present above Preston Falls and in Hetch Hetchy Reservoir, likely descendants of fish originally stocked during the 1800s and subsequent stocking efforts (Yoshiyama et al. 2001).. Stocking is no longer practiced within Yosemite National Park and the Hetch Hetchy Reach.

Naturally variable hydrologic conditions in Sierra Nevada rivers can be both physically and bioenergetically challenging for fish (Kiernan & Moyle 2012). Native fish species have presumably adapted to survive these conditions, yet extremes remain challenging. For example, high flow events in very wet years can result in scour of spawning sites and displacement of fry. However, the very wet years also inundate some off channel habitats, such as Poopenaut Valley, which may promote salmonid growth. Pre-dam, low flow reference conditions during summer and fall, particularly during very dry years, likely limited adult trout habitat and caused some thermal stress, although deep pools may have provided thermal refugia. Flow regulation typically reduces hydrologic variability and reverses thermal regimes (see Section 3.2.2.3). The existing environmental flow releases augment flows in summer and fall, further reducing extremes and resulting in generally more stable flow and thermal regimes than would have been the case under pre-dam conditions. The post-dam flow and temperature regime may change fish growth patterns, relative to reference flow conditions, as colder temperatures in the spring and summer may limit bioenergetic efficiency of trout. Given these changes, corresponding post-dam changes to the fishery in the Hetch Hetchy Reach would be expected; however, no quantitative data for the pre-dam fishery are available for comparison.

Fisheries studies to date have focused almost exclusively on trout species due to their recreational value. The USFWS conducted snorkel and rotenone surveys in the Hetch Hetchy Reach dating back to the 1970s, and the SFPUC has conducted snorkel surveys since 2007 at up to 14 study sites within the Hetch Hetchy Reach (Figure 14). The SFPUC has surveyed all subreaches within the Hetch Hetchy Reach except for the Gorge Subreach, focusing on trout abundance and distribution. The 2007–2021 SFPUC snorkel survey data were compiled, analyzed, and compared to historical fish surveys conducted by the USFWS (Vondracek 1985, USFWS 1976, USFWS 1981) to detect relationships among trout species abundance and environmental variables, including the annual hydrograph and thermograph (Appendix B). Overall, results indicate that Rainbow Trout and Brown Trout abundance has high spatial and temporal variability. Annual temporal variation in abundance is generally within about one-fold to three-fold within a subreach, and nearly abundances are within an order of magnitude, but no consistent trends are evident in trout abundance over time within or among subreaches or habitat units (e.g., pool, riffle). Although results indicate that post-dam variability is high, such variability may be typical for a snowmelt-driven system like the upper Tuolumne River.

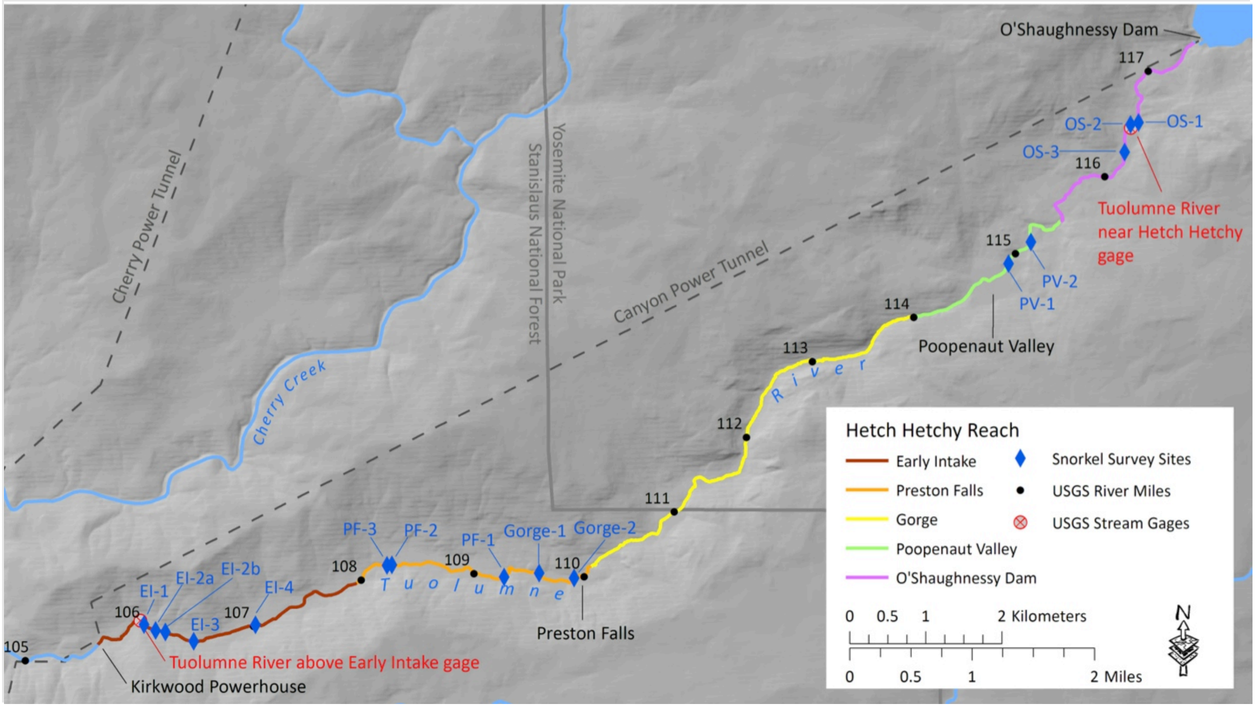

Figure 14. Hetch Hetchy Reach map, showing subreach boundaries and 14 fish survey locations surveyed by the SFPUC in 2007–2021. (EI-2a and EI-2b were combined as one site.) Fish surveys were conducted in portions of all subreaches except for the Gorge Subreach. (Sites labeled "Gorge" were actually located in the Preston Falls Subreach.)

Generally, the Hetch Hetchy Reach provides significant habitat for juvenile and adult Rainbow Trout and Brown Trout; boulder and cobble substrates and large deep pools are relatively abundant. Cobble and boulder substrates offer fry (age-0) and juveniles (age-1) abundant cover, and interstitial spaces offer refuge from high flow during winter and spring. Adult trout require deeper water and access to cover. In addition to using deep pools, adult stream-dwelling trout will establish feeding stations in bioenergetically efficient locations behind boulders in faster flowing, moderately deep (>1.6 ft [>0.5 m]) reaches with access to cover (Fausch 1984). In north temperate streams, trout must switch at a relatively small size (8–12 in [200–300 mm]) from a diet of invertebrates to fish or crayfish if they are to grow any larger (Allen 1969, Bachman 1984, Bannon and Ringler 1986, Cada et al. 1987, Bachman 1991, Fausch 1992). Large, mostly piscivorous adult Brown Trout and Rainbow Trout in the Hetch Hetchy Reach would not require prominent feeding stations at the head of a pool, but rather would focus their foraging where prey (e.g., roach, sucker, trout) are abundant and available for capture. Large pools in the reach also offer suitable winter refuge habitat (areas with large boulders and low velocity) for all life stages and are particularly important for adults since this life stage prefers deeper water habitats.

Food supply usually is not limiting to adult resident trout abundance, but it can affect size and therefore survival and fecundity. Moyle (2002) reported that Rainbow Trout in their first four years typically grow to 3 in (75 mm), 5.5 in (140 mm), 7.5 in (190 mm), and 9.3 in (235 mm), respectively, with higher growth rates in warmer and more productive streams. Based on the 1970 and 1977 rotenone survey data, Rainbow Trout growth rates in the Hetch Hetchy Reach appear to be similar to those described by Moyle (2002) for small, steep-gradient streams. Brown Trout growth rates appear to be slightly higher, although scale analysis or some other aging method would be needed to confirm length and age.

Length-frequency data from the 1970 and 1977 rotenone studies indicate that:

- Both Rainbow Trout and Brown Trout populations show relatively high numbers of age-0 fish (≤4 in [≤100 mm]) in September, leading to substantial recruitment and supporting the hypothesis that spawning and fry rearing habitat is not limiting;
- There is a substantial number of juvenile (4–7.9 in [100–200 mm]) trout available to recruit to the adult (>7.9 in [>200 mm]) population, further supporting the hypothesis that juvenile rearing habitat is not limiting;
- Age-0 and age-1 Brown Trout (and older age classes) are slightly larger than Rainbow Trout of the same age class because Brown Trout spawn and emerge earlier than Rainbow Trout, are able to feed and grow earlier, and are expected to have a competitive advantage over Rainbow Trout of the same cohort provided water temperature and food sources are not limiting;
- Abundance of age-0 Brown Trout and Rainbow Trout can vary substantially between years and is likely strongly influenced by environmental conditions such as flows (e.g., redd scour; fry displacement); and
- Nearly all trout >9.8 in (>250 mm) are Brown Trout.

These studies suggest that adult Brown Trout likely have a competitive advantage over adult Rainbow Trout due to differences in water temperature tolerances, particularly once diets shift to being predominantly piscivorous, which is consistent with predictions from Moyle and Marchetti (1992). Brown Trout have been shown to have a competitive advantage over Rainbow Trout in occupying preferred habitats when both trout species are present (Lewis 1969, Gatz et al. 1987) and water temperatures are suitable for both species. For example, Gatz et al. (1987) found no difference in Rainbow Trout and Brown Trout habitat preference in allopatric populations but documented a shift in Rainbow Trout preference to faster-shallower water, with no change in Brown Trout preferences, in sympatric populations. Gatz et al. (1987) also found that adult Rainbow Trout biomass was reduced by 50% and age-0 biomass was reduced by 80% in the presence of Brown Trout.

In conclusion, review of habitat conditions in the reach and available trout survey data suggest that:

- Age-0 and age-1 trout habitat is relatively abundant, and abundance at these life stages is likely not limiting the adult trout population (i.e., there are typically far more juvenile trout available to recruit into the adult population than needed to replace the number of adults that die during the year);
- Varying numbers of all age and size classes are probably strongly influenced by environmental conditions;
- Brown Trout have a competitive advantage over Rainbow Trout due to their life history timing (i.e., Brown Trout fry emerge three months or more before Rainbow Trout fry and are able to attain a larger size and competitive advantage by the onset of summer); and
- Spawning habitat likely is not limiting based on the abundant numbers of fry and juveniles.

3.2.4.3 Avifauna

No data are available for pre-dam or historical distribution and abundance of avifauna in the Hetch Hetchy Reach. Recent work has focused entirely on the Poopenaut Valley Subreach, where species diversity is high (see NPS 2009–2014b). The NPS has conducted extensive annual surveys to estimate avian community species abundance, composition, and habitat use in Poopenaut Valley wet meadow and montane riparian habitats. One hundred and four bird species were detected between 2007 and 2013. Twenty-two species were confirmed to be breeding in Poopenaut Valley. The Riparian Habitat Joint Venture (RHJV), a group of 18 federal, state, and non-profit partners that work to restore and protect California's functioning riparian habitat, consider seven of the twenty-two species detected to be riparian-associated priority management species (RHJV 2004): the Black-headed Grosbeak (*Pheuticus melanocephalus*), Song Sparrow (*Melospiza melodia*), Spotted Sandpiper (*Actitis macularius*), Warbling Vireo (*Vireo gilvus*), Wilson's Warbler (*Wilsonia pusilla*), Yellow-breasted Chat (*Icteria virens*), and Yellow Warbler (*Setophaga petechia*). The Yellow Warbler and Yellow-breasted Chat are also California Species of Special Concern. An invasive brood parasite, the Brown-headed Cowbird (*Molothrus ater*), has also been observed in Poopenaut Valley.

Riparian-dependent birds are susceptible to flow regulation because they forage and nest in the riparian zone, which is prone to inundation during high flow releases during the spring snowmelt spill period. Nesting for these species can start in late April and extend through June. Nest inundation is a natural phenomenon in unimpaired systems but can be exacerbated in typical regulated systems where low baseflows extend into the snowmelt runoff period while a reservoir fills, encouraging low elevation nest building, followed by a series of pulse flows to control reservoir elevation when the reservoir is nearly full. Some species, including the Warbling Vireo and Song Sparrow, may attempt to build another nest and produce offspring if a nest is inundated; however, the delay and lost energy in doing so may reduce overall productivity of the population (S. Stock, pers. comm.). Song sparrows are year-round residents in Poopenaut Valley and concentrate their activity along the river's edge. Because Song Sparrows are understory nesters that build their nests on or near the ground, their nests are especially vulnerable to flooding. Other RHJV focal species in Poopenaut Valley are not as vulnerable to flooding due to their higher nesting position in riparian vegetation (NPS 2014b).

Along with potential inundation during high flows, extended periods of low flows have resulted in observed decreases in the species richness of the breeding community and the number of breeding individuals in the floodplain meadows of the Upper Tuolumne River (Desrosiers et al. 2022). Desrosiers et al (2022) compared the relationships between hydrological variables and bird communities from downstream Hetch Hetchy reach to an unregulated reach of the Merced River and found a stronger relationship in the Upper Tuolumne, which suggests that the presence of the dam may be inflating the negative impacts of drought on the area's riparian bird community.

3.2.4.4 Bats

In 2010, the NPS initiated acoustic monitoring to gather data on bat species in Poopenaut Valley (see NPS 2014b). In Poopenaut Valley, the NPS has detected all 17 bat species known to occur in Yosemite National Park, an indication of the biodiversity present in Poopenaut Valley (NPS 2013, NPS 2014b). Five of the 17 species documented have special status; Townsend's Big-eared Bat (*Corynorhinus townsendii*) is a candidate for listing as threatened or endangered under the California Endangered Species Act, while Pallid Bat (*Antrozous pallidus*), Spotted Bat (*Euderma maculatum*), Western Mastiff Bat (*Eumops perotis*), and Western Red Bat (*Lasiurus blossevillii*) are California Species of Special Concern. Two species, the little brown bat (*Myotis lucifugus*) and hoary bat (*Lasiurus cinerus*) are up for federal discretionary review in 2024 and 2027, respectively. Western Red Bat was detected for the first time in August–September 2013, during the period when the Rim Fire burned through the upper Tuolumne River area. Results show that bat assemblages in Poopenaut Valley vary by year, site, and season. Most species tend to arrive in late spring/early summer, peak in detection frequency during late summer, and depart sometime during the fall. Three species – Spotted Bat, Western Mastiff Bat, and Mexican Free-tailed Bat – stand out with considerably higher detection frequencies, and one, Mexican Free-tailed Bat, remains year-round.

Bats appear to make extensive use of the North Pond and wetlands for nighttime foraging, making the timing of inundation of these features important. North Pond appeared to be particularly important to Spotted Bats and Western Mastiff Bats during summer 2012, when both species exhibited significantly higher detention frequencies. The NPS is continuing work to investigate possible food web relationships among bat diversity and abundance, Poopenaut Valley wetland habitats, and regulated flows. Preliminary results suggest that aquatic prey in the North Pond and inundation duration are important food resources for bats in Poopenaut Valley (Jackson et al. 2020).

3.2.4.5 Herpetofauna

Pre-dam and historical data regarding herpetofauna in the Hetch Hetchy Reach is limited. Since 2008, SFPUC, NPS, and USFS staff have conducted collaborative surveys for amphibians and reptiles in portions of the Hetch Hetchy Reach, from O'Shaughnessy Dam downstream to Poopenaut Valley, and from Preston Falls downstream through the Early Intake Subreach (Appendix A). No herpetofauna surveys have been conducted in the Gorge Subreach. Commonly encountered species include Sierra Garter Snake (*Thamnophis couchii*), Sierra Newt (*Taricha sierrae*), Northwestern Pond Turtle (*Actinemys* [=*Clemmys; Emys*] *marmorata*), and Sierra Chorus Frog (*Pseudacris [Hyla] sierrae*). Foothill Yellow-legged Frog (*Rana boylii*) were observed but appear to be present in very small numbers, concentrated in areas of suitable habitat within the Early Intake Subreach. These species all use riverine habitats or hydrologically connected wetland habitats in Poopenaut Valley. The Foothill Yellow-legged Frog in the southern Sierra region is listed as endangered at the state and federal level (USFWS 2023a). The Northwestern Pond Turtle is a California Species of Special Concern (Thomson et al. 2016) and is proposed as threatened under the Endangered Species Act (USFWS 2023b). Presence of the non-native American Bullfrog (*Lithobates catesbeianus*) was confirmed in the Preston Falls Subreach in 2010 (Appendix A). This species not only preys on and competes with native herpetofauna, but could also carry the chytrid fungus Batrachochytrium dendrobatids (Bd), a known killer of many frog species (Adams et al. 2017). Recent eradication efforts by the NPS appear to have been effective (Colleen Kamoroff, pers. comm.; SFPUC unpublished data). Overall distribution of this invasive frog within the Hetch Hetchy Reach is not well known, and continued surveillance monitoring is advised for early detection in the event of reinvasion from potential pathways including sites such as Birch Lake, Mud Lake, Swamp Lake, and Gravel Pit Lake. Given the bullfrog's preference for warm, slow-moving waters, prolonged periods of low flow conditions favor their establishment, so providing more natural flows could likely support resiliency of the river and prevent the survival and spread of this invader (Fuller et al. 2010, Adams et al. 2017).

The Sierra Garter Snake, Sierra Newt, Sierra Chorus Frog, and Northwestern Pond Turtle appear to be common in suitable habitats within the Hetch Hetchy Reach, with multiple life stages present, and thus are presumed to be successfully reproducing. The Sierra Garter Snake was reliably detected in all survey periods. Multiple age classes of Northwestern Pond Turtle are present in the terrace ponds in Poopenaut Valley, and the NPS observed a turtle exhibiting nesting behavior in an erosional feature between Poopenaut Valley's North Pond and the mainstem Tuolumne River in 2007. The off channel habitat in Poopenaut Valley is likely important for Northwestern Pond Turtles given the lower water temperatures from O'Shaughnessy Dam releases. Turtles also occupy calmer portions of the river in Poopenaut Valley and the Preston Falls Subreach. Suitable habitats for turtles have access to a combination of aquatic and terrestrial habitats to meet life history requirements (Bury et al. 2012). Aquatic habitats are used for foraging, courtship and mating, and refuge during their active season (spring and summer). Aquatic sites with emergent basking structures for thermoregulation are preferred. Terrestrial habitats are used for nesting and overwintering. Nesting occurs above the high-water line in relatively open areas with compact soils and sparse vegetation. Periodic floods in winter or spring can be helpful in maintaining appropriate nesting conditions, and wildfire may also help by resetting vegetative succession on nesting areas. Early life stages (eggs, hatchlings, small juveniles) are vulnerable to a wide variety of predators and environmental extremes, but turtles that reach adult size are relatively safe and can have reproductive life spans exceeding 50 years (Bury et al. 2012).

The federal- and state-listed Foothill Yellow-legged Frog uses cobble bars, boulder bars, and other shallow riverine habitats for egg laying and tadpole rearing. Population abundance in the Early Intake Subreach is very low (SFPUC unpublished data), possibly due to channel simplification and reduced sunlight resulting from riparian encroachment, which may decrease suitable oviposition and larval rearing habitat for Foothill Yellow-legged Frog. The main factors suppressing the Foothill Yellow-Legged Frog abundance in the Early Intake Subreach are hypothesized to include the rapid fluctuations of stage and velocity during the snowmelt recession that can alternately scour and desiccate egg masses and tadpoles, in combination with colder post-dam thermal regimes in spring and summer and scarcity of tributaries to provide refuge in wetter years.

There is no observational data on the presence of Foothill Yellow-legged Frogs in the Hetch Hetchy Reach prior to dam construction. Pre-dam mainstem Tuolumne River hydrology was not likely conducive to successful recruitment in wetter years due to large variable snowmelt season flows that delayed onset of breeding, egg laying, and successful tadpole rearing, but drier years and some normal years would have provided suitable conditions in the mainstem (Appendix A; and see Section 9.5). Given the occurrence of Foothill Yellow-legged Frogs in nearby watersheds from Snow Creek to Fern Spring and Sherlock Creek, it is assumed that they were historically present in the Hetch Hetchy Reach (R. Grasso, NPS Biologist, pers communication).

3.2.4.6 Benthic macroinvertebrates

The health and richness of BMI communities are commonly used as indicators of ecosystem health and water quality, and BMI are important food sources for Rainbow Trout as well as birds and bats in the Upper Tuolumne River (Jackson et al. 2020). BMI can be an especially important component of diets of birds and bats in dryer years in Sierra Nevada rivers (Jackson et al. 2020, Desrosiers et al. 2022, Stock et al. 2021). Since 2007, scientists from the University of California White Mountain Research Station have collected data on BMI assemblages in the Hetch Hetchy Reach to investigate and monitor the linked physical and biological environments downstream of Hetch Hetchy Reservoir (Holmquist and Schmidt-Gengenbach, 2020, Stock et al. 2021). During 2007–2009, samples were collected over a 12-month period to characterize the invertebrate assemblage in the Poopenaut Valley and O'Shaughnessy subreaches in relation to spring floods and as a function of wetland type. In relation to flow, the data in these studies show that water releases similar to a natural hydrograph, and those that target certain physical and ecological objectives from year to year, can mitigate many of the impacts of regulated flows (Holmquist and Schmidt-Gengenbach 2010–2020, Stock et al. 2021).

Assemblages of BMI in the riffles of the O'Shaughnessy and Poopenaut Valley subreaches were similar to assemblages in riffle habitats of the nearby unimpaired upper Merced River (Holmquist and Schmidt-Gengenbach 2012). BMI communities in the riffles below O'Shaughnessy Dam exhibit high taxonomic richness and evenness and uniform division of ecological resources and are dominated by taxa considered to be indicator of good water quality. There is some evidence that the quality of BMI assemblage may increase with distance downstream from O'Shaughnessy Dam (J. Holmquist, pers. comm.) as water temperatures increase from the below average, uniform diurnal temperature ranges in the O'Shaughnessy Subreach. As substrate size increases longitudinally, however, the decrease in suitable substrate in lower subreaches may confound the relationship with temperature and BMI assemblage quality as abundance, taxonomic richness, and densities may decrease as substrate size increases (McBain Associates 2022, unpublished data).

Drifting invertebrates (invertebrates floating in the water column) are important for the distribution and structuring of stream BMI assemblages and provides an important food source for both aquatic organisms (e.g., fish, frogs) and terrestrial organisms (e.g., birds, bats; Jackson et al. 2020). The availability drift can change with alterations to the flow regime. Drift has been shown to respond positively to pulse flow events (Nelson & Lieberman 2002, Naman et al. 2016, Adámek et al. 2024). For example, the University of California White Mountain Research Station studied the drift response of terrestrial BMI and aquatic BMI in riffle habitat to high flow releases from O'Shaughnessy Dam in 2010 (Holmquist and Schmidt-Gengenbach 2012). They found that aquatic BMI drift had the highest densities during falling flows, while terrestrial BMI drift had the highest densities with increasing flows. Aquatic drift densities were almost ten times greater during falling flows than during baseflows, and terrestrial drift densities were five or more times greater (Holmquist and Schmidt-Gengenbach 2012).

Alterations to flow regimes from dams can also affect BMI assemblage through changes in benthic biofilm and algal communities (Nelson and Lieberman 2002, Gillett et al. 2016, Jansen et al. 2020). In the Upper Tuolumne River, riverine algae can be scoured and reduced by especially high discharge releases below O'Shaughnessy Dam, essentially "cleaning" the substrate. The clean substrate is then available for more specialist macroinvertebrates to move in and thrive, with the benefits of scouring persisting for years after high flows (Holmquist and Schmidt-Gengenbach 2012). Didymo ("rock snot") is a nuisance, mat-forming diatom that is a growing concern nationally (Spaulding and Elwell 2007) and a recent concern in the Upper Tuolumne that can influence the community of benthic macroinvertebrates (Anderson et al. 2014, Richardson et al. 2014, Niedrist et al. 2018). Didymo may also be flushed out with scouring flows (Cullis et al. 2015), and there is a need to document if it can be scoured with high flows in the Hetch Hetchy Reach.

4 Constraints, opportunities, and uncertainties

In addition to the well-known, broadly observed effects of dams on river ecosystems (e.g., Williams and Wolman 1984, Ligon et al. 1995, Wang et al. 2018, Brown et al. 2024), project facilities and the resulting conditions within the Hetch Hetchy Reach present specific constraints, opportunities, and uncertainties for river ecosystem management. Ecological and climate change-related uncertainties also pose challenges for long-term river management. Constraints, opportunities, and uncertainties include the following:

- *Hetch Hetchy Reservoir storage capacity and the Water First Policy* — The relatively small storage volume of Hetch Hetchy Reservoir compared to the typically larger volume of annual unimpaired inflow results in frequent spills, particularly during the April–August snowmelt runoff season (see Section 3.2.2.1). The Water First Policy typically results in higher reservoir storage at the beginning of the snowmelt season, further increasing frequency of spills. These frequent spills provide an opportunity to mimic, via "shaped" spill releases, key components of the reference conditions spring and early summer snowmelt hydrology. The small storage volume of the reservoir limits the ability to store large quantities of water for specific high flow releases, such that high flow releases must occur at times when the reservoir is nearly full and projected inflows would be sufficient to refill the reservoir (e.g., trending toward a "run of the river"-type of operation).
- *Hetch Hetchy Reservoir thermal stratification* — Reservoirs often stratify thermally during warmer months of the year, with cooler, denser water at depth and warmer, less dense water at the surface. This stratification results in cooler water being released from the environmental flow or face valves (which draw from intakes located near cooler, deeper water), and warmer surface waters being released during drum gate operations when the reservoir is full. Thermal stratification presents opportunities during spring and summer by providing options for cold and warm water releases to better represent natural conditions, as further discussed in Appendix D.
- *O'Shaughnessy Dam drum gates* — The drum gates located on the crest of the spillway can be used to smooth high magnitude flow changes and better mimic the shape of the reference conditions hydrology, particularly once the reservoir is full during the snowmelt recession. To protect infrastructure near the spillway, valve releases and reservoir water surface elevations are managed to ensure that flows over the drum gates are maintained at less than 2,500 cfs. The ability to release water via the drum gates and spillway creates an opportunity to provide warmer water temperatures in spring, which should enhance Rainbow Trout,Foothill Yellow-legged Frog, and Northwestern Pond Turtle growth rates.
- *Snowmelt management release flexibility* — Due to the relatively small reservoir storage capacity, prioritization of water supply reliability, dynamic inflow patterns, spring storms, California Division of Dam Safety valve testing requirements, and other operational considerations, operators require flexibility to manage reservoir releases in April through June. This necessary operational flexibility constrains the implementation of prescriptive releases during the spring snowmelt period.
- *O'Shaughnessy Dam face valve release capacity* — The limited capacity (approximately 8,000 cfs) of the face valves on O'Shaughnessy Dam when the reservoir is at lower elevations constrains maximum controlled releases in the spring before the reservoir is full (see Section 3.2.1). Valve releases greater than 8,000 cfs are possible only when Hetch Hetchy Reservoir is full or nearly full, constraining peak magnitude and timing of controlled high flow releases. The face valves are also limited to a nominal minimum release magnitude change of approximately 50 cfs; release changes less than 50 cfs (for

example, during ramping operations) may be accomplished with the face valves, but with considerably less precision.

- *Runoff variability and inflow forecasting* — Annual runoff in the upper Tuolumne River watershed is highly variable. The volume of inflow and available spill is challenging to predict from year to year and significant efforts are made to forecast near-term and long-term inflow timing to provide data for planning operational and ecological releases. Snowmelt season inflow volume can be more reliably estimated; however, the actual timing and pattern of inflows are particularly challenging to forecast given variable spring and early summer weather patterns. Uncertainty regarding inflow timing and pattern constrains operators' ability to plan releases in advance, resulting in shorter planning horizons on the order of days to weeks. The Airborne Snow Observatory lidar data has greatly improved forecasted inflow volumes and has helped managers increase their confidence to release substantial volumes of water prior to filling the Reservoir. Hetch Hetchy Project operators continue to improve forecasting tools and streamflow monitoring in order to better support water supply reliability, power generation, and environmental flow needs.
- *Ecological uncertainties* — Because each river ecosystem is unique, relationships between flow and biotic responses can also be unique. While many of the important relationships between environmental flow releases and physical processes or habitat area can be quantified, ecological response to changes in these physical parameters (e.g., hydrology, sediment transport) is difficult to predict, particularly over short time periods. The ecological response is typically understood only in a qualitative, directional sense (e.g., more habitat area should produce more fish) based on the scientific literature, which allows the development of informed hypotheses about likely river ecosystem outcomes. In addition, the effects of large landscape-level events within the Hetch Hetchy Reach, such as wildfire, on ecosystem response and outcomes are not predictable and may be difficult to discern from the effects of environmental flow management over time.
- *Climate change-related uncertainties* – In the coming decades, global climate change is expected to increase average air temperature, alter precipitation patterns, and alter wildfire regimes throughout the Sierra Nevada range (Dettinger et al. 2015). While the magnitude and rate of change in temperature, precipitation, and runoff patterns are uncertain and will vary by region, current climate and hydrologic models (e.g., Maurer and Duffy 2005, Miller et al. 2003, Young et al. 2009, Null et al. 2013, Harpold et al. 2017, Maina et al. 2022, Tonina et al. 2022) suggest that Sierra Nevada rivers will experience (1) changes in the timing, intensity, and variability of precipitation; (2) increased proportion of precipitation falling as rain instead of snow; (3) reduced average annual snowpack; (4) a shift in snowmelt runoff to earlier in the year; and (5) increased water temperatures. Hydrologic modeling conducted by the SFPUC to estimate effects of climate change scenarios on upper Tuolumne River hydrology found that potential reductions in median annual runoff ranged from 0.7% to 8.6% due to changes in temperature and precipitation (Hydrocomp 2012). The most recent information from the SFPUC's Long Term Vulnerability Assessment (Francois et al. 2021) suggests that the upper Tuolumne River watershed hydrology is sensitive to changes in precipitation, but that there is a range of uncertainty on the directionality of precipitation changes. The study predicts that by 2070 there could be changes to Hetch Hetchy inflow ranging from -27% to +37% (Francois et al. 2021). Thus, climate change is a particularly difficult uncertainty to incorporate within recommendations for environmental flows.

5 Analytical approach

There is no standardized methodology for developing environmental flow recommendations, and no single analytical strategy or field methodology can effectively assess the role of environmental flows in sustaining the diversity of habitats and species present in the Hetch Hetchy Reach. To best characterize the relationship between the river ecosystem and environmental flow, a variety of inter-related studies, analyses, and models (listed in Section 5.1) were used to develop quantitative information from which new environmental flow releases could be developed and potential ecological outcomes could be assessed.

Ecosystems are complex, with multiple non-linear and indirect relationships; thus, it is not feasible to directly manage all species and habitats within an aquatic ecosystem. Instead, this EFS focused on a subset of physical processes, habitats, and species, collectively termed focal elements, occurring within the Hetch Hetchy Reach. The focal elements (described in Section 5.2) were developed in collaboration with the NPS, USFS, and USFWS, and are relatively well-known components of the river ecosystem that are likely to represent the environmental flow needs of the broader river ecosystem given current understanding.

Existing baseflows required as part of the 1987 Stipulation maintain suitable water temperatures for Rainbow Trout and Brown Trout within the Hetch Hetchy Reach, based on temperature monitoring conducted in recent years (Stillwater Sciences and McBain Associates 2019). The draft USFWS Physical Habitat Simulation (PHABSIM) analysis (USFWS 1992) proposed revising the baseflow requirements in the 1985 Stipulation to further optimize for trout physical habitat and temperatures, but did not consider broader ecosystem objectives or other riverine species such as Foothill Yellow-legged Frog. The 1987 Stipulation also specified the development of a framework for releasing additional springtime flows to "enhance the variability of flows and…simulate to the extent possible the natural conditions of the Tuolumne River."

Given the requirements of the 1985 and 1987 stipulations and guidance provided by the Stewardship Policy, a broad set of focal elements (see Section 5.2) were considered in developing new environmental flow recommendations. The focal elements depend on the full range of natural hydrograph components that were historically present in the Hetch Hetchy Reach; thus, recommendations are provided for a broad range of flows. To best use available operational flexibility for environmental flow management, two general operational environmental flow release components are recommended:

- *Baseflow management* – Minimum year-round releases, representing the baseflow (or low flow) component of the annual hydrograph.
- *Snowmelt management* – Seasonal (April through August) high flow releases driven by snowmelt inflow to Hetch Hetchy Reservoir.

Recommended baseflow and snowmelt management environmental flows are designed to work in tandem to support focal elements while facilitating practical operational implementation. Baseflow management releases are prescribed releases that provide a year-round foundation for management of the river ecosystem in the Hetch Hetchy Reach. Baseflows support snowmelt management releases during spring and early summer when inflows recede between peak snowmelt events and sustain the river ecosystem during the remainder of the water year (Figure 15). Snowmelt management "shapes" snowmelt spill releases to mimic the ecologically important functions of snowmelt hydrograph components during the period of snowmelt runoff (generally April through August).

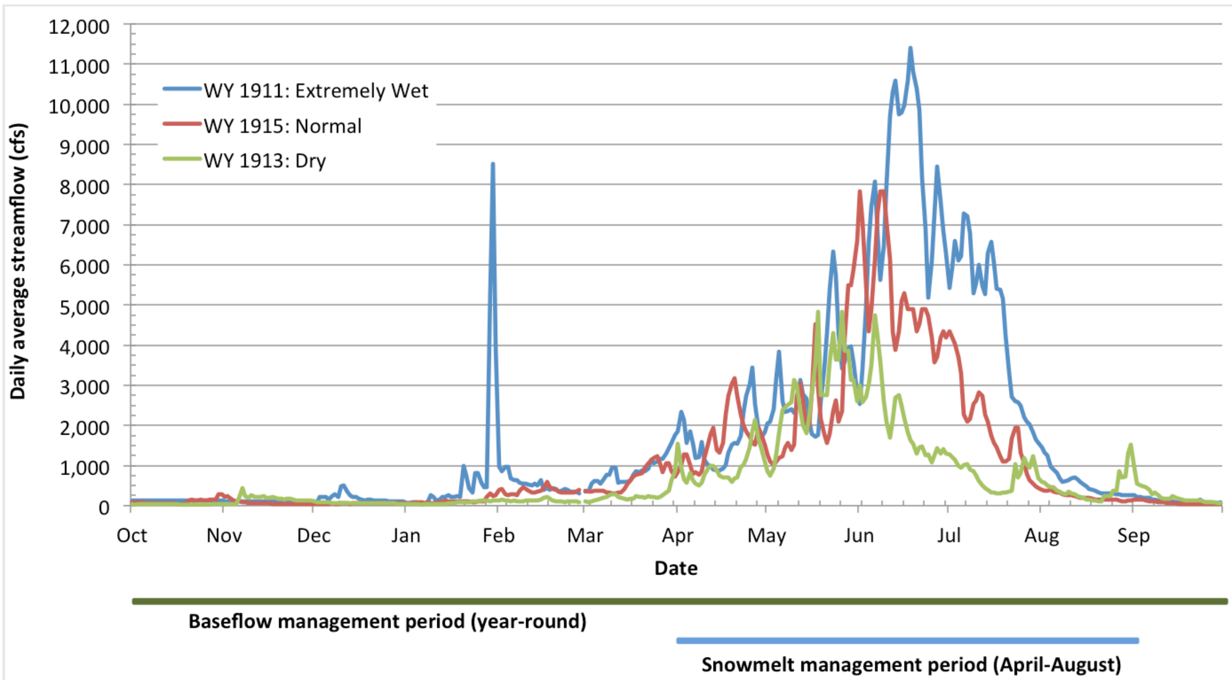

Figure 15. Baseflow and snowmelt management periods in relation to selected reference conditions hydrographs for a range of water year classes (see new water year classification in Section 6.1), at the Tuolumne River near Hetch Hetchy gage for WY 1911 (Extremely Wet), WY 1915 (Normal), and WY 1913 (Dry).

For each focal element described in Section 5.2, a set of ecological objectives and management targets were developed to guide environmental flow recommendations. An evaluation of the focal elements was conducted to determine if the ecological objectives and management targets are predicted to be met under the future flow regime. Each of these terms is described as follows:

- *Ecological objectives* – Simply stated desired outcomes for a specific focal element. Ecological objectives (discussed in Section 5.3) were derived from information gained during UTREP studies (listed in Section 5.1); discussions with the USFWS, NPS, and USFS; and the overall EFS approach (see Section 2.2).
- *Management targets* – Qualitative and quantitative flow magnitude, timing, duration, or temperature targets that, when achieved via baseflow and/or snowmelt management releases, should meet ecological objectives. The baseflow and snowmelt management target development process used relationships between flow and each focal element. These relationships were developed via field studies, values in scientific literature, contextualization with reference conditions, and model simulations. Qualitative baseflow and snowmelt management targets are listed in Section 5.3; quantitative management targets are developed and described in Section 7.2.
- *Environmental flow recommendations* – Recommended operational schedules or templates for releasing water from O'Shaughnessy Dam that are designed to meet management targets and

provide anticipated ecological outcomes when implemented. Baseflow and snowmelt management recommendations are described in Section 6.4 and Section 7.3.

5.1 Studies and analyses

An environmental flow study plan was developed in June 2009 (M&T 2009). Studies from that plan and additional follow-up studies were conducted and are listed below; methods, analyses, results, discussions, and application to the EFS for each of the studies are available in the referenced technical appendices. Studies and analyses directly applicable to the development of recommended environmental flows are summarized in Section 6, Section 7, and Section 8, and include:

- Geomorphic and hydrologic surveys to quantify inundation thresholds for wetlands in Poopenaut Valley (Appendix G), inundation thresholds for bars in the Early Intake Subreach (Appendix A), and bed mobility and scour thresholds for various geomorphic surfaces in the Hetch Hetchy Reach (Appendix E);
- Fish and wildlife surveys to document presence and relative abundance of aquatic and riparian species in the Hetch Hetchy Reach and to inform focal species selection (Appendix A and Appendix B; Jackson et al. 2020, Desrosiers et al. 2022);
- Wetland and riparian vegetation surveys to quantify vegetation in the Hetch Hetchy Reach, particularly for Poopenaut Valley (Appendix F); and
- Two-dimensional (2-D) physical habitat modeling, validated with direct habitat mapping (DHM) to assess flow-habitat relationships for Rainbow Trout, Foothill Yellow-legged Frog, and BMI in the Hetch Hetchy Reach (Appendix C).

To provide support, tools for integrating data, iterative analyses, and comparisons between existing and future environmental flow releases, the following analytical tools and models were developed:

- A Hetch Hetchy Reach Water Temperature Model to assess thermal regimes for focal species (Appendix A) in the Hetch Hetchy Reach (Appendix D);
- A Hetch Hetchy Reservoir Release Water Temperature Model to predict release temperatures, used as boundary conditions for the Hetch Hetchy Reach Water Temperature Model (Appendix D);
- An individual based model (IBM) to evaluate growth and population effects on Rainbow Trout and a spreadsheet model to compute the availability of habitat under future flows compared to existing flows (Appendix K);
- The “Bedload Assessment in Gravel-bedded Streams” (BAGS) sediment transport capacity model to assess potential changes in sediment transport capacity (Appendix E);
- Foothill Yellow-legged Frog Assessment Model to assess the effects of baseflows on reproductive success (Appendix A);
- A spreadsheet model to predict snowmelt recession rates needed for woody riparian vegetation seedling initiation (Appendix F);
- O’Shaughnessy Dam Spill Simulation spreadsheet analysis (Spill-Sim analysis) for average daily flow, to evaluate the operational feasibility and comparisons between existing and future spill management (Appendix I), including anticipated changes in bed mobility, water temperature, Poopenaut Valley

wetland and North Pond inundation and saturation, and the effects of drum gate operations (Appendix H); and

- Ramping rate analyses to inform development of more natural snowmelt recession ramping rates (Appendix H).

The environmental flow recommendations focus on the following elements:

- Baseflow release schedules that follow an updated water year classification (see Section 6);
- Ecological objectives associated with the snowmelt season (see Section 7); and
- Updated baseflow and high flow ramping rates (see Section 8).

The recommendations that are made in Section 6, Section 6, and Section 8 were evaluated by developing flow scenarios and evaluating them with ecological and physical models (Figure 16; described above). To develop flow scenarios, the baseflow schedule, snowmelt management objectives, and ramping rate recommendations were combined with operational guidelines using Spill-Sim. Spill-Sim is a spreadsheet-based reservoir operations tool that was developed and used to construct a future flow scenario that was evaluated against an existing flow scenario and reference conditions hydrology (see Section 8; Figure 16).

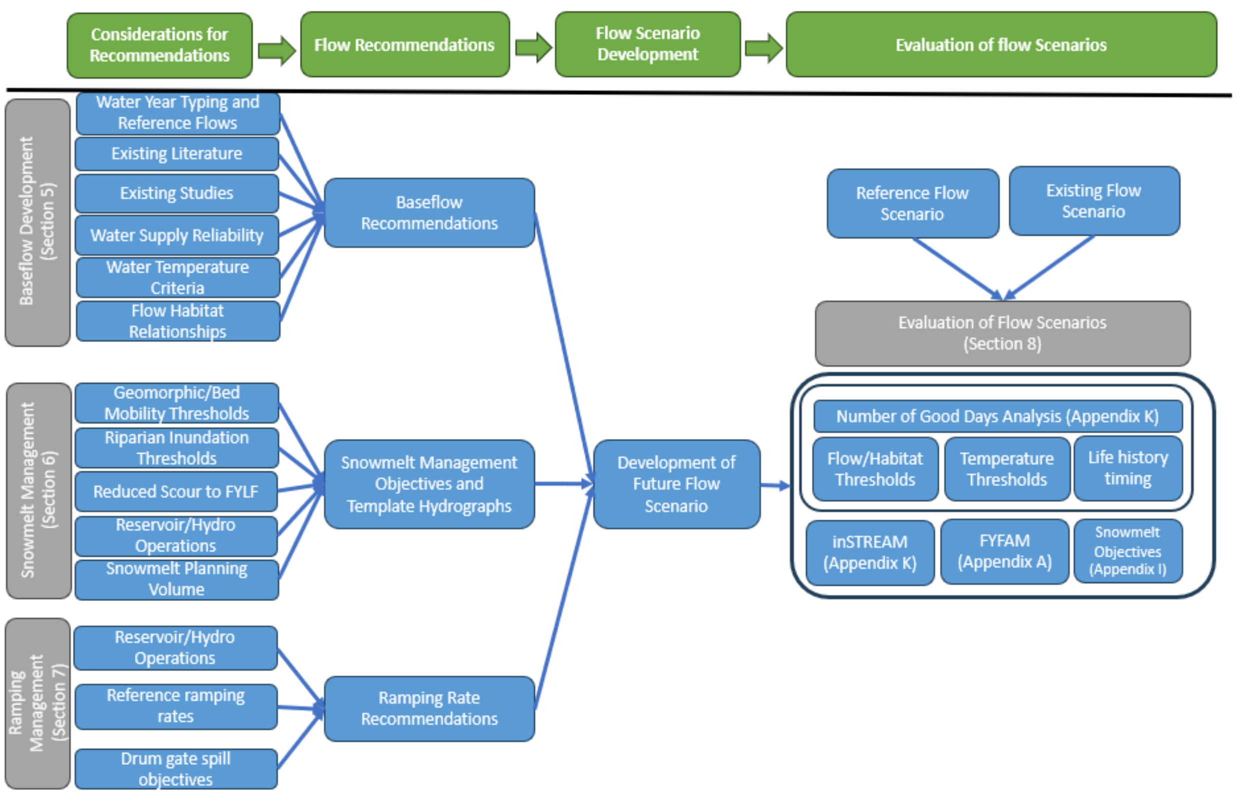

Figure 16. Flow chart describing the analytical process used in the environmental flow recommendations, the development of flow scenarios, and the evaluation of the flow scenarios using ecological and physical tools. Tools used to evaluate the flow scenarios are described in Section 8.

5.2 Focal elements

Based on the approach and goals of this EFS (see Section 2.3), data from previous studies, and discussions with the USFWS, NPS, and USFS, a broad range of physical processes, habitats, and species were identified as potential focal elements. The selection of focal elements was guided by historical and present-day USFWS and NPS priorities, representation of natural hydrograph components, associated geomorphic processes (e.g., spring snowmelt floods and bed mobility), and habitats and species of conservation interest (e.g., wetlands and Foothill Yellow-legged Frog). Other native species, including Sierra Newt, Sierra Garter Snake, and Northwestern Pond Turtle, and native bats were found to be relatively abundant and will also benefit from the natural hydrograph components used, but were considered to be less affected by the range of flows being considered and thus were not included as focal elements.

Undesirable non-native species are often included in management plans to develop control or eradication strategies. This EFS considered management of non-native species but does not provide specific measures for discouraging them because of the challenges of controlling non-native salmonids such as Brown Trout. Himalayan blackberry (*Rubus armeniacus*) and American Bullfrog (*Lithobates catesbeianus*) are present within the Hetch Hetchy Reach and are actively managed by the NPS.

Given the selection factors above and the rationale described below, the following focal elements were selected and developed to guide development of recommendations:

- *Rainbow Trout* — Native Rainbow Trout and non-native Brown Trout are both important recreational sport fish and have been the focus of previous USFWS Hetch Hetchy Reach flow-habitat studies and management efforts aimed at maximizing trout abundance (USFWS 1976, 1992). The life stages of Rainbow Trout can have different physical and ecological needs which are directly tied to the local hydrologic regime (**Error! Reference source not found.**). Within a year, Rainbow Trout While Brown T rout will continue to be a member of the Hetch Hetchy Reach fish community, this study focuses on recommendations for native species; thus, Rainbow Trout were selected as a focal element.
- *Benthic macroinvertebrates (BMI)* — BMI integrate physical, chemical, and biological processes and are thus highly valued as indicators of aquatic habitat quality (Karr 1999, Kenney et al. 2009). Health and richness of species – Mayflies (*Ephemeroptera*), Stoneflies (*Plecoptera*), and Caddisflies (*Trichoptera*) – are commonly used as indicators of ecosystem health and water quality, and these species, present year round (**Error! Reference source not found.**) are important food sources for r earing juvenile and adult salmonids (including Rainbow Trout) and other aquatic, semi-aquatic and terrestrial animals (including non-trout fishes, amphibians, reptiles, turtles, birds, bats).
- *Foothill Yellow-legged Frogs* — Observations of Foothill Yellow-legged Frogs have been made in the Hetch Hetchy Reach, and the species is a focus of conservation efforts throughout California due to significant declines in their populations. The East/Southern Sierra Clade is listed as endangered under the California Endangered Species Act (CESA 1972, CDFW 2019) and the Southern Sierra Distinct Population Segment (DPS) is listed as endangered under the federal Endangered Species Act (ESA 1973; USFWS 2023a). The egg mass and tadpole life stages (**Error! Reference source not found.**) are v ulnerable to the synergistic hydrologic, geomorphic, and thermal effects of flow regulation, particularly pulse flows that occur in late spring and summer, and cold spring and summer baseflows.
- *Bed mobility and scour* — Sediment deposits typically provide the physical template for aquatic and riparian habitat in riverine ecosystems and therefore represent an important linkage between channel

morphology and aquatic/terrestrial habitats. These basic fluvial geomorphic processes help organize and maintain river channel habitats for numerous species and depend on high magnitude winter floods and/or spring snowmelt floods to mobilize sediments and scour floodplain surfaces that define the river corridor. Both processes play a role in maintaining Rainbow Trout spawning gravels and preventing encroachment of woody riparian vegetation into the channel, which can degrade cobble bar habitats that Foothill Yellow-legged Frog rely on for egg masses and tadpole rearing.

- *Flow recession (ramping) rates* – One of the key hydrologic effects of flow regulation downstream of dams is an increased rate of change during variable flows. Artificially rapid flow recessions, or downramping, can have a variety of effects on riverine biota and ecosystem function, including (1) unnatural stranding of fish (all life stages) in shallow isolated pools and substrate interstices where they are vulnerable to predation and desiccation; (2) dewatering and desiccation of fish redds and amphibian egg masses and larvae; (3) desiccation of BMI and thus reduced prey-base available for invertebrate-foraging species; and (4) rapid dewatering and desiccation of riparian vegetation seedlings, preventing initiation and establishment of new riparian cohorts. The snowmelt recession hydrograph component is particularly important in the rivers of the Sierra Nevada because numerous native species time their reproduction based on its predictable characteristics (Yarnell et al. 2010, M&T and RMC 2008). Ramping rates manage flow magnitude transitions and are best described as an operational focal element.
- *Poopenaut Valley wetlands* — The Poopenaut Valley wetlands, including the North Pond, support a diverse riverine-wetland ecosystem that relies on frequent, sustained high magnitude spring snowmelt floods to maintain soil saturation and wetland vegetation (NPS 2009). Inundation frequency and duration for higher elevation meadow surfaces have been reduced under Hetch Hetchy Reach flow regulation compared to reference conditions, potentially reducing wetland extent and quality, and reducing nutrient inputs to the mainstem river (Appendix I). Given the reduced magnitude of peak runoff, it’s possible that the wetlands of Poopenaut Valley were much higher historically. The Poopenaut Valley wetlands are an important resource management area for Yosemite National Park. The North Pond sustains a diverse wetland ecosystem and unlike other wetlands in Poopenaut Valley, once filled, the North Pond can hold water for six to seven and a half weeks after inundation (NPS 2010, C. Fong pers. comm.), supporting a robust food web into the late spring and summer. As with other wetland habitats in Poopenaut Valley, the North Pond experiences less frequent inundation events compared to reference conditions, potentially affecting related food webs and productivity (NPS 2012).
- *Riparian vegetation encroachment* — Riparian vegetation can provide habitat for riparian birds and riverine wildlife but may also reduce available physical habitat for aquatic organisms when impaired peak flow regimes allow encroachment of vegetation onto formerly mobile alluvial deposits in the river channel. Vegetation encroachment in the Hetch Hetchy Reach is evident, resulting from flow regulation by O’Shaughnessy Dam and changes in Hetch Hetchy Reach facilities over time, which has caused modest amounts of channel simplification in some areas (Appendix F).
- *Riparian plant species recruitment* — The development of a complex woody riparian vegetation mosaic outside of the active channel on higher floodplain surfaces can provide important habitat for the life history needs of riparian birds and other wildlife, as well as providing stream shading, cover, and food for aquatic organisms. The life histories of many riparian plants in the Sierra Nevada are tied to the snowmelt hydrograph, and particularly the snowmelt recession, during which they release seeds, and seeds germinate and initiate growth. The successful initiation of many riparian woody

plants in the Sierra Nevada relies on the presence of bare sediment recently scoured by spring snowmelt floods and maintenance of groundwater levels via a slow snowmelt recession to maintain water within reach of initiating plant roots. Both hydrograph components (snowmelt peak flow and the recession) have been affected by flow regulation in the Hetch Hetchy Reach (RMC and M&T 2007; Appendix F).

- *Riparian Habitat Joint Venture (RHJV) bird nesting* — Song Sparrows and other RHJV focal bird species are susceptible to high magnitude spring snowmelt releases because they forage and nest in the riparian zone, which is prone to inundation during the spring snowmelt period. While nest inundation was likely a natural occurrence under reference conditions, flow regulation may exacerbate nest loss due to high magnitude pulse flows interspersed with periods of low baseflows, which may foster low-elevation nesting that is vulnerable to subsequent inundation. Rapid ramping rates under regulated conditions can raise river levels prior to nesting season, which can act as a cue for birds to nest higher in the riparian zone. Under reference condition normal and wetter water year conditions, low-lying riparian vegetation would likely have remained inundated for much of the duration of the nesting season, encouraging higher elevation nesting and reducing the risk of nest loss due to inundation.

5.3 Ecological goals and management objectives

A set of ecological goals and management objectives were compiled to guide environmental flow recommendation development. The ecological goals and management objectives were paired with applicable natural hydrograph components for reference and one or more targeted environmental flow management categories (Table 4). Specific management targets were then developed under the relevant flow management category to address each objective using data from UTREP studies and supporting analyses.

Table 4. *Focal elements, ecological goals, management objectives, associated natural hydrograph components, and environmental flow management categories.*

Focal element	Ecological goals	Management objectives	Natural hydrograph component	Environmental flow management category
Rainbow Trout	Maintain and/or increase native Rainbow Trout	Provide abundant rearing habitat for adults and juveniles	(A) Snowmelt peaks and recession (B) Summer baseflows	Baseflow management
		Provide sufficient spawning habitat	(A) Snowmelt peaks and recession (B) Spring baseflows	Baseflow and snowmelt management
		Provide water temperatures that promote Rainbow Trout growth in spring and summer	(A) Snowmelt peaks and recession (B) Summer and early fall baseflows	Baseflow and snowmelt management
		Manage daily average and maximum water temperatures in summer	Summer baseflows	Baseflow and snowmelt management
BMI	Maintain BMI production in the spring to support Rainbow Trout growth, providing food web support for riparian birds and bats	Provide abundant instream habitat	(A) Snowmelt peaks and recession (B) Summer baseflows	Baseflow management
		Provide suitable water temperatures		
		Provide disturbance (bed scour) to mediate benthic algae and biofilm growth	Snowmelt peaks and recession	Snowmelt management
		Provide abundant wetland habitat		
Foothill Yellow-legged Frogs	Maintain or increase Foothill Yellow-legged Frog abundance	Provide abundant habitat for egg laying and tadpole development	Snowmelt recession and early summer baseflows	Baseflow and snowmelt management
		Provide suitable water temperatures for appropriate timing of breeding		
		Provide suitable water temperatures for egg and tadpole development	Summer baseflows	Baseflow management
		Avoid late season spill and rapid snowmelt recession downramping rates to reduce egg scour or	Snowmelt recession	Snowmelt management

Focal element	Ecological goals	Management objectives	Natural hydrograph component	Environmental flow management category
		desiccation or tadpole dislocation		
Bed mobility and scour	Improve fluvial geomorphic processes	Increase frequency of exceeding bed mobility and scour thresholds	(A) Snowmelt peaks (B) Winter peaks	Snowmelt management
Ramping rates	Reduce potential stranding, displacement, and/or excessive ramping-related energetic expenditures for native aquatic species, and promote riparian vegetation recruitment in wetter water years	Provide high flow downramping rates that more closely mimic downramping rates in the reference condition	Spring snowmelt and winter high flows	Snowmelt management (and winter high flows)
Poopenaut Valley wetlands	Maintain extent of Poopenaut Valley wetlands, and fill the North Pond at a frequency closer to pre-dam conditions (i.e., once every one to two years)	Increase the frequency and duration of inundation and saturation of wetlands and the North Pond	Snowmelt peaks and recession	Snowmelt management
Riparian vegetation encroachment	Reduce channel encroachment by riparian vegetation to maintain aquatic habitat	Increase frequency of exceeding bed mobility and scour thresholds	Snowmelt peaks	Snowmelt management
Focal riparian plant species recruitment	Increase recruitment of woody riparian vegetation on higher elevation geomorphic surfaces to provide riparian habitat	Provide slow snowmelt recession downramping rates that support woody riparian vegetation recruitment	(A) Snowmelt peak and recession (B) Summer baseflows	Snowmelt management
RHJV focal bird species nesting	Reduce risk of nest inundation during snowmelt season spill releases	During the snowmelt season, maintain higher flow releases to inundate lower elevation woody riparian plants and shrubs	(A) Snowmelt peaks (B) Winter peaks	Snowmelt management

(A) = Primary and (B) = secondary natural hydrograph components supporting a focal element.

6 Baseflow management

Baseflows are defined as the required minimum flow targets for year-round releases from O'Shaughnessy Dam, all of which are less than 300 cfs. Baseflows were developed to meet management objectives for each focal element (Table 4). The development of the baseflow release schedule considered (1) temperature needs and flow-habitat relationships for EFS focal elements, (2) seasonal patterns and components of reference condition hydrology, and (3) the need to support water supply reliability.

The first step in developing baseflows was to organize the ecological goals and management objectives for each focal element seasonally by baseflow period (Table 5). Baseflow periods were derived from reference condition hydrograph components (Table 1). Quantitative flow-habitat relationships and water temperature criteria were developed to guide baseflow targets in different baseflow periods and water year types (see Section 6.2). Based on methods used by Hetrick et al. (2009) on the Klamath River, 80% of maximum habitat was used to identify a high-capacity threshold for focal species (Rainbow Trout, Foothill Yellow-legged Frogs) on the Tuolumne River. This target cannot be met for all focal elements in all seasons and water year types, however, because of differences in the focal species respective habitat curves. For example, flows that create more than 80% maximum habitat capacity for adult Rainbow Trout do not necessarily create abundant habitat for breeding Foothill Yellow-legged Frogs. Similarly, "optimizing" flow at 80% maximum for any one individual species does not embrace natural ecological variation that is observed in snowmelt hydrographs (Poff et al. 1997). Furthermore, those flows might not have been observed under reference conditions in all water year types. Developing baseflows required balancing needs for different focal elements at different times of the year and prioritizing different focal elements across water year types, mimicking natural ecological and hydrologic diversity, and supporting water supply reliability. Creating recommendations that allow for flexibility for the benefit of the ecosystem as a whole and can mimic natural conditions have been more successful over relying on precise targets to dictate management (Hiers et al. 2016).

The baseflow recommendations are specific to each water year type of an updated water year classification system that represents the full range of refence condition hydrology (i.e., greater variability among water years than the existing classification). While there are recommended releases during all water years and baseflow periods, it is important to recognize that seasonal and especially spring snowmelt flow releases typically exceed the minimum baseflows during normal, wet, and extremely wet water year types. As a result, it is unusual for baseflows to be the only flow releases throughout the wetter water year types, so biological outcomes of baseflows were evaluated together with spring snowmelt releases to simulate the entire hydrograph that focal species would experience (see Section 9).

In summary, the steps for developing the baseflow schedule were as follows:

- Organize and synthesize ecological objectives for baseflow management, reference condition hydrology, and water supply reliability considerations by baseflow period (Table 5);
- Develop a new water year classification to better represent the natural variability of upper Tuolumne River hydrology (see Section 6.1);
- Quantify flow-habitat relationships for focal elements to inform baseflow recommendations needed to create habitat (see Section 6.2);
- Quantify water temperature requirements for focal elements (see Section 6.3); and
- Integrate all information on ecological objectives for baseflow management, reference condition hydrology, and water supply reliability considerations into baseflow recommendations (see Section 6.4).

Table 5. *Ecological objectives for baseflow management, reference condition hydrology, and water supply reliability considerations by hydrograph component for Rainbow Trout (RBT), Benthic macroinvertebrates (BMI), and Foothill Yellow-legged Frog (FYLF). Ecological objectives and water supply reliability considerations differ among water year types.*

Baseflow period	Focal element	Ecological objectives for baseflow management	Reference condition hydrology and water supply reliability considerations
Fall baseflows October 1–November 30	RBT	Sustain RBT habitat capacity similar to reference conditions and maintain suitable water temperatures for rearing	Low reference flows and precipitation during end of summer and fall Low inflows to Hetch Hetchy Reservoir, Management priority is to maintain storage levels
	BMI	Sustain habitat for BMI production	
	FYLF	Provide habitat and temperature for continued FYLF growth	
Winter baseflows*⁺ December 1–March 15	RBT	Maintain RBT habitat when growth potential is low	Variable higher baseflows, with periodic winter rain and snowstorms Management priority is to fill Hetch Hetchy Reservoir, Incoming precipitation often falls as snow and is uncertain until early spring (March/April)
	BMI	Maintain BMI habitat when production potential is low	
Early snowmelt* March 16–April 30 and Snowmelt runoff/spring and early summer baseflows* May 1–August 15	RBT	Provide abundant RBT habitat in normal and wet years, RBT spawning in all years, maintain water temperatures for growth	High flow release resulting from snowmelt followed by the snowmelt recession Increase inflows to Hetch Hetchy Reservoir, Management priority is to fill the reservoir High flow releases are common in Normal, Wet and Extremely Wet water years
	BMI	Provide abundant BMI habitat in all years	
	FYLF	Provide abundant habitat and suitable temperatures for egg laying and tadpole development, especially in dry and extremely dry years	
Late summer baseflows June 1–September 30	RBT	Maintain RBT habitat and suitable water temperatures for rearing	Low reference condition baseflows after the snowmelt period with minimal precipitation Low inflows to Hetch Hetchy Reservoir, Management priority is to maintain storage levels
	BMI	Maintain BMI habitat	
	FYLF	Provide abundant habitat FYLF breeding and rearing habitat, especially in Dry and Extremely Dry years	

**Snowmelt management objectives also guide valve and spill releases during winter and spring.*
⁺Adult Foothill Yellow-legged Frogs are in upland habitats and have not begun breeding. Winter and spring high flows are needed for habitat maintenance (e.g., fine sediment flushing and reduce riparian encroachment) and are discussed in the snowmelt management section (Section 6).

6.1 Development of the new baseflow water year classification

The annual water yield, or total volume of flow from a watershed (e.g., ac-ft per year), is an important hydrologic variable and varies widely from year to year on the upper Tuolumne River. Scaling the baseflow release schedule proportionally to the water year class (or water year “type”) is a common environmental flow management strategy, as it better represents typical variability in local hydrology.

The existing classification described in the 1985 Stipulation uses three water year classes that emphasized managing baseflows for drier years: Schedule A (normal/wetter), with an expected frequency of 60%; Schedule B (dry), with an expected frequency of 32%; and Schedule C (driest), with an expected frequency of 8%. Under this existing classification, years that were wetter than normal (Schedule A) did not result in correspondingly higher magnitude baseflow releases. Most normal and wetter years will experience spring spill events resulting in releases greater than baseflows in those years, but only during the spill period of approximately April/May through June in many cases.

To support the development of a baseflow release schedule that better represents the full range of reference condition hydrology and related ecosystem processes, the existing classification was modified to include five water year classes symmetrical around the median precipitation and inflow values (Figure 17). The new water year classification served as the basis for developing the baseflow release schedule, but it was not used in developing the snowmelt management framework (see Section 7).

The new water year classification was developed using precipitation data and reference flow data for the 1924–2021 period of record. To determine a monthly water year class, the new classification uses precipitation data for the October–May period, then switches to computed inflow for the June–July period. After July 31, the water year does not change again until January 1 of the following year.

To develop the classification, daily precipitation data were compiled for the Hetch Hetchy rain gage (HEM) (operated by the SFPUC). Daily unimpaired inflow data were computed by mass balance by the SFPUC from Hetch Hetchy Reservoir elevation changes, releases to the Tuolumne River, power draft releases into Canyon Power Tunnel, and evaporation. Then, cumulative precipitation and cumulative calculated unimpaired inflow to Hetch Hetchy Reservoir for the 1924–2021 period were ranked and plotted as an exceedance probability, and divided into five asymmetrically weighted classes separated by annual exceedance probabilities (p). The five classes are named “Extremely Wet” (p = 0 to 0.15), “Wet” (p =0.15 to 35), “Normal” (p = 0.35 to 0.65), “Dry” (p = 0.65 to 0.85), and “Extremely Dry” (p = 0.85 to 1.00). The resulting water year classification is compared to the existing 1985 and 1987 stipulations water year classification in Figure 17.

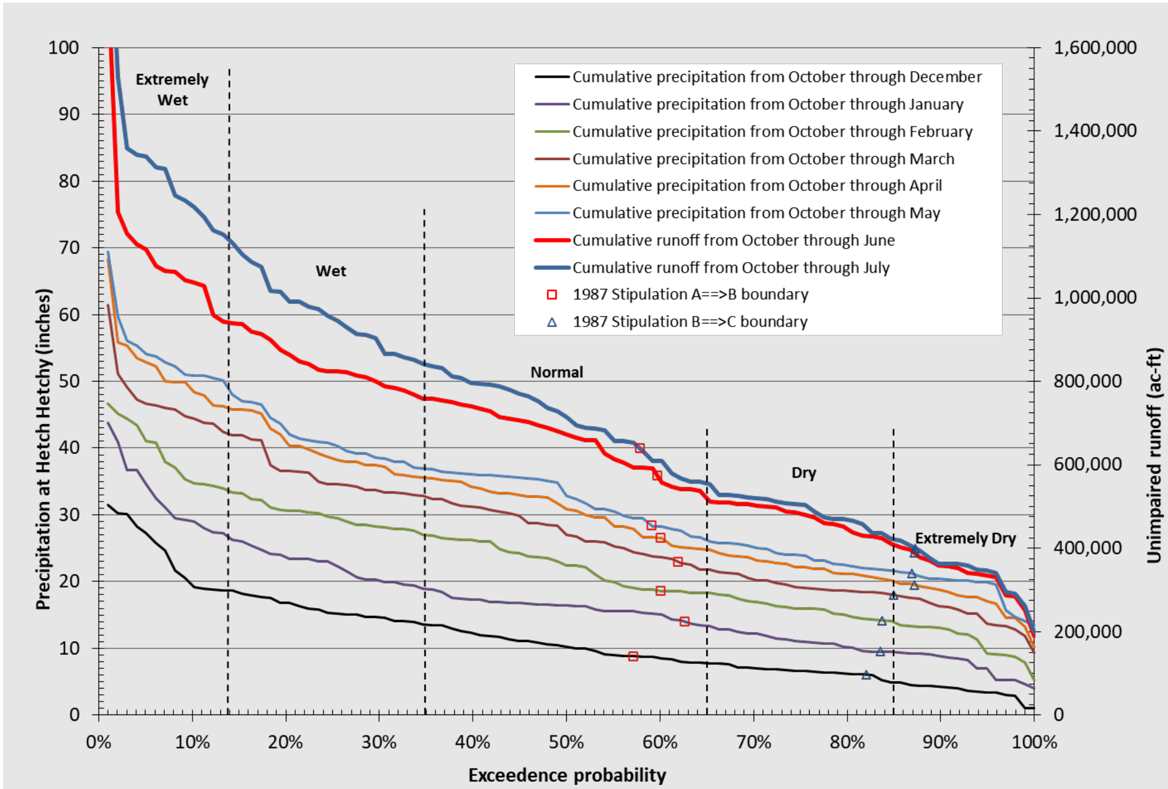

Figure 17. Cumulative precipitation and inflow computed from October 1 through a particular month. Reference condition flow was calculated from a mass-balance estimate using Hetch Hetchy Reach inflows (see Section 9.1).

As with the existing water year classification, the future water year classification is updated monthly, depending on antecedent watershed hydrology (precipitation or inflow). The water year class is determined as follows:

- Beginning on October 1, cumulative precipitation and inflow "reset" from the previous year and start to accumulate from zero inches;
- On January 1, the cumulative precipitation between October 1 and December 31 is computed and compared to the thresholds listed in Figure 17 (e.g., cumulative precipitation of 8.0 inches would result in a Normal water year baseflow release for January 1–31);
- The same precipitation summation and water year classification occur on February 1, March 1, April 1, May 1, and June 1;
- On July 1, cumulative computed inflow between October 1 and June 30 is compared to the thresholds listed in Table 6 (e.g., cumulative inflow of 800,000 ac-ft would result in a Wet year release for July 1–31);
- On August 1, cumulative computed inflow between October 1 and July 31 is compared to the thresholds listed in Figure 17 and Table 6; and

- The water year classification defined on August 1 is carried through to December 31 and is considered to be the final water year class (i.e., no more changes in water year classification until January 1).

Table 6. *Precipitation and reservoir inflow amounts used to classify water year types in the upper Tuolumne River. The 1985 and 1987 stipulations and the recommended future criteria are listed.*

Precipitation or inflow as of [date]	Water year classification and frequency (%)					1985/1987 stipulations water year classification and frequency (intended/actual %)		
	Extremely Wet	Wet	Normal	Dry	Extremely Dry	A	B	C
	15%	20%	30%	20%	15%	60/57%	32/30%	8/13%
Cumulative water year precipitation (inches)								
January 1	≥18.3	≥13.6	≥7.8	≥4.9	<4.9	≥8.8	≥6.1	<6.1
February 1	≥26.1	≥18.9	≥13.4	≥9.4	<9.4	≥14.0	≥9.5	<9.5
March 1	≥33.3	≥26.9	≥18.3	≥13.9	<13.9	≥18.6	≥14.2	<14.2
April 1	≥41.9	≥32.7	≥21.7	≥18.0	<18.0	≥23.0	≥18.0	<18.0
May 1	≥45.8	≥35.5	≥24.8	≥20.1	<20.1	≥26.6	≥19.5	<19.5
June 1	≥47.4	≥36.9	≥26.2	≥21.6	<21.6	≥28.5	≥21.3	<21.3
Cumulative calculated water year inflow (ac-ft)								
July 1	≥938,300	≥758,200	≥519,600	≥408,500	<408,500	≥575,000	≥390,000	<390,000
August 1	≥1,112,400	≥839,800	≥555,200	≥420,800	<420,800	≥640,000	≥400,000	<400,000

6.2 Development of flow-habitat curves

Flow-habitat relationships for focal elements were developed to inform the baseflow management schedule. Flow-habitat curves are a frequently used tool in regulated river management where the amount of habitat provided at a discharge for a focal taxon is estimated across a range of flows. Habitat is defined by specified habitat suitability criteria (HSC) that describe suitable depth, velocity, and cover requirements for each focal species taxa and life stage. The quantity and quality of habitat change as flows increase and decrease. Typically, habitat area increases with flows, until a certain point where velocities are too high in many places in the channel, leading to a decrease in available habitat. The results below report flow with the predicted maximum suitable habitat area, as well as the range of flows where habitat is at or greater than 80% of the maximum. This range of flows is considered the high habitat capacity range (Hetrick et al. 2009). The days when flows were within the high habitat capacity were considered "good days" to quantitatively assess flow scenarios in the Number of Good Days (NGD) analysis (see Section 9.3).

Flow-habitat curves were developed for the upper Tuolumne River using 2-D hydraulic models and habitat suitability curves. Given the complex hydraulic properties of the upper Tuolumne River, flow-habitat curves from the 2-D hydraulic models were validated with field-based DHM. Detailed methods and results are described in Appendix C, but in general, the 2-D models and DHM produced similar trends, so curves from 2-D models were used to develop baseflows given their greater range of flows.

Two study sites were selected for flow-habitat curve development that represent the dominant morphology and ecological functions of the Hetch Hetchy Reach: the Early Intake 2-D model site (EI site) and the O'Shaughnessy Dam 2-D model site (OSD site) (Figure 18). Mesohabitat types defined and mapped by the USFWS (1992) were used to compare the percentages of mesohabitats in the study sites with those of the entire Hetch Hetchy Reach to ensure the sites were representative. The breakdown of dominant mesohabitats found in the Hetch Hetchy Reach and in the two 2-D modeling sites can be found in Appendix C. Not every focal element group and life stage were considered at both sites because of the presence or absence of species or because of difficulty modeling certain life history components. For example, Rainbow Trout spawning habitat is only modeled at the OSD site because there are abundant spawning gravels where hydraulic conditions can be accurately represented. That contrasts with the EI site, which has a much larger (boulder) substrate, and spawning is believed to occur at very small (<0.5-square-meter) patches that are not realistically represented by hydraulic modeling. Similarly, Foothill Yellow-legged Frogs have only been observed within the Early Intake Subreach and were modeled there. At the OSD site, Foothill Yellow-legged Frogs have not been observed despite prior surveys; their absence is thought to be driven by the cold temperature releases from O'Shaughnessy Dam. Table 6 identifies the sites where flow-habitat curves were developed for each focal taxa and life stage.

Table 7. *Focal elements (BMI and life stages for Rainbow Trout and Foothill Yellow-legged Frog) assessed for two study sites. An X indicates that element was considered at that site.*

Focal element and life stage	OSD site	EI site
Rainbow Trout adult habitat	X	X
Rainbow Trout juvenile rearing	X	X
Rainbow Trout spawning	X	
BMI	X	X
Foothill Yellow-legged Frog eggs		X
Foothill Yellow-legged frog tadpoles		X

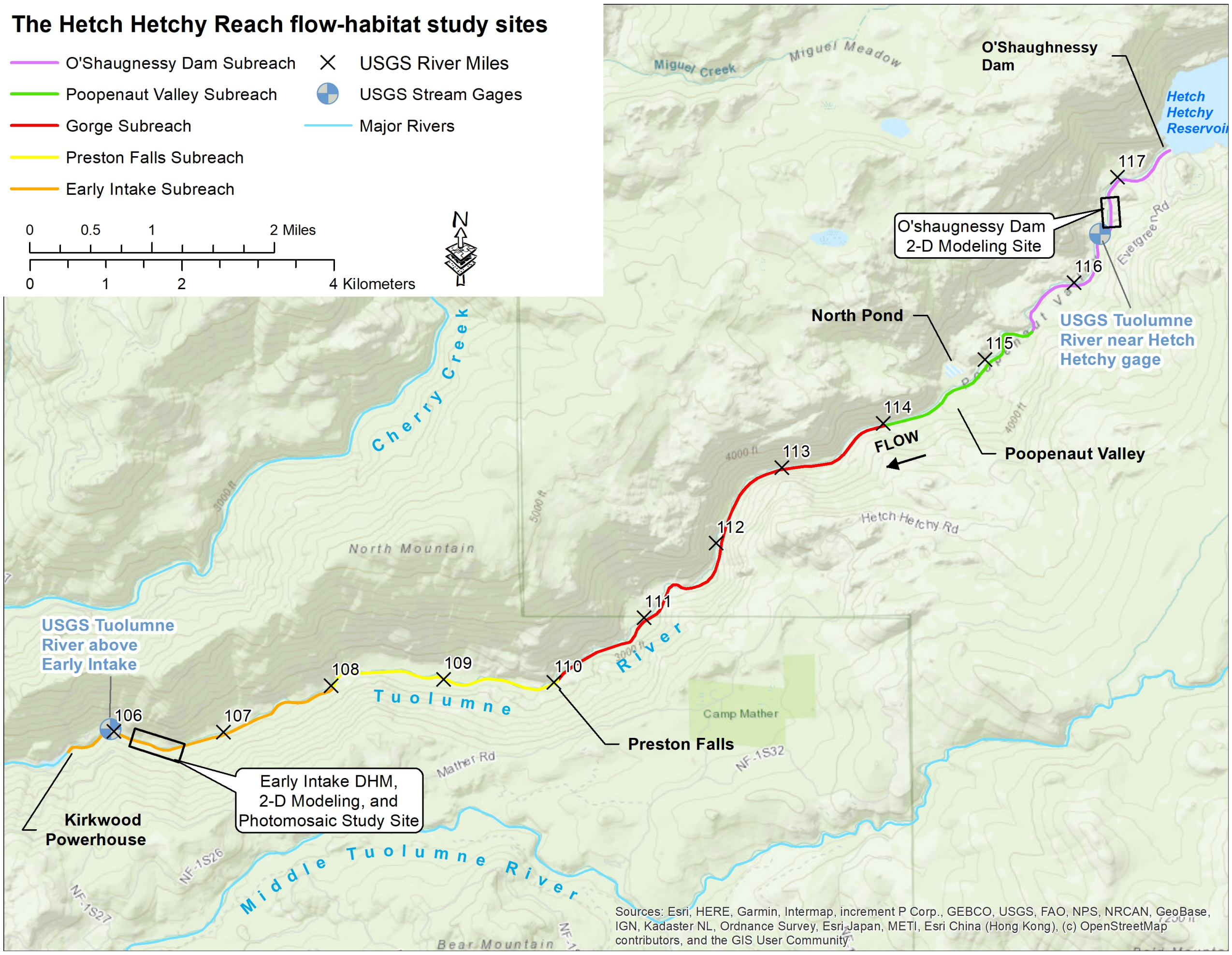

Figure 18. Location of the flow-habitat relationship study sites in the Hetch Hetchy Reach.

6.2.1 Habitat suitability criteria

HSC were developed for each focal taxa and life stage to develop flow-habitat curves from the 2-D hydraulic model outputs (Table 8). HSC can be developed using site-specific information or by using HSC developed for regional rivers with similar characteristics for the same taxa. HSC are a collection of environmental criteria that are preferred and determined suitable for the focal taxa. Depth, velocity, and substrate (spawning) and cover habitat are commonly used to describe habitat for salmonids, Foothill Yellow-legged Frogs, and BMI. These parameters were all used for different life stages of the focal taxa except for cover because cover is considered ubiquitous in the upper Tuolumne River. Further details about HSC are provided in Appendix C.

Table 8. *Focal taxon binary HSC used for DHM and 2-D modeling.*

Focal element	Life stage	Parameter	Criterion	Sources
Rainbow Trout	Adult	Depth	≥2.5 ft[a]	USFWS 2004
		Velocity	0.5–2.5 feet per second (ft/sec)[a]	
	Juvenile	Depth	1.4–3.35 ft	USFWS 2004
		Velocity	0.08–1.58 ft/sec	
	Spawning[b]	Depth	0.6–1.5 ft	TRPA 2002
		Velocity	1.1–1.8 ft/sec	
		Substrate	Gravel (D_{85} = 0.25–3 inches)	
Foothill Yellow-legged Frog[c]	Egg mass and tadpole[d]	Depth	0.2–1.5 ft	Yarnell et al. 2008, Bondi et al. 2013, Hayes et al. 2016
		Velocity	0.0–0.3 ft/sec	
		Substrate	Gravel – boulder	
BMI	All	Depth	1.5–3.5 ft[a]	USFWS 2006
		Velocity	1.5–3.5 ft/sec[a]	
		Substrate	Large cobble to small boulder (D_{50}=6–15 inches)[a]	

[a] Criteria developed from source HSC were adjusted for use in the upper Tuolumne River.
[b] Substrate criteria were applied to the adult Rainbow Trout spawning life stage in the OSD site only.
[c] HSC were not applied at the OSD site for Foothill Yellow-legged Frog because water temperatures are unsuitable and Foothill Yellow-legged Frogs have never been observed above Preston Falls.
[d] The depth preferences for Foothill Yellow-legged Frog egg mass and tadpole rearing were virtually identical, and the differences in velocity preferences were minor. Therefore, for simplicity, the life stages were combined, using the egg mass depth (0.2–1.5 ft) and velocity (0.0–0.3 ft/sec) criteria as the controlling HSC criteria.

6.2.2 Flow-habitat curves for Rainbow Trout

Habitat for adult Rainbow Trout at the OSD site peaked from 500 to 900 cfs; at these flows, suitable habitat was located within the middle of the channel. Habitat area was at 80% of the maximum habitat area from 250 to 1,700 cfs (Figure 19). Habitat declines at magnitudes greater than 900 cfs, as suitable depths and velocities shift to the edge of the channel and then become less suitable. Habitat for adult Rainbow Trout at the EI site was highest near 500 cfs and was at 80% of that maximum from 250 to 1,150 cfs (Figure 20). Similarly, habitat peaks when the middle of the channel reaches suitable depths and velocities, then declines when the remaining suitable habitat is at the edge of the channel.

Habitat for juvenile Rainbow Trout is at its maximum at much lower flows than habitat for adults, due to the lower depth and velocity requirements. At the OSD site, habitat peaks at 200 cfs and is at 80% of its maximum from 45 to 250 cfs (Figure 21). At the EI site, habitat peaks at 100 cfs and is at 80% of its maximum from less than 35 to 250 cfs (Figure 22).

Habitat for Rainbow Trout spawning at the OSD site displayed an unusual pattern with flow (Figure 23). There was an initial, small peak with 840 square feet of spawning habitat from 85 to 105 cfs, and then a second larger peak with 1130 square feet of spawning habitat near 500 cfs as suitable depths and velocities on the spawning gravel patch shift. Spawning habitat was at 80% of the maximum from 380 to 620 cfs. Planform images of flow-habitat curves are provided in Appendix C.

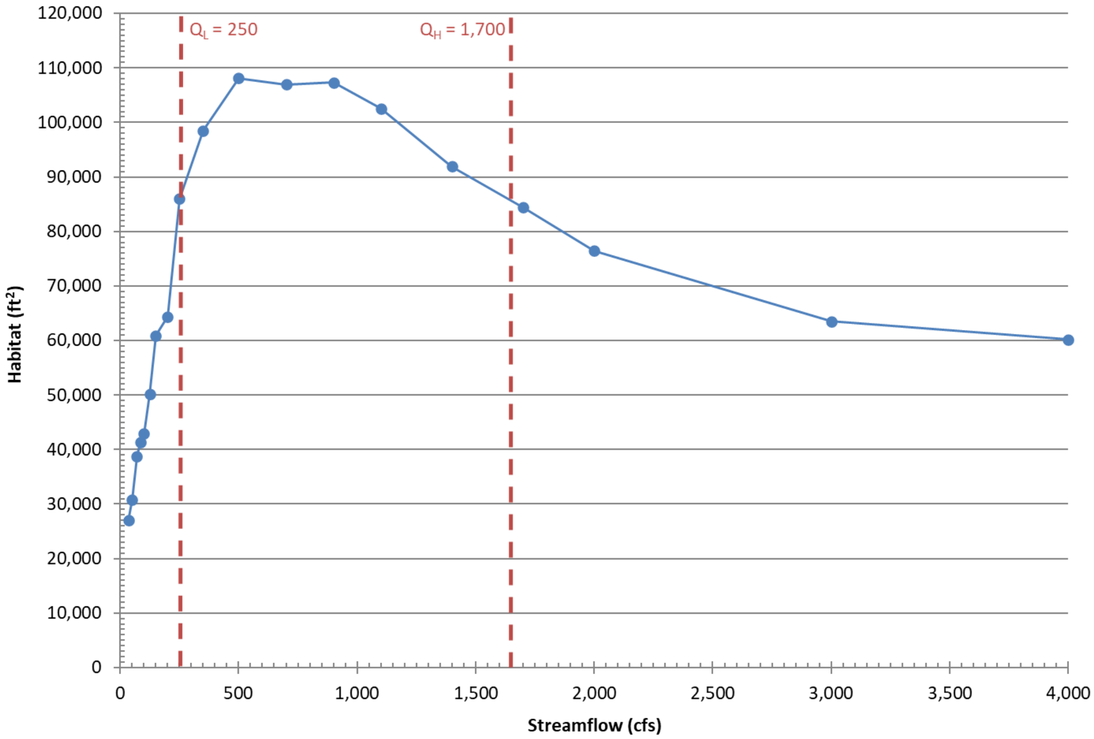

Figure 19. Flow-habitat curve for adult Rainbow Trout at the OSD site. The vertical red dashed lines represent the lower (Q_L) and upper (Q_H) flows required to achieve greater or equal to 80% of maximum habitat area.

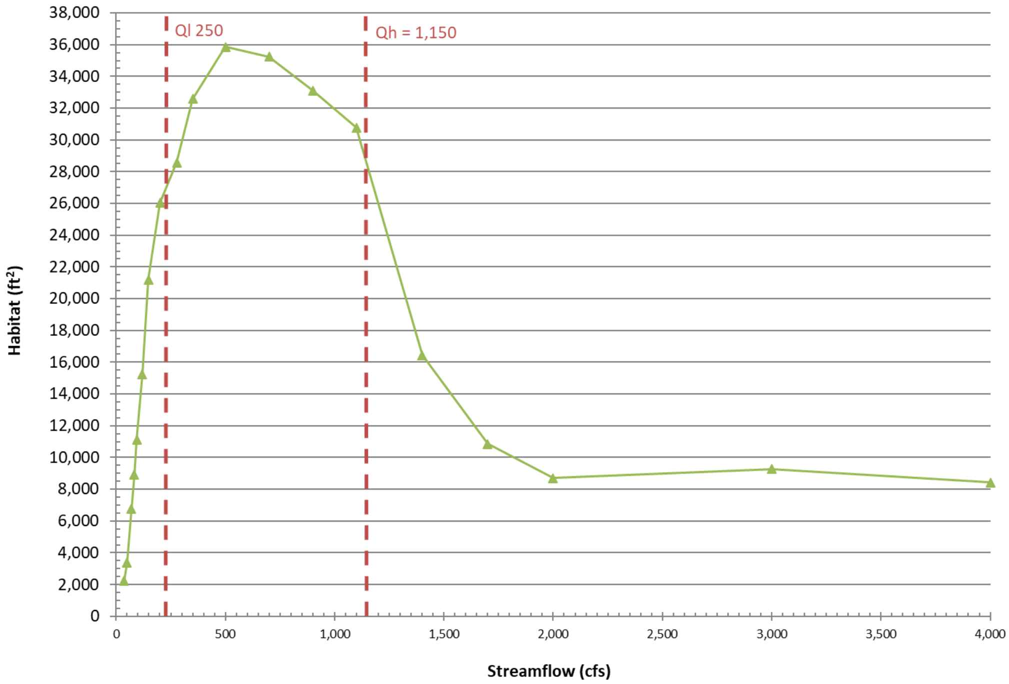

Figure 20. Flow-habitat curve for adult Rainbow Trout at the EI site. The vertical red dashed lines represent the lower (Q_L) and upper (Q_H) flows required to achieve greater or equal to 80% of maximum habitat area.

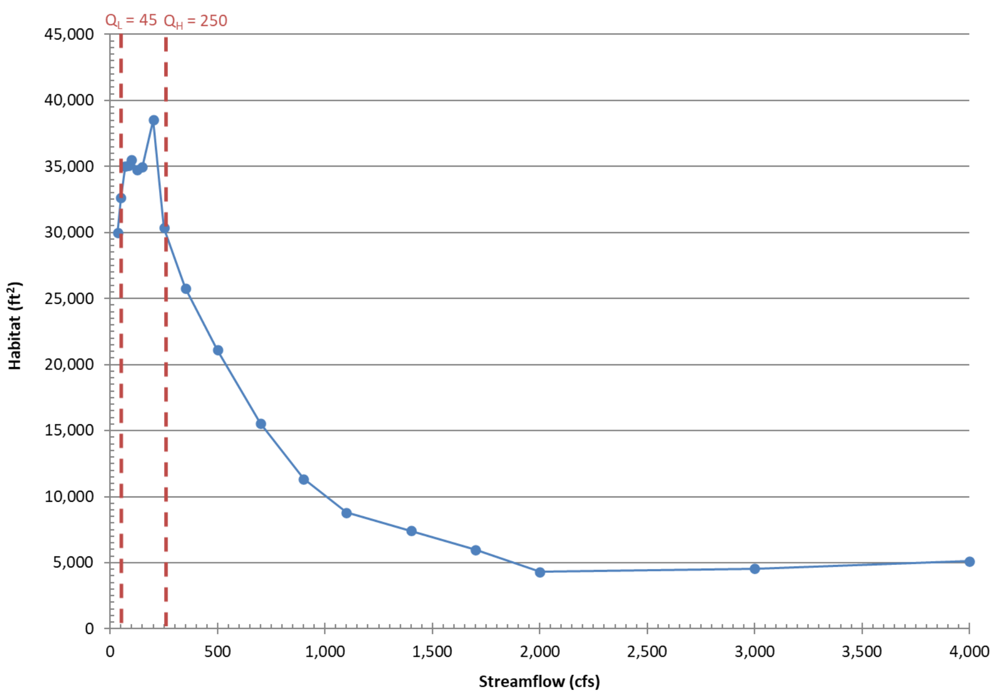

Figure 21. Flow-habitat curve for juvenile Rainbow Trout at the OSD site. The vertical red dashed lines represent the lower (Q_L) and upper (Q_H) flows required to achieve greater or equal to 80% of maximum habitat area.

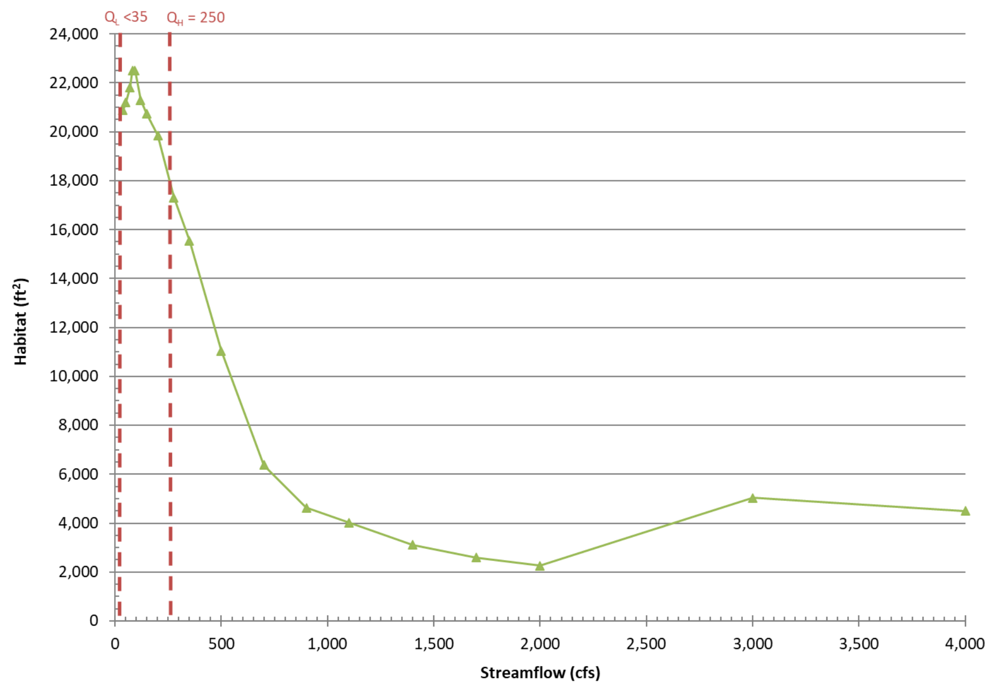

Figure 22. Flow-habitat curve for juvenile Rainbow Trout at the EI site. The vertical red dashed lines represent the lower (Q_L) and upper (Q_H) flows required to achieve greater or equal to 80% of maximum habitat area.

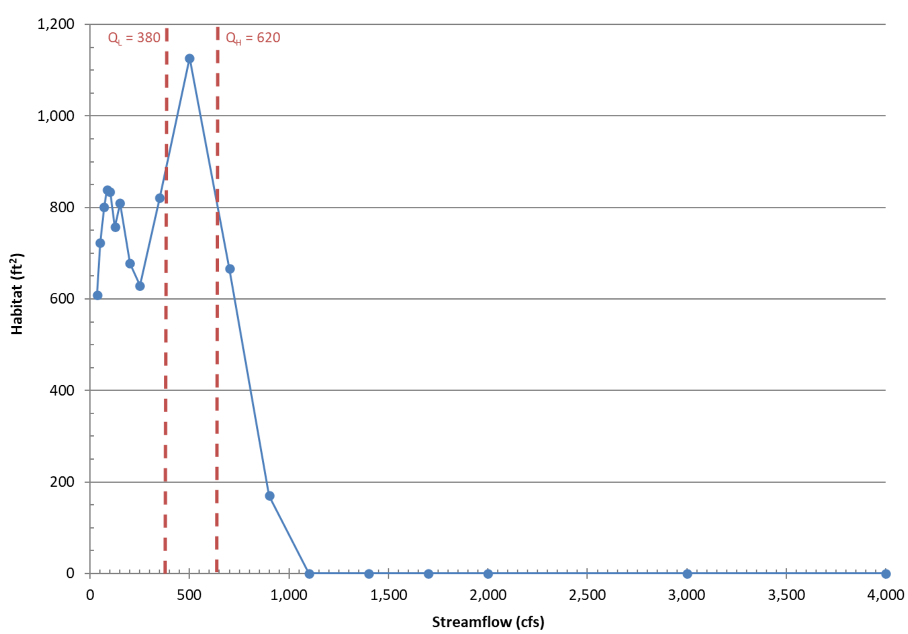

Figure 23. Spawning habitat for adult Rainbow trout at the OSD site. The vertical red dashed lines represent the lower (Q_L) and upper (Q_H) flows required to achieve greater or equal to 80% of maximum habitat area.

6.2.3 Flow-habitat curves for BMI

Habitat for BMI was greatest at the OSD site near 500 cfs and was at 80% of its maximum from 280 to 900 cfs (Figure 24). The amount of habitat at the OSD site increases quickly as flows approach 500 cfs because depths and velocities become more suitable in substrate best suited for BMI production. At the EI site, suitable substate for BMI production was ubiquitous and as a result suitable BMI habitat was greatest between 350 cfs and 1,100 cfs was at 80% of its maximum from 250 to 1,450 cfs (Figure 25). Planform images of flow-habitat curves are provided in Appendix C.

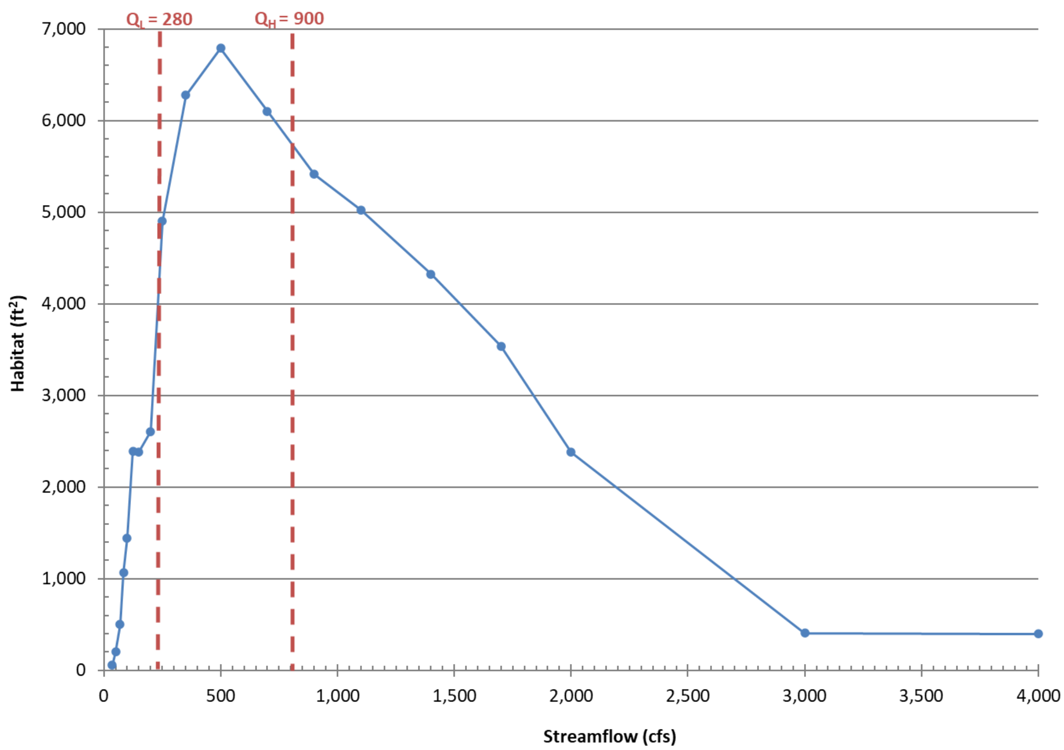

Figure 24. Productive BMI habitat with flow at the OSD site. The vertical red dashed lines represent the lower (Q_L) and upper (Q_H) flows required to achieve greater or equal to 80% of maximum habitat area.

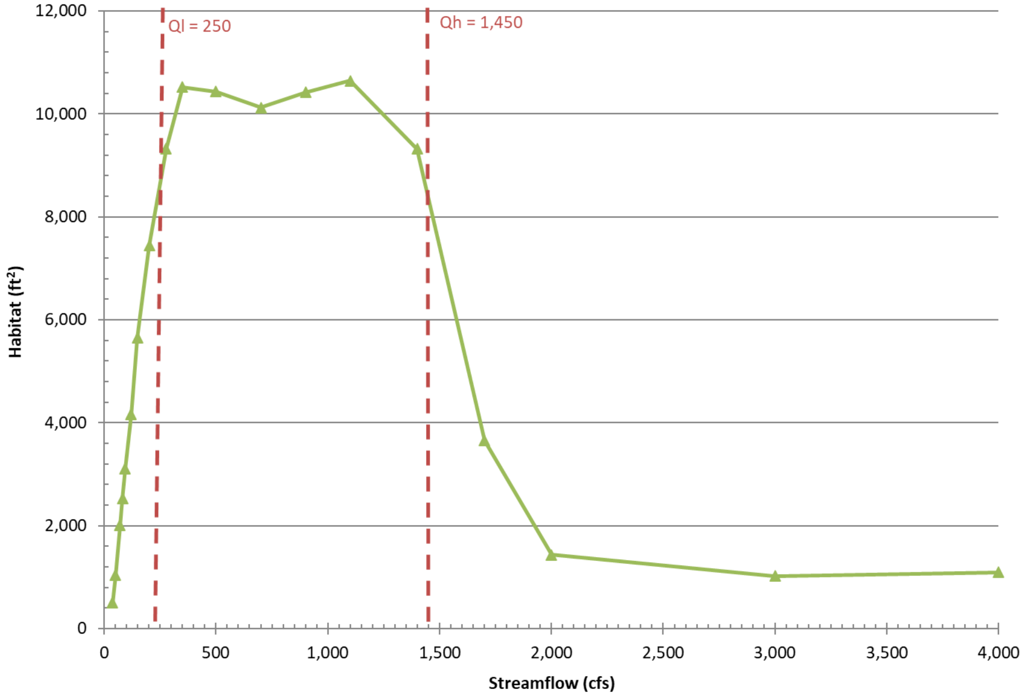

Figure 25. Productive BMI habitat with flow at the EI site. The vertical red dashed lines represent the lower (Q_L) and upper (Q_H) flows required to achieve greater or equal to 80% of maximum habitat area.

6.2.4 Flow-habitat curves for Foothill Yellow-legged Frog

Foothill Yellow-legged Frogs typically prefer shallow depths and slow velocities, and thus suitable flows for Foothill Yellow-legged Frog egg masses and tadpoles were lower than for adult Rainbow Trout and BMI. Suitable habitat was the greatest at 35 cfs before decreasing rapidly as flows increase. 80% of maximum habitat occurred at flows less than 40 cfs to 130 cfs (Figure 26). Regardless of flow, suitable habitat was typically located near the wetted edge of the river and moved laterally as flows increased and decreased. Planform images of flow-habitat curves are provided in Appendix C.

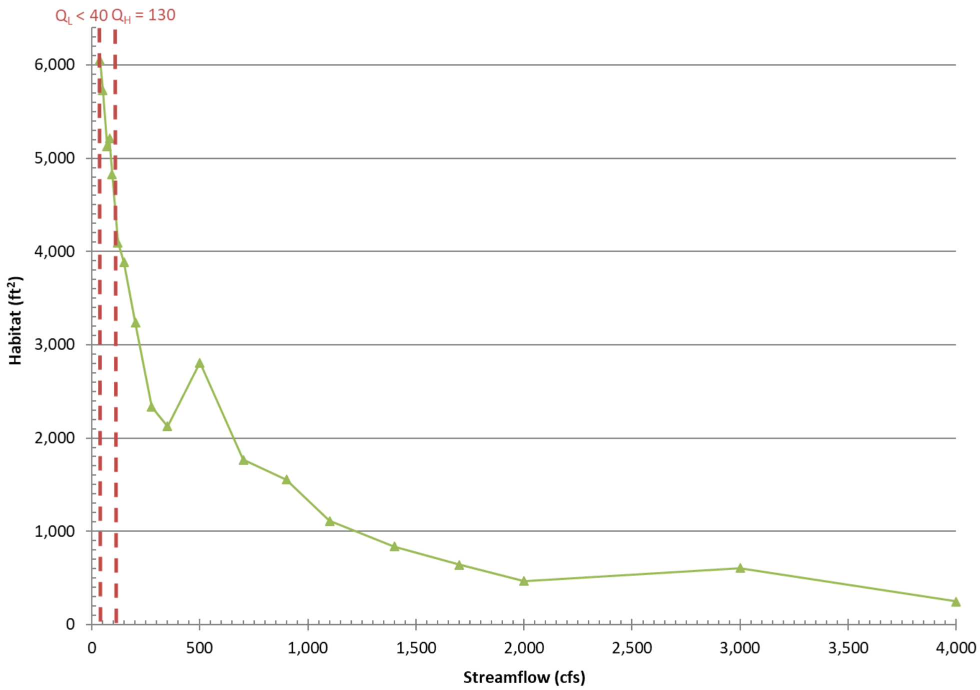

Figure 26. Foothill Yellow-legged Frog egg mass and tadpole habitat with flow at the EI site. The vertical red dashed lines represent the lower (Q_L) and upper (Q_H) flows required to achieve greater or equal to 80% of maximum habitat area.

6.3 Thermal objectives for focal elements

Thermal preferences and tolerances were synthesized for focal elements through a literature review that relied on regional data when possible (Table 9). These water temperature preferences were used to guide the development of baseflows with focus on avoiding stressful temperatures and providing optimal temperatures for growth. The ability of recommended baseflows to produce water temperatures within the suitable ranges was quantified with water temperature models and the NGD analysis (see Section 9.3).

Table 9. *Thermal (water temperature) objectives for focal elements and the associated component of their life history.*

Focal element	Life history component	Time window	Water temperature
Rainbow Trout	Promote growth for juveniles and adults	Spring–Fall March 15 to October 31	Daily average: 10–22°C[a,b,c,d]
	Manage daily average and maximum water temperatures	Year-round, of concern in Summer July 1 to August 31	Daily average: ≤25°C[d,e,f] Daily maximum: ≤28°C[e.f]
	Suitable spawning and egg incubation temperatures	Spring March 15 to May 31	Daily average: 8–13°C[g]
BMI	Promote growth and reproduction and reduce periphyton cover	Year-round	Daily average: ≥5°C [h,I,j]
Foothill Yellow-legged Frogs	Suitable water temperatures for breeding	Late Spring and Early Summer May 1 to June 31	Daily average: ≥12°C [,k,l,m,n]
	Suitable water temperatures for tadpole and metamorph development	Summer June 1 to September 15	Daily average: 16–24°C [k,l,m,n,o]

[a]Railsback and Rose (1999), [b]Jager et al. (1999), [c]Myrick and Cech (2000), [d]Verhille et al. (2016), [e]Hokanson et al. (1977), [f]Matthews and Berg (1997), [g]Railsback et al. (2021), [h](Brittain 1982), [i]Elliott (1987), [j]Gallepp (1977), [k]Catenazzi and Kupferberg (2013), [l]Catenazzi and Kupferberg (2018), [m]Wheeler et al. (2015), [n]Rose et al. (2023), [o]Olson and Davis (2009)

6.4 Baseflow release schedule

The recommended baseflow release schedule is provided in Table 10 and illustrated in Figure 27. Based on the water year classification (Table 6), flows may change monthly or bi-monthly between January and June due to a change in cumulative precipitation, and between July and August due to a change in measured cumulative inflow, which trigger changes to the water year type and thus changes to baseflows.

Overall, the recommended baseflow release schedule seeks to balance environmental flow needs for Rainbow Trout and Foothill Yellow-legged Frogs, the seasonal variation in the reference condition, and to support water supply reliability considerations (Table 5). This approach takes into consideration that not all water years will be favorable for all aquatic focal species. For example, higher baseflows during wet and very wet water years may result in more favorable conditions for Rainbow Trout and less favorable conditions for Foothill Yellow-legged Frog, but the reverse is true in dry and very dry years. In general, greater baseflow magnitudes during the spring and early summer were a high priority in developing baseflows to mimic reference conditions and provide high habitat capacity during an ecologically productive and important season. Baseflows in other seasons (e.g., winter) were typically lower than reference flows to support water supply reliability during a time when adult Rainbow Trout are not compromised by lower flows because growth conditions are naturally low due to cold water temperature.

The recommended winter baseflows also support the ability to conserve water that can later be released to meet priority spring snowmelt management objectives during other seasons (see Section 7).

The recommended baseflow release schedule represents the minimum required release from O'Shaughnessy Dam to meet the ecological objectives for baseflow management (Table 5). Natural accretion and recommended snowmelt management releases (see Section 7) will provide additional flow magnitude, particularly during winter and spring. Accretion between O'Shaughnessy Dam and Kirkwood Powerhouse is relatively low during the late summer and fall periods (typically 0 cfs to 10 cfs) but is more substantial in the winter and spring due to precipitation and snowmelt runoff. See Appendix J for a discussion of accretion calculations.

Specific rationale for the recommended baseflow release schedule is provided in Appendix K.

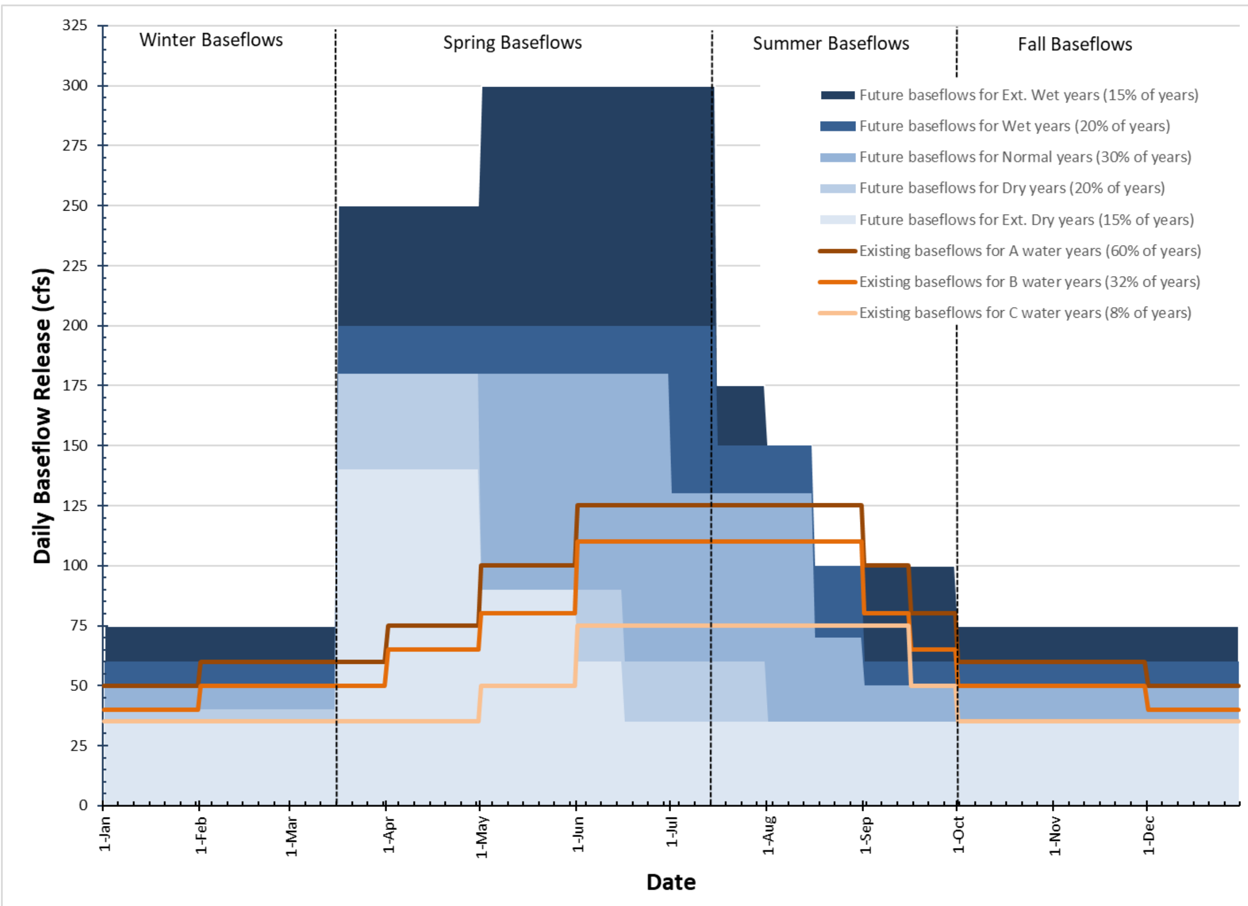

Figure 27. Comparison of existing and future baseflow release schedules for O'Shaughnessy Dam for each respective water year class, illustrating the shift in recommended baseflow releases from summer and fall (existing baseflows) to spring and early summer (future baseflows). Expected frequency of water year class occurrence is shown in parentheses in the legend. Chart represents flows for single water year classes, i.e., without monthly or bi-weekly changes in water year class based on precipitation and inflow, as would occur under actual operations.

Table 10. *The recommended O'Shaughnessy Dam baseflow release schedule.*

Baseflow period	Timing with reference condition hydrograph components	Extremely Wet (cfs)	Wet (cfs)	Normal (cfs)	Dry (cfs)	Extremely Dry (cfs)
January 1–15	Winter baseflows	75	60	50	40	35
January 16–31		75	60	50	40	35
February 1–15		75	60	50	40	35
February 16–28		75	60	50	40	35
March 1–15		75	60	50	40	35
March 16–31	Early snowmelt runoff	250	200	180	180	140
April 1–15		250	200	180	180	140
April 16–30		250	200	180	180	140
May 1–15	Snowmelt runoff/ spring and early summer baseflows	300	200	180	90	90
May 16–31		300	200	180	90	90
June 1–15		300	200	180	90	60
June 16–30		300	200	180	60	35
July 1–15		300	200	130	60	35
July 16–31		175	150	130	60	35
August 1–15		150	150	130	35	35
August 16–31	Late summer baseflows	100	100	70	35	35
September 1–15		100	60	50	35	35
September 16–30		100	60	50	35	35
October 1–15	Fall baseflows	75	60	50	35	35
October 16–31		75	60	50	35	35
November 1–15		75	60	50	35	35
November 16–30		75	60	50	35	35
December 1–15	Winter baseflows	75	60	50	35	35
December 16–31		75	60	50	35	35
Total Baseflow Volume (ac-ft):		**111,868**	**84,119**	**71,722**	**46,602**	**39,045**

7 Snowmelt management

Hetch Hetchy Reservoir has a relatively small storage capacity compared to the typically larger volume of annual unimpaired inflow from the upper Tuolumne River watershed. This relatively small storage capacity results in frequent spills in spring and early summer during normal and wetter years. As initially described in Section 5, recommended snowmelt management releases should mimic the ecologically important functions of snowmelt hydrograph components during the period of snowmelt runoff (generally April through August). Thus, the snowmelt management period is defined as April through August to represent the broad range of months in which snowmelt occurs in the upper Tuolumne River watershed based on reference conditions. Snowmelt management recommendations use spill releases greater than 300 cfs (above baseflow releases) to achieve management objectives (see Section 5.3) via implementation of quantitative management targets that vary in magnitude, timing, and duration depending on available spill volume. Snowmelt management does not rely on the baseflow management water year classification scheme; instead, a series of template hydrographs (see Section 7.4) organize implementation of snowmelt management targets by forecasted available spill volume, known operationally as the “planning volume.”

7.1 Development of planning volumes

The planning volume is the amount of spill available to achieve snowmelt management targets (listed in Table 13 in Section 6.3 below) each year. It is conceptually defined as the total forecasted inflow to Hetch Hetchy Reservoir, subtracting the volume needed to fill the reservoir, maintain baseflow releases, and support water supply reliability and hydropower uses. The planning volumes are linked to template hydrographs (Figure 33 through Figure 43 in Section 6.3 below) that are designed to implement appropriate combinations of snowmelt management targets (see Section 7.3). The planning volume is used to determine which snowmelt management targets can be achieved in a particular year. The planning volume is calculated using a suite of models, weather forecasting products, and other analyses to estimate potential future weather conditions, anticipated inflow volume, and total resulting spill volumes. Given the inherent hydrological variability and uncertainty in inflow forecasting and natural hydrologic variability, actual spill volumes will inevitably vary from forecasted planning volumes and real-time decision-making regarding achievement of snowmelt management targets will need to be accommodated.

7.2 Development of quantitative snowmelt management targets

To develop quantitative snowmelt management targets, flow magnitude thresholds for major geomorphic and hydrologic processes, such as bed mobility and scour, and Poopenaut Valley wetland inundation and saturation were identified. These data, combined with reference condition hydrology, wetland function, and stage/inundation relationships for selected RHJV bird and Foothill Yellow-legged Frog habitats, provided the information necessary to develop quantitative snowmelt management targets.

The summaries provided below emphasize the important findings from each study as they relate to the development of quantitative snowmelt management targets; more technical readers are referred to appendices and reports specified in the text for detailed descriptions of methods and results.

7.2.1 Bed mobility and scour flow thresholds

To develop bed mobility and scour flow targets for snowmelt management, the SFPUC conducted a series of experiments in the Hetch Hetchy Reach to record flow thresholds for mobilization and/or scour of various sized sediment during annual peak flow events. Experiments were installed prior to experimental peak flow events and were subsequently revisited to document results (Appendix E). The studies used tracer rock and scour core studies at sediment deposits of various types and scale during peak flows ranging from 3,770 cfs to greater than 8,000 cfs, including:

- Gravel and small cobble pool tail in the O'Shaughnessy Subreach, immediately upstream of the Tuolumne River near the Hetch Hetchy gaging station (tracer rocks and scour cores);
- Sand bars and riffles in the Poopenaut Valley Subreach (scour cores);
- Sand pockets in the Early Intake Subreach (scour cores);
- Gravel riffles in the Early Intake Subreach at Mystery Bar (tracer gravel patches and scour chains);
- Gravel/cobble deposits in the lee of boulders in the Early Intake Subreach (tracer rocks and scour cores); and
- Large cobble to medium boulder point bars in the Early Intake Subreach (tracer rocks).

Findings of the bed mobility and scour studies include the following:

- Flows >1,200 cfs mobilize and transport sand through the Hetch Hetchy Reach, as well as scour and replace lee sand deposits behind boulders, resulting in potentially reduced risk of future riparian encroachment on sand deposits.
- Flows >4,100 cfs mobilize and scour sand and pea gravels in lee deposits of boulders within the low flow channel at Early Intake and mobilize 50% of the surface layer of spawning gravels at Mystery Bar. This flow also begins to fill and inundate the North Pond in Poopenaut Valley (see Section 7.2.2; full pond fill requires 5,000 cfs for 12 hours).
- Flows >6,500 cfs mobilize and scour sand, pea gravels, and small gravels from lee deposits of boulders along channel margins at Early Intake, as well as gravel pool tail deposits at the Tuolumne River near the Hetch Hetchy gage site; and may be sufficient to inhibit woody riparian encroachment on sediment deposited within boulder pockets. Flows of this magnitude also initiate bed scour at Mystery Bar spawning riffles.
- Flows ≥8,000 cfs mobilize gravels from lee deposits of boulders along channel margins at Early Intake, as well as gravels and a few small cobbles on point bars at Early Intake.

Once flow magnitude thresholds were developed for mobilizing and scouring sediment, a flow duration was estimated to efficiently move and scour sediment to maximize the quantity of sediment transported per ac-ft of water released. Generally, field measurements of coarse sediment transport rates show that rates decrease over time for a given steady state flow magnitude. Recent bedload transport measurements on the Trinity River in northern California and Rush Creek in eastern California show that coarse and fine bedload transport rates are steady for two to three days, then drop by 50% or more thereafter (Pittman 2018, McBain & Trush 2007). Based on these studies, a two-day flow duration is estimated to be most efficient at transporting coarse sediment within the entire length of the Hetch Hetchy Reach. The 12- hour 5,000 cfs release for filling the Poopenaut Valley North Pond (discussed below) during years with low planning volume projections is an exception since the primary function is to fill the North Pond.

7.2.2 Poopenaut Valley wetland management

Developing snowmelt management targets for maintaining wetlands (Figure 29) and North Pond function in Poopenaut Valley required two steps: (1) establishing flow magnitude thresholds for inundating and saturating various wetlands, and (2) establishing hydrologic criteria for maintaining wetland function over time. Since 2006, the NPS and SFPUC have collaborated in a series of wetland-related studies focused on Poopenaut Valley, including experimental flood releases, wetland delineation, groundwater monitoring and modeling, surface water monitoring, mapping of flood inundation extent, and repeat photopoint and time lapse photography (NPS 2009, 2010, 2011; Russo et al. 2012; Appendix G). These studies relied on an extensive surface and groundwater monitoring network established and maintained in Poopenaut Valley by the NPS (Figure 29).

7.2.2.1 Establishing flow thresholds for wetland inundation

Over time the SFPUC and the NPS collaborated in a series of experimental flood releases from O'Shaughnessy Dam to establish basic information on wetland hydrology in Poopenaut Valley. Important findings included the following:

- Wetland hydrology is dependent on mainstem river hydrology, particularly during the snowmelt runoff period, and to a lesser extent, rainfall runoff from adjacent hillslopes. Groundwater levels respond rapidly to increasing river stage and remain low during fall, winter, and early spring (generally more than 6.5 ft below the ground surface) (NPS 2009).
- At 4,960 cfs, the North Pond began filling via water backing up the North Tributary channel from the mainstem Tuolumne River. Surveys of the topographic divide elevation and comparisons with a local rating curve predicted flows greater than 3,322 cfs would cause water to flow over the divide (NPS 2011).
- The North Pond was dry before a 2009 experimental flood flow, filled during a three-day approximately 6,500-cfs pulse flow, and drained over the following six weeks. Except for the initial spillage during the flood recession limb and evaporation, all drainage from the pond (ignoring evaporation) took place as seepage in the subsurface, consequently maintaining high groundwater levels around the pond (NPS 2011).
- In 2022, a four-hour 4,100-cfs experimental release did not result in sufficient wetland inundation or pond fill. A follow-up analysis conducted by McBain Associates that compared observed fill rates to streamflow magnitude showed that a higher magnitude flow (5,000 cfs) for a longer duration (12 hours) would fill the pond. Filling the North Pond was also achieved with a 4,100 cfs flow for a full day.
- River stage at 3,600 cfs was sufficient to inundate low-lying meadow areas immediately adjacent to the river and the Southwest Tributary, as well as the large sandbar in the east-central part of the valley (NPS 2011).
- River stage at 6,800 cfs was sufficient to inundate much of the primary meadow area in the southern portion of the valley (NPS 2011).

7.2.2.2 Establishing hydrologic criteria for maintaining wetland function

While determining flow magnitude thresholds for wetland inundation and saturation was useful in estimating the general magnitude of flows needed to inundate the various Poopenaut Valley wetlands, the combination of magnitude and duration is needed to maintain or enhance wetland function over time. There are numerous criteria for evaluating wetland function and the success of wetland rehabilitation. To provide criteria for maintaining wetland function in Poopenaut Valley, the NPS used the United States Army Corps of Engineers (ACOE) definition of wetland function, which requires a minimum saturation of wetland soils within 30 cm (11.8 inches) of the ground surface for at least 14 consecutive days during the growing season, in 5 out of every 10 years (ACOE 2008). While satisfying these criteria alone cannot guarantee wetland health, they provide a practical basis from which to begin managing Poopenaut Valley wetlands.

To evaluate the most efficient use of water for maintaining wetlands in Poopenaut Valley under the ACOE criteria, a 14-day experimental flood hydrograph was released from O'Shaughnessy Dam in the spring of 2009. Researchers from University of California, Santa Cruz (UCSC) assisted the NPS in evaluating shallow groundwater and soil moisture response to the controlled flooding, focusing on Wetlands 5, 6, and 7 (NPS 2011). UCSC installed additional equipment in the existing groundwater monitoring network, including drive-point piezometers; vertical soil moisture arrays measuring water content at 40-, 70-, and 100-cm depth; infiltration capacity testing; and vertical seepage measurements along the Tuolumne River (Russo et al. 2012).

Measurements during the experimental flood were used to develop and calibrate a numerical shallow groundwater model and evaluate surface and groundwater dynamics to meet the ACOE wetland criteria. Once calibrated, the model was used to evaluate several idealized flooding scenarios (Figure 28) that could meet the ACOE wetland criteria (Russo et al. 2012). Surface water, groundwater, and soil moisture monitoring through Wetlands 5, 6, and 7 at cross section 1920+60 (Figure 29) verified when and where water surface elevation and saturation criteria were met, and how long the criteria were met as flows receded (NPS 2011, Russo et al. 2012). UCSC found that all modeled scenarios could achieve and maintain the target of soil saturation of the upper 30 cm (11.8 inches) for 14 consecutive days.

Due to the larger water volume required for Scenario #1, and concerns about tributary bank stability in Scenario #3 (see Appendix H), Scenario #2, a two-day pulse followed by at least 12 days of saturation (11.8 inches, 30 cm lower), was chosen for use in developing snowmelt management targets for Wetland 5, 6, 7, and 11. Table 11 and Figure 29 summarize resulting inundation thresholds and saturation elevations assuming a 30-cm soil saturation depth.

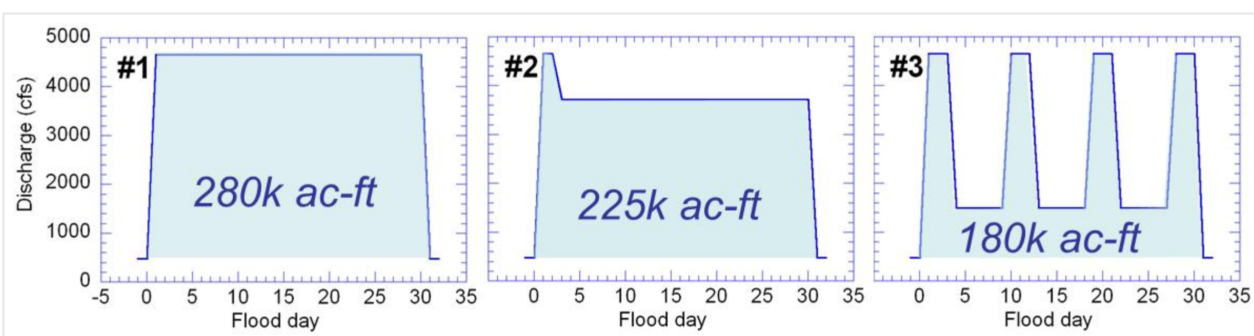

Figure 28. Alternative flood scenarios tested with the UCSC model. Scenario #1: constant stage reaching Piezometer #2; Scenario #2: Short pulse flow reaching Piezometer #2 followed by a constant lower stage; and Scenario #3: Multiple cycles of high and low stage with high stages reaching Piezometer #2 (Russo et al. 2012).

Table 11. *Poopenaut Valley wetland inundation and saturation thresholds.*

Surface	Elevation threshold (ft)	Inundation flow threshold (cfs)	Saturation elevation (ft)	Saturation flow (cfs)	Basis
Wetland 1 (North Pond)	3,326.12	4,100	Not applicable	Not applicable	Control elevation separating Wetland 1 from the North Tributary and Tuolumne River. Estimate from cross section 1932+80.
Wetland 5	3,321.0	1,700	3,320.0	1,300	Ground surface at Piezometer #3 (Appendix G) June 2011 photopoint.
Wetland 6	3,326.9	5,400	3,325.9	4,600	Water surface response in Piezometer #2 during May 2008 peaks; May 2011 photopoint.
Wetland 7	3,327.2	5,700	3,326.2	4,800	Ground surface at Piezometer #1.
Wetland 11	3327	4,700	3,326.0	4,100	Inundation Map (NPS 2011).

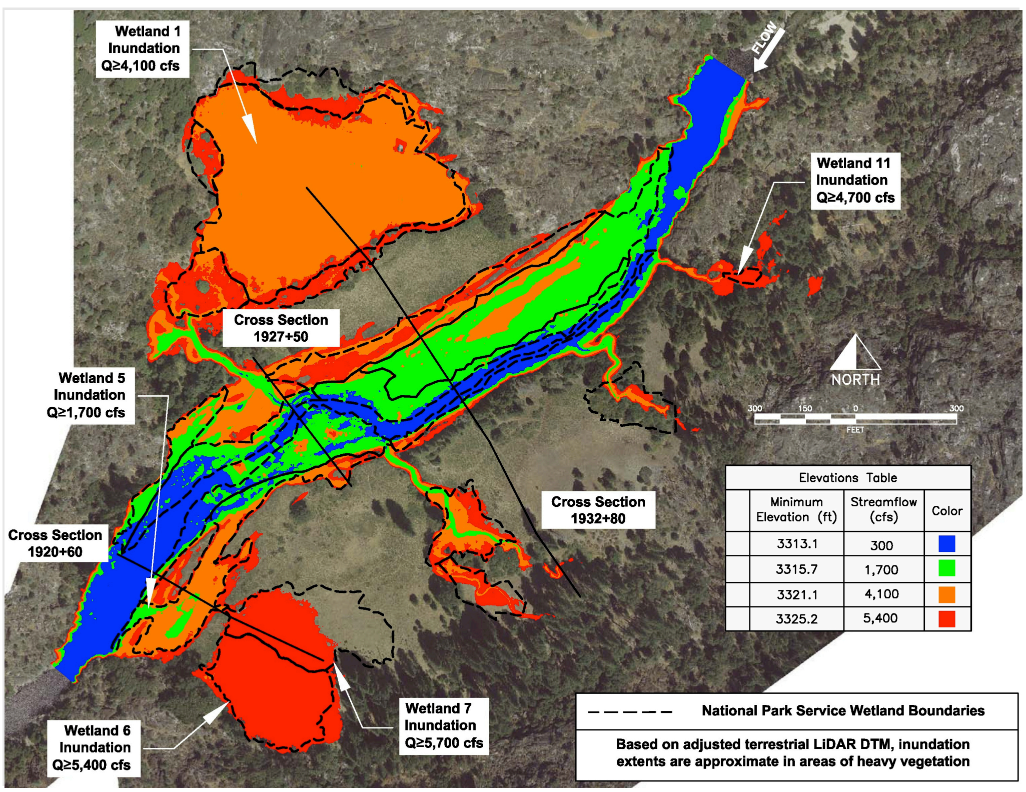

Figure 29. AutoCAD-generated inundation map from adjusted 2010 Light Detection and Ranging (LiDAR) data showing color-coded elevations and corresponding flows within Poopenaut Valley.

7.2.3 Riparian vegetation encroachment

To support the development of snowmelt management targets, the SFPUC investigated woody riparian vegetation dynamics and in-channel encroachment within the Hetch Hetchy Reach in the spring and summer of 2010 (Appendix F), in coordination with bed mobility and scour studies (Appendix E). The study focused on boulder pockets, nested gravel, and other habitat features that may be desirable to maintain for aquatic species. Selected study sites included Boulder Garden, Albino Rock Pool, Mystery Bar, and Tuolumne River near Hetch Hetchy gage (Figure 30).

Important findings included the following:

- Tree coring found numerous in-channel trees older than 15 years, suggesting that the 1997 flood (instantaneous peak flow of approximately 16,000 cfs) was unable to remove all woody riparian vegetation growing in-channel and along the low water channel margin.
- However, between 23% and 54% of all woody plant recruitment has occurred since 1997, indicating that many previously vegetated nursery sites likely became available after the 1997 flood.
- At all of the study sites, Ponderosa Pine recruited lower and closer to the channel over time and could be considered to be encroaching into the riparian corridor.
- 27% of all measured White Alder could be considered to be encroaching the low water channel and in-channel alluvial deposits.
- Infrastructure limitations constrain releases greater than approximately 8,000 cfs, which are the flows that would be most effective in managing vegetation encroachment. Infrequent high magnitude rain-on-snow events will likely occur in the future, and may remove some established in-channel vegetation, but are not expected to remove all in-channel vegetation based on observed vegetative response to the 1997 flood.
- Increasing the frequency of moderate floods between 6,500 cfs and 8,000 cfs has been sufficient to turn over gravels and cobbles, inhibit sand build-up and additional vegetation encroachment, encourage age and size class diversity of riparian vegetation, and reduce risk of encroachment on in-channel gravel deposits.

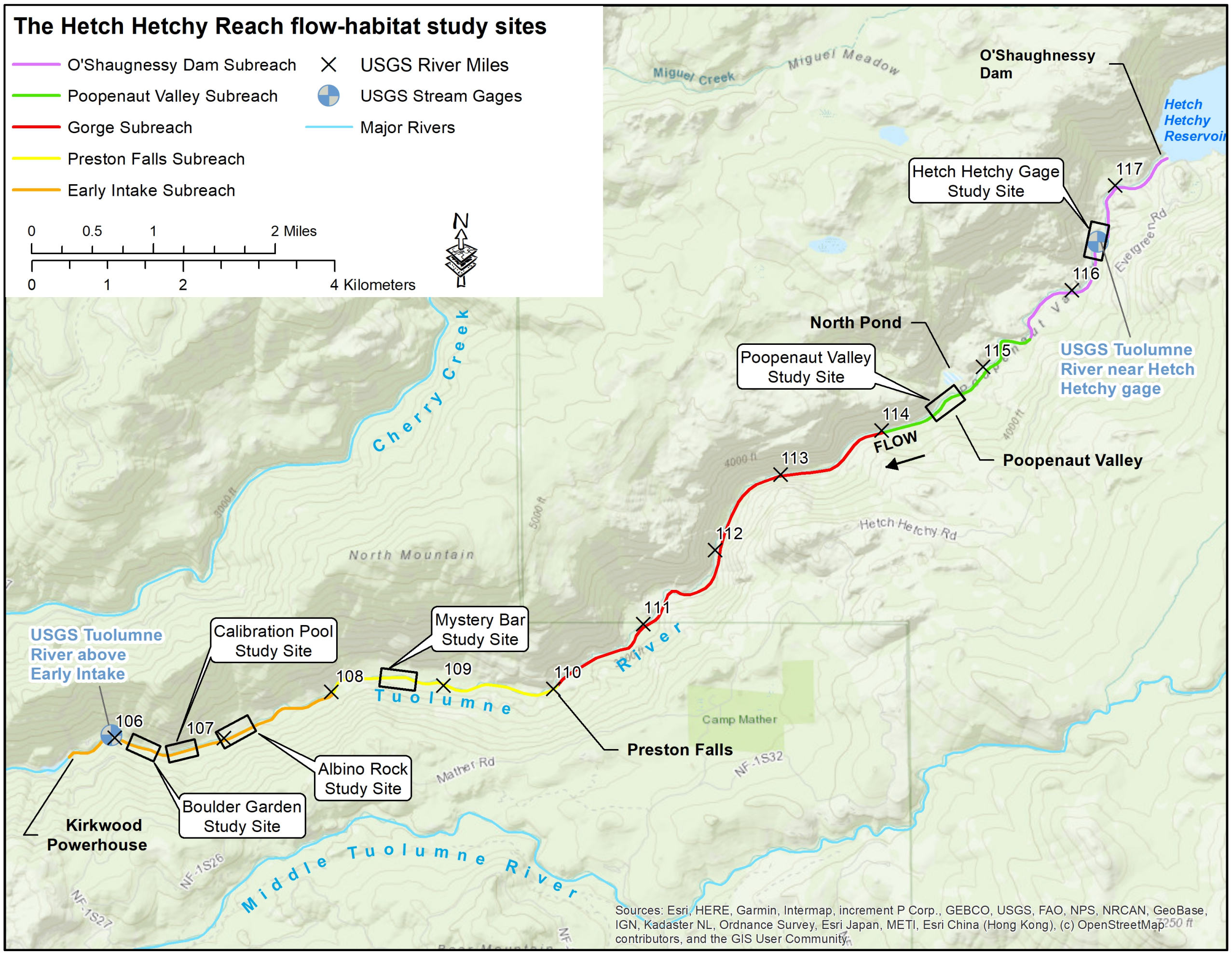

Figure 30. Riparian vegetation study sites within the Hetch Hetchy Reach.

7.2.4 Focal riparian plant species recruitment

As part of SFPUC riparian vegetation dynamics studies conducted in 2010, and to inform development of snowmelt management ramping rates, the SFPUC analyzed snowmelt recession rates needed to regenerate focal woody riparian plant species (e.g., willows and cottonwood) on higher elevation bars, scour channels, and floodplains in the Poopenaut Valley and Early Intake subreaches (Appendix F). Recession rates were evaluated using water surface elevation vs. flow relationships developed for four study sites: Boulder Garden, Calibration Pool, Albino Rock Pool, and Poopenaut Valley (Figure 30).

The combination of seed dispersal timing, flow magnitude, duration, and channel morphology determines where woody riparian vegetation initiation can successfully occur. In locations near the channel where substrate includes a high percentage of fine sediment (less than 2 mm), capillary action increases the height above the shallow groundwater where water can be reached by plant roots. The capillary fringe is about 1.0 ft. for fine sand and 0.5 ft. for coarse sand. If the shallow groundwater elevation recedes below approximately 1.0 ft. of the ground surface during seed germination and primary root formation, the ground surface will dry out in hours and the initiating seedling will die. If groundwater elevations can be maintained long enough during seed germination and root formation, then the soil profile up to the ground surface would be saturated and would meet the soil moisture requirements of initiating plants. Once root formation has occurred, groundwater would need to recede at a rate no faster than the growth of the root.

Key findings of the recruitment study included the following:

- Release of 1,200 cfs may promote woody riparian plant initiation on small benches, high water channels, and upper bars, but the zone of successful woody riparian plant establishment above 1,200 cfs will vary depending on the location downstream of O’Shaughnessy Dam and soil texture.
- Releases are recommended to be steady at 1,200 cfs for approximately 21 days (HVT et al. 2011) to create soils wet enough for woody plant seed germination and root formation at bank locations targeted for deciduous woody plant recruitment.
- Recession rates varied between sites, with valley confinement, slope, and low water channel width affecting rates the most. Idealized recruitment recession rates were slowest in Poopenaut Valley (about 6% per day) and fastest at the Boulder Garden site (about 10% per day).

Due to uncertainty about whether riparian vegetation could be naturally recruited on the coarse sands of Poopenaut Valley, the slow recession ramping rates predicted for riparian recruitment were not incorporated into the snowmelt management targets (see Section 8.1.3). However, snowmelt recession rates needed for riparian recruitment in the Early Intake Subreach may occur in wetter water years via drum gate spill (see Section 8.1.2).

7.2.5 RHJV focal bird species in Poopenaut Valley

In 2010, the NPS began conducting assessments in the Poopenaut Valley Subreach investigating bird nesting locations, elevations, and timing to better evaluate the effects of high magnitude spring snowmelt spill releases on nesting success of RHJV focal bird species. As described in Section 3.2.4.3, occasional nest inundation is a natural phenomenon in unimpaired systems during the spring snowmelt, but nest losses may be exacerbated in regulated systems where low baseflows extend into the spring snowmelt runoff period while a reservoir fills, potentially encouraging low elevation nest building, followed by a series of pulse flows to control reservoir elevation when the reservoir is nearly full. Between 2007 and 2012, the NPS observed a single flooded Song Sparrow nest, which was inundated during an experimental flood release from O’Shaughnessy Dam sometime between May 8 and May 12, 2010 (NPS 2014b).

Song Sparrows are year-round residents in Poopenaut Valley and concentrate their activity along the river’s edge; breeding in Poopenaut Valley appears to occur between April and June (NPS 2014b). Because Song Sparrows are understory nesters that build their nests on or near the ground, their nests are especially vulnerable to flooding. Other RHJV focal species nests are not as vulnerable to flooding due to their higher nesting position in riparian vegetation (NPS 2014b). Song Sparrows are known to attempt more than one clutch and produce offspring if an early nest is inundated, and thus can reproduce after floodwaters subside (NPS 2010). However, it is possible the delay and energy used in producing multiple clutches could reduce overall productivity of the population within the Hetch Hetchy Reach (S. Stock, pers. comm.).

To develop potential snowmelt management targets that may reduce the risk of Song Sparrow or other RHJV bird nest inundation, the NPS and SFPUC conducted additional field surveys and cross section-based hydraulic analyses (Appendix G). Based on NPS identification of important bar nesting locations for the RHJV focal bird species, a cross section was established (1927+50) across the mainstem Tuolumne River, through the apex of a heavily vegetated bar, and up to the elevation of the Poopenaut Valley meadows and wetlands (Figure 29). Water surface elevation measurements made by NPS hydrologists at cross section 1920+60 (approximately 700 feet downstream of cross section 1927+50) were correlated with flow magnitudes at the Tuolumne River near Hetch Hetchy gage to develop a rating curve. Comparing the elevation of the bar with the rating curve enabled estimates of a flow threshold to inundate the bar and associated nesting habitat. Based on the cross section and rating curve in Figure 31, the flow at the Tuolumne River near Hetch Hetchy gage that begins to inundate the Poopenaut Valley bar is approximately 620 cfs. Accounting for topographic variability of the bar upstream and downstream of the cross section, an additional 2 ft of depth was added, translating to a flow of approximately 1,000 cfs at the Tuolumne River near Hetch Hetchy gage. Thus, peak releases conducted at the beginning of snowmelt releases, followed by maintained releases of 1,000 cfs in wetter years until the snowmelt recession (as spill volume allows), may help avoid nest loss in the mid-May through June period by encouraging nesting at higher elevation nesting sites.

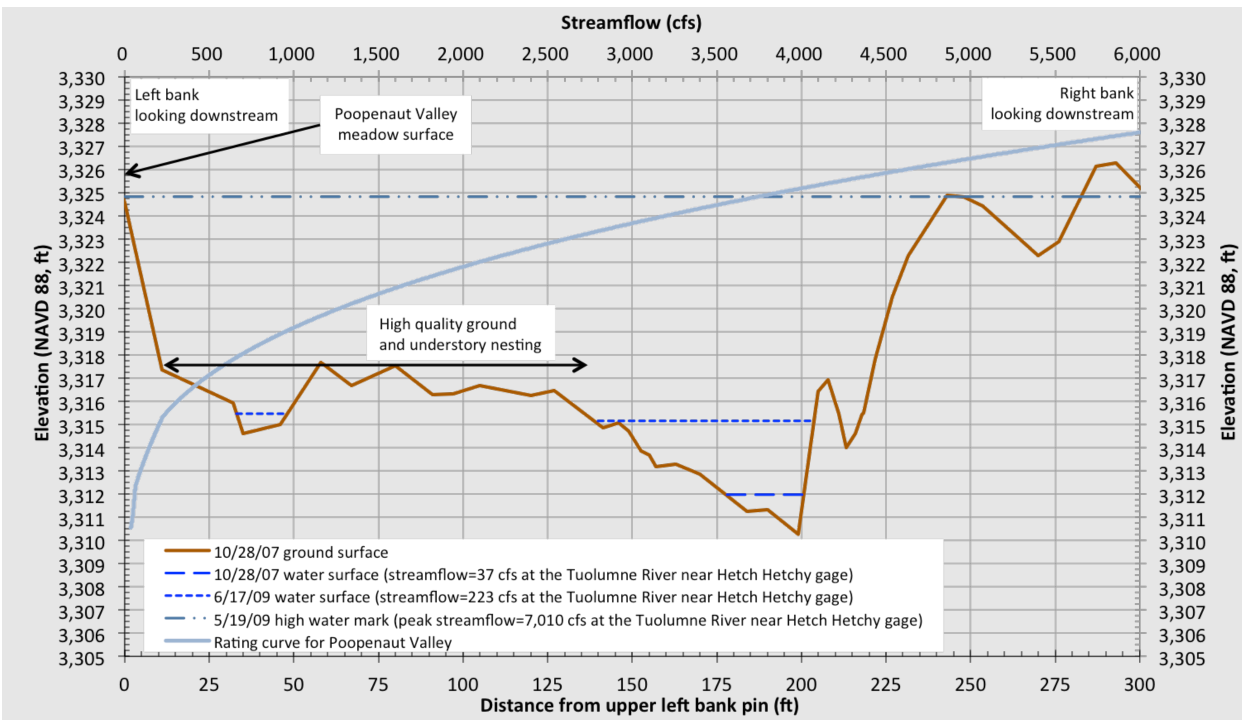

Figure 31. Poopenaut Valley cross section 1927+50, with the cross section 1920+60 flow rating curve, water surface elevations, and indicated high quality nesting habitat for RHJV focal bird species.

7.2.6 Foothill Yellow-legged Frog stage change and water temperature analysis

Scour and desiccation of egg masses and tadpoles due to pulse floods during the snowmelt recession are hypothesized to be a primary limiting factor for successful recruitment of Foothill Yellow-legged Frog. The gently sloping boulder bar at cross section 1484+70 provides potentially high-quality breeding habitat up to 900 cfs and is representative of similar high quality breeding areas in the Early Intake Subreach. If higher releases occur during the breeding period, then are subsequently reduced to summer baseflows during egg incubation, desiccation of the egg masses could occur if the stage drop exceeds egg-laying depth (see Table 3 for timing of life history for FYLF, Figure 32).

To analyze this risk, numerous water surface elevations were surveyed at the cross section and related to flow measured at the Tuolumne River above Early Intake gage, providing a rating curve that estimates flow at any given water surface elevation on cross section 1484+70. An analysis was conducted that defined the range of flow releases from O'Shaughnessy Dam (including seasonal downstream accretion) that would inundate the boulder bar, and the subsequent change in stage that would occur when releases were reduced to lower summer baseflows. Average accretion values between O'Shaughnessy Dam and Early Intake were computed for Normal, Dry, and Extremely Dry water years over the 1971–2021 period. The stage change was then compared to estimates of an average Foothill Yellow-legged Frog egg laying depth of 2.23 ft, based on Mokelumne River egg depths in PG&E (2014), to define the range of flows that would avoid desiccating egg masses when releases transitioned from higher magnitude snowmelt management releases to lower magnitude baseflows. This water depth estimate is consistent with the only Foothill Yellow-legged Frog egg mass observed in the Early Intake Subreach (at stationing 1522+00 ft). This egg mass was two to three weeks old (Gosner stage 18-22) when discovered at a water depth of about 14 inches on June 25, 2018. Flow was estimated to have been about 900 cfs when the egg mass was deposited, and flow had dropped to about 300 cfs by the time the egg mass was discovered. The egg mass was attached to a boulder in the river channel. If it had been deposited on the flood plain gravel bar, it would have desiccated when flow dropped from about 900 cfs to about 300 cfs.

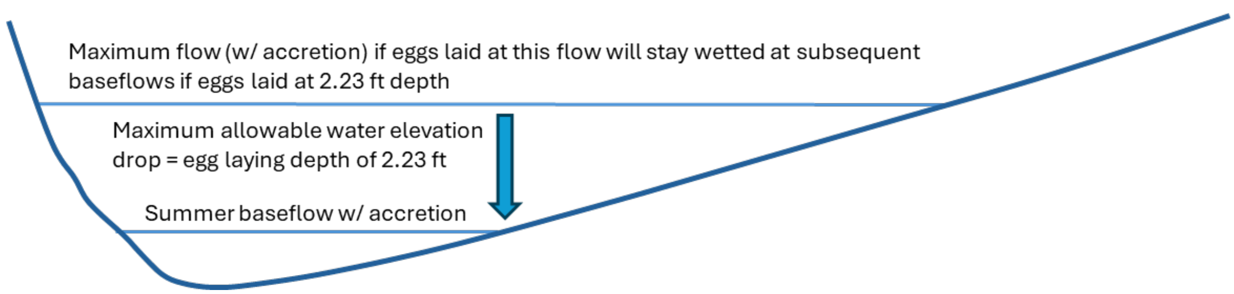

Figure 32. Conceptual approach for estimating maximum O'Shaughnessy Dam release after May 15 to reduce risk of Foothill Yellow-legged Frog egg desiccation.

For Extremely Dry, Dry, and Normal water years, the average May 15–June 15 accretion value ranges from 13 cfs to 80 cfs. Wet and Extremely Wet water year types were not analyzed because FYFL objectives are for drier year types. Adding these accretion values to the summer baseflow releases for these water years results in expected summer baseflows at Early Intake (Table 12). Adding the flow represented by a 2.23-ft stage change to these baseflows represents the maximum flow at Early Intake that would avoid egg mass desiccation if the eggs were laid at a 2.23-ft depth, and then subtracting the average accretion values from the maximum flows at Early Intake cross section 1480+70 translates to an O'Shaughnessy Dam flow release between 614 cfs and 1,037 cfs (Table 12). Assuming late season flow events are less likely in Extremely Dry water years, the primary years to manage for avoiding higher late season releases are Dry and the drier half of Normal years. Based on the values for these two years in Table 12, late season releases less than 700 cfs should reduce the risk of egg mass desiccation if breeding occurs during that release and flows subsequently decrease to summer baseflows. Thus, maintaining more stable releases less than 700 cfs, rather than implementing larger magnitude releases greater than 700 cfs, will maintain inundation of the egg-laying habitat and reduce the risk of egg mass desiccation. Lastly, use of drum gates for releases less than 700 cfs during Normal and Dry water years should increase water temperatures in the Early Intake and Preston Falls subreaches, promoting faster development of egg masses, and thus reducing the length of time this immobile life stage is exposed to desiccation risk.

Table 12. *Maximum releases at O'Shaughnessy Dam to avoid Foothill Yellow-legged Frog egg mass desiccation at cross section 1484+70 in the Early Intake Subreach in different water years using average accretion between the USGS Tuolumne River near Hetch Hetchy and Tuolumne River above Early Intake gages.*

Ending water year class (as of July 31)	May 16–June 15 future baseflow release (cfs)	Average accretion (cfs)	May 16–June 15 baseflow at cross section 1484+70 (cfs)	Maximum flow at cross section 1484 to avoid desiccation (cfs), assuming egg laying depth of 2.23 ft	Maximum release to avoid egg mass desiccation (cfs)
Normal	180	80	260	1,117	1,037
Dry	60	17	77	689	673
Extremely Dry	50	13	63	627	614

7.3 Summary of snowmelt management targets

Given the results of analyses described above, recommended quantitative snowmelt management targets (summarized in Table 13) were developed to address the ecological goals and management objectives described in Section 5.3. Based on the volume of water each target (or set of targets) uses, implementation of each target (or set of targets) is guided by the planning volume, which is a forecasted spill volume available for snowmelt management in any particular year (see Section 7.1 for a discussion of how planning volumes are determined). Generally, the number of targets achieved increases as planning volumes increase.

Table 13. *Focal elements, snowmelt management objectives, and snowmelt management targets, with associated forecasted planning volumes.*

Focal element	Snowmelt management objectives	Snowmelt management target	Target snowmelt management planning volume (ac-ft)	Location of supporting information
BMI	Provide abundant wetland habitat	Wetland 1 (North Pond): 5,000 cfs inundation for at least 12 hours.	≥9,800	Section 3.2.4.6
		Wetland 6: At least 14 days of 5,400 cfs inundation.	≥190,000	
BMI	Increase BMI diversity	At least two days at >8,000 cfs to mobilize bed, which will reduce algal growth and increase BMI diversity.	>190,000	
Foothill Yellow-legged Frogs	Avoid late season spill to reduce egg scour or tadpole dislocation	Release peak flows before May 15.	<42,000	Appendix A
		Avoid valve and drum gate releases that will result in flows >700 cfs after May 15.		
Bed mobility and scour	Increase frequency of exceeding bed mobility and scour thresholds	At least two days at 1,200 cfs to mobilize sand (frequently occurs now, so a lower priority objective).	≥9,800	Appendix E
		At least two days at 4,100 cfs to mobilize sand and pea gravels.	≥66,000	
		At least two days at 6,500 cfs to mobilize sand, pea gravels, and small gravels.	≥178,000	
		At least two days at >8,000 cfs to mobilize gravels and small cobbles.	≥190,000	
Poopenaut Valley wetlands	Increase frequency and duration of inundation and saturation of wetlands and the North Pond	Wetland 1 (North Pond): At least 12 hours of inundation at ≥5,000 cfs prior to May 15 (supports Foothill Yellow-legged Frog in drier years). No saturation criteria.	≥9,800	Appendix G
		Wetland 1 (North Pond): One or more releases for at least 12 hours of inundation at ≥5,000 cfs. No saturation criteria.	>30,000 and <104,000	
		Wetland 5: At least two days of inundation at 1,700 cfs	≥66,000	

Focal element	Snowmelt management objectives	Snowmelt management target	Target snowmelt management planning volume (ac-ft)	Location of supporting information
		and at least 12 days of saturation at 1,300 cfs.		
		Wetland 11: At least two days of inundation 4,700 cfs and at least 12 days of saturation at 4,100 cfs	≥133,000	
		Wetland 6: At least two days of inundation at 5,400 cfs and at least 12 days of saturation at 4,600 cfs.	≥178,000	
		Wetland 7: At least two days of inundation at 5,700 cfs and at least 12 days of saturation at 4,800 cfs.	≥190,000	
Riparian vegetation encroachment	Increase frequency of exceeding bed mobility and scour thresholds	At least two-day release >6,500 cfs.	≥178,000	Appendix F
Focal riparian plant species recruitment	Provide slow snowmelt recession downramping rates that support woody riparian vegetation recruitment	No quantitative objectives for recession; snowmelt recession rates needed for woody riparian vegetation recruitment in the Early Intake Subreach may occur in wetter water years via drum gate releases.	None	Appendix F
RHJV focal bird species nesting	During the snowmelt season, maintain higher flow releases to inundate lower elevation woody riparian plants and shrubs	Maintain minimum flows >1,000 cfs between peak snowmelt release and final snowmelt recession.	≥66,000 or planned wetland inundations of ≥4,700 cfs	Section 3.2.4.3
		Schedule peak magnitude snowmelt management targets early in the snowmelt management hydrograph, as feasible.	<66,000	

The targets incorporate the following general strategies:

- Increase the frequency of bed mobility and Poopenaut Valley wetland and meadow inundation in wetter water years, providing related habitat maintenance benefits; and
- Improve management of spill releases in drier years to support Foothill Yellow-legged Frog reproduction.

In addition, a strategy of releasing peak flows for ecological and operational purposes earlier in the spring snowmelt period is recommended to avoid critical life stages for focal species (Foothill Yellow-legged Frogs, RHJV bird nesting); however, this strategy may be challenging to implement in some years because of operational limitations (higher reservoir storage required early in the spring to release highest flows) and runoff forecast uncertainty (late season spills if more runoff occurs than expected).

7.4 Template hydrographs

Snowmelt management “template hydrographs” were developed to synthesize the snowmelt management targets summarized in Table 13 into idealized spill release scenarios. These templates were designed to provide examples for maximizing the ecological benefits of snowmelt spill. The templates assume ramping procedures summarized in Section 8.3, but do not illustrate drum gate releases (see template hydrograph development methods described in Appendix I).

The template hydrographs range from a minimum spill volume of 6,000 ac-ft to greater than 190,000 ac-ft (Figure 33 through Figure 43, Table 14). Each template guides releases for a range of planning volumes and provides guidance for using additional water to maximize the ecological benefit achievable from that release volume.

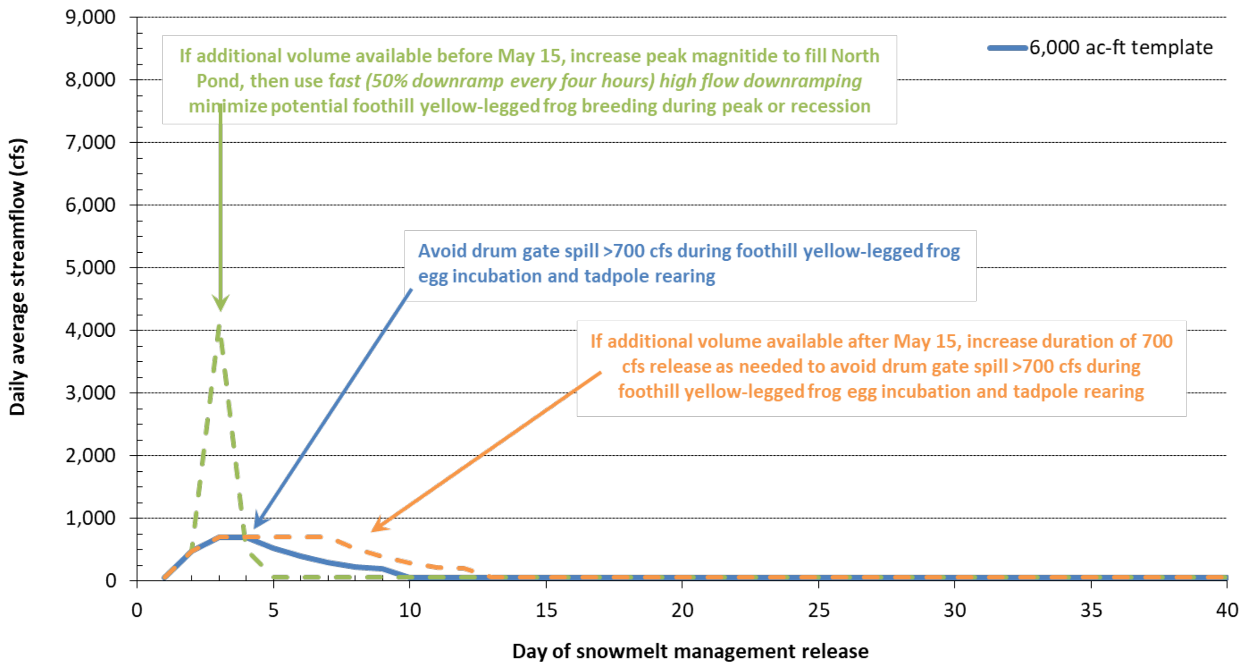

Figure 33. Template hydrographs for snowmelt management planning volumes exceeding 6,000 ac-ft. Dotted lines indicate how additional available spill volume may be allocated.

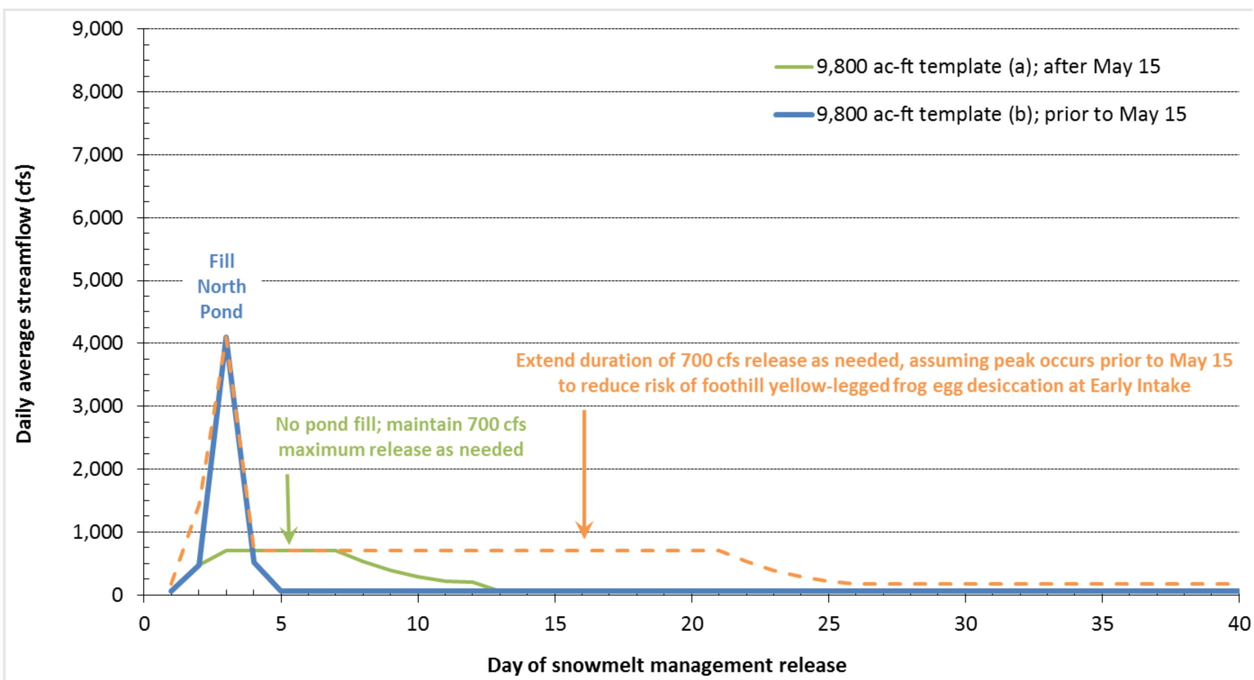

Figure 34. Template hydrographs for snowmelt management planning volumes exceeding 9,800 ac-ft. Template (a) is used if snowmelt management release begins after May 15, and template (b) is used if snowmelt management release begins prior to May 15. Dotted lines indicate how additional available spill volume may be allocated.

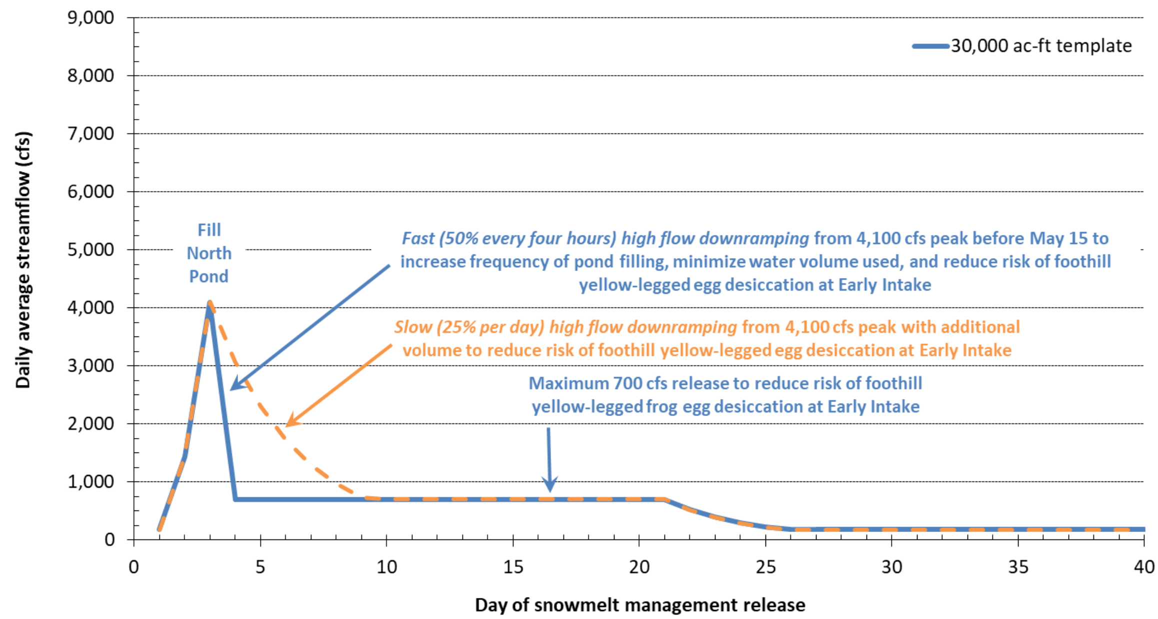

Figure 35. Template hydrographs for snowmelt management planning volumes exceeding 30,000 ac-ft. Dotted lines indicate how additional available spill volume may be allocated.

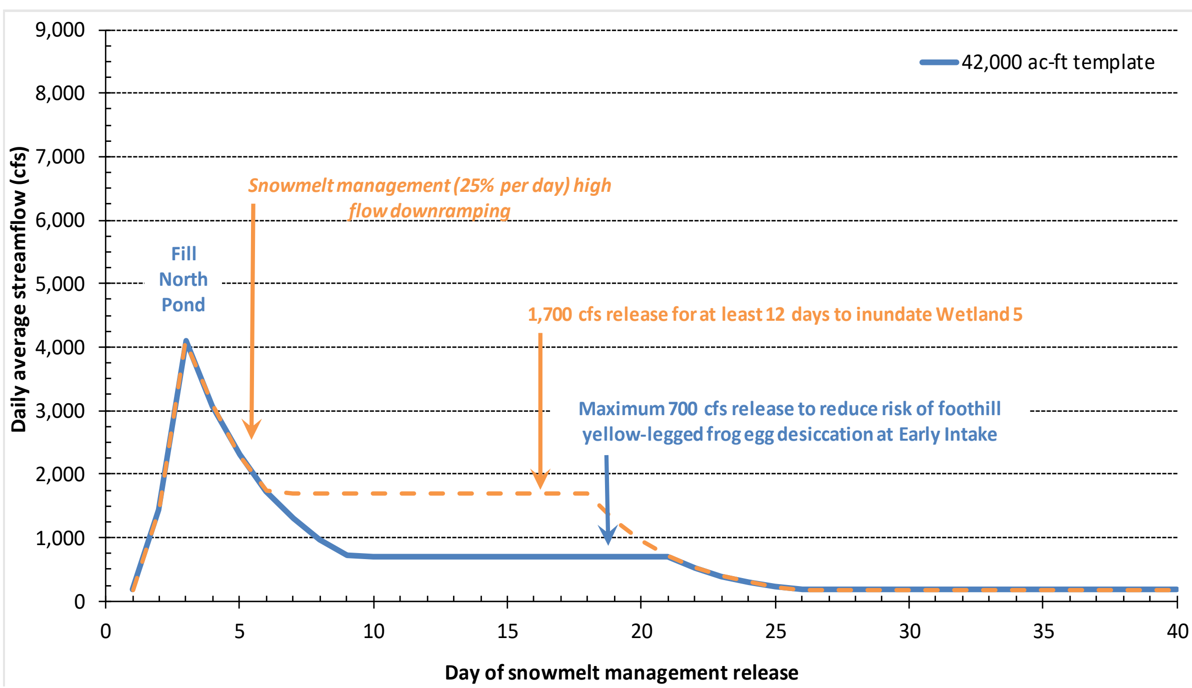

Figure 36. Template hydrographs for snowmelt management planning volumes exceeding 42,000 ac-ft. Dotted lines indicate how additional available spill volume may be allocated.

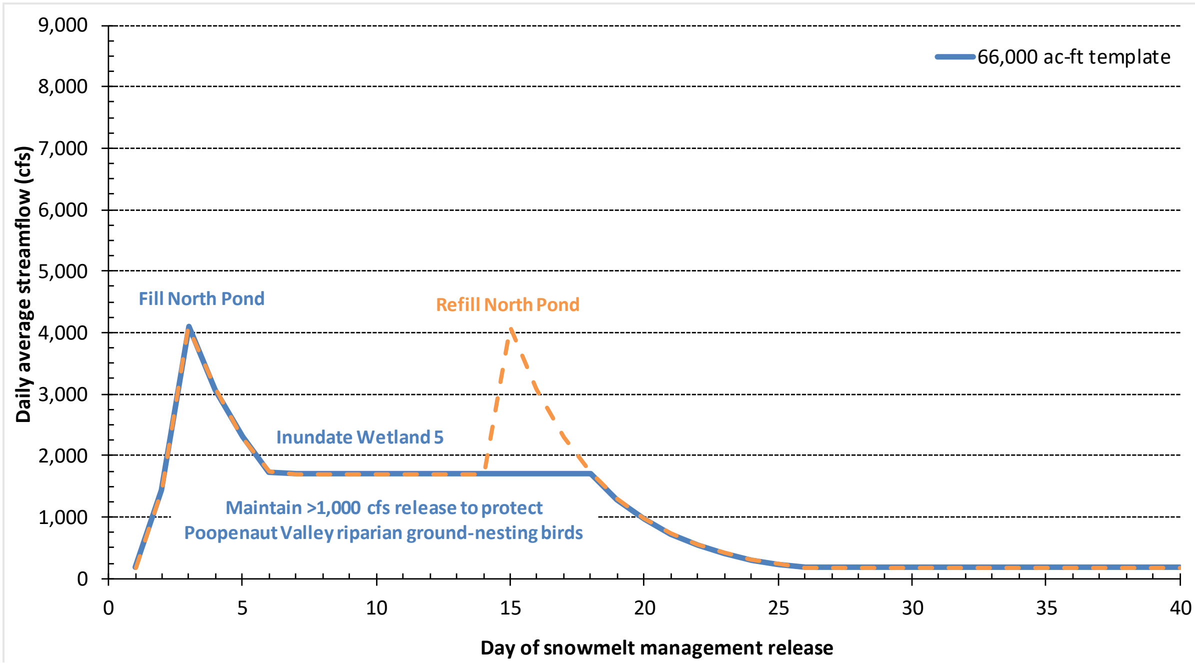

Figure 37. Template hydrographs for snowmelt management planning volumes exceeding 66,000 ac-ft. Dotted lines indicate how additional available spill volume may be allocated.

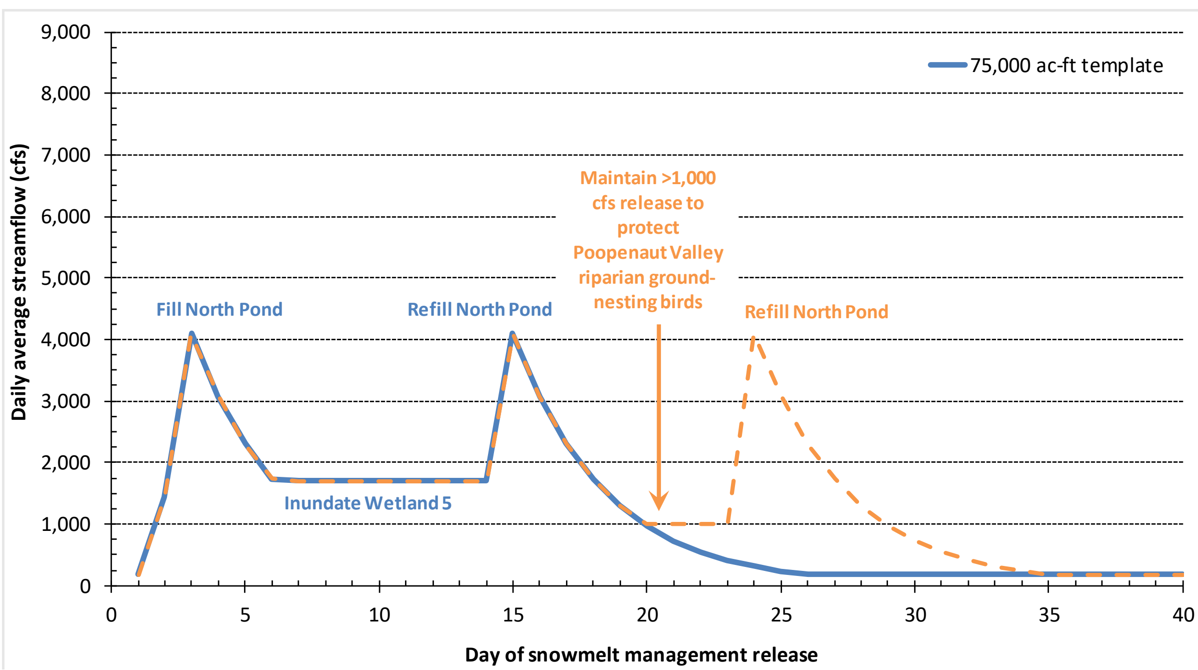

Figure 38. Template hydrographs for snowmelt management planning volumes exceeding 75,000 ac-ft. Dotted lines indicate how additional available spill volume may be allocated.

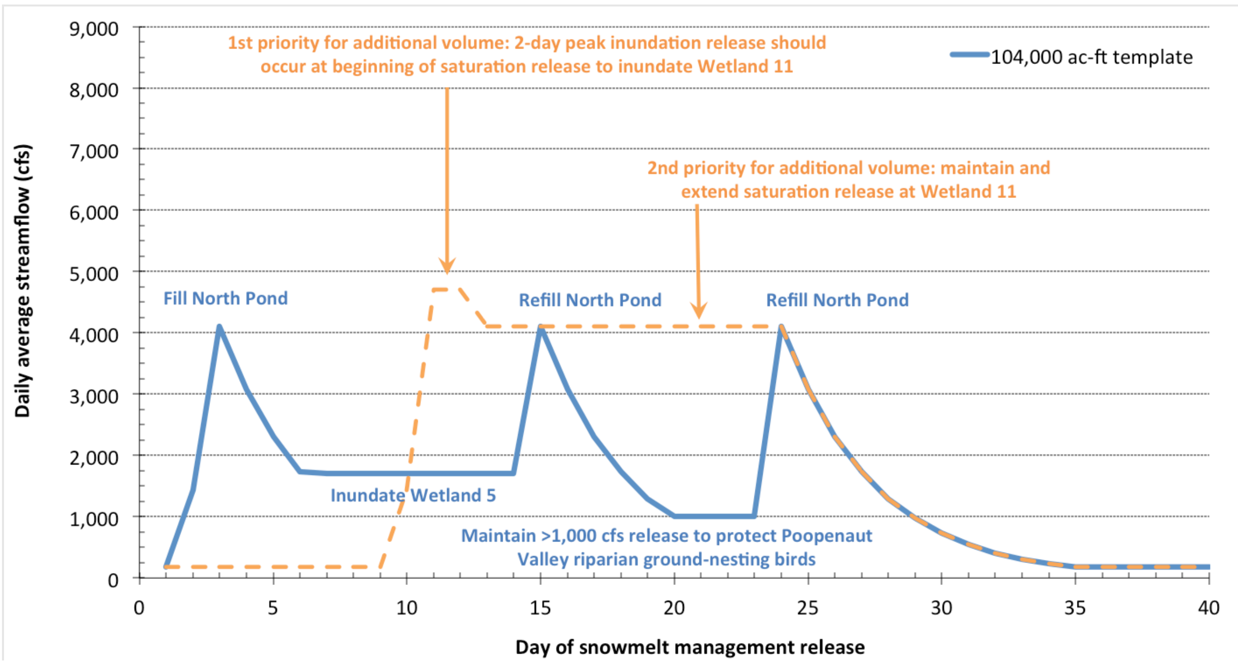

Figure 39. Template hydrographs for snowmelt management planning volumes exceeding 104,000 ac-ft. Dotted lines indicate how additional available spill volume may be allocated.

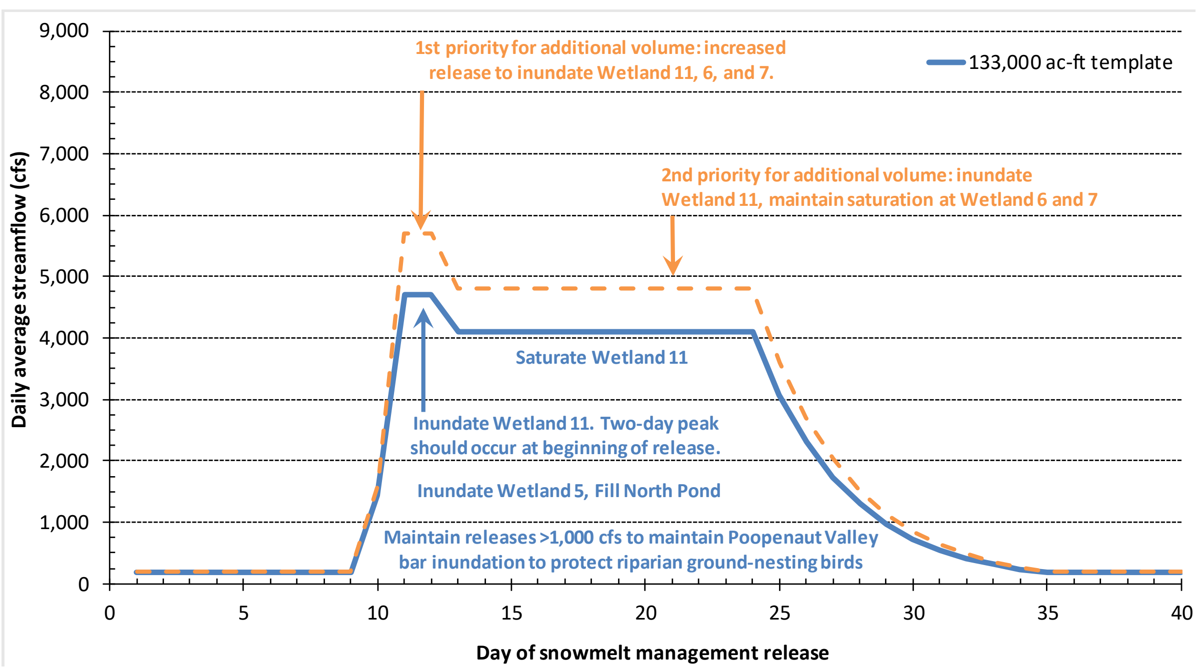

Figure 40. Template hydrographs for snowmelt management planning volumes exceeding 133,000 ac-ft. Dotted lines indicate how additional available spill volume may be allocated.

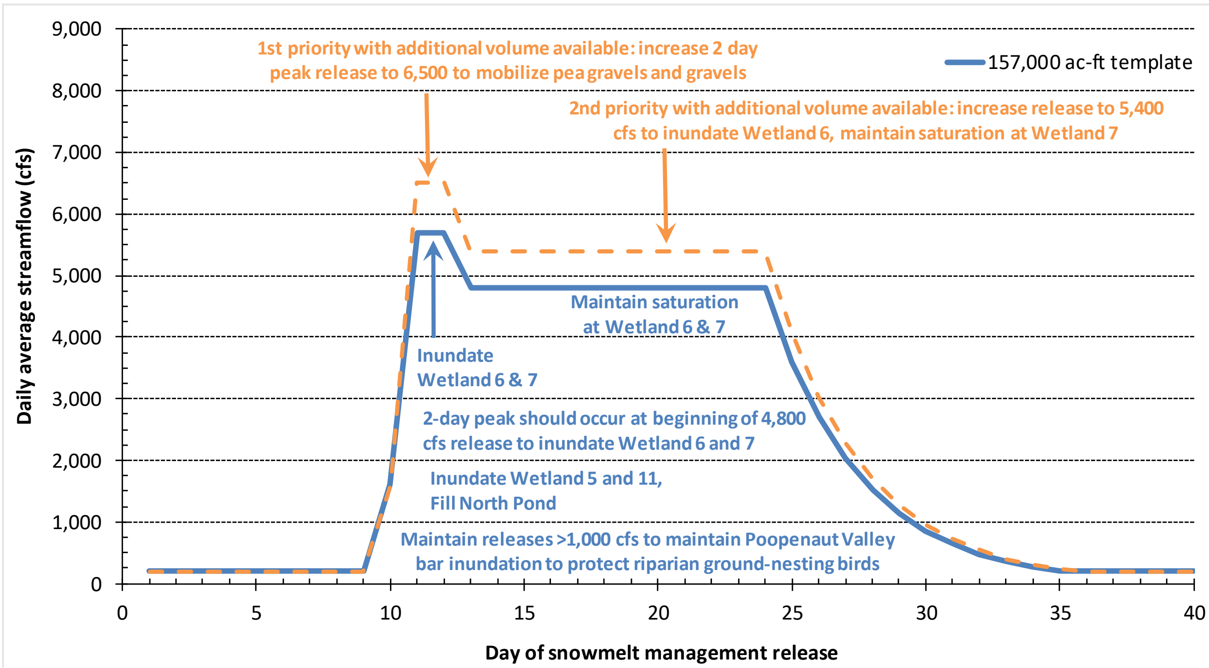

Figure 41. Template hydrographs for snowmelt management planning volumes exceeding 157,000 ac-ft. Dotted lines indicate how additional available spill volume may be allocated.

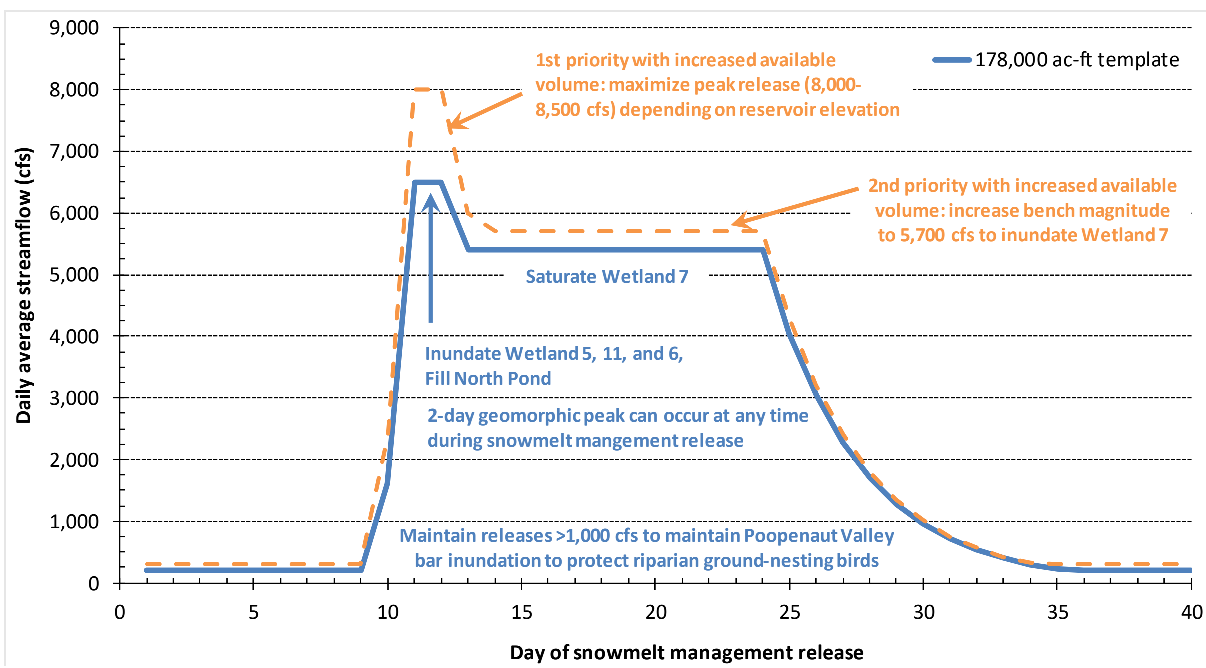

Figure 42. Template hydrographs for snowmelt management planning volumes exceeding 178,000 ac-ft. Dotted lines indicate how additional available spill volume may be allocated.

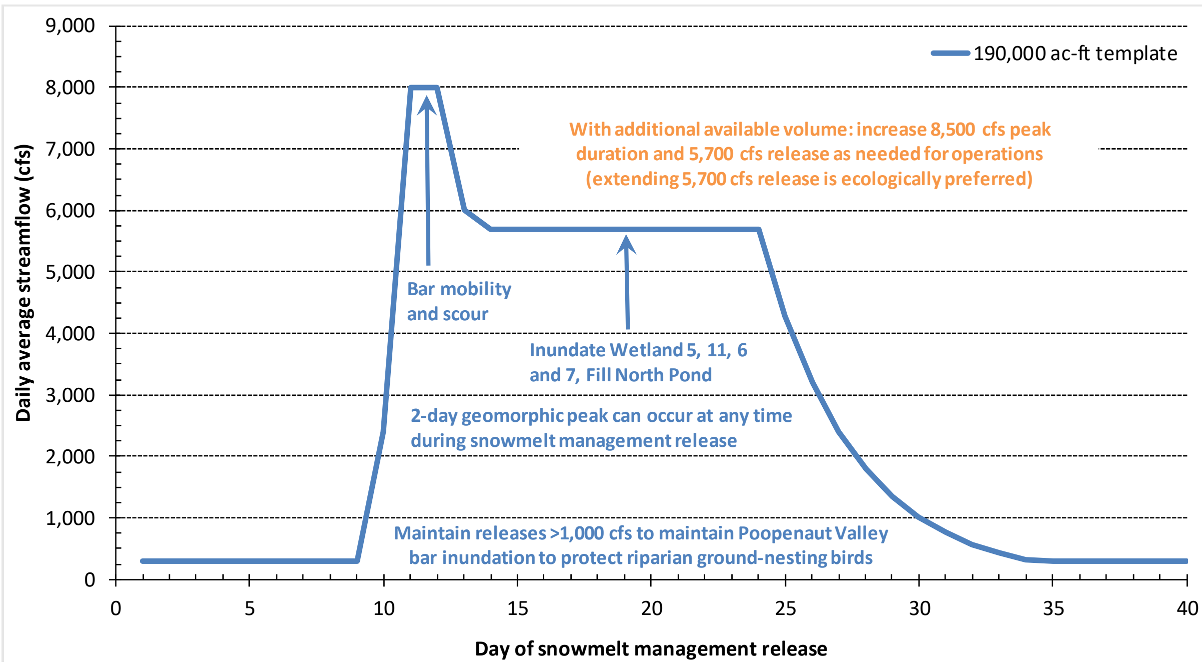

Figure 43. Template hydrographs for snowmelt management planning volumes exceeding 190,000 ac-ft.

Table 14. *Summary of template hydrograph magnitude and duration attributes. Ramping rates and procedures are summarized in Section 8.3.*

Template hydrograph	Snowmelt management target	Description
zero[a]	Not applicable	None
6,000 ac-ft	700 cfs for two days	Avoid late season spill to reduce Foothill Yellow-legged Frog egg scour or tadpole dislocation
Template (a): 9,800 ac-ft after May 15	700 cfs for seven days	Avoid late season spill to reduce Foothill Yellow-legged Frog egg scour or tadpole dislocation
Template (b): 9,800 ac-ft before May 15	4,100 cfs for one day, fast high flow downramping	Fill North Pond once, avoid late season spill to reduce Foothill Yellow-legged Frog egg scour or tadpole dislocation
30,000 ac-ft	4,100 cfs for one day, fast high flow downramping, 700 cfs for 18 days	Fill North Pond once, avoid late season spill to reduce Foothill Yellow-legged Frog egg scour or tadpole dislocation
42,000 ac-ft	4,100 cfs for one day, snowmelt management high flow downramping, 700 cfs for 13 days	Fill North Pond once, avoid late season spill to reduce Foothill Yellow-legged Frog egg scour or tadpole dislocation
66,000 ac-ft	4,100 cfs for one day, snowmelt management high flow downramping, 1,700 cfs for 13 days, 1,200 cfs for two days	Fill North Pond once, inundate Wetland 5 >14 days
75,000 ac-ft	4,100 cfs for one day, snowmelt management high flow downramping, 1,700 cfs for nine days, 4,100 cfs for one day, 25% per day downramping	Fill North Pond twice, inundate Wetland 5 >14 days (includes ramping days)
104,000 ac-ft	4,100 cfs for one day, snowmelt management high flow downramping, 1,700 cfs for nine days, 4,100 cfs for one day, snowmelt management high flow downramping, 1,700 cfs for six days, 4,100 cfs for one day, snowmelt management high flow downramping	Fill North Pond three times, inundate Wetland 5 >14 days, preserve inundation of Poopenaut Valley bars to protect riparian ground-nesting birds
133,000 ac-ft	4,700 cfs for two days, 4,100 cfs for 12 days, snowmelt management high flow downramping	Inundate and saturate Wetland 11 >14 days, fill North Pond, inundate Wetland 5 >14 days
157,000 ac-ft	5,700 cfs for two days, 4,800 cfs for 12 days, snowmelt management high flow downramping	Inundate and saturate Wetland 6 and 7 >14 days, inundate Wetland 11 >14 days, fill North Pond, inundate Wetland 5 >14 days
178,000 ac-ft	6,500 cfs for two days, 5,400 cfs for 12 days, snowmelt management high flow downramping	Mobilize pea gravels and gravels, inundate and saturate Wetland 6 and 7 >14 days, inundate Wetland 11 >14 days, fill North Pond, inundate Wetland 5 >14 days
190,000 ac-ft	>8,000 cfs for two days, 6,375 cfs for one day, 5,700 cfs for 11 days (for a total of 14 days above 5,700 cfs), snowmelt management high flow downramping	Mobilize gravels and cobbles, inundate Wetland 6 >14 days, inundate Wetland 7 >14 days, inundate Wetland 11 >14 days, fill North Pond, inundate Wetland 5 >14 days

[a] In years when the planning volume is 0 ac-ft, there is no template hydrograph because no snowmelt management objectives are able to be met.

8 Ramping management

O'Shaughnessy Dam operations alter natural hydrograph components, including the natural rate of change in flow magnitude throughout the annual hydrograph, increasing rates of change for both increasing (upramping) and decreasing (downramping) changes in flow magnitudes (see Section 3.2.2.1). Given the important role the spring snowmelt recession plays in the reproductive life cycles of river-dependent species, including Foothill Yellow-legged Frog, woody riparian plant species, and native fish rearing, the EFS focused on developing new downramping procedures for high flow releases (>300 cfs) during the spring snowmelt management period and winter. Revised baseflow ramping rates and high flow upramping rates were considered, but these existing ramping rates were not identified as a risk to focal elements. Therefore, the existing requirements in the 1985 Stipulation (Condition 2) are recommended for baseflow ramping (flows <300 cfs) and high flow upramping (flows >300 cfs).

The effects of high flow spring snowmelt management and winter downramping rates on aquatic biota are influenced by channel morphology and hydraulic response to flow changes, habitat availability, presence and abundance of sensitive species at various life stages, and behavior of sensitive species at various life stages. Developing ramping rates, therefore, is highly site-specific and thus requires extensive site-specific data. Due to the complex and heterogeneous terrain present within the Hetch Hetchy Reach, it is impractical to derive protective ramping rates from empirical studies; thus, recommendations were developed by examining reference conditions.

The reference condition approach is founded on the principle that aquatic biota evolved under natural flow regimes and thus have developed innate characteristics and behaviors to survive and persist under natural flow fluctuations. This principle is also incorporated into guidance provided in the Stewardship Policy (see Section 1). The reference condition approach recently has been used to establish downramping rate limits for several hydropower projects in California. For example, recent Federal Energy Regulatory Commission (FERC) licenses and settlement agreements for the Mokelumne River Project (FERC No. 137), Rock Creek-Cresta Project (Feather River) (FERC No. 1962), and Pit River Project (FERC No. 233-081) include limits to winter and snowmelt downramping to minimize project-induced flow fluctuations uncharacteristic of the natural hydrograph to protect biota (FERC 2000a, 2000b, 2007).

8.1 Snowmelt management period downramping and drum gate operations

The snowmelt recession hydrograph component occurs after peak snowmelt runoff in the late spring or early summer and eventually transitions to summer baseflows. This period is particularly important in the rivers of the Sierra Nevada since numerous native species key the timing of their reproduction to the predictable characteristics of the recession (Yarnell et al. 2010, M&T and RMC 2008). While flow ramping is naturally variable, increased downramping rates (or flow "recession") during the snowmelt recession have been linked to stranding of fish; dewatering and desiccation of amphibian egg masses, tadpoles, and woody riparian vegetation seedlings; and prevention of initiation and establishment of new cohorts.

Reference condition snowmelt recession rates were analyzed from multiple locations and used to provide context for development of recommended snowmelt management period downramping rates. Other temporal, flow magnitude, and rate of change characteristics of the reference snowmelt recession hydrology were also evaluated for context. The approach characterized the following:

- Average "daily" and "event-constrained" reference condition recession rates from May 1 to July 31, which typically included all recession "limbs" of the snowmelt runoff hydrograph (fast and slow)

  - "Daily" consists of all daily recession rates from May 1 to July 31.
  - "Event-constrained" consisted of daily recession rates from days when recession was occurring.
- Changes in recession rates relative to flow magnitude
- Snowmelt recession hydrograph limbs and nodes that define recognizable and repeated patterns in the snowmelt recession between peak runoff and summer baseflows
- Daily average recession rates at the end of the snowmelt runoff hydrograph (post-inflection node recession limb), where flow is dominated by subsurface return flow
- Drum gate spill characteristics and downramping rates
- Modeled bank stability at varying downramping rates to assess ramping-related risk of bank collapse in Poopenaut Valley tributaries (Stillwater Sciences 2011)

Recommended downramping rates and drum gate operations relied on the reference condition daily average and event-constrained analyses. Other studies described above were also considered but were not the primary drivers of recommendations.

This effort also examined diurnal flow fluctuations for inflows and drum gate releases from O'Shaughnessy Dam. Detailed methods and results for all ramping-related analyses are described in Appendix H.

8.1.1 Average daily and event-constrained recession rates

The analysis of reference condition snowmelt recession rates sought to quantify declines in daily average and event-constrained flow over the entire period of the snowmelt hydrograph, defined for this analysis as May 1 through July 31. Pre-dam streamflow records for the Tuolumne River near Hetch Hetchy gage were available for the period 1911–1922 (12 years). To provide a longer period of record for analysis, the Merced River at Pohono Bridge gage (USGS gage 11266500) was used as an unimpaired reference gage, with a 62-year period of record (1960 to 2021). The Merced River gage is located 17 miles southeast of the Tuolumne River near Hetch Hetchy gage and is situated at a similar elevation and drainage area (see Appendix H for details).

To compute daily average snowmelt flow recession, daily average flow data for the May 1–July 31 analysis period at both gages were compiled, and absolute change (i.e., cfs per day) and relative change (i.e., percent per day) were computed. Relative change in daily average flow was computed as $(Q_{day\ 2} - Q_{day\ 1})/Q_{day\ 1}$. Results for both gages are illustrated in Figure 44 and Figure 45.

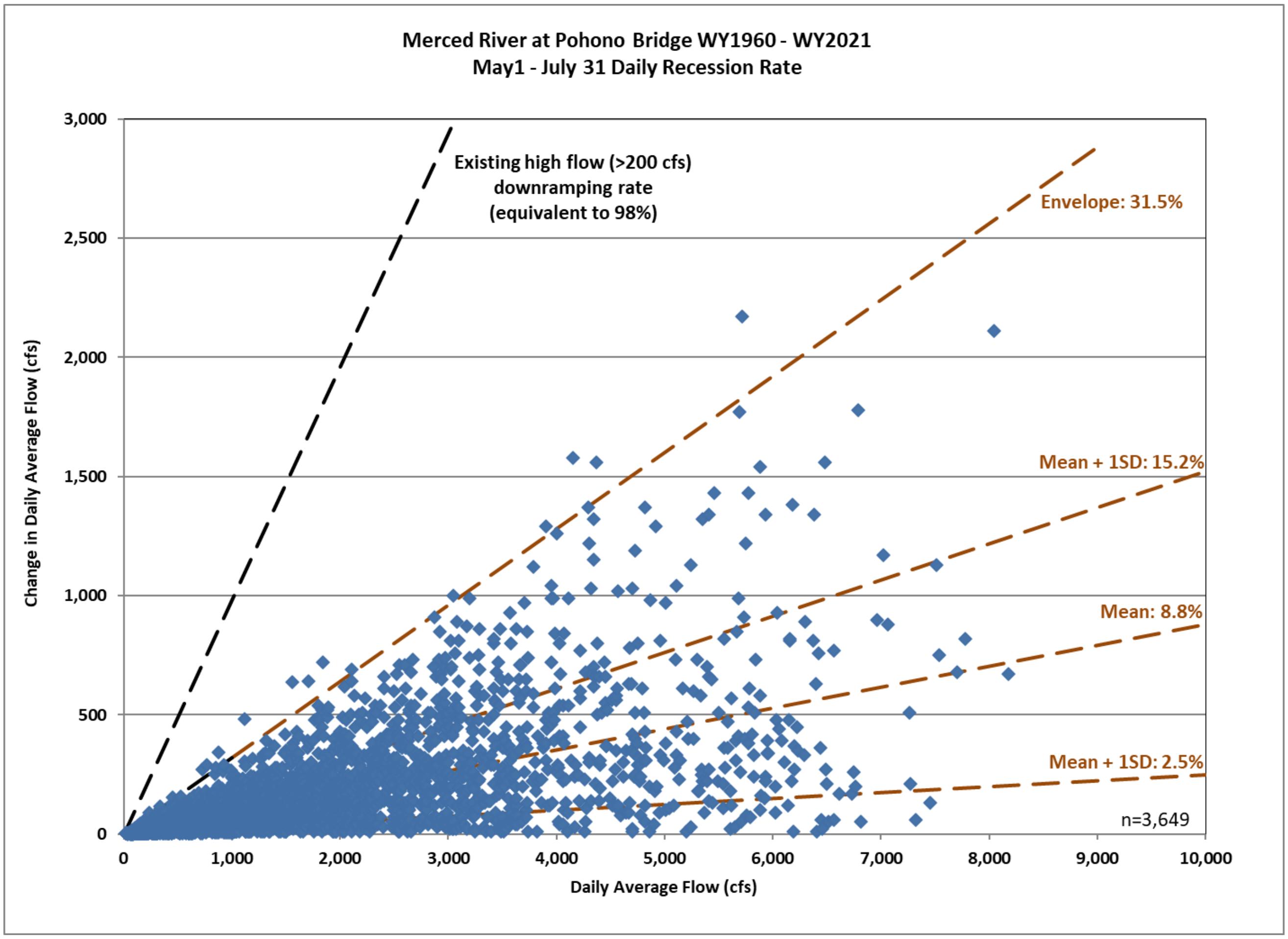

Figure 44. Measured daily average flow decline at the Merced River at Pohono Bridge gage (May 1–July 31) for the 62-year record (1960–2021). Points indicate absolute change in daily average flow for each declining flow day. Dashed lines indicate the relative rate of change for measured rates, including the envelope of the upper end of natural ramping rates (31.5%) and the existing high flow downramping rate (see Section 3.2.3).

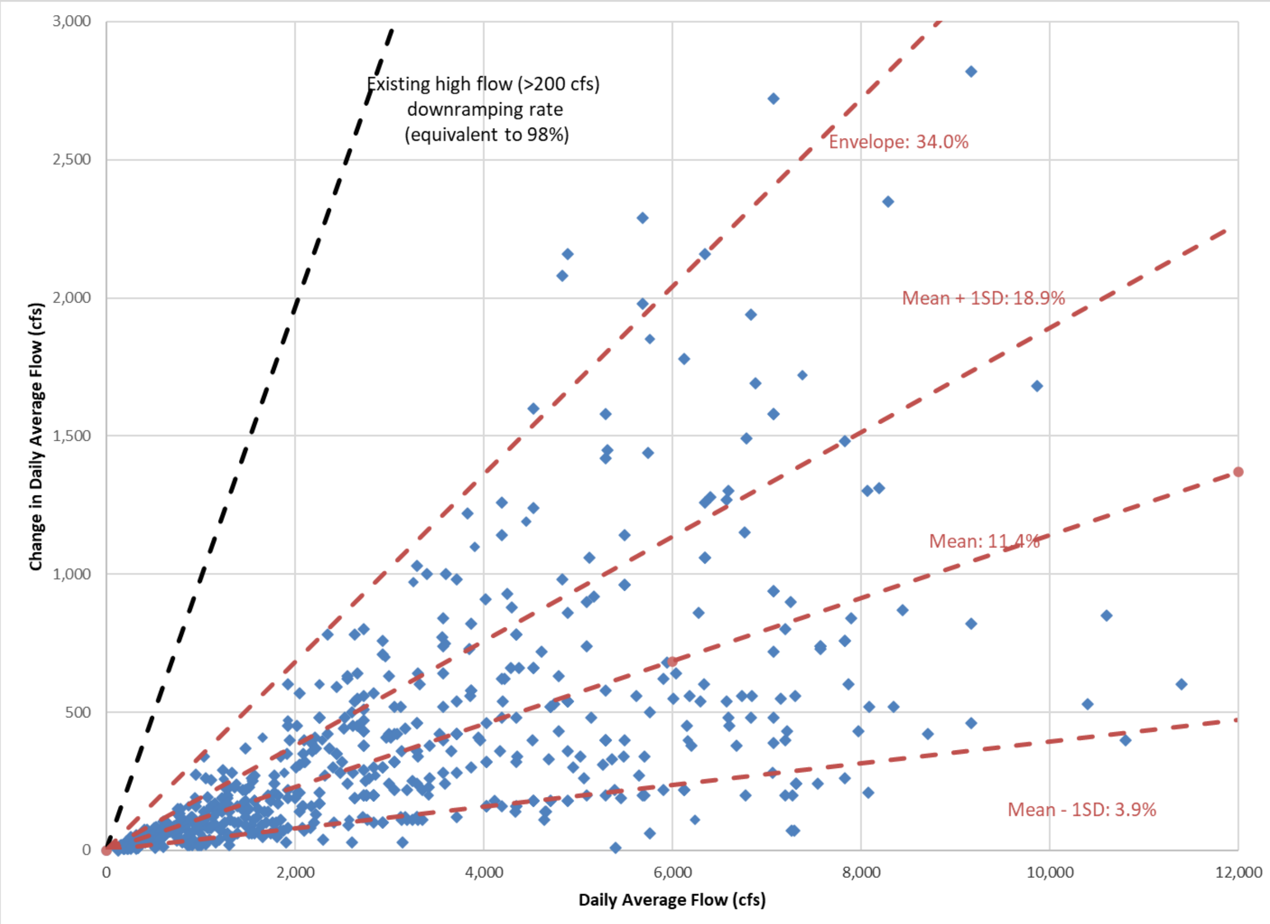

Figure 45. Measured daily average streamflow decline for the 1911–1922 pre-dam record at the Tuolumne River near Hetch Hetchy gage (May 1–July 31). Points indicate absolute change in daily average flow for each declining flow day. Dashed lines indicate the relative rate of change for measured rates, including the envelope of the upper end of natural downramping rates (34.0%) and the existing high flow downramping rate (see Section 3.2.3).

Despite the difference in period and duration of record, drainage area, and watershed physiography, the range, mean, and variability of daily average snowmelt flow recession rates were similar for the pre-dam Tuolumne River near Hetch Hetchy and unimpaired Merced River at Pohono Bridge gages. Daily average snowmelt recession rates on the Tuolumne River for the pre-dam period ranged from 0.2% to 44.2% per day (n=606) and averaged 11.4% ±7.5% per day (mean±standard deviation). Daily average snowmelt recession rates on the Merced River ranged from 0.2% to 43.0% per day (n=3,649) and averaged 8.8% ±6.4% per day. The 1985 Stipulation high flow (>200 cfs) downramping rate is equivalent to approximately 98% per day and greatly exceeds the maximum observed daily average recession rate at both gages.

A similar analysis was conducted on event-constrained recession rates, and these rates were similar to those estimated for daily average downramping rates. Additional details are in Appendix H.

To compute event-constrained daily average flow recession, daily average pre-dam data from the Tuolumne River near Hetch Hetchy gage and recent flow data from the Tuolumne River at Grand Canyon gage, from 2007 to 2021 (USGS 11274790), were used. The Tuolumne River at Grand Canyon gage measures unimpaired inflow to Hetch Hetchy Reservoir from approximately half of the reservoir's watershed. The period from May 1 through July 31 was plotted and reviewed to identify all sustained recession events, each of which lasted one to several days. Event-constrained recession rates were slightly higher than average daily rates. The pre-dam Tuolumne River near Hetch Hetchy gage ranged from 1.5% to 43.1% per day and averaged 14.3% ±7.9% per day (Figure 46). At the Tuolumne River above Hetch Hetchy (at Grand Canyon) gage, event-constrained recession rates were somewhat slower, ranging from 0.7% to 32.4% per day and averaging 8.8% ±7.1% per day (Figure 47).

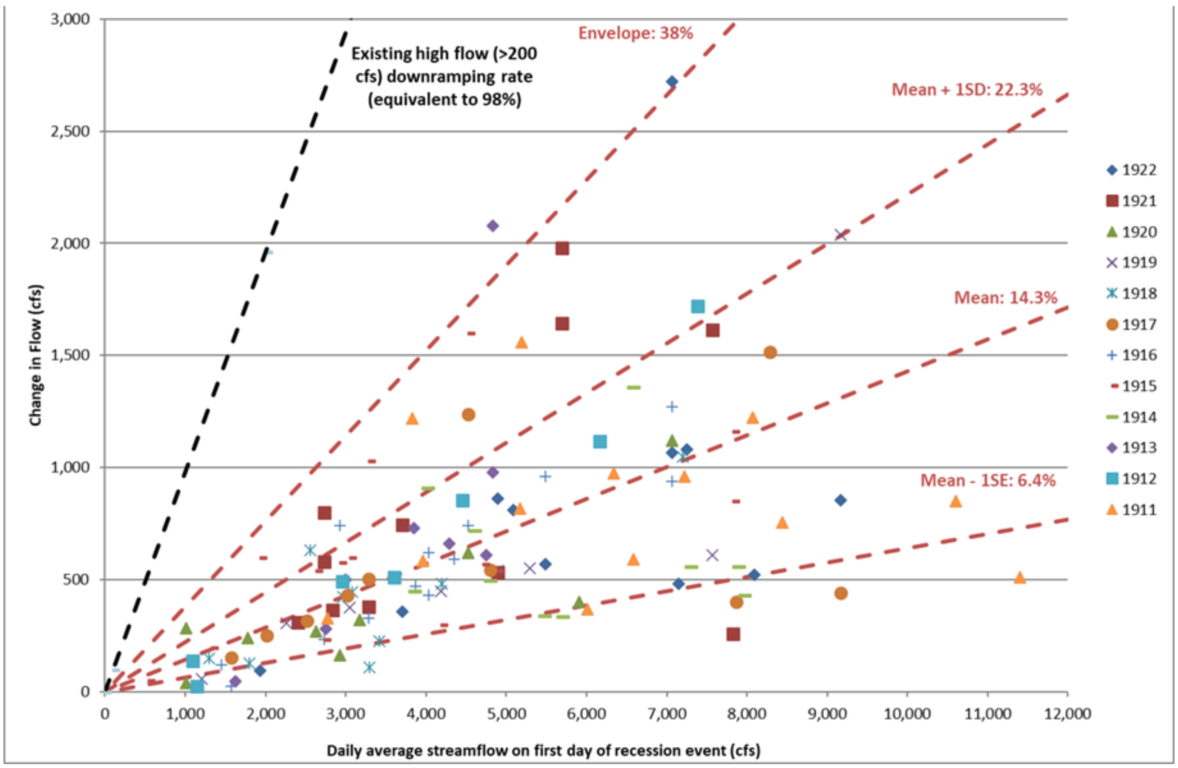

Figure 46. Pre-dam, measured event-constrained recession rates at the Tuolumne River near Hetch Hetchy gage (May 1–July 31) from 1911-1922. Points indicate absolute change in daily average flow for each declining flow day. Dashed lines indicate the relative rate of change for measured rates and the existing high flow downramping rate (see Section 3.2.3).

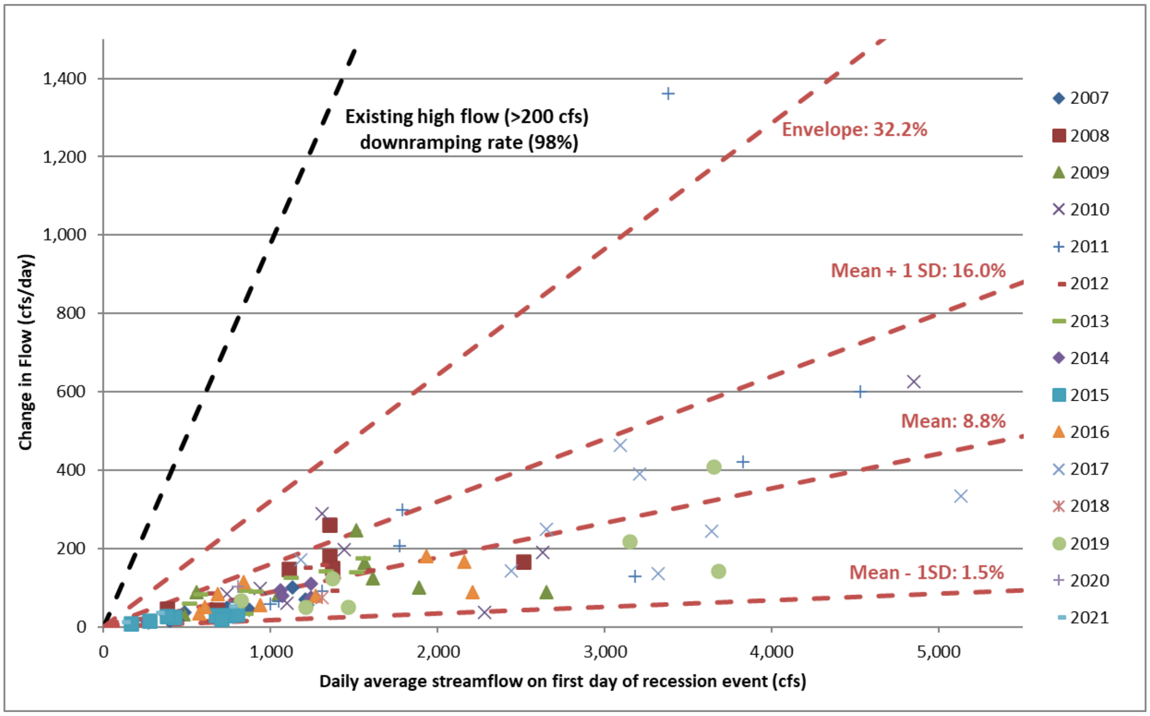

Figure 47. Measured, event-constrained recession rates at the Tuolumne River above Hetch Hetchy (at Grand Canyon) gage (May 1–July 31) from 2007 to 2021. Points indicate absolute change in daily average flow for each declining flow day. Dashed lines indicate the relative rate of change for measured rates and the existing high flow downramping rate (see Section 3.2.3).

8.1.2 Drum gate spill characterization

In wetter years, once Hetch Hetchy Reservoir has filled in late spring or early summer, spill begins to flow over the drum gates and down the spillway to the Tuolumne River. Continued utilization of the drum gates and spillway has the potential to mimic components of the natural snowmelt hydrograph downstream of O'Shaughnessy Dam and improve operational efficiency by:

- Allowing for a more natural release pattern and ramping rate (including diurnal snowmelt variation), as the amount of flow being released is largely a function of inflow minus Canyon Power Tunnel diversions;
- Better mimicking natural diurnal flow periodicity and thus potentially mimicking important life history cues for aquatic fauna in the reach;
- Resulting in warmer water temperatures during late spring from surface water passing over the drum gates, similar to the reference condition late spring snowmelt runoff thermal regime;
- Reducing the frequency of valve adjustment during snowmelt management releases; and
- Allowing for valve releases to eventually be set to the baseflow release for the current water year class during drum gate spills, such that as inflows recede, downstream releases slowly recede down to the baseflow.

During the spring of 2010, the drum gates were used operationally to provide a preliminary characterization of the effects of drum gate releases on downstream flows in the Hetch Hetchy Reach

(Figure 48). These investigations focused specifically on the effects of drum gate releases on diurnal flow fluctuations, downramping/flow recession, and water temperatures.

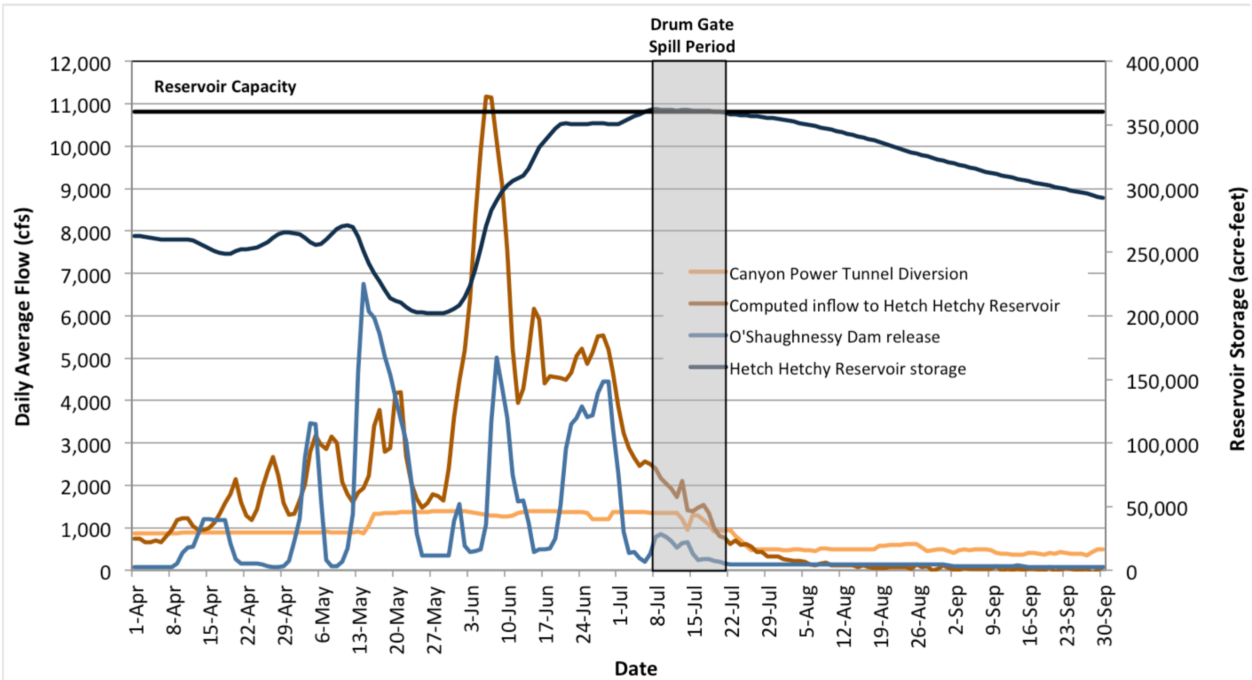

Figure 48. Example of drum gate releases from WY 2010, showing the duration of snowmelt management releases and drum gate spills.

The 2010 drum gate experimental releases demonstrate the potential changes to end-of-season flow recession rates (Figure 49). In 2010, prior to the drum gate spills, downramping in the Hetch Hetchy Reach was controlled via O'Shaughnessy Dam face valves. The last valve-controlled flow recession event prior to the drum gate spills occurred over five days from June 29 through July 3. Flow declined from 4,450 cfs to 404 cfs, averaging 1,012 cfs per day (23% per day). When the drum gates were spilling (i.e., passing inflow minus the Canyon Power Tunnel diversion), flow recession rates ranged from 4% to 10% per day, a rate consistent with the range of observed unimpaired daily pre-dam recession rates for the Tuolumne River (Appendix H).

After the drum gate spill was initiated near the first of July, flow increased for six days based on reservoir inflow. The drum gate recession at the end of that brief pulse occurred from July 9 through July 16. Flow declined from 857 cfs to 234 cfs over this seven-day period, averaging 89 cfs per day (10% per day). Reference condition inflow declined over a period of 32 days (July 6 through August 6) at a rate of 4% to 5% per day. Although the final snowmelt recession in the Hetch Hetchy Reach was shorter and steeper than the reference condition snowmelt recession, the recession rate is much closer to the reference condition post-inflection node recession rate of 5.5%, more gradual than the 23% per day valve release recession, and much slower than the 1985 Stipulation recession (98% per day).

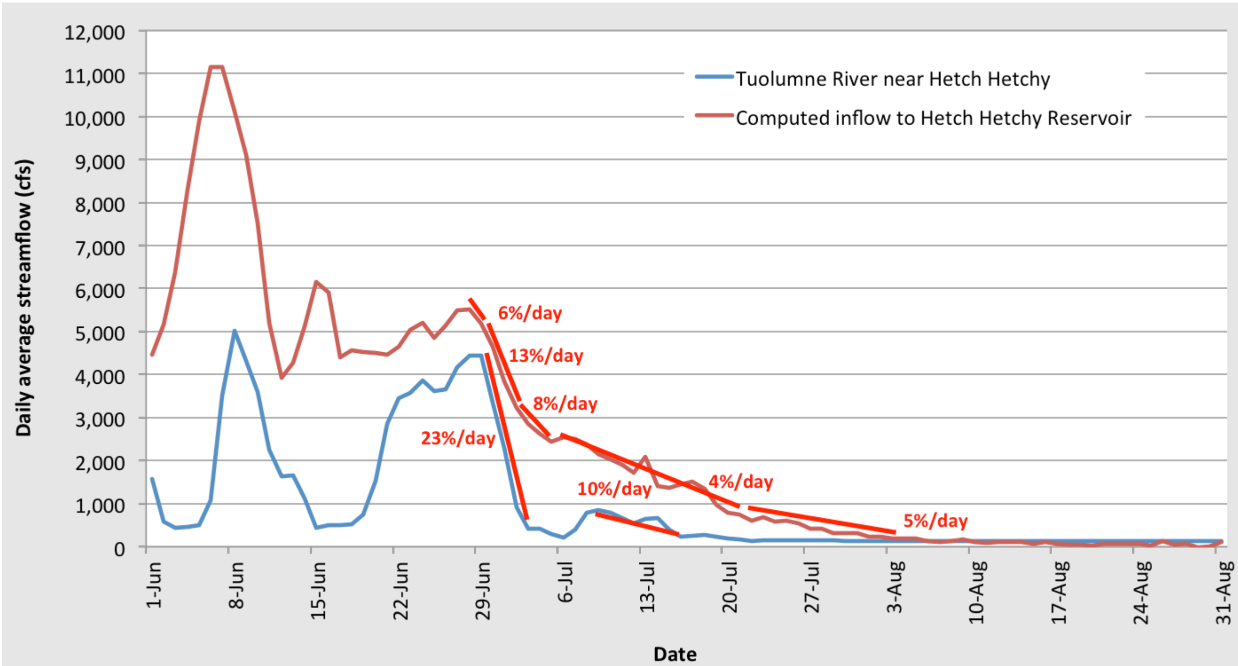

Figure 49. End-of-season 2010 daily average snowmelt recession rates for computed unimpaired Hetch Hetchy Reservoir inflow and measured release to the Hetch Hetchy Reach with drum gate operation. Red lines are event-based downramping rates using linear regression. Flows without drum gate operation would have been steady valve releases of unknown magnitude.

8.1.3 Snowmelt management period downramping targets

For downramping events during the snowmelt management period, a rate of 25% per day for releases >300 cfs is recommended, balancing operational needs while providing a rate that is more protective of vulnerable focal elements and closer to the reference condition than the existing 1985 Stipulation high flow ramping rate of 98% per day.

The 25% per day downramping rate (the snowmelt management high flow ramping rate) exceeds the mean ± 1 standard deviation (SD) rate observed at all of the gages in the reference condition analysis, but is within the envelope of observations in the Hetch Hetchy Reach and the Merced River reference reach, and only slightly exceeds the envelope of observations for the Tuolumne River above Hetch Hetchy (at Grand Canyon) gage (see Figure 45 through Figure 47). The 25% downramping rate is more than four times faster than the reference condition post-inflection node recession rate, but overall downramping is likely to be much less during drum gate spill in wetter years (see Section 8.1.2).

Using the 25% ramping rate for flows greater than 300 cfs reduces the risk of significant stage drops in Poopenaut Valley as releases transition from drum gate spill to baseflows in wetter years, and is slow enough to reduce the likelihood of bank failure in the Poopenaut Valley tributaries based on bank stability modeling (Stillwater Sciences 2011).

To allow for more frequent filling of the Poopenaut Valley North Pond, the existing 1985 Stipulation high flow downramping rate of no more than 50% reduction every four hours is recommended as an alternative in drier water years. This alternative downramping rate is only recommended for use for valve releases greater than 300 cfs, when snowmelt management planning volumes are ≥9,800 and <42,000 ac-ft and when filling the North Pond during the snowmelt management period prior to May 15, to reduce potential impacts on Foothill Yellow-legged Frog.

Because drum gate spill is representative of unimpaired inflow passing through Hetch Hetchy Reservoir, there is no recommended downramping rate for drum gate operations. However, it is recommended that valve changes continue to use the 25% per day downramping rate, which should help maintain drum gate spill while avoiding large spikes in the downstream hydrograph. Because the Tuolumne River near Hetch Hetchy gage is downstream of the face valves, environmental release valves, and the spillway, it measures total release from all of these facilities.

8.2 Winter ramping

Winter high flows are generated by rainfall and rain-on-snow events and occur infrequently over the historical record due to the high elevation watershed upstream of O'Shaughnessy Dam. Winter releases in the Hetch Hetchy Reach rarely exceed baseflow releases, but when rain- and rain-on-snow-driven high flow events do occur, the largest of these events result in high flow releases from O'Shaughnessy Dam.

The primary ecological concerns regarding winter high flow release ramping and resulting recession rates in the Hetch Hetchy Reach are (1) stranding of trout and other native fish (particularly juveniles and fry) on cobble bars and isolated pools, (2) desiccation of BMI, and (3) stimulation of increased BMI drift. Thus, reference condition recession rates were examined to support development of protective winter ramping rates. The analysis approach characterized:

- Daily average and "event-constrained" reference condition recession rates from January 1 to March 31, which typically included all rainfall and rain-on-snow events; and
- Changes in recession rates for winter high flow events relative to flow magnitude.

8.2.1 Average daily and event-constrained recession rates

Reference conditions for winter high flow daily average recession rates used the same gage data and method described for snowmelt daily average recession rates (see Section 8.1.1) but used data for the January 1–March 31 period. Because this analysis does not differentiate between winter recession events and sequential days over which minor flow changes occurred, small declines in flow that were not part of a rainfall or rain-on-snow recession event are retained in the data. Therefore, small declines in flow are overrepresented and skew the results downward (i.e., toward slower recession rates). To avoid underestimating reference condition daily flow recession rates, results were used only to define an upper boundary or envelope for daily recession rates, which is not affected by the downward skewing.

For all observations at the Merced River reference site (n=2,974), winter recession rates exceeded the 99th percentile envelope of 34.7% on 25 occasions (Figure 50). For the pre-dam Hetch Hetchy Reach (n=477), winter recession rates exceeded the 99th percentile envelope of 48% per day only three days (Figure 51). For the Merced River total data set, daily recession rate exceeded 30% per day fewer than 1% of the days, and only exceeded 50% on one day. For the pre-dam Tuolumne River total data set, daily recession rate exceeded 30% per day on 24 days (5% of total), and 50% per day on three days (1% of total).

To compute event-constrained daily average recession for winter high flow events, daily average pre-dam data from the Tuolumne River near Hetch Hetchy gage (1911–1922) and data from the Merced River at Pohono Bridge gage for the period from 1960 to 2021 were used. Hydrographs for the period from October 1 to March 31 were plotted and reviewed to identify peak winter events for each year, and declines in daily average flow for each event were computed. The maximum observed daily average flow recession rate for each event was compiled and used as an indicator of the upper range of winter recession rates. For the Merced River, winter high flow events occurred in 10 of the 62 years analyzed. The observed maximum rate of daily average flow recession ranged from 36% per day to 73% per day and averaged 55% ±11% per day (mean ±SD). For the pre-dam Tuolumne River, winter peaks occurred in two years for the period analyzed. For these peaks, the maximum daily average flow recession rates were 34% per day (1911) and 76% per day (1916) (mean = 55% per day).

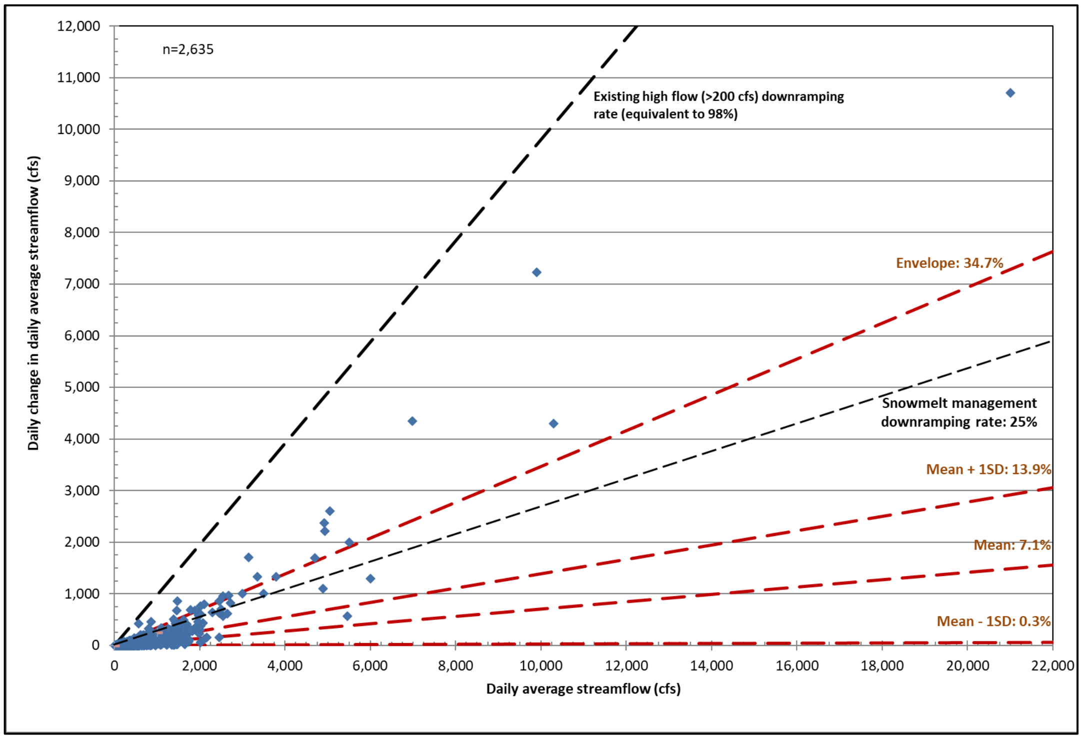

Figure 50. Measured daily average flow decline at the Merced River at Pohono Bridge gage (January 1–March 31) from 1960 to 2021. Points indicate absolute change in daily average flow for each declining flow day. Dashed lines indicate the relative rate of change for measured rates and the existing high flow downramping rate (see Section 3.2.3).

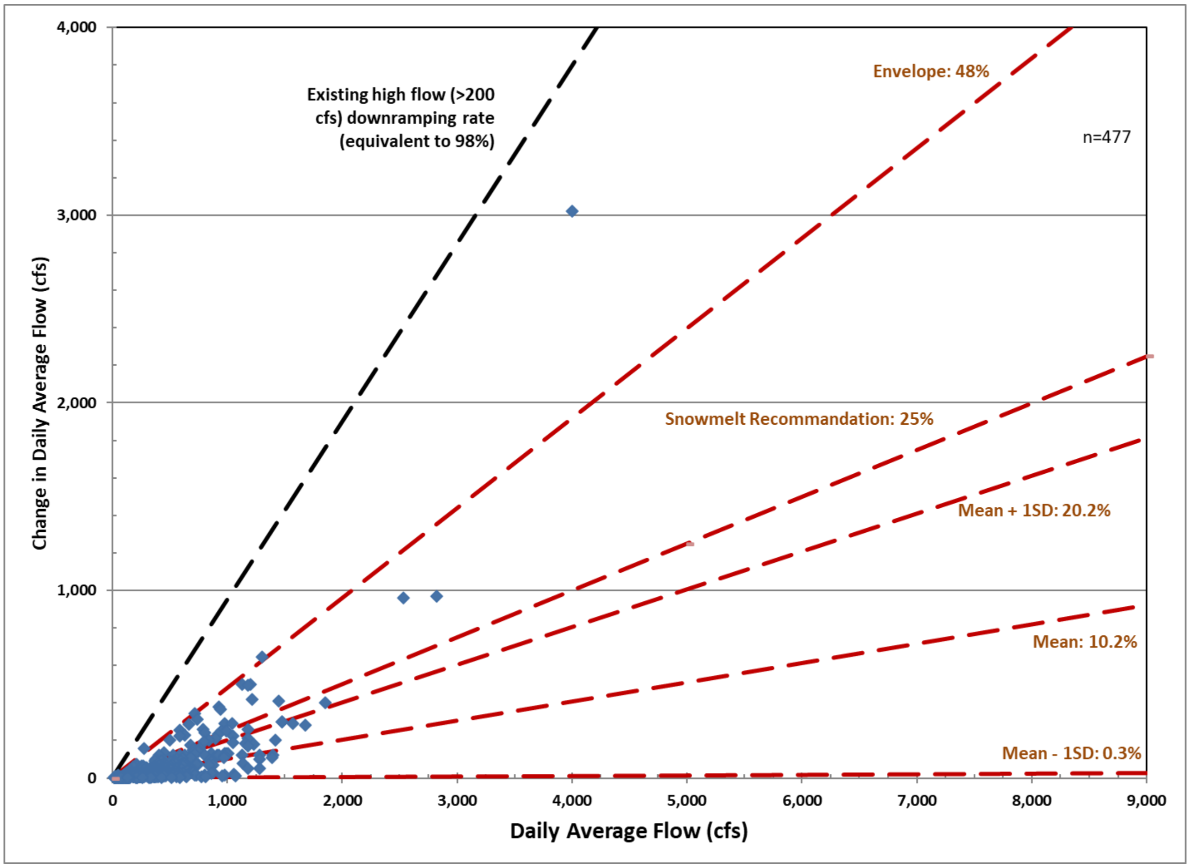

Figure 51. Measured daily average streamflow decline for the 1911–1922 pre-dam record at the Tuolumne River near Hetch Hetchy gage (January 1–March 31). Points indicate absolute change in daily average flow for each declining flow day. Dashed lines indicate the relative rate of change for measured rates and the existing high flow downramping rate (see Section 3.2.3).

8.2.2 Changes in recession rates relative to flow magnitude

To test whether daily average winter flow recession rates were faster at higher flow magnitudes, the daily average recession rate data for the pre-dam Tuolumne River near Hetch Hetchy and Merced River at Pohono Bridge were truncated at various flows and re-analyzed. Unlike spring snowmelt flow recession rates, winter daily average flow recession rates exhibited a general pattern of increasing recession rate relative to flow magnitude, reflecting the flashier nature of winter rain and rain-on-snow events. For both the Merced River and pre-dam Tuolumne River, moderate-to-large magnitude flows receded at rates generally exceeding 30% per day. On the Merced River, the moderate-to-large flow threshold was approximately 2,200 cfs (3.4 times the mean annual flow). Winter flows above this threshold (n=27) receded at rates ranging from 7% per day to 73% per day and averaging 36% ±15% per day (mean ±SD). On the Tuolumne River, the moderate-to-large flow threshold was approximately 2,000 cfs (1.9 times the pre-dam mean annual flow). Flows exceeding 2,000 cfs (n=4) receded at rates ranging from 34% per day to 76% per day and averaging 50% ±19% per day (mean ±SD). For both rivers, daily recession rates for flows smaller than the flow threshold varied widely, ranging from 0.2% per day to 75% per day on the Merced River (n=2,608) and 0.3% per day to 56% per day on the Tuolumne River (n=473).

8.2.3 Winter downramping recommendations

To balance management of ecologically protective winter ramping and safe management of heavy rain and rain-on-snow events, particularly as they relate to cooperative basin-wide winter flood response, a downramping rate of 55% per day is recommended for winter high flow valve releases greater than 300 cfs. If winter drum gate spills occur, it is recommended that the winter downramping rate be applicable only to valve releases. The recommended winter downramping rate is consistent with (1) the upper envelope for observed declines in daily average flow at the Merced River at Pohono Bridge and pre-dam Tuolumne River near Hetch Hetchy gages for the period from January 1 through March 31, and (2) the mean value for observed maximum rates of decline in daily average flow for individual winter recession events for the period from October 1 through March 31 for the periods of record analyzed. Therefore, the recommended winter high flow recession rate is representative of peak winter recession rates under reference conditions. The recommended winter downramping rates were developed based on pre-dam daily recession rates in the Hetch Hetchy Reach and in a nearby unregulated reach of the Merced River for the period from January 1 through March 31, but are recommended for the period of September 1 to March 31.

8.3 Summary of ramping management recommendations

A set of new downramping targets are recommended for spring snowmelt management and winter downramping to better mimic natural recession rates and reduce potential stranding, displacement, and/or unnatural ramping-related energetic expenditures for native aquatic species (especially larvae and young-of-year life stages). A summary of the new recommended ramping targets is provided in Table 15.

Existing requirements in the 1985 Stipulation (Condition 2) are recommended for baseflow ramping and high flow upramping year-round. For baseflows, the rate of upramping or downramping should not exceed 50 cfs over a four-hour period. For high flow upramping, the rate should not be more than double the previous release over a four-hour period. The baseflow ramping rate would apply to flows less than 300 cfs and the high flow upramping rate would apply to flows greater than 300 cfs.

Table 15. *Recommended qualitative and quantitative ramping management targets, with target snowmelt management planning volume (if applicable) and timing.*

Focal element	Ecological goal	Management objective	Quantitative ramping management target	Target snowmelt management planning volume (ac-ft) and timing
Ramping rates	Reduce potential stranding, displacement, and/or excessive ramping-related energetic expenditures for native aquatic species, and promote riparian vegetation recruitment in wetter water years	Provide high flow downramping rates that more closely mimic downramping rates in the reference condition	*Fast high flow downramping*: For valve releases >300 cfs, maximum of 50% reduction every four hours. This limited use ramping rate allows more frequent filling of the Poopenaut Valley North Pond in drier water years, while protecting Foothill Yellow-legged Frog reproduction.	≥9,800 and <42,000 and filling North Pond prior to May 15 (April–August)
			Snowmelt management high flow downramping: For valve releases >300 cfs, maximum of 25% per day.[a]	Any planning volume (April–August)
			Drum gate ramping operations: Utilize drum gate releases as often and early as possible once Hetch Hetchy Reservoir is full and spilling and after other selected snowmelt management targets have been prioritized and achieved. Pass as much snowmelt spill as possible (typically a maximum of 2,500 cfs) via the drum gates. Use the *high flow upramping rate* and *snowmelt management high flow downramping* rate for valve releases >300 cfs to maintain drum gate spill while avoiding large spikes in total release.	Any planning volume (April–August)
			Winter high flow downramping: For valve releases >300 cfs, maximum of 55% per day.[a]	(September–March)

a. When downramping from high flows (>300 cfs) to the baseflow release for the current water year class, if the target flow is less than 300 cfs when calculated using the *fast, snowmelt management,* or *winter* high flow downramping rates, use the high flow downramping rate to achieve the target flow, then use baseflow ramping for subsequent transitions between baseflow releases.

9 Evaluation of flow scenarios

A series of quantitative analyses were conducted to evaluate the differences among existing flows, recommended future environmental flows, and reference condition flows at two locations within the Hetch Hetchy Reach: the EI site and the OSD site. The analyses were designed to evaluate streamflow and water temperature changes, and the relative effects on focal elements described in Section 5.2. Northwestern Pond Turtle was also evaluated because it is a listed species that uses the Tuolumne River for habitat. Quantitative analyses included:

- Measured and estimated water temperature and streamflow at the near Hetch Hetchy gage (applied to the OSD site) and the Above Early Intake gage (applied to the EI site)
- NGD analysis for Rainbow Trout, Foothill Yellow-legged Frog, and BMI
- Rainbow Trout population and growth analysis (individual-based Stream Trout Research and Assessment Model [inSTREAM])
- Foothill Yellow-legged Frog Assessment Model (FYFAM)
- Northwest Pond Turtle qualitative evaluations
- Frequency of achieving bed-mobility and riparian inundation flow thresholds
- Sediment transport capacity analysis
- Drum grate release timing

9.1 Development of streamflow and temperature scenarios

Three flow scenarios were developed to represent existing flows, recommended future environmental flows, and reference condition flows. The three flow scenarios were developed at two locations: at the above Early Intake gage and at the near Hetch Hetchy gage (0.9 mi downstream of O'Shaughnessy Dam). The existing and recommended future flows were simulated using the "Spill-Sim" simulation tool (Appendix I). Reference condition flows were estimated using computed inflow into Hetch Hetchy Reservoir and estimated accretion and are included in the analysis for context. The Spill-Sim tool operates on a daily time step and simulates operations during the months of April to August each year. Spill-Sim simulates reservoir storage, valve releases, and drum gate spills using inputs that include predicted reservoir inflows, Canyon Tunnel diversions and powerdraft, baseflow requirements, and spill. The months of September to March were assumed to be baseflows for the existing and future flows, respectively.

A summary of the flow scenarios is as follows:

(1) Existing flows scenario (1993–2021) – The existing operations scenario developed using the Spill-Sim tool that simulates existing baseflow, ramping, and spill management practices. This scenario assumes existing operations and excludes experimental spill releases conducted since 2006, routine valve testing, and scheduled Hetch Hetchy Project maintenance shutdowns.

(2) Recommended future flows scenario (1993–2021) – The recommended future environmental flow scenario simulated using Spill-Sim, including recommended baseflows, ramping rates, and spill management. This scenario excludes routine valve testing and scheduled Hetch Hetchy Project maintenance shutdowns.

(3) Reference flow scenario (2008–2021) – Developed from computed inflow to Hetch Hetchy Reservoir and estimated accretion.[4] Reference conditions were analyzed for context; see Section 2.3 for additional discussion. The reference flow scenario here was developed using the same hydrology described in Appendix J and in Sections 2.3 and 3.2.2.1.

Flow scenarios were developed at the above Early Intake gage (for use at the EI site) and at the near Hetchy Hetchy gage (for use at the OSD site). The following process was used to develop the existing and future flow scenarios (Figure 52 through Figure 56):

1. A timeseries of predicted flows at the near Hetch Hetchy gage for the OSD site was developed and includes baseflows for January to April and September to December (see Section 6), and baseflows plus simulated spill for April to August ("Spill-Sim"; Appendix I).
2. Water temperatures at the near Hetch Hetchy gage was predicted using the Hetch Hetchy Reservoir Water Temperature Model (Appendix D).
3. A flow time series at the above Early Intake gage was developed by adding accretion to flows at O'Shaughnessy Dam (Appendix J).
4. Water temperatures at the above Early Intake gage were predicted using the Hetch Hetchy Reach Water Temperature Model (Appendix D), using O'Shaughnessy Dam reservoir outflow water temperature as boundary conditions.

The following process was used to develop the flow and temperature reference condition scenario from 2008 to 2021 (water temperature data was unavailable prior to 2008):

1. For reference flows at the near Hetch Hetchy gage, a timeseries of smoothed daily Hetch Hetchy Reservoir inflow data was developed. Data was "smoothed" to eliminate negative values that are inherent in computed reservoir inflow data.
2. For reference water temperatures at the near Hetch Hetchy gage, water temperatures were assumed to be the same as those recorded at the Tuolumne River above Hetch Hetchy gage (USGS gage no. 11274790) from 2008 to 2021.
3. For reference flows at the above Early Intake gage, accretion estimates (Appendix J) were added to the Hetch Hetchy Reservoir inflow timeseries.
4. Water temperature reference conditions the above Early Intake gage were predicted using a river temperature model (Appendix D), using Above Hetch Hetchy gage water temperatures as boundary (input) conditions to the water temperature model.

9.2 Comparisons of predicted flow and temperature under existing, future, and reference condition scenarios

Recommended future baseflows would shape the resulting hydrograph more frequently in drier years, while recommended future snowmelt management would have a larger impact on the hydrograph in normal and wetter years. This result is driven by (1) the addition of spring and summer spill releases to

[4] The reference condition flows and temperature scenario were developed for a shorter time period (2008–2021) than the existing and future scenarios due to a lack of temperature data above Hetch Hetchy Reservoir prior to 2008, when a temperature sensor was installed at the Tuolumne River above Hetch Hetchy USGS gage.

the hydrograph in normal and wetter years when a substantial snowpack is present, and (2) the limited amount of spill volume available in drier years.

Stream temperatures are generally similar between existing and future scenarios at both the OSD and EI sites. Hypolimnetic releases from Hetch Hetchy Reservoir remain stable and cool (near 10°C) for most of the year, resulting in relatively stable and cold temperatures at the OSD site, while substantial in-channel warming occurs between the OSD and EI sites for both scenarios. In all water year classifications and at both sites, water temperatures would be colder in the winter but warmer in the summer under reference conditions. Example water years from each water year classification are plotted to demonstrate shifts in the hydrograph and water temperature (Figure 52 through Figure 56). Plots for all years simulated, grouped by water year, are available in Appendix K.

In drier years, the future scenario is characterized by earlier and higher spring baseflows and lower summer baseflows (Figure 52 and Figure 53) compared to the existing scenario. The lower summer baseflows result in slightly warmer temperatures at the EI site, bringing temperatures closer to reference conditions (Table 16). A key difference between future and existing scenarios is that large snowmelt spill releases after May 15 are minimized in drier years in the future scenario to avoid scour of Foothill Yellow-legged Frog egg masses (see Section 7.2.6). In drier years, the spring flow releases in both existing and future scenarios are lower in magnitude and duration compared to the reference scenario.

In normal and wetter years, spring releases achieve higher magnitudes under the future scenario than the existing scenario to meet recommended snowmelt management objectives (Figure 54 through Figure 56). These releases are typically much higher than recommended baseflows in the spring of normal and wetter years. Flow releases associated with recommended future snowmelt management approach the magnitude of reference condition peak flow events but are often shorter in duration. The spring recession limb of the snowmelt hydrograph in the future scenario is also “smoother” than the existing scenario due to snowmelt management recommendations that reduce flow pulses at the end of the recession limb. Water temperatures are very similar in the future scenario compared to the existing scenario, except for slightly warmer water temperatures during late spring and summer spill events when drum gates are used.

Table 16. *Summary of mean monthly temperatures under existing and future scenarios at the OSD and EI sites. Temperatures are slightly warmer in July and August (in bold) in the future scenario. Water temperatures would be colder in the winter but warmer and more variable in the summer under reference conditions.*

		Mean (SD) temperature (°C)				
	OSD site			EI site		
Month	**Existing**	**Future**	**Reference**	**Existing**	**Future**	**Reference**
January	7.6 (0.2)	7.6 (0.2)	2.6 (1.3)	6.6 (0.4)	6.6 (0.4)	6.3 (0.6)
February	7.4 (0.4)	7.4 (0.4)	3.5 (1.3)	6.8 (0.3)	6.7 (0.3)	6.4 (0.1)
March	6.8 (0.2)	7 (0.1)	5.0 (1.6)	8.9 (0.7)	8.9 (0.7)	7.8 (0.7)
April	7.1 (0.3)	7.3 (0.3)	6.2 (1.5)	9.6 (0.6)	9.5 (0.6)	8.0 (0.9)
May	7.8 (0.8)	7.6 (0.4)	8.0 (2.0)	11.5 (1.7)	11.5 (1.6)	9.7 (1.8)
June	10.2 (1.8)	10 (1.8)	12.3 (3.5)	14.3 (2.5)	14.5 (2.7)	14.0 (3.8)
July	**10.3 (2.1)**	**11.2 (2.5)**	**17.3 (3.0)**	**18.4 (2)**	**19.2 (1.8)**	**20.1 (3.5)**
August	**10.1 (1)**	**10.4 (1.3)**	**18.5 (1.8)**	**18.6 (0.3)**	**19.5 (0.8)**	**22.1 (1.6)**
September	10.2 (0.2)	10.2 (0.2)	16.7 (1.9)	16.9 (1.4)	17.8 (1.6)	20.0 (2.1)
October	10.1 (0.4)	10.1 (0.4)	11.1 (2.4)	13.3 (1.5)	13.4 (1.6)	13.6 (2.7)
November	10 (0.4)	10 (0.4)	5.3 (1.9)	9.3 (0.5)	9.3 (0.5)	7.7 (0.8)
December	9.7 (0.5)	9.7 (0.5)	2.4 (1.5)	7.7 (0.7)	7.7 (0.7)	6.4 (0.4)

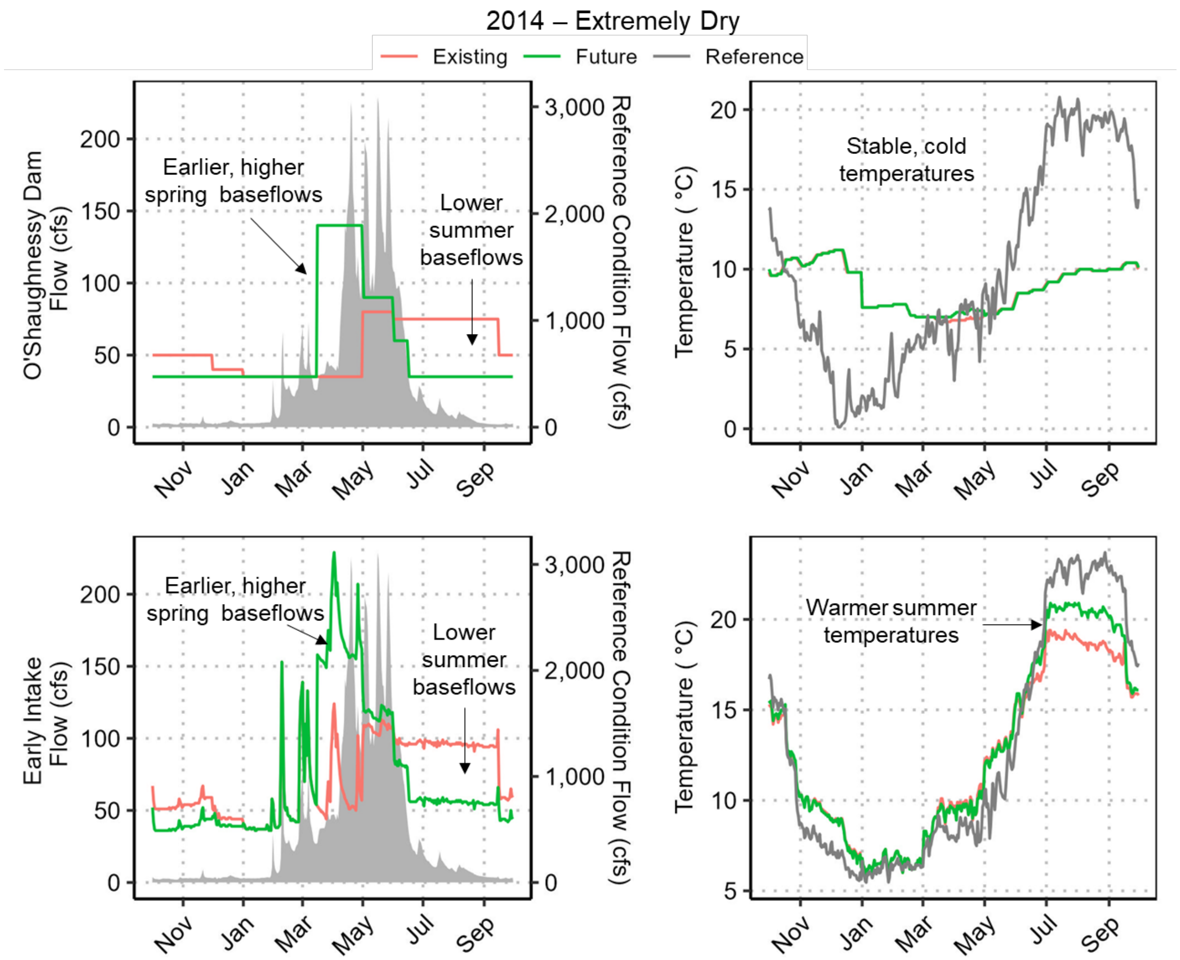

Figure 52. Flow and temperature at the OSD and EI sites under existing and future scenarios in an Extremely Dry year, WY 2014. Notations compare the future to the existing scenario; estimated reference flows (on the secondary Y axis) and water temperatures are provided for context.

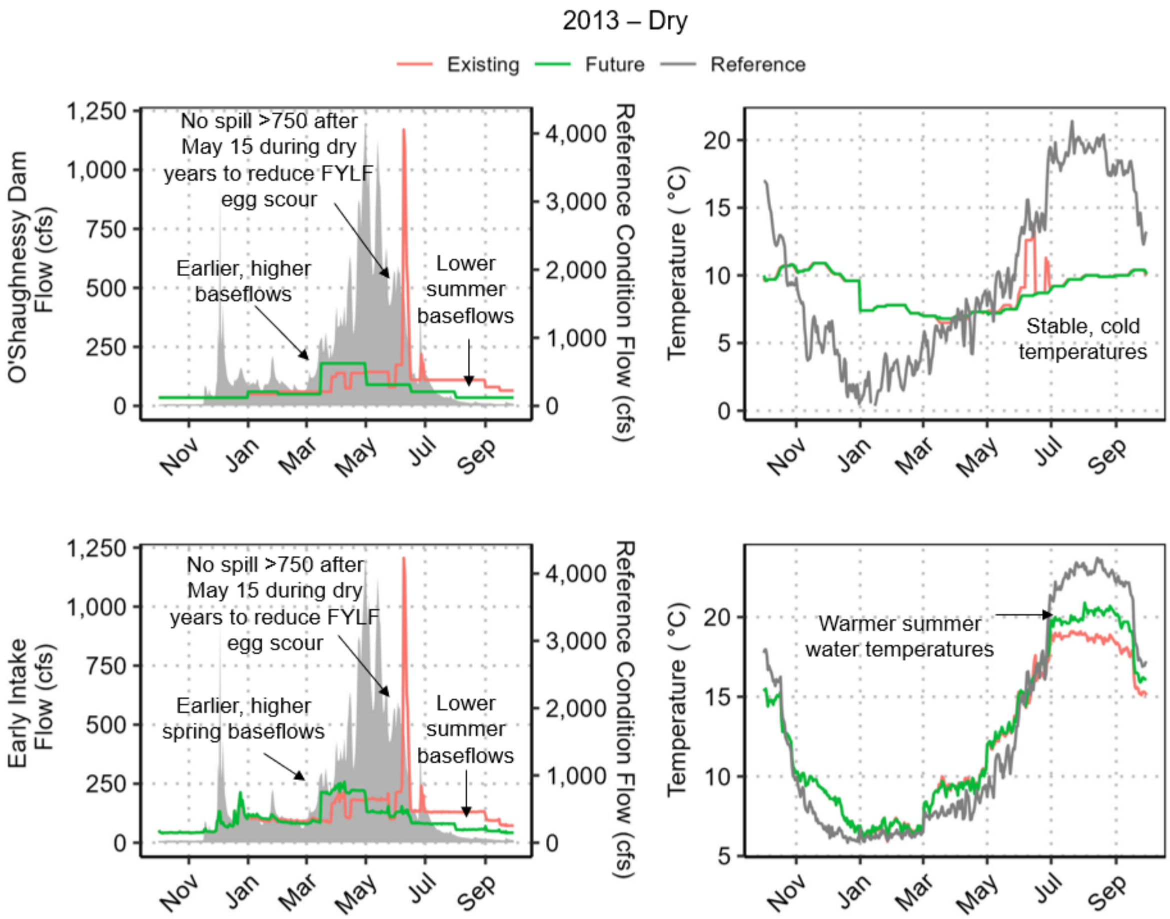

Figure 53. Flow and temperature at the OSD and EI sites under existing and future scenarios in a Dry year, WY 2013. Notations compare the future to the existing scenario; estimated reference flows (on the secondary Y axis) and water temperatures are provided for context.

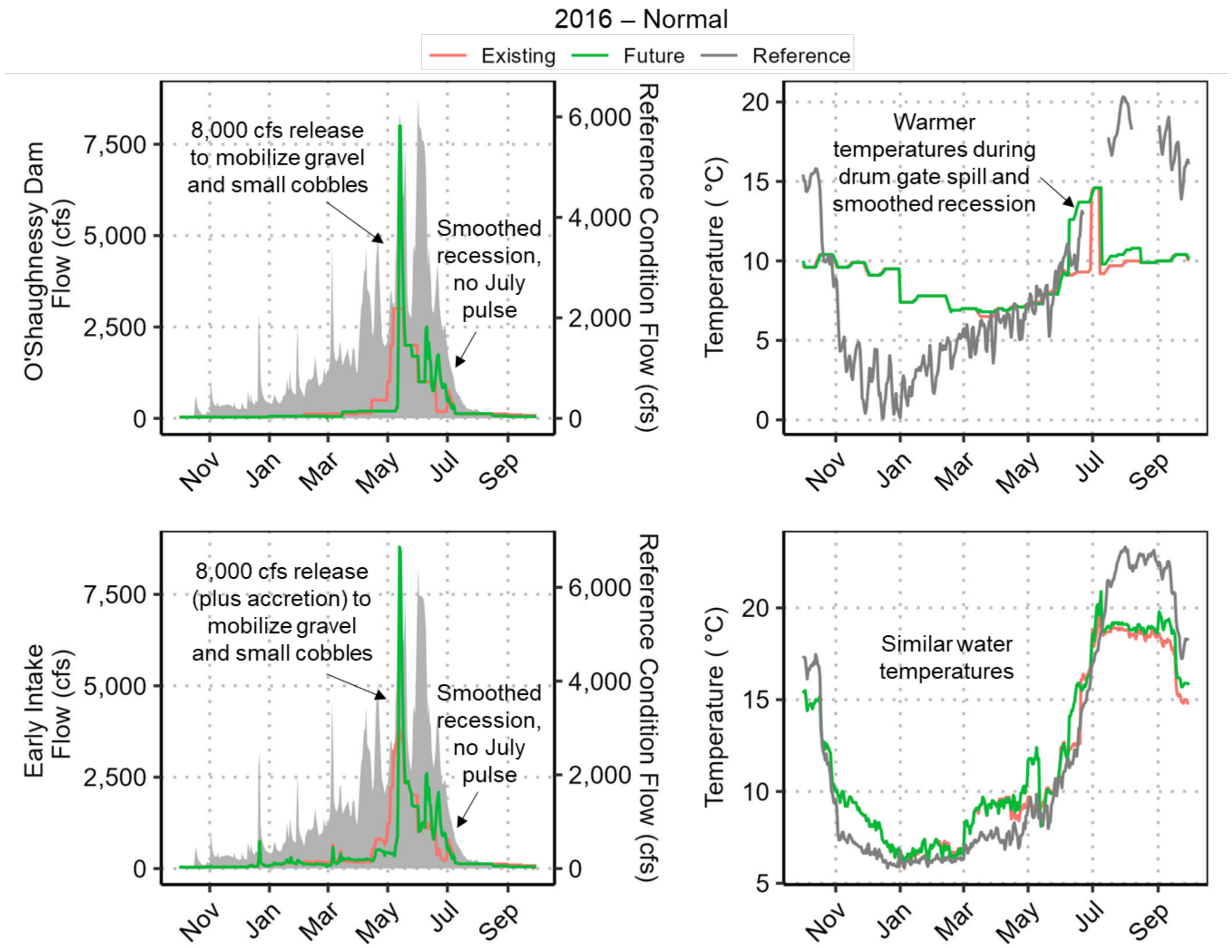

Figure 54. Flow and temperature at the OSD and EI sites under existing and future scenarios in a Normal year, WY 2016. Notations compare the future to the existing scenario; estimated reference flows (on the secondary Y axis) and water temperatures are provided for context.

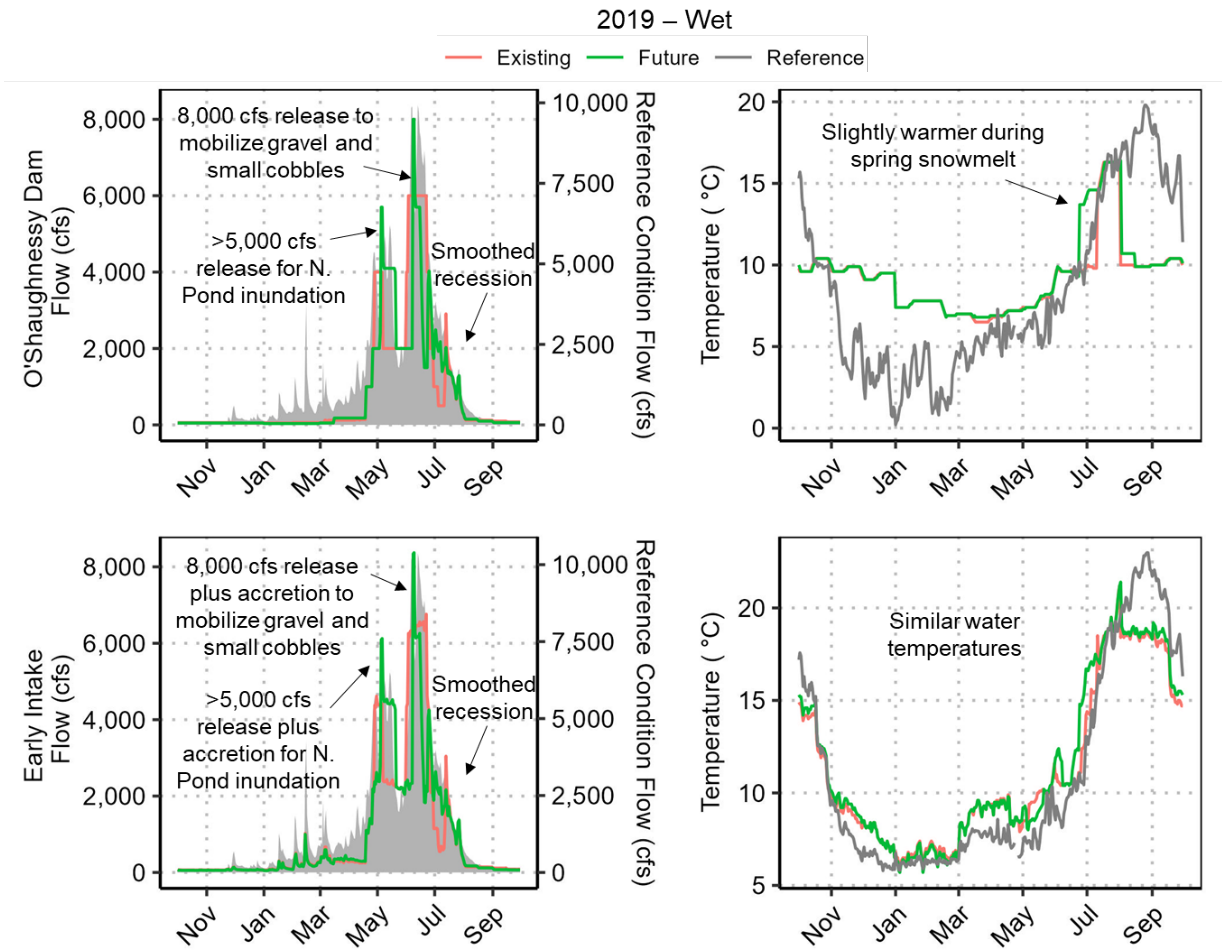

Figure 55. Flow and temperature at the OSD and EI sites under existing and future scenarios in a Wet year, WY 2019. Notations compare the future to the existing scenario; estimated reference flows (on the secondary Y axis) and water temperatures are provided for context.

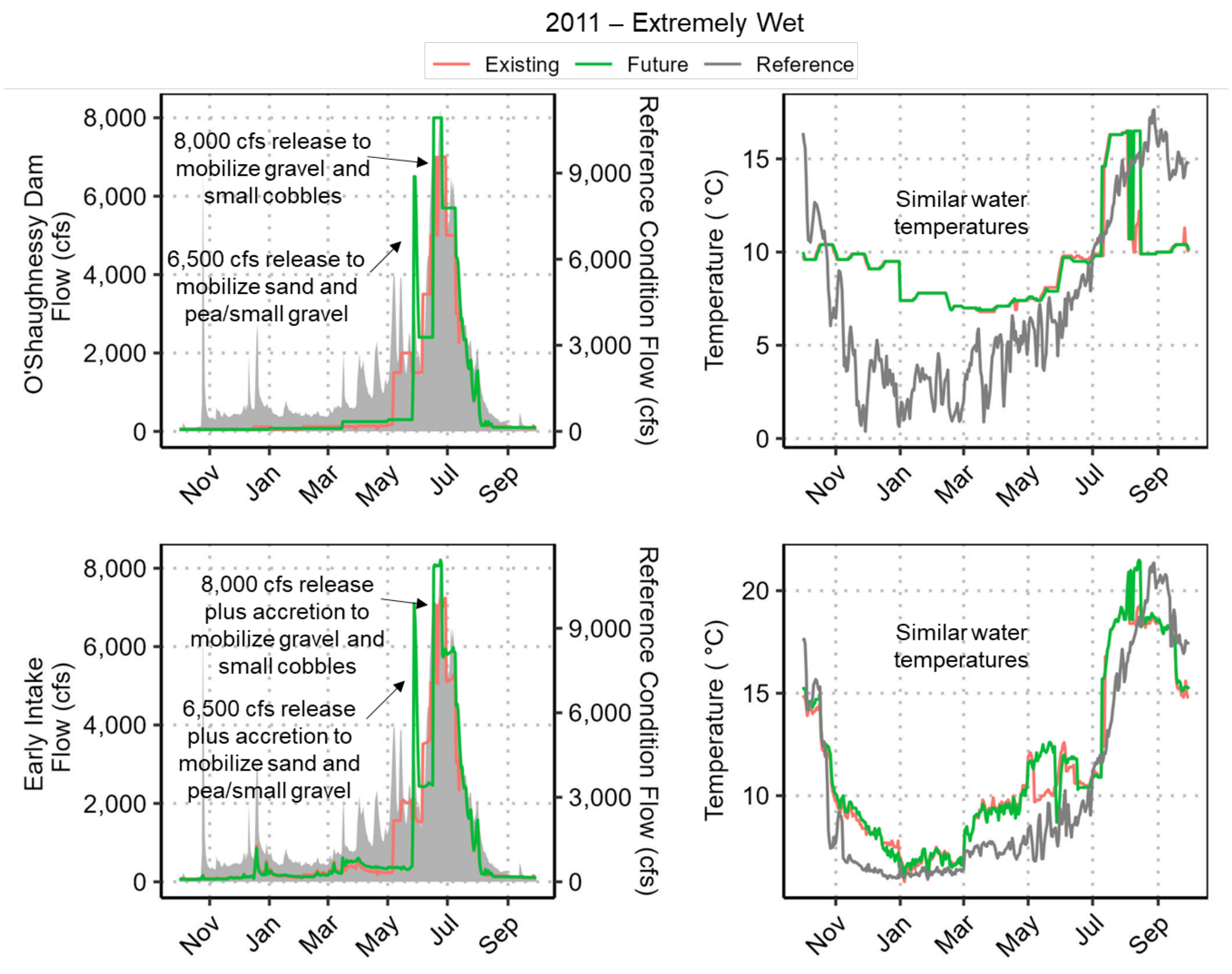

Figure 56. Flow and water temperature at the OSD and EI sites under existing and future scenarios in an Extremely Wet year, WY 2011. Notations compare the future to the existing scenario; estimated reference flows (on the secondary Y axis) and water temperatures are provided for context.

9.3 Number of Good Days analysis

The NGD analysis was developed to quantify differences among flow scenarios. The analysis quantifies the number of days that near-optimal flows and water temperatures are met for focal elements (taxa and life stages, Table 4). A "Good Day" occurs when daily average flow and water temperature create physical habitat conditions that meet flow and temperature thresholds that should optimally support growth, survival, or successful reproduction in a specific life history timing window (Figure 57). Not meeting the criteria for a Good Day does not imply that there is no habitat. Rather, meeting the criteria quantifies the number of days that meet near-optimal conditions for the species, as defined in Figure 57 below. The NGD analysis integrates multiple drivers such as suitable habitat area, temperature, and flow into the single variable (a "Good Day") that is a direct result of flow management. The NGD analysis is similar to the habitat duration analysis described in Bovee et al. (1998), in which the goal of the analysis is to understand how a time series of flows alters habitat availability. The NGD analysis builds on the habitat duration analysis by considering temperatures in addition to habitat area.

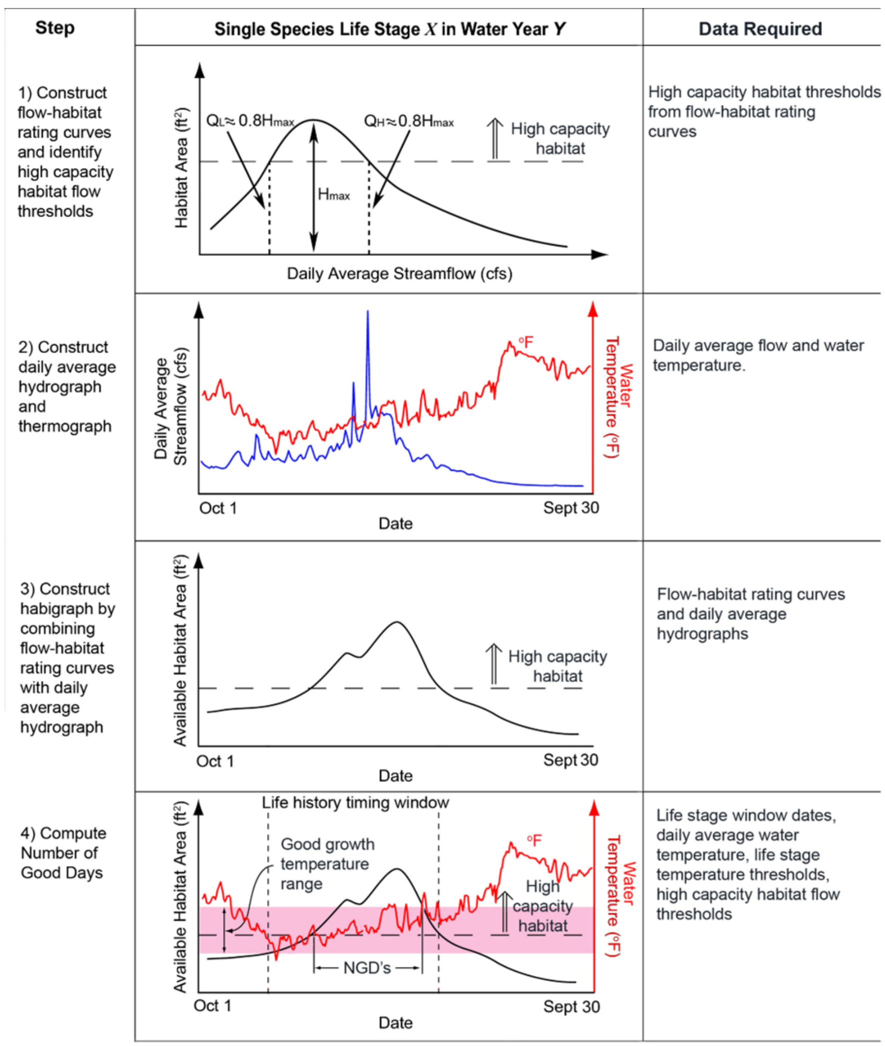

Figure 57. Conceptual figure demonstrating the NGD analysis, which counts the number of days in a water year that meet streamflow and temperature criteria within a species life stage time window.

The focal taxa that were considered in the NGD analysis were the same as those that were considered when developing baseflow recommendations (see Section 6): adult Rainbow Trout, juvenile Rainbow Trout, spawning Rainbow Trout (at the OSH site only), BMI, and Foothill Yellow-legged Frog eggs and tadpoles (at the EI site only). Spawning was only evaluated at the OSD site because suitable spawning gravels are widely available at that site (Appendix E), while spawning gravels at the EI site appear to be confined to small patches. This spawning is likely taking place at the micro-habitat level (e.g., in lee deposits behind large boulders), which is challenging to map and model with available tools.

Flow thresholds for each focal species and life stage were developed from the weighted useable area (WUA) flow-habitat curves at the OSD and EI sites (see Section 6.2). Low and high flow thresholds were chosen at flows where habitat capacity is at least 80% of the maximum (Hetrick et al. 2009). Temperature thresholds were developed from synthesis of literature for temperatures that support growth and breeding. Time windows for each species and life history stage are relatively broad to encompass variability in timing among water year types. Thresholds that constitute a “Good Day” for each focal element are summarized in Table 17.

Table 17. *The time windows, flow, and temperature thresholds used to tabulate “Good Days” for focal species and life stages.*

Species and life stage	Site	Time window		Flow (cfs)		Temperature (°C)	
		Start	End	Q_L	Q_H	Minimum	Maximum
Rainbow Trout – adult	EI	March 1	October 31	250	1,150	10	22
Rainbow Trout – juvenile	EI	March 1	October 31	30	250	10	22
Rainbow Trout – adult	OSD	March 1	October 31	250	1,700	10	22
Rainbow Trout – juvenile	OSD	March 1	October 31	45	250	10	22
Rainbow Trout – spawning	OSD	April 1	June 30	380	620	7	13
BMI	EI	March 1	October 31	250	1,450	5	-
BMI	OSD	March 1	October 31	280	900	5	-
Foothill Yellow-legged Frog – egg and tadpole	EI	May 1	August 31	20	130	10	24

The NGD analysis was used to evaluate the habitat capacity and temperature suitability of existing and future scenarios for WY 1999–2021 and reference condition flow scenarios for WY 2009–2021. Results are summarized by water year type.

The NGD varied with water year type and site for Rainbow Trout. For adult Rainbow Trout (Figure 58), Good Days are predicted to increase under the future scenario compared to the existing scenario in Normal, Wet, and Extremely Wet water year types at both the OSD and EI sites. In drier years, Good Days were fewer under the future scenario at the OSH site. At the EI site, Good Days were slightly greater in Extremely Dry water years and fewer in Dry water years.

At the OSD site, Good Days for adult Rainbow Trout were limited by low water temperatures and low summer baseflows which extend into late summer during most Dry and Extremely Dry years for both existing and future scenarios (Figure 52). Water temperatures at the OSD site are colder than 10°C most often in drier years because flow is mostly released from the environmental flow release valves that pull water from the hypolimnion and there are fewer spill opportunities for mixing. In wetter years, mixing will occur when warm epilimnion water spills over the drum gates or comes from higher elevation valves. In some drier years, however, there are small spill events (i.e., 2007 and 2020) for both the existing and future scenarios; these spill events are short (approximately 15 days), but they provide flows higher than 250 cfs (see NGD criteria in Table 16) and water temperatures warmer than 10°C (see NGD criteria in Table 17) when spilling over the drum gates. There were more days with spill in the existing scenario because future scenarios limit high drum gate spills greater than 700 cfs (Table 13) to avoid mortality to Foothill Yellow-legged Frog egg masses. The reference scenario resulted in a greater NGD (during Dry and Extremely Dry years) or similar NGD (during wetter years) at both sites due to higher flows and warmer temperatures during the recession limb.

For juvenile Rainbow Trout (Figure 59) at the EI site, NGD was similar under the existing and future scenario for all water year types, and existing and future scenarios exhibited similar NGD for Normal and wetter water year types at the OSD site. In Dry and Extremely Dry water years at the OSD site, the existing scenario provides more Good Days for juveniles than the future scenario. This is due to higher existing scenario baseflows (50 cfs) in the late summer (August to October) while future scenario baseflows are lower (35 cfs) in drier water years to mimic reference condition flows and water temperatures (Table 10) and to provide more suitable conditions for Foothill Yellow-legged Frog reproduction in those years. For both existing and future scenarios, there are more Good Days at the EI site than at the OSD site because water temperatures warm earlier in the spring at the EI site (see Section 9.2), flow threshold for juveniles at the EI site is lower (30 cfs), and flow is augmented by accretion, leading to more days that meet the flow threshold under warmer temperatures. In the reference scenario, the NGD was higher during drier years but lower during wetter years at the OSD site compared to existing and future scenarios. Reference scenario NGD was relatively consistent across all water year types. The higher NGD resulting from the reference scenario compared to the existing and future scenarios during drier years at OSD is aligned with the spring recession period, in which many years in the reference scenario include a period when declining flows from the spring recession are high and warm enough to allow classification as Good Days. The lower NGD under reference conditions compared to existing and future scenarios during wetter years at the OSD site is a result of flows higher than the NGD threshold (>250 cfs, Table 17) for much longer during the summer.

For Rainbow Trout spawning (Figure 60), there were few Good Days for all water year types and flow scenarios at the OSD site. In Dry years, baseflow releases are lower than the low-flow threshold developed from the habitat curves. In wetter years, flows resulting from spill management tend to be much higher than the high flow threshold. Notably, there are also very few predicted NGD under reference conditions. The lack of NGD predicted even under reference conditions suggests that Rainbow Trout spawning likely takes place at localized patches with suitable hydraulics even at very high or low flows. The stable population of Rainbow Trout (Appendix B) suggests that spawning is successful in the Tuolumne River under most water year types and that quantification of physical spawning habitat through habitat suitability curves and 2-D hydraulic models is poor.

For Foothill Yellow-legged Frog (Figure 61), Good Days increased under the future scenario compared to the existing scenario in drier years, with lower Good Days in Normal years. The increase in NGD is due to reduced future scenario spring/summer baseflows in drier years (compared to the existing scenario) and the snowmelt management recommendation to maintain flows less than 700 cfs after May 15 in drier years. Fewer or similar NGD between future and existing scenarios in Normal and wetter water year types is due to recommended snowmelt management releases. There are fewer Good Days under reference conditions relative to existing and future scenarios for all water year types due to the large and extended reference snowmelt runoff events that result in flows greater than the high flow threshold for egg and tadpole development.

The NGD for BMI is similar, or slightly higher, under the future scenario compared to the existing scenario at both the OSD site and the EI site (Figure 62). Under the reference condition scenario, there would be many more Good Days than either the existing or future scenarios. The flow thresholds for BMI are wider and include much higher flows than any of the other focal taxa, leading to more Good Days that would occur under the reference condition scenario during storm events and snowmelt compared to the future and existing scenarios.

In summary, the NGD analysis illustrates how the future scenario creates conditions that balance Rainbow Trout and Foothill Yellow-legged Frog flow and water temperature needs. In wetter years, there will be more Good Days for Rainbow Trout adults under the future scenario compared to existing, and more Good Days for Foothill Yellow-legged Frog in drier years in future scenarios compared to existing. This balancing of flow releases to create habitat that favors different focal elements in alternating water year classifications better represents the variability that would occur under reference conditions and supports the goals of the EFS to manage for ecosystem benefits, rather than optimization for a single focal element.

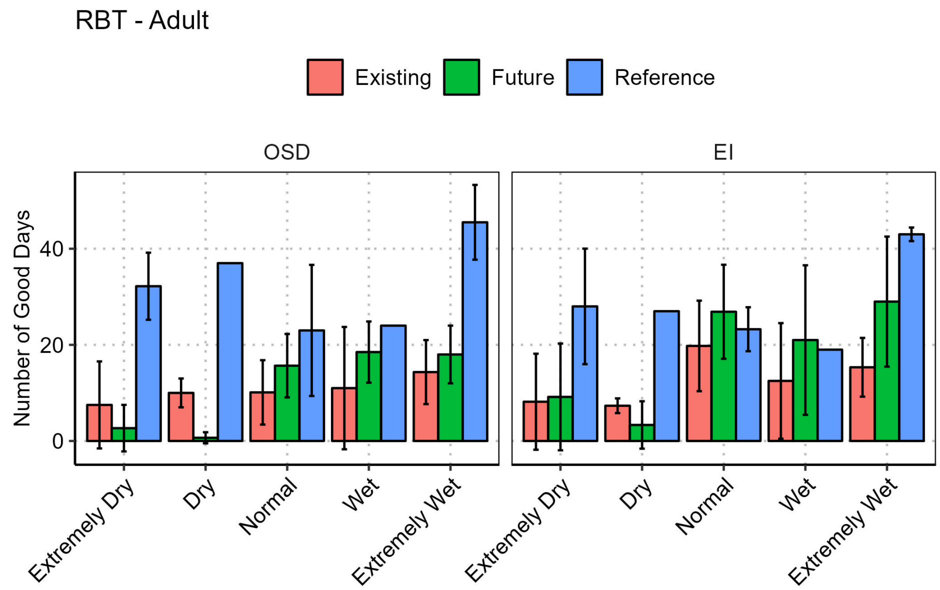

Figure 58. NGD predicted under existing, future, and reference flow scenarios for adult Rainbow Trout.

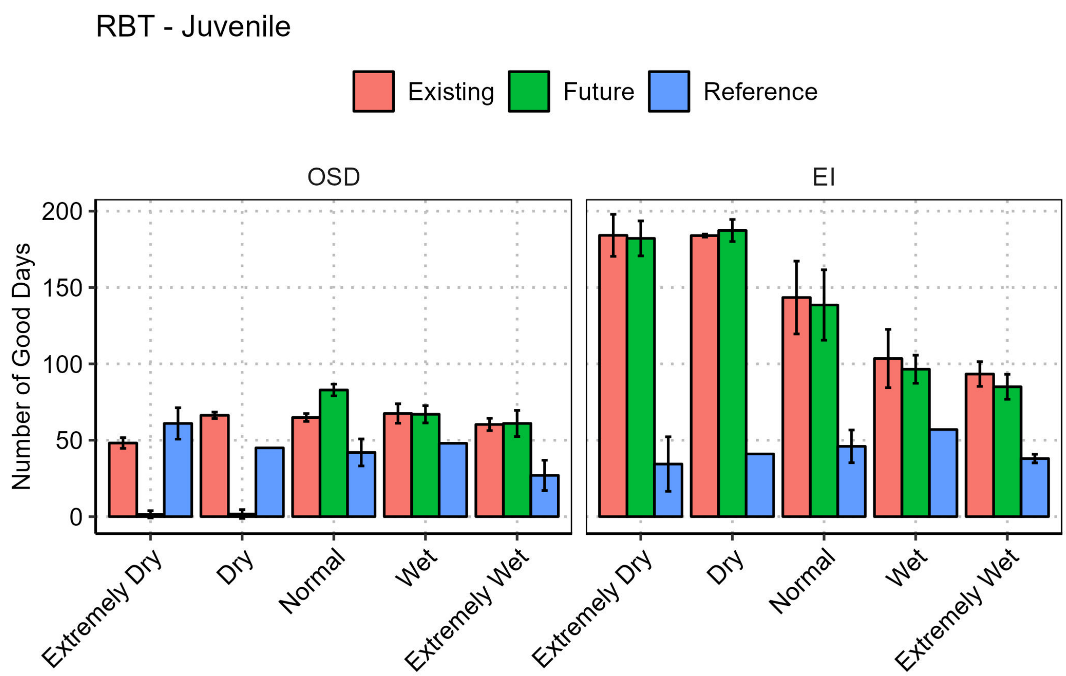

Figure 59. NGD predicted under existing, future, and reference flow scenarios for juvenile Rainbow Trout.

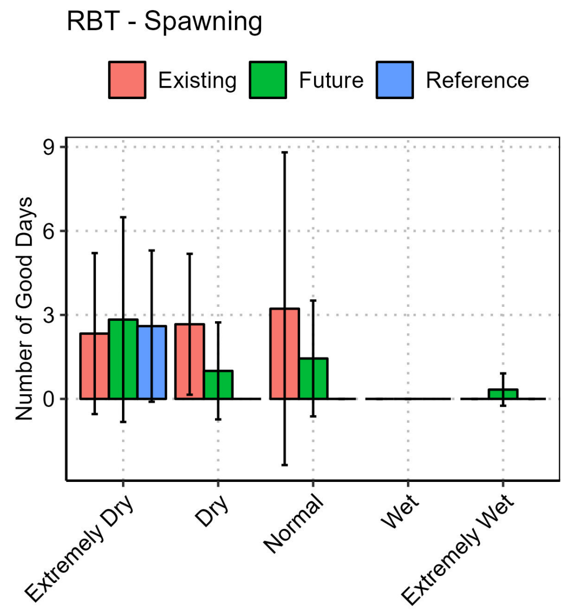

Figure 60. NGD predicted under existing, future, and reference condition scenarios for Rainbow Trout spawning. Rainbow Trout spawning habitat was only estimated at the OSD site.

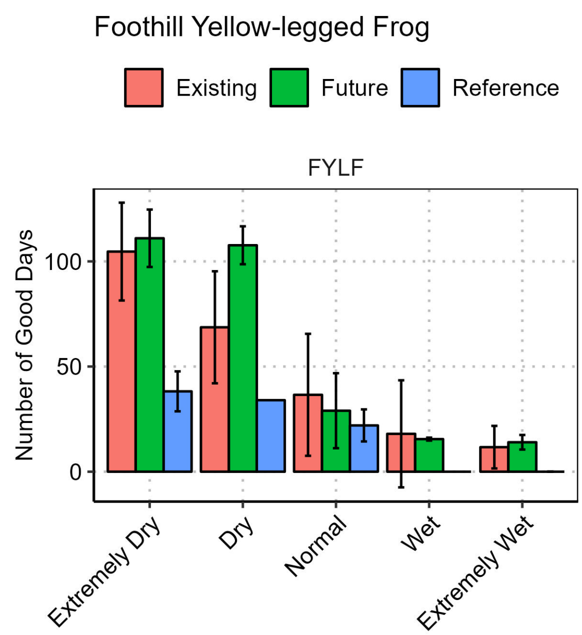

Figure 61. NGD predicted under existing, future, and reference condition scenarios for Foothill Yellow-legged Frogs. Foothill Yellow-legged Frog habitat was only evaluated at the EI site, where temperatures are suitable.

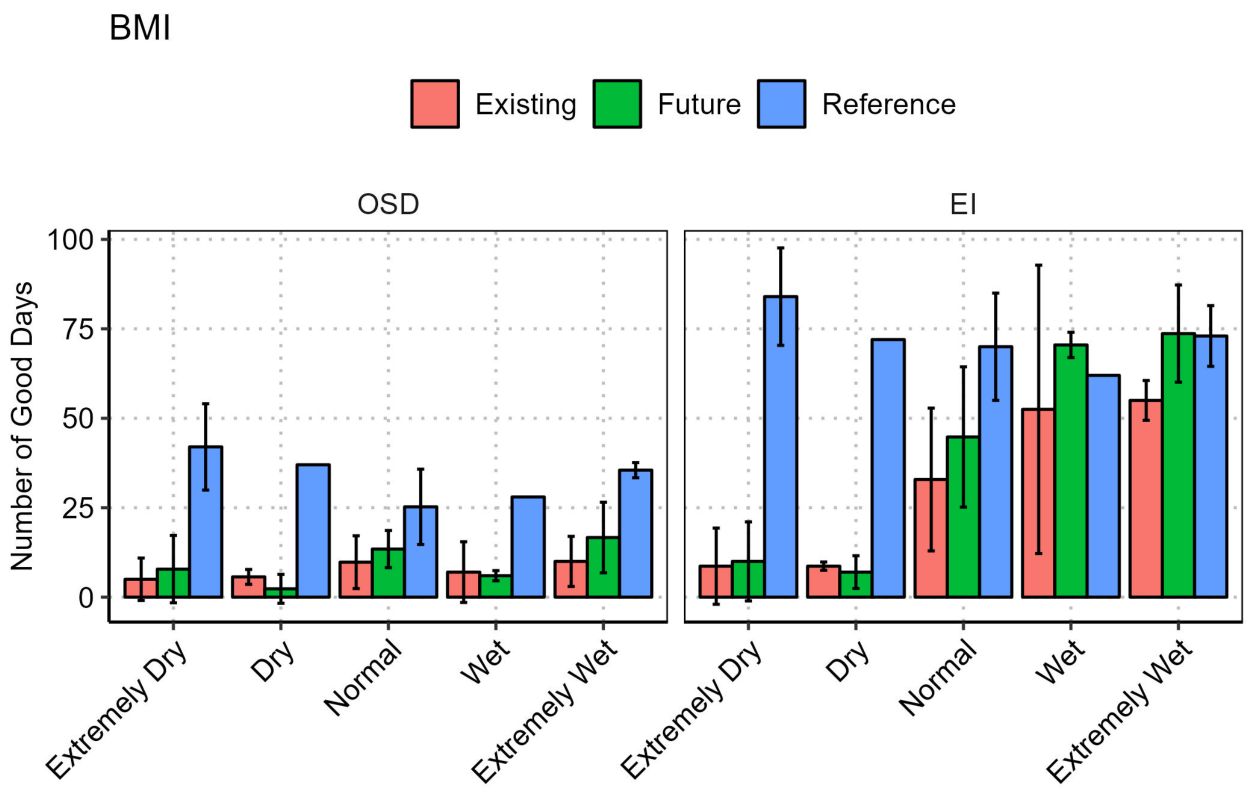

Figure 62. NGD predicted under existing, future, and reference condition scenarios for BMI.

9.4 Rainbow Trout production using inSTREAM

Individual based models (IBMs) are an emerging tool in river management that use process-based predictions on the interplay between biology, thermal, and physical habitat properties to model species success. IBMs function by creating individual agents that can move, grow, and die, within a virtual physical habitat template according to a set of pre-determined rules that are based in fundamental ecology (e.g., competition, predation, foraging success). IBMs follow the trajectory of individuals through the suite of physical and biological conditions that they face throughout development, making them a useful tool for organisms such as salmonids that have different needs throughout their life cycle (Dudley 2018). These process-based and integrative properties of IBMs can complement tools that focus on physical habitat modeling (PHABSIM, or the NGD analysis) by providing spatially and temporally explicit and detailed (life-stage-specific) predictions on how management scenarios might affect populations (Railsback and Rose 2013, Grimm et al. 2017).

InSTREAM uses streamflow, flow-specific depth and velocity derived from a hydraulic model, water temperature, cover, food availability, and spawning habitat to estimate production and population structure of salmonid species. The combination of these variables creates a spatially explicit virtual habitat that represents river conditions where simulated fish carry out their life history. In addition to the river's physical and thermal characteristics, fish are subjected to density-dependent interactions, predation from both aquatic and terrestrial predators, and inter- and intra-specific competition (Railsback et al. 2023).

To evaluate how the existing, future, and reference flow scenarios support native Rainbow Trout populations, inSTREAM was applied to the OSD and EI sites (Figure 18; Appendix C). At the OSD site, where spawning gravels are more abundant than at the EI site, Rainbow Trout egg and fry survival were used as metrics for evaluating flow scenarios to specifically evaluate spawning success. At the EI site, which experiences additional flow due to accretion and warmer water temperatures, growth and abundance of young of the year (age-1) and adult (age 2+) Rainbow Trout were selected as metrics for evaluation. Growth and abundance results were not analyzed for the OSD site because water temperature is largely independent of flow (driven by Hetch Hetchy hypolimnetic temperatures), while water temperatures at the EI site are more representative of the entire Hetch Hetchy Reach. Supplemental results that support rationale for selecting metrics for evaluation, evaluate growth at the OSD site and spawning at the EI site, and other information that supported the analyses presented in this section are available in Appendix K.

To evaluate how flow scenarios may affect fish populations in different water years, metrics described above were compared across four years that represent four of the five water year types: 2011 – Extremely Wet, 2013 – Dry, 2014 – Extremely Dry, and 2016 – Normal. A Wet water year type was not analyzed due to similarities in flow and temperature between the Wet and Extremely Wet years (Figure 55 and Figure 56). To isolate the effects of flow scenarios within each water year type, each of the four years was treated as independent and was run as separate time series in the model from January 1 to December 31 of that year with the same population characteristics. InSTREAM was also run continuously for the full time series period of 1999–2021 for the existing and future scenarios and 2008–2021 for the reference scenarios to evaluate how implementation of flow scenarios would influence fish populations over time. These model runs represent a complete population model, meaning that a population was initiated at the beginning of the time series (1999 or 2008) and its annual abundance, survival, and growth was continued into the next year until the end of the time series (2021).

9.4.1 O'Shaughnessy Dam site spawning success and egg/fry survival

The inSTREAM model represents spawning habitat by combining depth, velocity, substrate, and water temperature criteria during different times of year (Railsback et al. 2023). Within inSTREAM, only adult (age 2+ fish that are greater than 12 cm) fish spawn. To evaluate flow scenarios on spawning habitat, the daily average area of suitable spawning habitat as predicted by inSTREAM was plotted for each example water year. Results were similar to the NGD analysis (see Section 9.3). During all years, the average daily amount of habitat was similar in the future and existing scenarios (Figure 63). During drier years, the reference scenario spawning habitat was higher than in both the existing and future scenarios, but during wetter years the reference scenario was similar to both the existing and future scenarios (Figure 63).

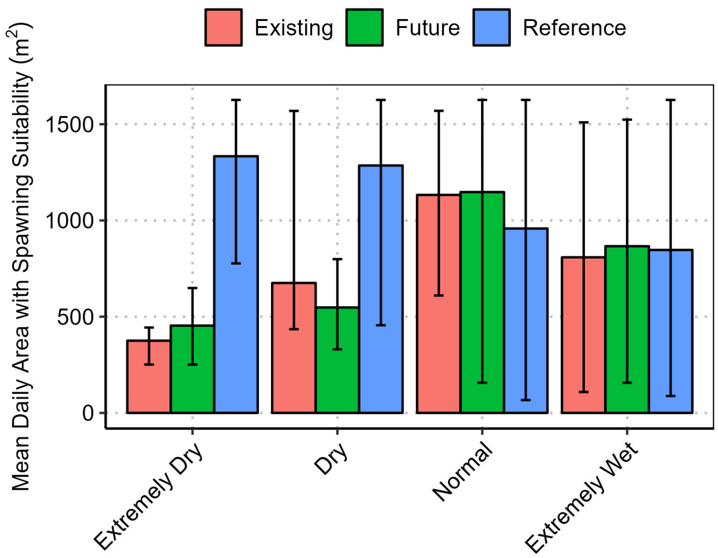

Figure 63. Spawning habitat predicted by inSTREAM at the OSD site for the example water year types (Extremely Dry = 2014, Dry = 2013, Normal = 2016, Extremely Wet = 2011). Bars represent the mean daily area (error bars are minimum and maximum) during the spawning period (April 1–June 30) for each year.

In general, inSTREAM predicted high egg incubation success at the OSD site, with greater than 60% egg survival for all three scenarios in all water year types (Figure 64). Egg survival corresponded with the duration and magnitude of high flows events during the Rainbow Trout egg incubation period (spring). In years when peaks in flow were relatively high, percent survival decreased due to higher rates of redd scour. In years with no peaks in flow or with peak flows that were relatively low during that period, percent egg survival was nearly 100%. The existing and future scenarios generally result in higher egg survival rates when compared to the reference scenario due to less frequent high flows in the existing and future scenarios in Extremely Dry, Dry, and Normal water year types.

When comparing the existing and future scenarios, percent egg survival was similar in Dry, Extremely Dry, and Extremely Wet water years. In the Normal water year, percent egg survival was lower under the future scenario but effect size was small (5% less survival), due to the high snowmelt management releases (peaking at 8,000 cfs under the future scenario compared to <3,000 cfs under existing management, Figure 54) in the selected year, which resulted in redd scour. However, egg survival was relatively high for all water year types and scenarios and was not a significant limiting factor for overall Rainbow Trout population growth or contraction.

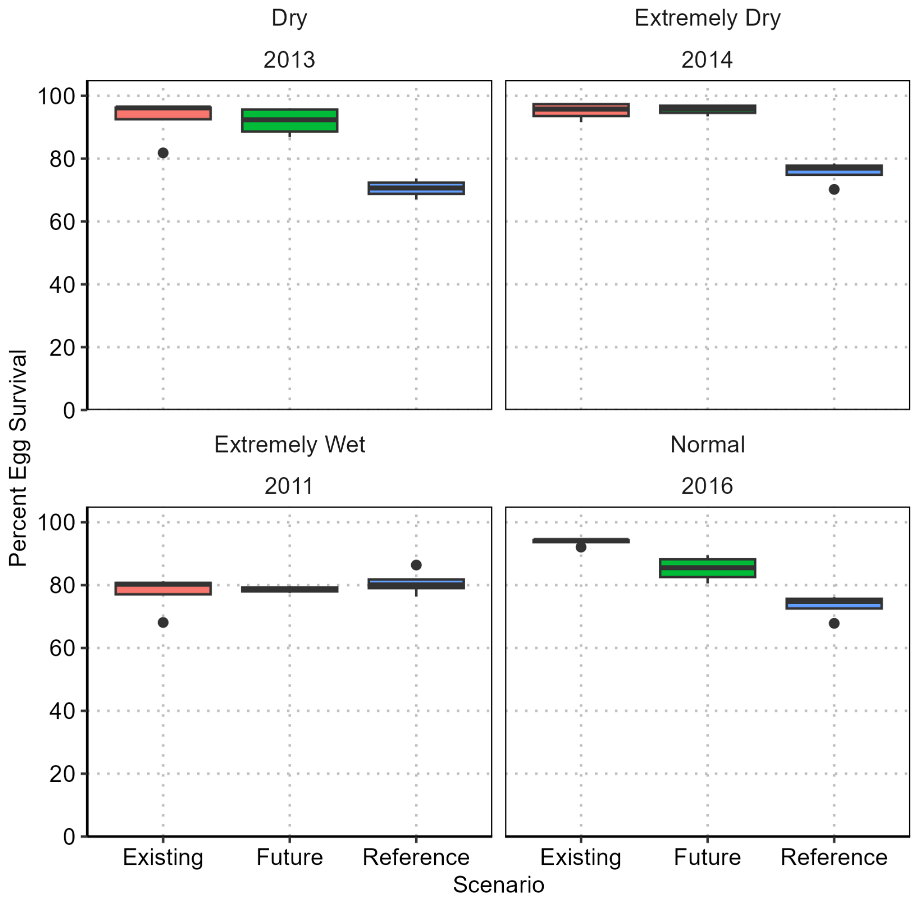

Figure 64. Percent of egg survival compared among the existing, future, and reference scenarios across the four water year types at the OSD site. Boxplots represent the variation of four replication simulations run for each water year type.

Rainbow Trout fry survival rates were also high at the OSD site for all flow scenarios and water year types, with very little difference in fry survival rates among the future, existing, and reference scenarios (Figure 65). Rainbow Trout fry typically emerge in the spring after peak winter and early spring flows, and are less vulnerable to scour than eggs, leading to low variability in survival rates among flow scenarios and water year types. The stability of temperatures immediately downstream of O'Shaughnessy Dam also contributes to the lack of variability in fry survival within the existing and future scenarios.

Decrease in percent fry survival between existing and future scenarios occurred under the Extremely Dry water year type and is likely due to a modeled increase in predation from both terrestrial and aquatic consumers rates under slightly lower future summer baseflows. However, the overall magnitude of change in fry survival rates between existing and future scenarios was small (<10 %). Overall, the percent fry survival rates in the existing and future scenarios are similar and the future recommended flows will have little impact on fry rearing success at the modeled location. Spawning was modeled at the OSD site because of the feasibility of modeling hydraulics at that site, but it is important to recognize that spawning on the upper Tuolumne River is likely to occur at the micro-habitat level throughout the reach (e.g., in lee deposits behind boulders) where the ability to model hydraulic conditions is difficult. Thus, actual egg and fry survival could vary throughout the reach.

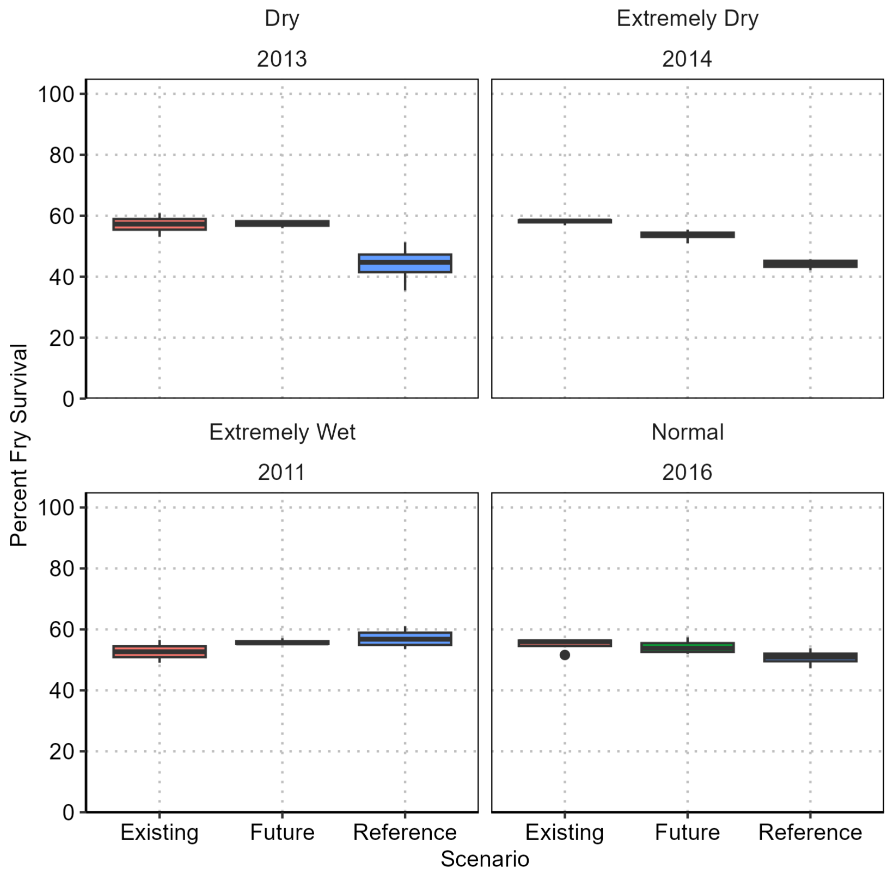

Figure 65. Percent of fry survival compared among the existing, future, and reference scenarios across the four water year types at the OSD site. Boxplots represent the variation of four replication simulations run for each water year type.

9.4.2 Early Intake site growth and abundance

Overall, growth and abundance for both age-1 and age-2+ fish at the EI site were similar in the existing and future scenarios, but those scenarios typically led to lower growth rates than reference conditions. When comparing existing and future scenarios, future end of year growth for age-1 Rainbow Trout was greater in wetter (Extremely Wet and Normal) water year types and similar to existing in drier (Dry and Extremely Dry) water year types (Figure 66). Similarly, end of year growth for age-2+ Rainbow Trout was higher in Extremely Wet conditions but lower under Extremely Dry conditions in the future scenario compared to the existing scenario. Predicted growth was always higher in the reference scenario regardless of water year type or age class due to a combination of higher flows (driving higher food delivery) and warmer water temperature in the summer, which increases growth rates.

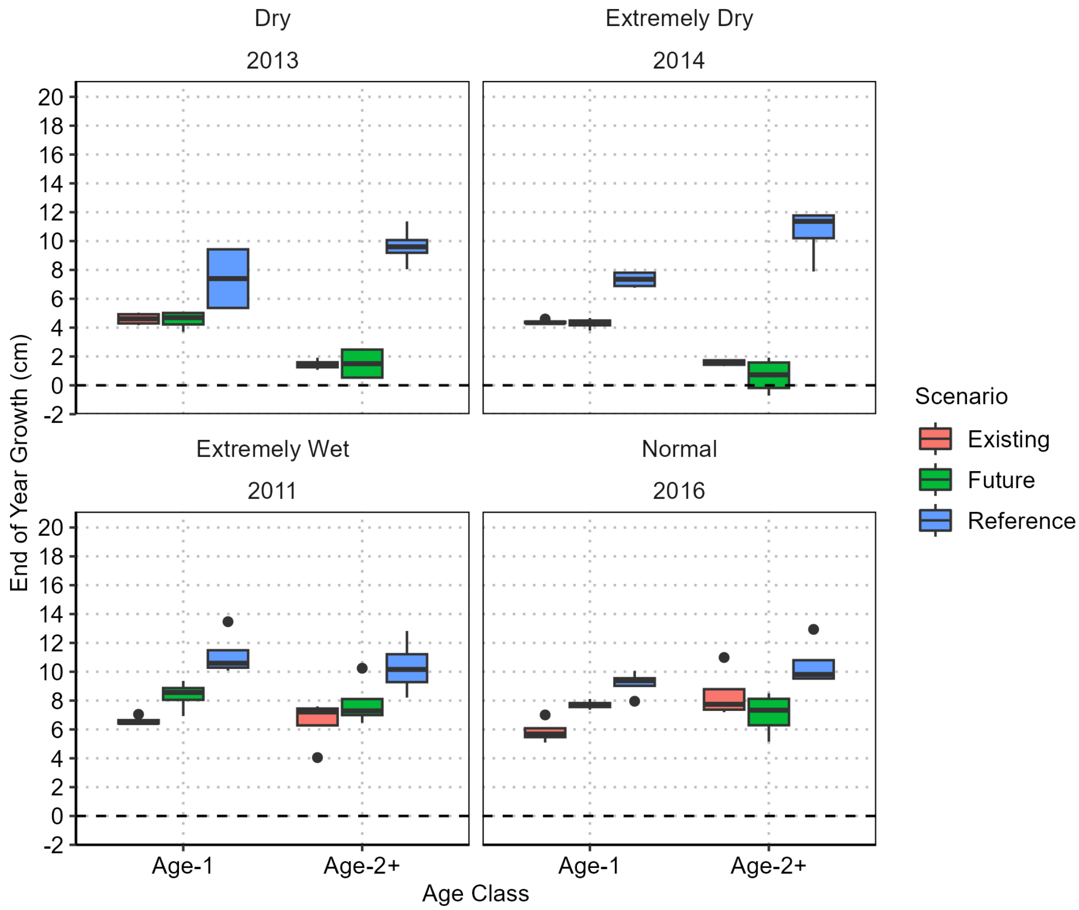

Figure 66. End of year growth for age-1 and age-2+ Rainbow Trout compared among the existing, future, and reference scenarios across the four water year types at the EI site. Boxplots represent the variation of four replication simulations run for each water year type.

Total abundances for Rainbow Trout were largely similar in the existing, future, and reference scenarios (Figure 67). In the future scenario, age-1 Rainbow Trout abundances were slightly lower in Extremely Dry, Dry, and Normal years and slightly higher in the Extremely Wet years when compared to existing conditions. Reference scenario results followed a similar pattern for age-1 Rainbow Trout. Age 2+ Rainbow Trout abundances were similar for all scenarios in all water year types.

While small, the differences in age-1 abundances are likely due to streamflow-mediated changes in modeled aquatic predation pressure. InSTREAM tends to predict higher aquatic predation rates when streamflows are lower (i.e., in summer in the future scenario during drier years) because fish have less wetted area to avoid predation by larger fish. However, the large boulder cover that is ubiquitous in the upper Tuolumne River provides significant cover and may not be adequately represented in the model; thus, inSTREAM is likely overestimating the effect of predation during drier years.

Abundances of age-1 Rainbow Trout were lower in the reference scenario than in the existing and future scenarios in Dry and Extremely Dry years, but higher in the Extremely Wet year (Figure 67). In the drier years, this difference may be due to higher mortality rates or energetic stress under warmer water temperatures (>22°C) and higher predation rates associated with very low flows at the end of the summer under the reference conditions (Figure 52 and Figure 53). In the Extremely Wet years, the difference may be due to higher flows in the early spring before snowmelt recessions peak, and the longer duration of optimal growth water temperatures (approximately 16°C) during the spring snowmelt recession (Figure 56).

In summary, the future flow scenario is predicted to maintain existing Rainbow Trout growth and abundance. The predicted differences varied across water year types, with Dry years predicted to result in lower Rainbow Trout growth for age-2+ and abundance for age-1, but wetter years predicted to result in higher abundance (especially for age-1) and growth (for both age classes). This predicted future variability mimics patterns that are predicted under the reference scenario, and validates the observed variation in the contemporary Hetch Hetchy Reach Rainbow Trout population (Appendix B).

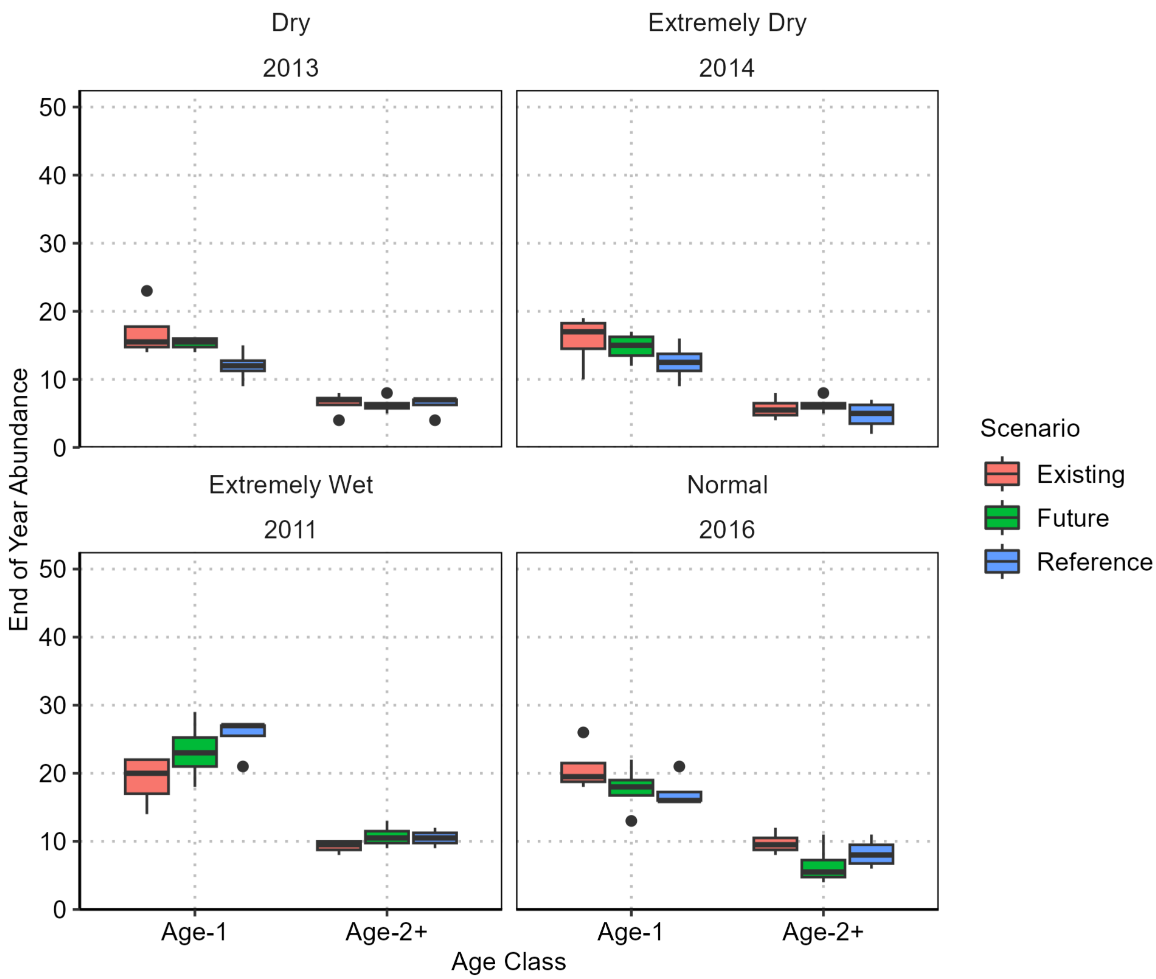

Figure 67. End of year abundance (number of fish) for age-1 and age-2+ Rainbow Trout compared among the existing, future, and reference scenarios across the four water year types at the EI site. Boxplots represent the variation of four replication simulations run for each water year type.

9.4.3 Predicted long-term Rainbow Trout population trends

Because growth and abundance varied by water year type under all three flow scenarios, the inSTREAM model was used to understand how this annual variability played out in long-term Rainbow Trout population trends. The results predict that end of year abundances for age-1 and age-2+ oscillate from year to year, but there are no population crashes or bottlenecks identified at the EI site (Figure 68). At the OSD site, Rainbow Trout populations for each scenario follow similar trends and trajectories; however, the future scenario is smaller than the existing scenario population but more than the reference scenario population (Figure 69). Smaller population sizes in future and reference scenarios compared to existing scenarios likely result from high flow events associated with 2011 and 2017 that likely resulted in lower survival in the higher snowmelt management objectives achieved during the future scenario, compared to the existing scenario. While these high flow objectives may be less beneficial for younger Rainbow Trout, they are often better for growth of larger trout (Figure 66) and are observed in the population above Hetch Hetchy Reservoir (Appendix B). The modeled stability over 20 years suggests that future flow management recommendations will likely continue to maintain the Rainbow Trout populations within the Hetch Hetchy Reach.

The existing and future scenario Rainbow Trout abundances mimic year-to-year trends predicted under reference flows but vary in magnitude and direction across years. This inter-annual variability has also been observed in field studies that quantify population trends of Rainbow Trout in the Hetch Hetchy Reach and those observed above Hetch Hetchy Reservoir in a reference site (Appendix B). Variation in population structure under unimpaired hydrology occurs naturally, as not all years provide ideal conditions for Rainbow Trout. This variability in the future flow management scenario supports biological diversity (i.e., benefits to federally and state listed Foothill Yellow-legged Frogs) and ecosystem function.

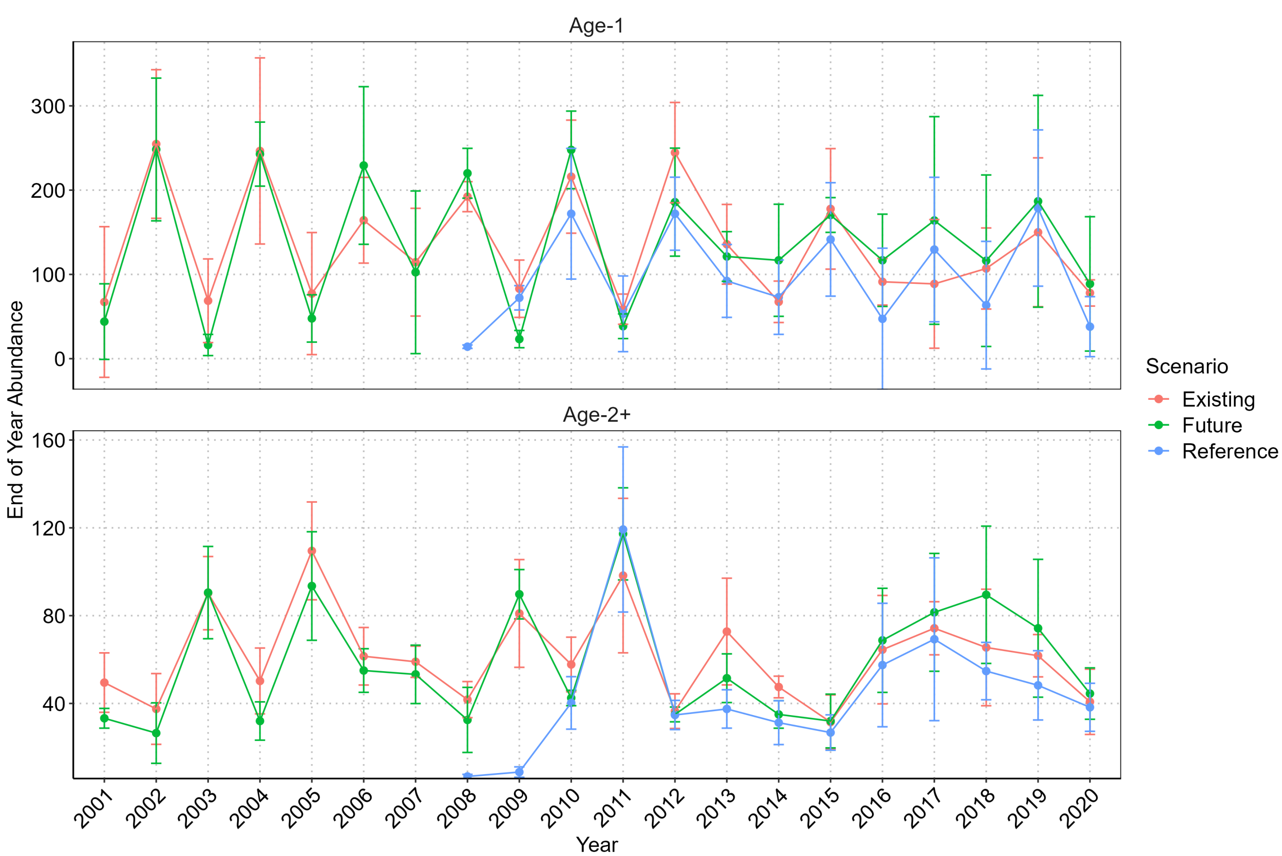

Figure 68. Long-term trends in end of year abundance for age-1 and age-2+ Rainbow Trout among the existing, future, and reference scenarios from 1999 to 2021 at the EI site.

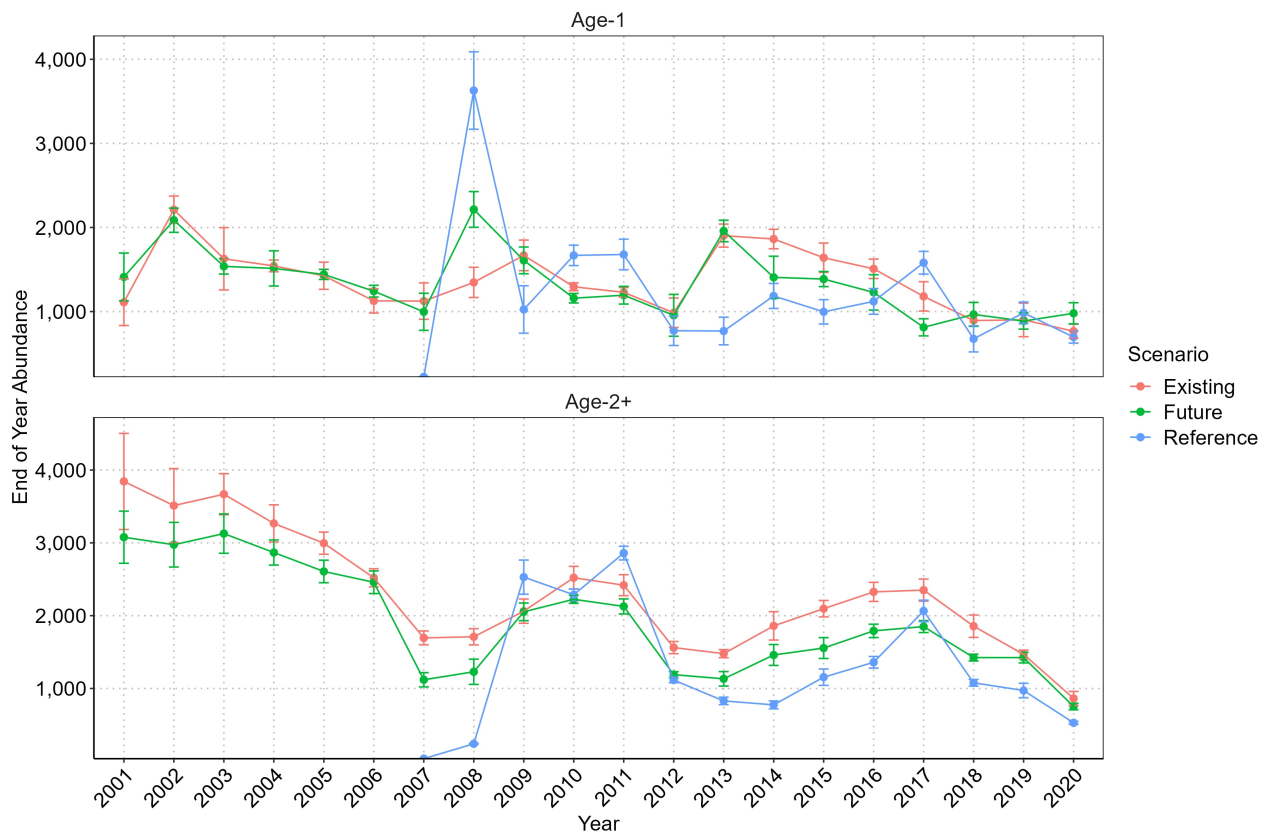

Figure 69. Long-term trends in end of year abundance for age-1 and age-2+ Rainbow Trout among the existing, future, and reference scenarios from 1999 to 2021 at the OSD site.

9.5 Foothill Yellow-legged Frog production using FYFAM

FYFAM (Railsback et al. 2016, 2021) provides a way to predict and compare flow scenarios, effects of water year type, or alternative site restoration designs on the reproductive success of Foothill Yellow-legged Frogs. FYFAM is an individual-based simulation model that uses channel geometry, flow, and water temperature to model predictions of timing of life history stages, risk of mortality due to scour and desiccation, recruitment of new froglets, and location for life stage transitions and mortality events, allowing for quantitative comparisons of reproductive success for an annual cohort. The timing of oviposition, developmental rate of eggs and tadpoles, and timing of metamorphosis to froglet are important aspects for predicting the success of a cohort. The shape and timing of the spring hydrograph, as well as spring and summer water temperatures, are the primary drivers of breeder behavior and development of offspring and are key components of the model.

Early oviposition increases the risk of scour and desiccation mortality for eggs and tadpoles, whereas later metamorphosis limits the time available for froglets to forage and grow prior to winter. Warmer water temperatures allow faster development of eggs and tadpoles leading to earlier metamorphosis dates, and in some cases, may help compensate for later oviposition dates. These simulated factors combine to provide a prediction of froglet production (i.e., embryos that succeed to metamorphosis). Froglets that emerge with sufficient time to forage and grow prior to winter dormancy have a higher probability of overwinter survival (e.g., Altwegg and Reyer 2003, Lance et al. 2012). Survival of offspring through their first year can be quite low (<1–5%), although annual survivorship of frogs after their first winter increases dramatically (>50%; Licht 1974, Duellman and Trueb 1986). Only froglets that survive through their first winter have a chance to contribute to realized population growth (Cook et al. 2022).

FYFAM was used to predict potential reproductive success of Foothill Yellow-legged Frogs under the three flow scenarios (existing, future, and reference) at the EI site. The five water year types were consolidated into three water year type groupings (Dry + Extremely Dry, Normal, and Wet + Extremely Wet) to facilitate analysis and presentation of results. The years 1999 through 2021 were used to evaluate the existing and future scenarios, and 2008 through 2021 were used for the reference scenario. To aid in the evaluation of FYFAM results, a metamorphosis cutoff date of October 30 was applied; froglets reaching metamorphosis after this date were expected to have a low probability of overwinter survival, and thus were not considered successful.

Water year type significantly influenced reproductive success (ANOVA, $p < 0.001$), with drier water years having the greatest reproductive success (Figure 70). This is an expected result because drier years exhibit lower peak flows in spring, reducing egg/tadpole scour and desiccation risks, and result in warmer water temperatures that allow for earlier oviposition dates. Warmer water temperatures also allow for faster development of eggs and tadpoles leading to earlier metamorphosis dates, giving more froglets sufficient time to forage and grow prior to overwintering.

Differences among the flow scenarios were generally subtle and not statistically significant ($p > 0.1$, Figure 70) but were most pronounced in the drier water years. The future scenario improved reproductive success over the existing scenario in the drier water years. In Normal and wetter water years, most of the metamorphosis dates occurred after the selected cutoff date (October 30), and thus were hypothesized to be too late to expect overwinter survival for most of the froglets produced. Improved success in drier years is important because drier years are likely to produce more froglets and those froglets are likely to have sufficient time for growth prior to winter, improving their chances of overwinter survival (e.g., Cook et al. 2022). Thus, at the EI site, Foothill Yellow-legged Frog offspring produced in drier water years can be expected to contribute to long-term population growth, while offspring produced in wetter water years have a far lower probability of survival to maturity and therefore are not expected to make a meaningful contribution to future generations. The results of these FYFAM simulations are further described in the accompanying Appendix A for herpetofauna.

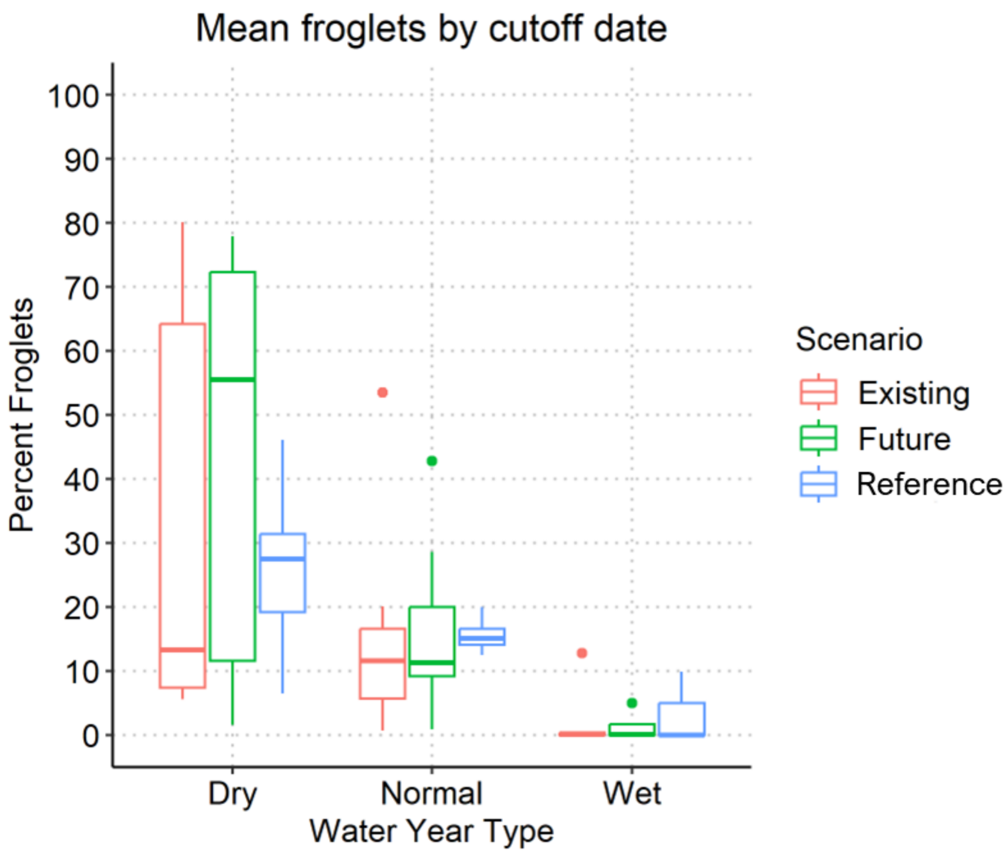

Figure 70. Percent of the Foothill Yellow-legged Frog cohort reaching metamorphosis by the cutoff date (October 30). Water year type had the greatest influence on cohort success, with dry water year grouping (Dry + Extremely Dry) having the highest froglet production by the cutoff date. In the drier years, the future flow scenario outperformed the existing and reference flow scenarios. There was considerable overlap between flow scenarios due to variability across years. Reference flows exhibited less variably due to the smaller number of years in the sample. Predicted reproductive success was lower for the Normal water year and the wet water year grouping (Wet + Extremely Wet) due to later oviposition dates and slower development leading to metamorphosis after the cutoff date.

9.6 Frequency of achieving bed mobility and Poopenaut Valley wetland inundation and saturation thresholds

To evaluate potential future improvements in bed mobility and Poopenaut Valley wetland inundation, the future and existing flow scenarios were compared to bed mobility and Poopenaut Valley wetland inundation and saturation flow thresholds (i.e., snowmelt management targets). The frequency at which existing and future scenarios met these thresholds was also compared to the frequency that these same thresholds were met under the reference scenario. Daily average flow data from 1993–2021 estimated at the Tuolumne River below Hetch Hetchy gage site was used for all scenarios. See Appendix E for a detailed description of methods and results.

The future scenario was anticipated to substantially increase the frequency of meeting bed mobility and Poopenaut Valley wetland thresholds when compared to the existing scenario. The frequency of meeting bed mobility objectives under the future scenario was also predicted to be similar to the frequency at which the reference scenario met the higher flow objectives (8,000 and 6,500 cfs; see Section 7.2), but slightly lower than reference conditions for the lower flow thresholds (Figure 71). The future scenario had a slightly lower frequency for the 1,200 cfs threshold (mobilize sand) compared to the existing scenario. The reduced frequency is driven by the snowmelt target that is intended to keep flows under 750 cfs later in the year to protect FYLF egg masses (Section 7.2.6). Thus, Under the future scenario, the reduced frequency of 1,200 cfs for sand transport thresholds is a tradeoff to help protect FYLF, and the slightly lower frequency of sand mobilization should be compensated for by the increased frequency of higher flows that occur more frequently in wetter years.

The North Pond in Poopenaut Valley is predicted to fill in 62% of years under the future scenario, compared to only 37% under the existing scenario and 86% of years under the reference scenario. These results indicate that the future scenario is a significant improvement over existing conditions. The actual frequency of Poopenaut Pond inundation under recommended snowmelt management may increase as a result of real-world operations. The Spill-Sim analysis is a daily time-step analysis and is unable to model the fast downramping rate recommended for normal to drier years where inundation of the Poopenaut Pond is the sole focus of snowmelt management releases; thus, it likely underestimates the frequency of pond filling.

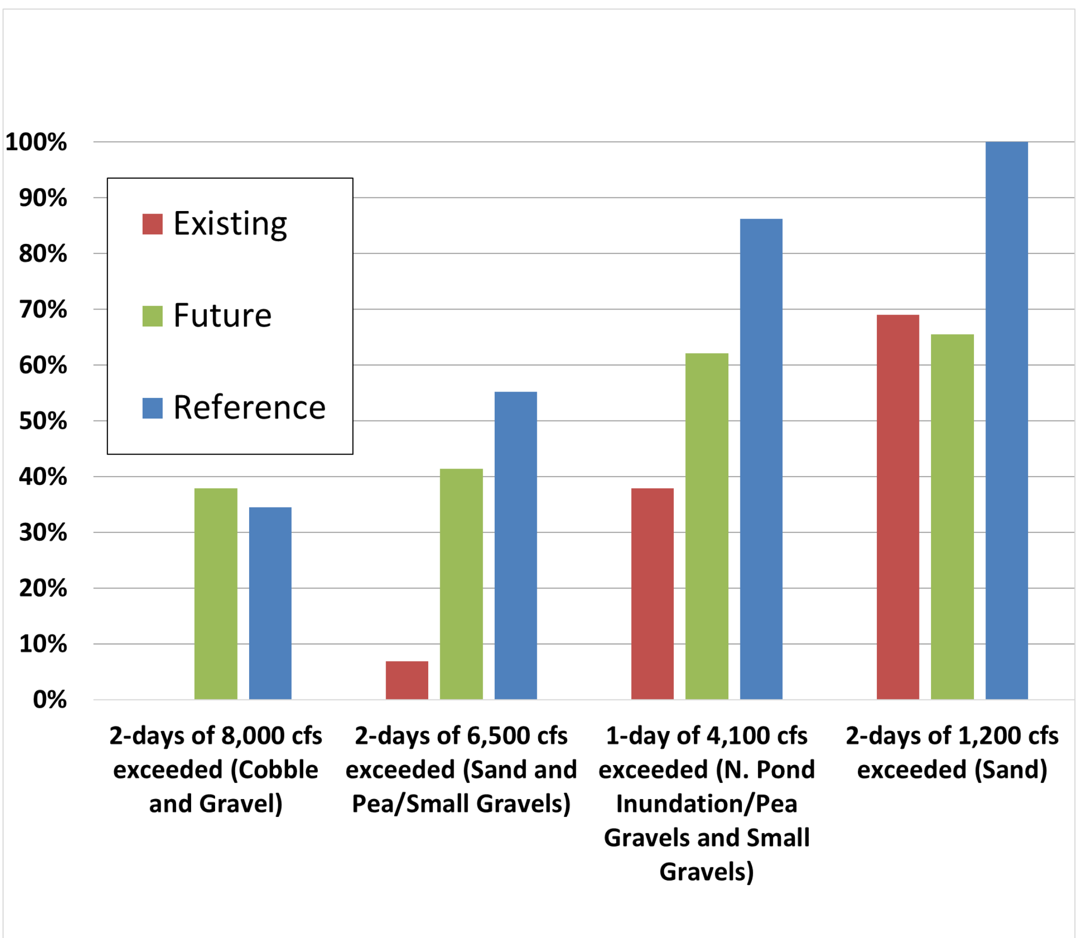

Figure 71. Estimated frequency of achieving bed mobility and North Pond inundation thresholds under the existing (simulated April to August spill management releases using Spill-Sim analysis from WY 1993-2021), future (simulated recommended spill management releases), and reference flow scenarios predicted in Spill-sim.

The frequency of meeting Poopenaut Valley wetland inundation and saturation thresholds under the future scenario increased for all objectives relative to the existing scenario. For higher flow thresholds (>5,400 cfs), the thresholds were met at a slightly higher frequency under the future scenario compared to the reference scenario.

The future scenario resulted in much higher inundation frequencies for Wetland 6, 7, and 11 thresholds compared to the existing scenario (Figure 72). Existing and future scenarios produced similar results for Wetland 5 because it is the lowest elevation wetland and is inundated regularly in the existing scenario. Increased inundation frequencies for Wetlands 6, 7, and 11 under the future flow scenario are expected to contribute to the persistence of wetland vegetation in those areas. Higher frequencies of inundation for Wetlands 6 and 7 may potentially increase wetland vegetation extent over time, assuming existing wetland extent is heavily influenced by mainstem river hydrology. However, Wetlands 6 and 7 may also be strongly influenced by soils, local runoff from hillslopes, and the depression that separates Wetlands 6 and 7 from the Tuolumne River at flows less than 5,400 cfs (see Appendix G).

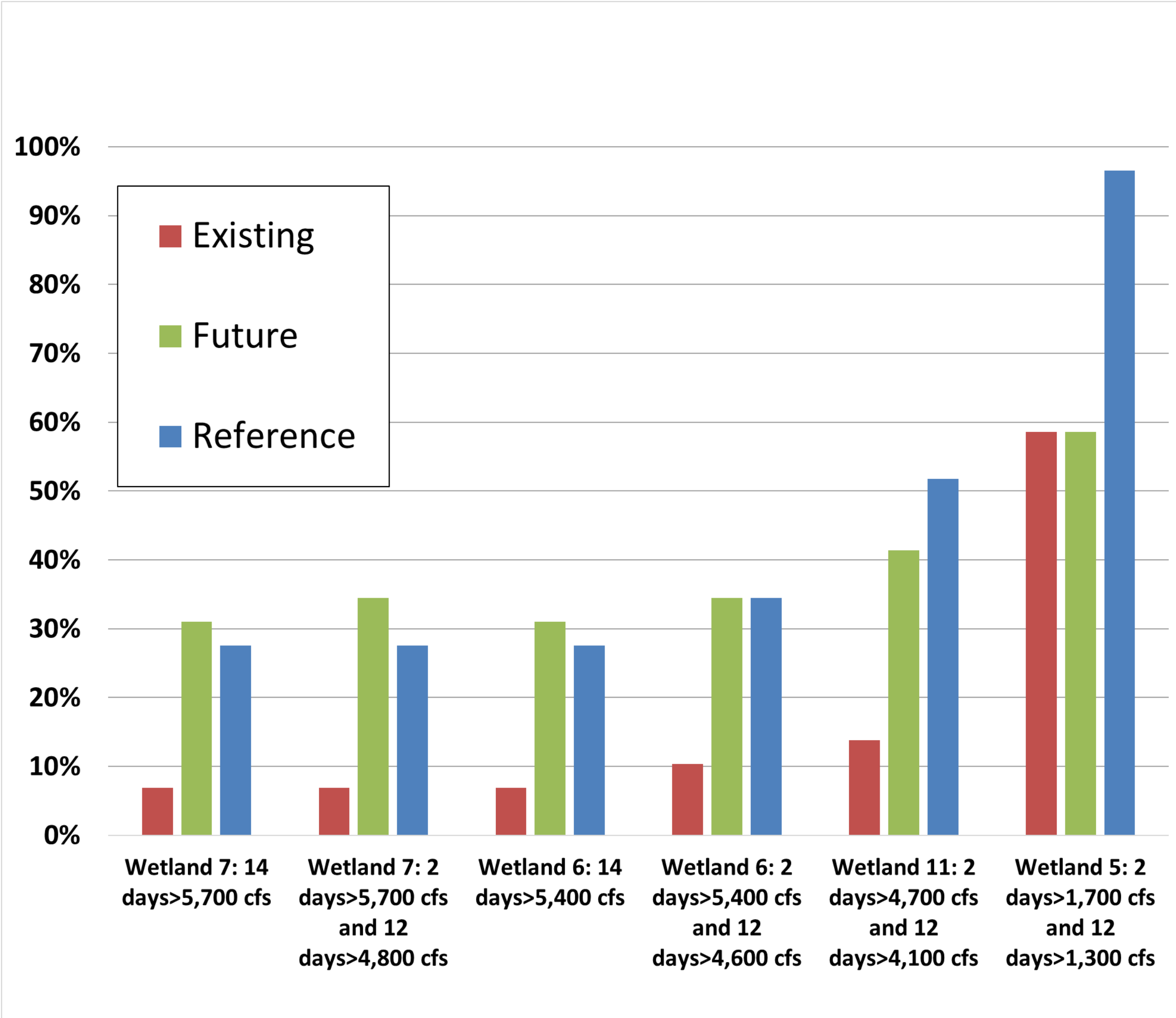

Figure 72. Estimated frequency of achieving Poopenaut Valley wetland inundation flow thresholds under the existing (simulated April to August spill management releases using Spill-Sim analysis from WY 1993-2021), future (simulated recommended spill management releases), and reference flow scenarios. See Figure 29 for location of wetlands.

9.7 Sediment transport capacity

Existing sediment storage in the river channel between O'Shaughnessy Dam and Poopenaut Valley appears stable despite the typical effects that dams have in reducing coarse sediment supply to reaches immediately downstream (McBain Associates 2021b). It is hypothesized that the sediment supply persists because of substantial glacial till deposits on the upper hillslopes above the Reach and Hetch Hetchy Valley acted like a natural sediment trap prior to dam construction (McBain Associates 2021b). However, a changing flow regime has potential to alter sediment transport dynamics.

To evaluate the potential reasons for the historical persistence of sediment storage immediately downstream of O'Shaughnessy Dam, 2-D hydraulic modeling was conducted to investigate whether the highly complex valley bottom topography between O'Shaughnessy Dam and Poopenaut Valley causes locations within that reach to be hydraulically shielded from high shear stress during high flows (McBain Associates 2021b). The 2-D modeling results suggested that even during very high flow events (35,000 cfs), shear stress was low at many locations in the reach. Therefore, the persistence of gravel and cobble in the upper end of the Hetch Hetchy Reach under existing conditions is likely supported by the hydraulic complexity of these sites enabling sediment to be retained in storage despite periodic high flow events. There may also be a small amount of supply derived from nearby hillslopes.

The future scenario has the potential to transport more sediment than the existing scenario due to higher flow magnitudes and durations in the recommended snowmelt management releases, thereby possibly depleting stored sediment downstream of O'Shaughnessy Dam. To investigate this concern, sediment transport capacity was evaluated for the reference, existing, and future scenarios using the BAGS sediment transport capacity model (Appendix E) at a cross section at the near Hetch Hetchy USGS gage station, and at a cross section in Poopenaut Valley. Both sites represent areas in the river that store sediment despite the presence of O'Shaughnessy Dam just upstream.

Sediment transport capacity is a metric that predicts the amount of sediment that can be transported by the hydraulic conditions of a flow regime and assumes that abundant sediment is available for transport. In other words, sediment transport capacity is a potential for sediment transport, not an actual transport rate. Nonetheless, it is a convenient metric to evaluate potential sediment transport difference in response to a different high flow regime. The existing scenario was compared to the reference scenario and resulted in a computed 70% and 71% reduction in sediment transport capacity at the near Hetch Hetchy USGS gage site and the Poopenaut Valley site, respectively. The future flow scenario compared to the existing scenario resulted in no change to sediment transport capacity at the Poopenaut Valley site, largely due to the extremely low slope in Poopenaut Valley. In contrast, the future flow scenario computed sediment transport capacity at the near Hetch Hetchy USGS gage resulted in a 20% increase in sediment transport capacity compared to the existing scenario, resulting from higher snowmelt management releases recommended in the future flow scenarios.

In summary, the sediment transport capacity (BAGS) analysis suggests that there is unlikely to be any substantial change in sediment transport capacity in the low gradient Poopenaut Valley between the existing scenario and future scenario recommendations, and thus it is unlikely that the future flow regime will result in a decrease of sediment storage in Poopenaut Valley. The computed 20% change in sediment transport capacity in the steeper site at the near Hetch Hetchy USGS gage is also assumed to result in a minimal risk of reduced sediment storage in the reach between Poopenaut Valley and O'Shaughnessy Dam due to the small change in sediment transport capacity (20%) and hydraulic complexity of the reach (McBain Associates 2021b). While the recommended snowmelt management flows in the future flow scenarios have peak flows that are intended to mobilize the bed more frequently to activate bars and limit riparian encroachment, future recommended peak flows are short in duration (two days), which should minimize the volume of sediment transported and reduce risk of long-term reductions in sediment storage out of the Hetch Hetchy Reach.

9.8 Drum gate release timing and water temperature

The magnitude, timing, and duration of drum gate spills vary each year depending on reservoir inflow and diversion rates at Canyon Power Tunnel. Drum gate spills typically begin toward the end of the snowmelt recession, after the peak reservoir inflow has passed, Hetch Hetchy Reservoir has filled, and continued inflows are driving spill releases. The existing and future scenarios were used to predict the timing and duration of drum gate spills for the 1993–2021 period. Under the Spill-Sim future release scenario, Hetch Hetchy Reservoir filled in all years modeled but did not necessarily spill in all years. Predicted drum gate spill typically began in early to mid-June and extended to early July in Normal and drier years. In Wet and Extremely Wet years, predicted spill extended from mid-June to early to mid-August (Figure 73).

Drum gate spill duration ranged from 0 day to 35 days and averaged 17.6 days. Spill duration was shorter for drier years, averaging 3.7 days in Extremely Dry years and 2.7 days in Dry years. Spill duration averaged 20.7 days in Normal years, 22.8 days in Wet years, and 32.2 days in Extremely Wet years. The Spill-Sim for the existing release scenario for the same period had generally shorter overall drum gate spill duration (16.4 days). In the existing scenario, spill was often longer during drier years but much shorter during wetter years. These results should be interpreted with caution, as the actual future drum gate spill dates and durations will be very sensitive to time-specific reservoir storage, inflow, forecasted runoff, meteorological conditions, and operator discretion.

Water spilling over the drum gates is derived from the epilimnion of the reservoir and water temperatures range from 16°C in June to 23°C in August. These water temperatures are warmer than valve releases that source from deeper and cooler layers in Hetch Hetchy Reservoir, leading to a valid potential concern regarding warmer in-river water temperatures and potentially stressful conditions for Rainbow Trout. However, modeled water temperatures at Early Intake during spill experiments using the Hetch Hetchy Reach Water Temperature Model predicted water temperatures would not exceed the 25°C threshold for Rainbow Trout, and are more likely to remain under 21°C in the summer months (Table 15). Additionally, even with increased drum gates operations, water temperatures are predicted to remain cooler at OSD and EI than reference conditions (Figure 52-Figure 55).

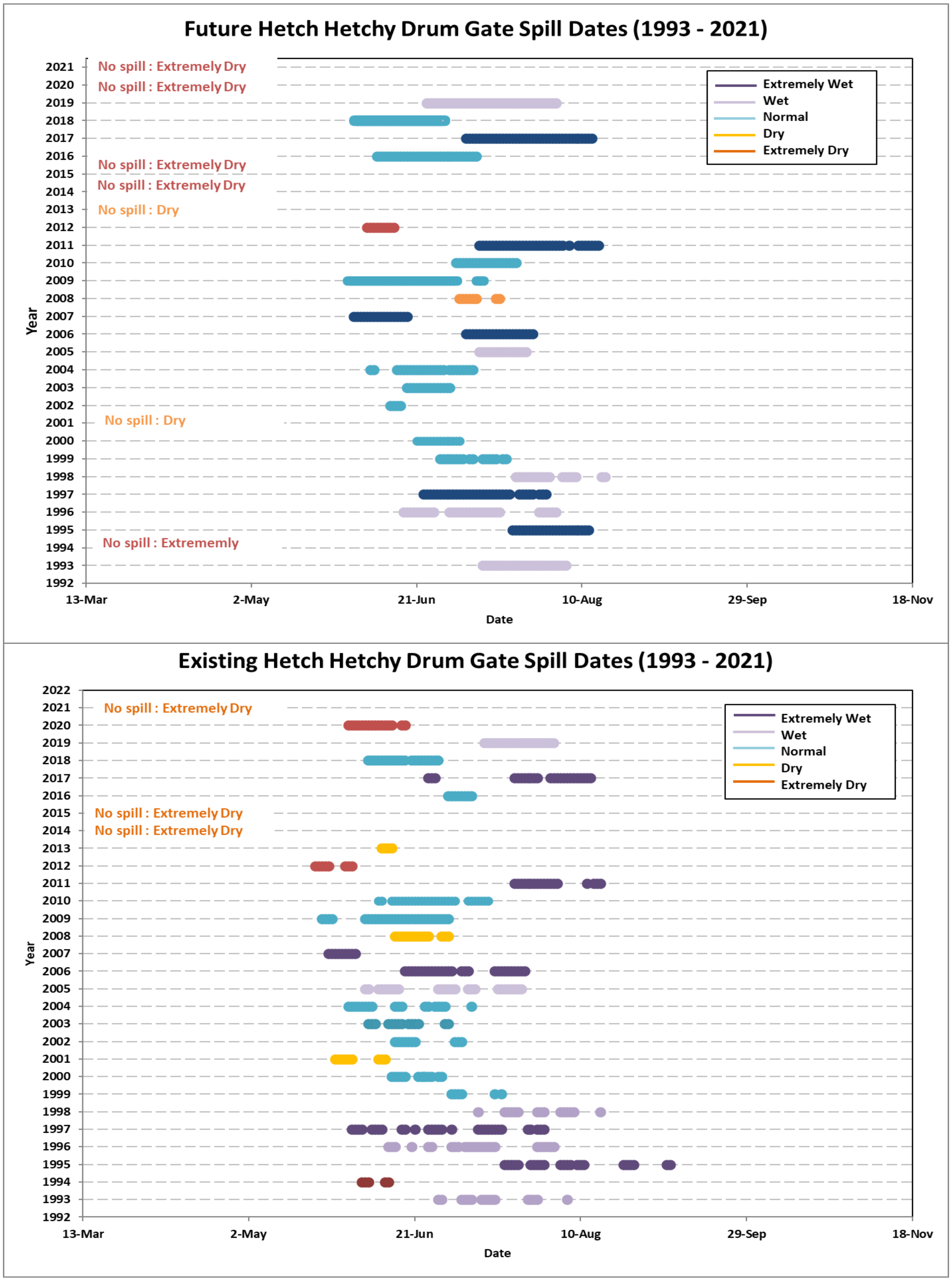

Figure 73. Timing of drum gate spill predicted by the Spill-Sim analysis under future snowmelt management for 1993–2021.

9.9 Discussion

The goal of the EFS (Section 1.3) was to develop recommendations that mimic the function of natural hydrologic variation, support productive native species populations and the conservation of special status species, and support water supply reliability and hydropower generation values. The recommendations strive to support hydrologic variation across water year types and support specific physical processes, habitats, and species in each water year type, and where possible (snowmelt season, summer baseflows) mimic the ecological function of flows in the upper Tuolumne River.

The results of the analyses presented in Sections 9.2 through 9.8 provide predictions around how the recommendations may affect the focal elements. However, individual focal species exhibit disparate responses to flow and water temperature (Railsback et al. 2016), thus, to understand whether the ecological objectives are being met under the future flow scenario, it is helpful to synthesize the results for all focal elements across water year types.

The response of the focal elements to the future flow scenario differed among water year types. This variable response in the focal elements was expected given the natural variability in inter-annual precipitation and hydrology in California's snowmelt-driven watersheds (Dettinger et al. 2011). In these highly variable watersheds, hydrologic variability supports the diversity of species and life history needs. For example, drier water years are often assumed and predicted to be more productive for Foothill Yellow-legged Frog reproduction (Kupferberg et al. 2012), while older and larger trout may encounter stressful conditions in the lower streamflows (Railsback et al. 2016). During wetter years, however, the longer recession limbs, inundated high flow surfaces, and extended high flow durations support longer growing periods for invertebrates and subsequently growth conditions for trout (Rhoades et al. 2023, Wenger et al. 2011).

Under the recommended future flow scenario, summer baseflows are lower relative to the existing flow scenario but more similar to the reference condition (see Section 9.2). Recommended summer baseflows are predicted to result in higher summer water temperatures that are closer to reference condition water temperatures (Table 16). These changes are predicted to result in greater Foothill Yellow-legged Frog reproductive success compared to existing and reference scenarios (Figure 70) during drier years due to a lower risk of scour and desiccation mortality, coupled with earlier, warmer water temperatures that support faster egg and tadpole development rates (Rose et al. 2021). Wetter years with higher spring flows increased risk of scour and desiccation of egg masses (Kupferberg et al. 2009) and colder summer water temperature delayed tadpole development (Wheeler et al. 2015; Rose et al. 2021, 2023). In drier water years, however, lower summer flows may have limited benefits and minor consequences for Rainbow Trout; modeled inSTREAM results reported lower growth rates and abundances at the end of these water year types (Figure 66 and Figure 67).

The NGD analysis predicted fewer good days for the future scenario compared to the existing scenario for adult and juvenile Rainbow Trout in the drier years at the OSD site (EI site was similar; Figure 59). The lower NGD for adults at the OSD site during drier years appears to be related to isolated drum gate spill events. These events occur in both existing and future flow scenarios, but operations during the future scenario focus on reducing high flow spill events after May 15 to reduce potential mortality of Foothill Yellow-legged Frog egg masses (see Section 7.3). To reduce the high flow spills, more water is released through valves, resulting in colder and lower magnitude flows, which do not meet the NGD thresholds. A similar pattern exists for juvenile Rainbow Trout at the OSD site, but the mechanism is different. Under the existing scenario, baseflows are sufficiently high to trigger the NGD flow threshold (45 cfs at the OSD site), but future scenario baseflows are lower (35 cfs during drier years) and do not meet the NGD criteria. The lower future scenario baseflows are intended to create flows more similar to unimpaired conditions and to support faster development time for Foothill Yellow-legged Frog, which is predicted by FYFAM modeling and the NGD analysis of Foothill Yellow-legged Frogs.

Wetter water years are characterized by higher spring and summer baseflows and peak flows, longer recession limbs, and high flow snowmelt management objectives that result in cooler summer water temperatures relative to drier years (see Section 9.2). InSTREAM predicted improved growth and end of year abundance for Rainbow Trout under the future scenario for wetter years relative to existing conditions, but growth and end of year abundance would still be lower in the future scenario than under reference conditions (Figure 66 and Figure 67). The improvement in the future flow scenario over the existing scenario is attributed to better growth conditions supported by (1) longer recessions that offer warming water, which is a component of the snowmelt management objectives; and (2) higher summer baseflows that increase food delivery throughout the summer. This result is also supported by the NGD analysis (see Section 9.3), which suggests there are more opportunities for trout and BMI production in wetter water years in the future flow scenario compared to the existing flow scenario at both the OSD and EI sites. These higher flow years, under all flow scenarios, are not predicted to support substantial Foothill Yellow-legged Frog production.

While not all individual water year types under the future flow scenario are predicted to improve conditions for Rainbow Trout, results suggest this inter-annual variability will continue to support a stable population over the long term. First, inSTREAM modeling predicted similar oscillating abundance in Rainbow Trout for all age classes, through different water year types for all streamflow scenarios (Figure 68 and Figure 69). Second, long-term trends in observed Rainbow Trout populations from empirical data (snorkel surveys) in the Early Intake Subreach and in a reference reach above Hetch Hetchy Reservoir (Appendix B) show similar oscillation between higher and lower abundances from year to year and age-dependent relationships with flow, as in the model results. For example, higher flow years are predicted to be less beneficial for smaller young-of-year fish under both existing and future scenarios, and this dynamic is reflected in empirical data. Like the modeled output for all three flow scenarios (existing, future, and reference), populations of Rainbow Trout in the upper Tuolumne River undergo fluctuations in abundance but overall remain relatively consistent over time. Consistency between modeled results and empirical data results indicates that the existing and future flow scenarios are likely to support stable long-term populations of Rainbow Trout, while modeled results indicate the future scenario is also likely to better support Foothill Yellow-legged Frog populations (Figure 70). Thus, flow variability among water year types in the future flow scenario reflects a shift from a trout-centric management strategy toward an ecosystem-based approach that better supports a broader range of species, including the federally and state listed Foothill Yellow-legged Frog.

Wetter years are projected to more frequently support aquatic, riparian, and wetland habitats in the Hetch Hetchy Reach through more frequent bed mobility and wetland inundation (Figure 71 and Figure 72). While the effects of more frequently meeting the various bed mobility and wetland inundation thresholds are expected to be broadly beneficial to the river ecosystem in the Hetch Hetchy Reach, it is difficult to model the direct responses in focal species (*sensu* Poff et al. 1997).

Another outcome of the future flow scenario is slower downramping rates and more spill routing over the drum gates during wetter years. This results in a warmer, longer recession limb that better mimics reference conditions. InSTREAM and FYFAM modeling results suggest that these conditions will support growth for native Rainbow Trout and reduce relative desiccation risk for Foothill Yellow-legged Frog (Figure 74).

Recommended future snowmelt management is also likely to support terrestrial species that use river carbon sources. For example, Jackson et al. (2020) studied the links between riverine processes and higher riparian trophic levels (birds and bats) in Poopenaut Valley. The authors show reliance on autochthonous carbon from the river, but were limited in their ability to test the relationship to water year type. In the one wet year analyzed, however, reliance on autochthonous carbon was higher in the regulated Tuolumne River than in their reference river (unregulated Merced River). The snowmelt management objectives also recommend that, during wet years after the first high flow release greater than 1,000 cfs, flows should not drop below 1,000 cfs (Table 13). Keeping flow above 1,000 cfs is recommended to discourage RHJV birds from nesting in lower elevations where flooding can occur and result in nest mortality in the riparian zone.

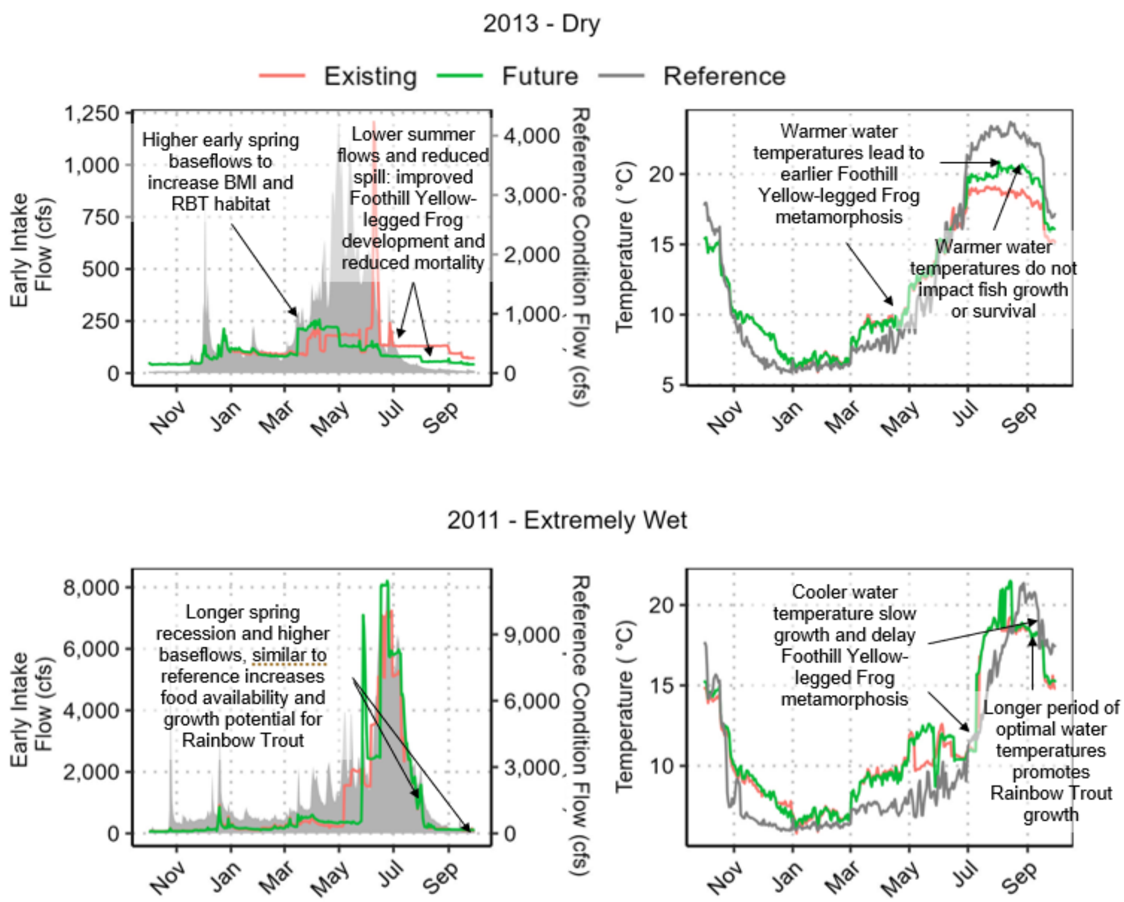

Figure 74. Examples of flows and temperatures in Dry and Extremely Wet water years at the EI site under existing and future scenarios and notations illustrating effects of recommended baseflow and spill management on Foothill Yellow-legged Frogs and Rainbow Trout based on the outputs of inSTREAM and FYFAM modeling results. Estimated reference condition flows and water temperatures are grey.

While Northwestern Pond Turtle was not selected as a focal species, it is anticipated that the future flow scenario will generally benefit Northwestern Pond Turtle populations in the Hetch Hetchy Reach. Periodic spring high flow events resulting in mobilization of sediment and inundation of wetlands are beneficial for long-term maintenance (sediment deposition) of Northwestern Pond Turtle nest habitat and maintenance of pool habitats favored by these turtles. Furthermore, typical Northwestern Pond Turtle nesting locations are not occupied during seasonal snowmelt peak flows, and thus negative impacts on turtle nests are not anticipated from recommended snowmelt management. Northwestern Pond Turtles tend to place their nests high on the floodplain or in the uplands, well above ordinary high flows, and thus are safe from all but the highest winter flows. Eggs in the nest chamber (June–September) rarely survive inundation of more than a few days, while hatchlings overwintering in the nest chamber (September–March) may survive inundation for a week or two. The Northwestern Pond Turtle is adapted to the Mediterranean climate regime of wet winters, spring snowmelt peaks, and hot dry summers. The anticipated benefits of habitat maintenance under the future flow scenario far outweigh the potential risks of periodic high magnitude flood events.

9.10 Climate change uncertainties

In the Sierra Nevada generally, and within the Tuolumne River watershed, climate change is expected to increase average air temperatures and alter precipitation patterns (Dettinger et al. 2015; Powers et al. 2024). Watersheds are predicted to experience changes in stream water temperatures, the timing and intensity of precipitation, with increased proportions falling as rain instead of snow, and reductions in average annual snowpack with shifts to earlier snowmelt runoff (Harpold et al. 2017). These changes will create challenges for the management of freshwater ecosystems.

9.10.1 Potential climate driven changes to water temperature

With continued increases in average air temperatures and alterations to precipitation patterns from climate change, water temperatures have the potential to increase. The average hypolimnetic water temperature in Hetch Hetchy Reservoir is unlikely to change significantly with projected increases in air temperature because of the reservoir's depth (approximately 100 meters). Water releases during summer baseflows when water temperature is warmest comes from the hypolimnion and is unexpected to have a significant change. However, as water flows downstream in warmer air temperatures, water temperatures downstream towards Early Intake have potential to increase with prolonged exposure to higher air temperatures, which may have direct and indirect consequences for the organisms and focal species in these reaches. However, water temperatures under both existing and recommended future flow scenarios are predicted to be cooler than reference conditions, suggesting that Hetch Hetchy Reservoir may help buffer river water temperature warming some distance downstream of the dam (Table 16).

Rainbow Trout are a cold-water species that have an upper incipient lethal temperature of 22 to 25°C (Hokanson et al. 1977; Mattews & Berg 1997; Wehrly et al. 2007), but lower Tuolumne River specific research shows Rainbow Trout maintaining their peak aerobic scope up to 24.6°C (Verhille et al. 2016). In the recommended future flow scenario, the water temperatures at the EI site are predicted to be approximately 19.5°C in the warmest summer months during extremely dry years, which remains within the thermal tolerance of Rainbow Trout. A water temperature increase of 3 to 5°C would be required to reach upper incipient lethal water temperature levels at the EI site, and based on lower Tuolumne River specific literature (Verhille et al. 2016), may continue to maintain their aerobic capacity within that range. While the EFS was not able to model water temperatures under climate change scenarios, it's also important to note that reference condition water temperatures were often 20-22°C, which is higher than those predicted in the recommended future flows scenario (Table 16). Thus, hypolimnetic releases are likely to keep water temperatures cooler than what would be predicted with climate change if no reservoir was in place.

Foothill Yellow-legged Frog egg masses and tadpoles have optimal temperature ranges of 10 to 16°C (Hayes et al. 2016; Gonsolon 2010; Wheeler et al. 2015) and 18 to 22°C (Catenazzi & Kupferberg 2013, 2017), respectively, and a critical maximum water temperature of 26°C (Zweifel 1995). Frogs and many other herpetofauna rely on temperature cues for their life history, so increases in water temperatures could promote earlier breeding and faster development of eggs and tadpoles. However, the water temperatures under the future recommended flows are still likely to be slightly cooler than reference flows (Table 16). Under climate change its possible that earlier metamorphosis may occur which may potentially increase the over-winter survival of first-year froglets. While higher water temperatures also promote exposure and spread of parasites and diseases, as was observed in tadpoles in the South Fork Eel River exposed to a thermophilic ectoparasite after a summer heat wave (Kupferberg et al. 2009), the water temperatures in the recommended future flow scenario are still cooler than those predicted to occur if Hetch Hetchy Reservoir were not in place. Increases in water temperature expected in the Hetch Hetchy Reach of the Tuolumne River may not directly drive changes in the Foothill Yellow-legged Frog populations, but changes in flow regimes are likely to play a larger role in their distribution and reproductive success,

9.10.2 Potential climate driven changes to streamflow

Climate change is expected to impact the timing, magnitude, and duration of runoff events with more years of extreme drought and higher intensity atmospheric rivers. The risk of severe droughts is anticipated to increase across many of the world's most populated regions (Dai 2012), including California. Within the last 15 years, the state of California has experienced some of its most extreme weather events with severe multi-year droughts (2012 to 2016 and 2018 to 2021) and a couple of the wettest years on record (2017 and 2023) (Power et al. 2024). The SFPUC's long-term vulnerability assessment and adaptation plan (Francois et al. 2021) agrees with these larger-scale predictions and expects high variability to inflow to Hetch Hetchy Reservoir continuing through 2070, but no detections of drier and wetter trends in the long-term projections.

The EFS flow recommendations are intended to scale with each water year. During wetter years, baseflow recommendations and snowmelt management objectives are intended to achieve higher flow objectives that would mobilize gravel and cobbles. Similarly, during drier years the objectives shift to those which are achieved with lower flows (reduce potential for FYFL egg scour). Hetch Hetchy Reservoir does not have sufficient volume to release high flows during dry years, nor is large enough to retain water volume during wet years, thus there is very little that reservoir operations can do to help mitigate for extended periods of drought or large floods.

While Hetch Hetchy Reservoir is not large enough to mitigate for drought or excessive floods, the impacts of climate change may still occur downstream. For example, a long period of extremely dry years would decrease the frequency of gravel and cobble mobilization which could result in more algal growth or decreased BMI diversity or abundance (Holmquist and Schmidt-Gegenbach 2012). Similarly, a long period of very wet years can also be concerning for age 1 and younger (fry) Rainbow Trout. SFPUC annual snorkel surveys show that fewer age-1 fish are observed after high flow years (Appendix B). The future hydrology of the Tuolumne River watershed is unclear but predicted to have more rain than snow and be more variable. While there are likely to be changes to the ecology of the river, it's unclear what they will be, but EFS flow recommendations are intended to scale naturally with interannual variation.

10 Potential outcomes of recommended flows

Recommended baseflow, snowmelt management, and ramping rates are intended to work together to meet the ecological goals and management objectives described in Section 5.3. Together, the recommendations are designed to:

- Shift flow releases and water temperatures towards a pattern, timing, and magnitude that more closely mimics the reference flow regime and benefit native aquatic, wetland, and riparian species;
- Better mimic inter-annual and intra-annual reference condition flow and water temperature variability to coincide with hydrologic trends within the watershed;
- Increase frequency of exceeding bed mobility and Poopenaut Valley wetland inundation and saturation thresholds to re-establish functional ecological processes; and
- Maintain conditions for Rainbow Trout that support growth, survival, and reproduction in all water year types while improving conditions for Foothill Yellow-legged Frog recruitment during drier water years.

The results described in Sections 8.2 through 8.8 indicate that recommended baseflow and snowmelt management releases in any single water year type are unlikely to provide support for optimal conditions for all focal physical processes, habitats, and species. However, it is anticipated that the portfolio of releases across different water year types will broadly support the various physical processes, habitats, and species within the reach.

10.1 Ecological outcomes

Ecological goals (see Section 5.3) were developed for each focal element to clearly describe the desired outcomes for the development of environmental flow recommendations. The discussion below uses results from the evaluation of flow scenarios in Section 9 to describe how the recommendations in this EFS are anticipated to support achievement of the ecological goals (Table 4), which are italicized below.

Maintain and/or increase native Rainbow Trout

The inSTREAM modeling results predict Rainbow Trout populations will remain stable (Figure 68 and Figure 69) over time under the future flow scenario. This suggests that recommended future baseflows and snowmelt management are likely to support the goal of maintaining native Rainbow Trout populations in the Hetch Hetchy Reach. While increases in the populations at the two study sites (OSD and EI) over time are not indicated, the population is likely to naturally fluctuate from year to year similar to past observed population trends (Appendix B).

Maintain BMI production in the spring to support Rainbow Trout growth, providing food web support for riparian birds and bats

The NGD analysis generally predicted more days of good BMI production under the future flow scenario, particularly in wetter years (Figure 62), with more days with high quality habitat for BMI than under existing conditions. The increased frequency of higher magnitude snowmelt management releases in the spring under the future flow scenario has the potential to increase rates of BMI drift (Holmquist and Schmidt-Gengenbach 2012) and increase BMI assemblage diversity (Stock et al. 2021). Higher and longer duration flows in wetter years will also increase the inundation periods of Poopenaut Valley and other riparian habitats, which is likely to increase invertebrate food production.

Maintain or increase Foothill Yellow-legged Frog abundance

In Dry years, the recommended future flows are anticipated to improve reproduction and growth conditions for the federally and state listed Foothill Yellow-legged Frog compared to existing and reference conditions. FYFAM predicted an increase of froglets under drier water year types (Figure 70), which has the potential to increase Foothill Yellow-legged Frog abundance. Less scour and desiccation of egg masses are also predicted; this is an outcome of slower recession limbs and the goal of limiting spill after filling during Dry and Extremely Dry years. While the wetter years are less favorable for Foothill Yellow-legged Frog reproduction and growth in the mainstem of the river, frogs may use the main channel in Normal years. When the main channel is not suitable in wetter years, it is hypothesized that successful reproduction may occur in tributaries where lower energy hydraulic conditions provide more favorable breeding habitat. Additionally, channel maintenance and periphyton disturbance from the wetter years will likely benefit Foothill Yellow-legged Frogs by maintaining a dynamic habitat and food web.

Reduce risk of RHJV focal bird species nest inundation during snowmelt season spill releases

Snowmelt management targets include maintaining releases above 1,000 cfs once the snowmelt management releases begin, which is anticipated to reduce the potential for inundation of RHJV focal bird species nests. In the future flow scenario, this target was achieved in every year it was identified for implementation. It is hypothesized to be protective when implemented in real-world operations.

Reduce potential stranding, displacement, and/or excessive ramping-related energetic expenditures for native aquatic species, and promote riparian vegetation recruitment in wetter water years

Recommended high flow (>300 cfs) downramping is 25% per day during the snowmelt management period (April–August) and 55% per day during winter (September–March), significantly slower than the existing rate of 98% per day and reflective of reference condition ramping rates. The slower downramping is anticipated to be more protective of native species, potentially reducing excessive stranding of Rainbow Trout life stages, including reducing the risk of dewatering and desiccation of redds, although no significant change was detected using inSTREAM between existing and future scenarios for egg survival. The slower and longer recession limb is anticipated to reduce desiccation of BMI, potentially providing more abundant food resources and slightly warmer water temperatures that are energetically favorable for Rainbow Trout growth and feeding during the snowmelt recession. The slower snowmelt recession limb will result in less egg mass and tadpole desiccation for Foothill Yellow-legged Frog (as predicted by FYFAM) and faster tadpole development times under warmer water temperatures (Appendix A). The recommended downramping rates are more protective of tributary channel erosion and may promote establishment of riparian vegetation on higher elevation surfaces in some years by providing suitable flow duration for seeds to germinate.

10.2 Physical process outcomes

Recommended snowmelt management releases are directed at improving geomorphic processes, maintaining Poopenaut valley wetlands, reducing riparian encroachment, and increasing recruitment of woody riparian plants on higher elevation surfaces within the Hetch Hetchy Reach. These ecological goals and associated flow, magnitude, and duration targets are intended to mimic the function of reference condition physical processes. There is significant overlap between the magnitudes and durations across many of the ecological goals and thus anticipated outcomes for these goals are discussed together below.

Increase bed mobility and scour through improved fluvial geomorphic processes.

Maintain the extent of Poopenaut Valley wetlands. Fill the North Pond at a frequency closer to pre-dam conditions (i.e., once every one to two years).

Reduce channel encroachment by riparian vegetation to maintain aquatic habitat.

Increase recruitment of woody riparian vegetation on higher elevation geomorphic surfaces to provide riparian habitat.

The effects of the future flow scenario on physical process-based ecological goals (bed mobility and Poopenaut Valley wetlands) were evaluated in Section 9.6. The results suggest that under recommended snowmelt management, many of the physical process-based objectives will be achieved at a higher frequency than under existing conditions (Figure 71 and Figure 72) and will approach (or in some cases exceed) frequencies estimated to have occurred in the reference condition. Achieving higher frequencies of bed mobility and wetland inundation is anticipated to improve and maintain Rainbow Trout, BMI, Foothill Yellow-legged Frog, and Northwestern Pond Turtle physical habitat. The higher frequency of these flows is anticipated to reduce riparian encroachment in the low flow channel while facilitating riparian vegetation recruitment on higher elevation surfaces. The future flow scenario was predicted to fill the Poopenaut Valley North Pond in approximately two out of every three years (Figure 72), which is anticipated to increase wetland and riparian food production for RHJV focal birds and other native species.

11 Summary

The EFS provides environmental flow recommendations for baseflows, snowmelt management, and ramping rates that incorporate a broad view for management of ecosystem-based objectives that include physical processes, habitat restoration and maintenance, native species conservation, and the recovery and persistence of state and federally listed species. The environmental flow recommendations do not restore the reach to pre-development, reference conditions, but aim to mimic the natural flow patterns and functionality of those conditions under which native species evolved while considering water supply reliability.

Using models, historical data, and novel tools, the EFS assesses the recommended flow scenarios under different water year types and provides options for managing snowmelt to benefit the ecosystem and meet the ecological and geomorphic goals. Climate change is expected to impact the Tuolumne River and all rivers across the western United States through increasing water temperatures, altering precipitation and snowmelt runoff patterns, and reducing average annual snowpacks, which will create more management challenges for these highly regulated freshwater systems. Understanding the physical system and the ecosystem surrounding it will help operators better manage the Upper Tuolumne and Hetch Hetchy Reservoir to meet human and ecological needs into the future.

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