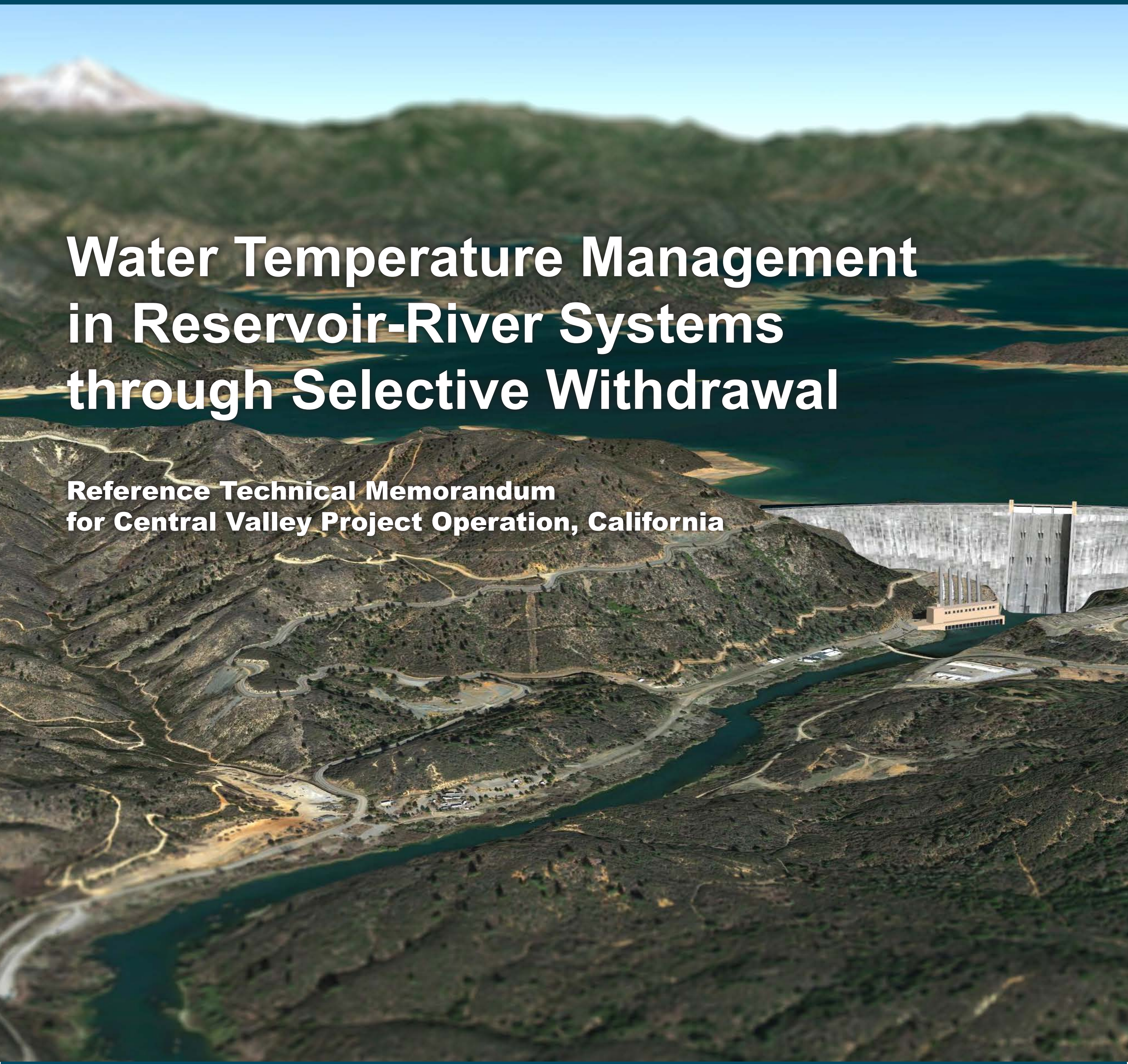
RECLAMATION

Managing Water in the West



Water Temperature Management in Reservoir-River Systems through Selective Withdrawal

Reference Technical Memorandum for Central Valley Project Operation, California

U.S. Department of the Interior
Bureau of Reclamation
Mid-Pacific Region

September 2017

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to American Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Water Temperature Management in Reservoir-River Systems through Selective Withdrawal

Reference Technical Memorandum
for Central Valley Project Operation, California

Prepared by:
United States Department of the Interior
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Preface

Operation of large, multipurpose reservoirs can include storage and regulation of flow for hydropower production, water supply, navigation, recreation, and flood risk management, as well as for helping to meet environmental objectives in downstream river reaches. Each reservoir-river system has distinct watershed characteristics, experiences inter- and intra-annual variability in hydrology and meteorology, and is subject to specific laws and regulations, thus presenting a range of challenges for resource managers. Successful operation of a reservoir-river system often requires collaboration and cooperation of different disciplines to effectively and prudently manage available water resources. Datasets, tools, and procedures are used by multidisciplinary groups to carry out the annual and seasonal management in a reservoir-river system.

Water temperature management in reservoir-river systems is a critical component for meeting downstream environmental objectives. In many reservoir-river systems, specific infrastructure to withdraw water from the reservoir at multiple elevations with different water temperatures is used to improve efficiency. Reservoirs with selective withdrawal capabilities are able to blend water from different depths and temperatures to achieve targeted downstream river temperatures from late spring through fall.

Managing water temperature in reservoir-river systems through selective withdrawal is challenging for many reasons, including inter- and intra-annual variability in hydrology and meteorology, year-specific demands and constraints, and unforeseen events and circumstances throughout the year. While these varying conditions are generally recognized, the major challenge in temperature management is to leverage the limited cold water resource to provide downstream temperatures for fishery species and their corresponding life-cycle stages, while considering other management objectives imposed on the reservoir. Therefore, developing and implementing a water temperature management strategy requires both common terminologies for communicating system-specific information to a broad range of resources managers and their continual collaboration. This group of resource managers must contribute their expertise and work cooperatively to synthesize available information to develop an initial strategy for the upcoming year and refine that strategy throughout the temperature management season.

The purpose of this technical memorandum, entitled *Water Temperature Management in Reservoir-River Systems through Selective Withdrawal*, is to provide a reference for resource managers that facilitates effective temperature management and supports achieving downstream temperature objectives in late-spring through fall months by improving communication and leveraging limited cold water resources.

This technical memorandum focuses on the technical aspects of water temperature management that are pertinent to the Sacramento and American River systems, which include infrastructure and facilities that are part of the Central Valley Project (owned and operated by the U.S. Department of the Interior, Bureau of Reclamation (Reclamation)). This reference is generally applicable throughout the western United States where temperature management in reservoir-river systems is necessary.

This technical memorandum covers basic water temperature theory (Section 1), elements of water temperature management in a reservoir-river system through selective withdrawal (Section 2), case studies from the Sacramento and American River systems (Section 3), and the importance of multidisciplinary synthesis in annual temperature management strategy development and subsequent updates (Section 4).

A common understanding of foundational information and knowledge among resource managers, coupled with successful communication, is increasingly important as the western United States continues to experience more severe and extended droughts that affect all aspects of managing multipurpose reservoir-river systems for the social, economic, and environmental needs of current and future generations.

(Right) Fall run salmon near Nimbus Hatchery on the American River
Photo Credit: Yung-Hsin Sun, used with permission.

(Left) Spring Chinook in Beegum Creek
Photo Credit: Doug Killam, California Department of Fish and Wildlife.

Table of Contents

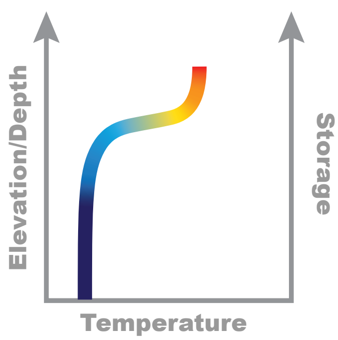
Abbreviations and Acronyms

°F	Degree Fahrenheit
AF	Acre-Foot
A_s	Water Body Surface Area
BTU or Btu	British Thermal Unit
cal	Calorie
C_p	Specific Heat of Water
cfs	Cubic Feet per Second
dT	Change in Temperature
dt	Change in Time
ft^3	Cubic Feet
H_a	Atmospheric Longwave Radiation
H_b	Water Longwave Radiation
H_{bed}	Bed Heat Conduction
H_c	Sensible Heat Flux
H_L	Latent Heat Flux
H_n or H_{net}	Net Heat Flux
H_s	Solar Radiation
lb_m	Pound
LLI	Low Level Intake
PH	Powerhouse
PRG	Pressure Relief Gate
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
S	Sources and/or Sinks of Heat Energy
t	time
T or T_w	Water Temperature
T_{air}	Air Temperature
TCD	Temperature Control Device
T_{eq}	Equilibrium Water Temperature
T_{river}	River Water Temperature
T_{trib}	Tributary Water Temperature
T_x	Temperature of Water Body x (e.g., x = tributary, river, downstream)
ρ	Density of Water
Q_x	Flow in Water Body x (e.g., x = tributary, river, downstream)
Θ_r	Residence Time
V	Volume of Water Body

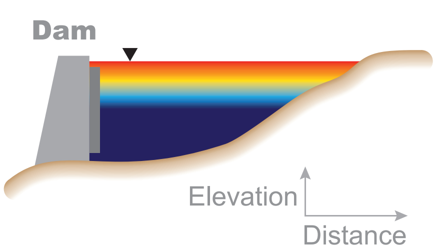
Guide to Graphic Representation

Graphics are used throughout this document to aid interpretation and communication of information related to water temperature and associated data. The following provides examples of graphics used in the document.

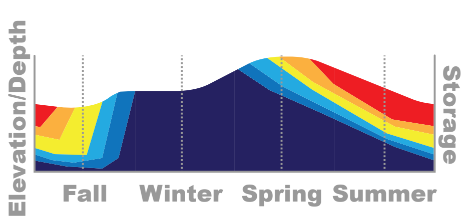
Water Temperature Color Scheme: Cold to warm water temperatures are consistently reflected with this color scheme.



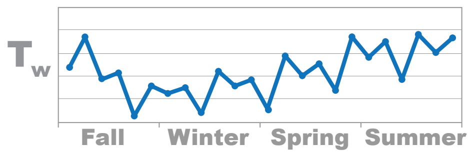
Vertical Reservoir Water Temperature Profile (Temperature and Elevation Relationship): The horizontal axis represents water temperature and the vertical axis represents elevation, depth, or storage as needed.



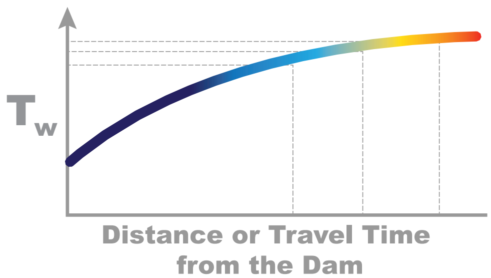
Reservoir Water Temperature Istotherm Profile at a Fixed Time: Reservoir water temperature isotherms (bands of equal temperature) as distance along the reservoir (horizontal axis) versus elevation (or depth) in the reservoir).



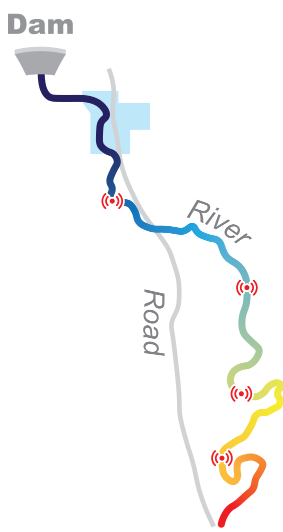
Reservoir Water Temperature Isotherm Profile at a Fixed Location through Time: Water temperature isotherms as a time progression (horizontal axis) versus elevation (or depth) in the reservoir at a fixed location. The reservoir surface reflects seasonal storage changes. A vertical line through this figure translates to a vertical reservoir profile.



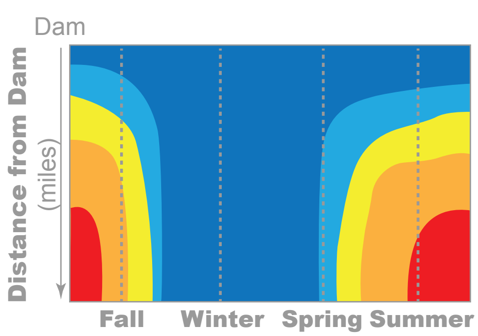
River or Release Water Temperature Time Series at a Fixed Location: Water temperature (horizontal axis) versus time (vertical axis) for a fixed location. The time step may vary from sub-daily to monthly or even annually depending on the analysis.



Water Temperature of River or Reservoir Release, Traveling Downstream: A longitudinal profile of water temperature (vertical axis) versus distance or travel time downstream of the dam (horizontal axis). Water temperature may be plotted at a specific time or the graph may represent a metric, such as a daily average.



Water Temperature of River or Reservoir Release, at a Specific Time: A longitudinal profile (above) plotted on the actual spatial representation (e.g., latitude and longitude) of a river course.



River Reach Isotherm Profile through Time: Water temperature isotherms as a time progression (horizontal axis) versus distance downstream for a specified river reach. A vertical line through this figure translates to a longitudinal profile at a specific time (see above).

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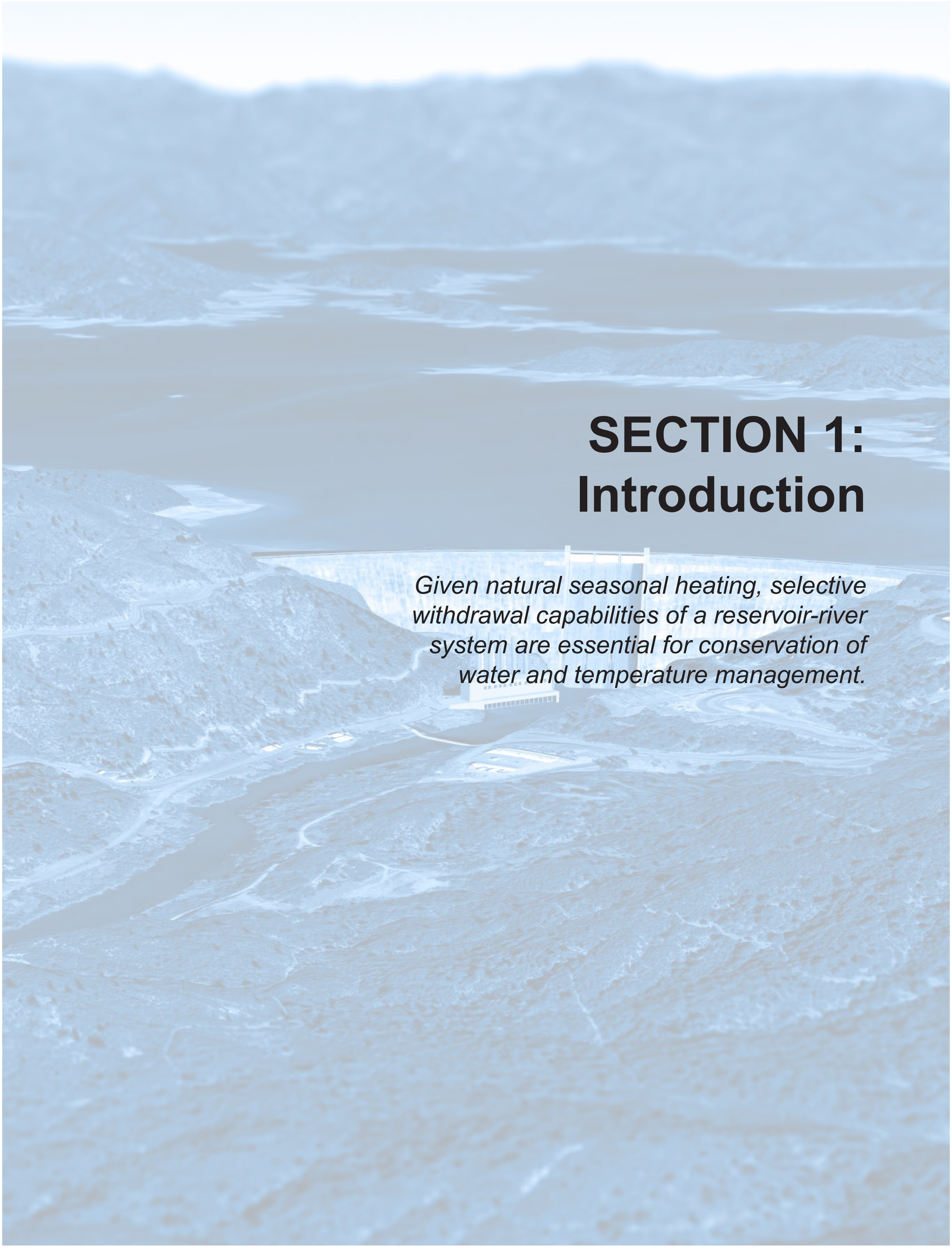

SECTION 1: Introduction

Given natural seasonal heating, selective withdrawal capabilities of a reservoir-river system are essential for conservation of water and temperature management.

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SECTION 1: Introduction

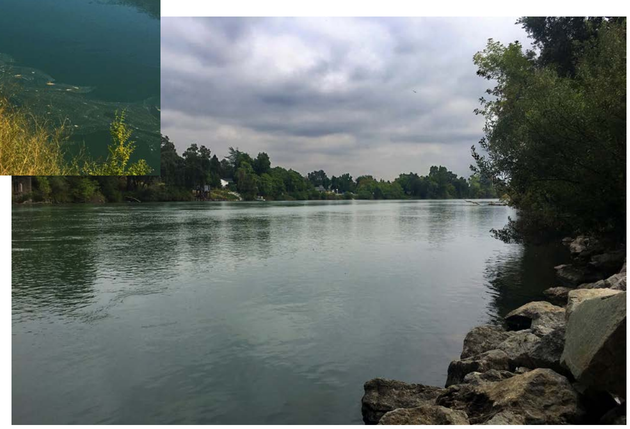
Water temperature management in reservoir-river systems is a critical element of meeting downstream environmental objectives. Natural heating in reservoirs and rivers is governed by the same basic principles, but characteristics of a water body impact how much heating occurs. Downstream water temperatures are also impacted by the operational flexibility available to resource managers. One key element of water temperature management in a reservoir-river system is a selective withdrawal facility to allow resource managers to more efficiently use the available cold water resources.

This section provides an overview of temperature management for a reservoir-river system, including the natural heating processes and general concepts related to water temperature management using selective withdrawal.

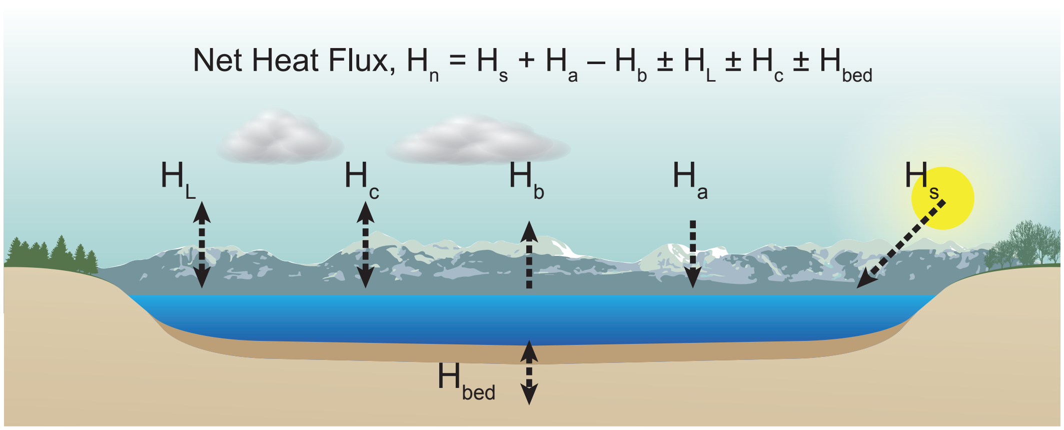
Natural Heating in a Reservoir-River System

Natural heating is the thermal response of a water body to meteorological conditions, which vary by location and season. The process occurs at all times through various heat exchanges between different parts of the natural environment. Temperature of a water body increases when the sum of the heat fluxes (discussed later) is positive (i.e., energy flux in exceeds energy flux out) and energy is stored. When the sum of the heat fluxes is negative, energy is emitted from the water body, resulting in a decrease in water temperature. The magnitude and timing of water temperature changes are primarily a function of meteorological conditions and water body location.

Natural heating in a water body is a function of meteorological conditions. Two different meteorological conditions, clear (left) and cloudy (below), result in different rates of heating in the river. *Photo credit: Watercourse Engineering, Inc.; used with permission.*



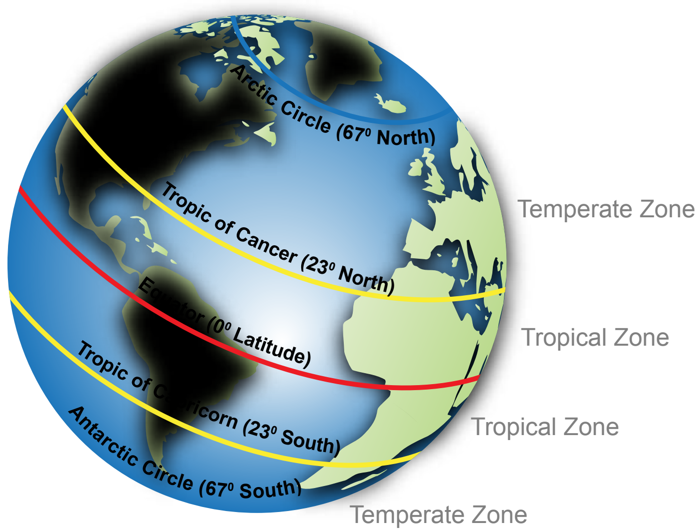
The illustration below provides a simplified view of the heat exchange of a water body in terms of the basic heat budget. Net heat flux (H_n) is the sum of all heat fluxes to and from the water body. Short-wave, or solar, radiation (H_s), is emitted by the sun and is an input of heat energy. Another heat energy input is long-wave radiation, which is emitted from the atmosphere (H_a) and is strongly a function of air temperature. Long-wave radiation emitted from the water body (H_b) is a strong function of water temperature and is an output of heat energy. Latent, or evaporative, heat flux (H_L) is associated with a change in water phase, such as condensation or evaporation, and is a function of water temperature, relative humidity, and wind. H_L can be an input (condensation) or output (evaporation) of heat energy. Sensible heat flux (H_c) is in response to conduction between two fluids of different temperature, in this case between the water surface and atmosphere, and can be can be an input (i.e., air temperature (T_{air}) exceeds water temperature (T_w)) or output ($T_{air}<T_w$) of heat energy. Ground, or bed heat, conduction (H_{bed}) occurs between the water and bed; is a function of water temperature, bed temperature (T_{bed}), and bed thermal properties; and can be can be an input ($T_{bed}>T_w$) or output ($T_{bed}<T_w$) of heat energy.



Heat Flux		Influencing Factor(s)	Effects on the Water Body: Energy input resulting in an increase in temperature	Effects on the Water Body: Energy output resulting in an decrease in temperature
H_L	Latent or evaporative heat flux associated with a change in water phase	air temperature, water temperature, relative humidity, wind	when water condenses	when water evaporates
H_c	Sensible heat flux in response to conduction between the water body and the atmosphere	air temperature, water temperature	when water temperature is lower than air temperature	when water temperature is higher than air temperature
H_b	Long-wave radiation from the water body	water temperature	not applicable	always
H_a	Long-wave radiation from the atmosphere	air temperature	always	not applicable
H_s	Short-wave radiation from the sun	solar radiation	always	not applicable
H_{bed}	Ground or bed heat conduction between the water body and the bed	water temperature, bed temperature	when water temperature is lower than bed temperature	when water temperature is higher than bed temperature

Solar radiation (H_s) is a significant component in the natural heating process and varies seasonally. In the United States, solar radiation is generally greatest in summer and weakest in winter. As a result, water temperature maxima usually occur in the summer and minima in winter.

Seasonal thermal loads have a profound effect on reservoirs in the form of seasonal stratification. Similar effects can be found in rivers; however, the impacts are generally less pronounced due to river flows and localized topography. Several key components of natural heating in reservoirs and rivers are discussed later in this section.



Some Helpful Information:

Temperature (T) is a measurement of heat energy of a fluid and is typically expressed in degrees Fahrenheit (°F).

Heat Energy is the energy associated with random movement or kinetic energy of a fluid. The flow of heat is from a higher temperature region toward a lower temperature region and is reported as the rate of energy flow, or flux, measured in calories (cal) or British Thermal Units (BTU).

Density is the mass of a substance per unit volume (e.g., pound per cubic foot (lb_m/ft^3)). Water density is greatest at a temperature of 39.2°F.

Specific Heat is the amount of heat energy that must be added to 1.225 lb_m of material to raise its temperature by one °F (BTU/lb_m°F).

Reservoirs

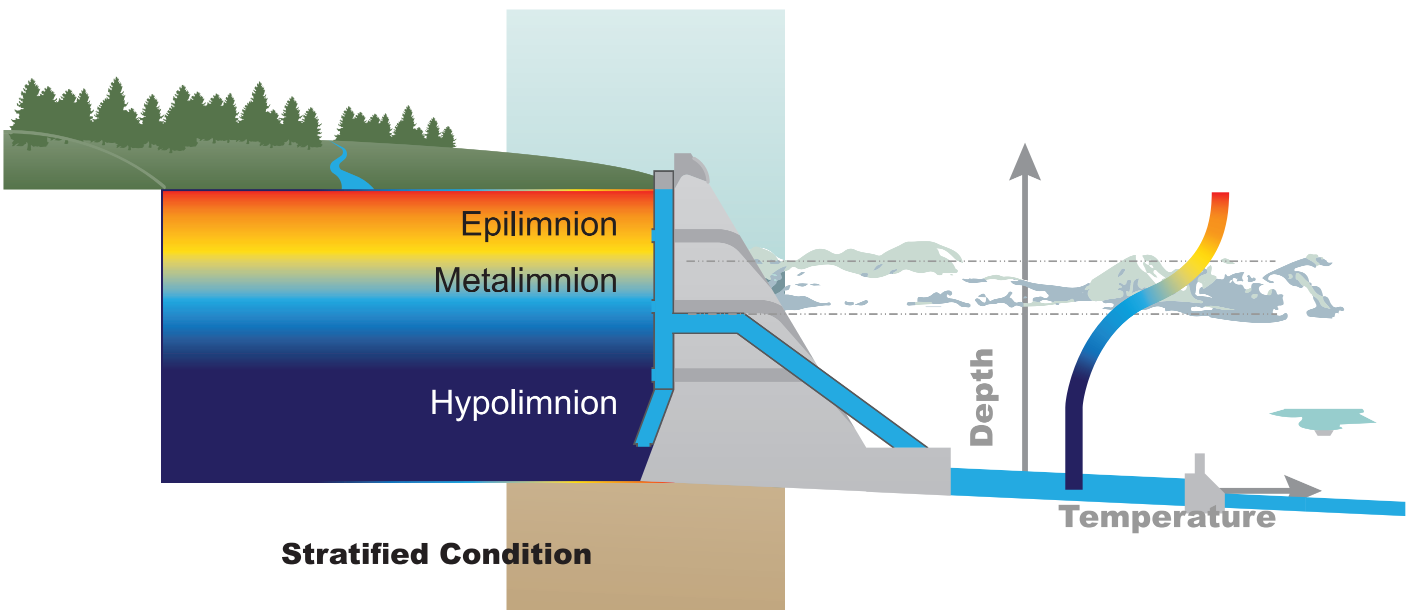
Stratification is an important phenomenon in a reservoir and is related to seasonal changes in natural heating through the temperature management seasons.

Stratification

During spring and summer months, thermal loading increases as day length and solar altitude increase, leading to warmer, less dense water overlying cooler, more dense water. This unequal distribution of water temperature results in seasonal stratification that is defined by:

- **Epilimnion:** the upper, warmest layer of a stratified reservoir.
- **Metalimnion (thermocline):** the middle layer of a stratified reservoir that represents the transition between the warmer surface layer (epilimnion) and the colder bottom layer (hypolimnion).
- **Hypolimnion:** the bottom, coldest, and most dense layer of stratified reservoir.

In large, deep reservoirs, this stratified condition persists from spring into fall.

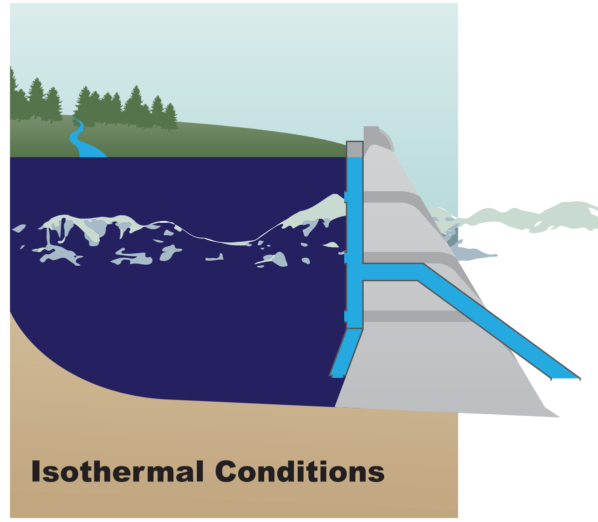


Stratified Condition

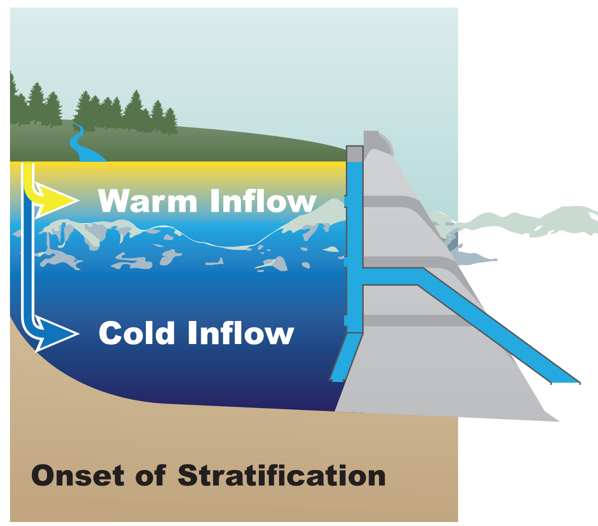
Seasonal Changes in Stratification

Natural seasonal changes in reservoir thermal conditions that lead to stratification are shown in the following pages. For illustrative purposes, these graphics are shown with a full reservoir throughout the seasons; however, reservoir storage changes often occur throughout the year.

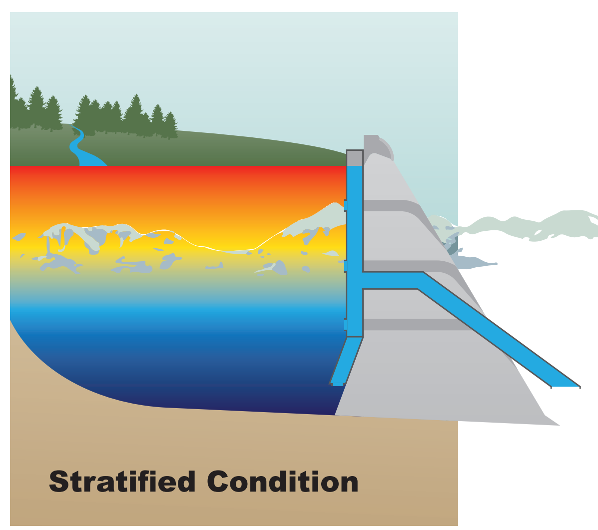
Winter: Low thermal loading rates and wind mixing result in isothermal conditions (same water temperature in the reservoir from top to bottom).



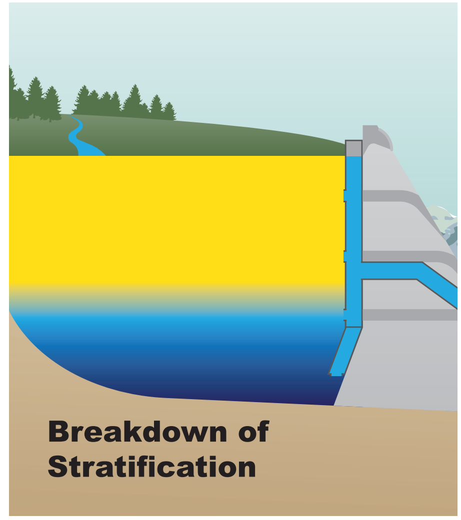
Spring: During spring, heat enters the reservoir faster than it can be mixed vertically by wind, leading to the onset of seasonal stratification. This stratification can persist through the summer period. Snowmelt runoff can yield cold, dense inflows that contribute to the cold water pool volume in reservoirs. Similarly, warm inflows from rainfall or heat-impacted tributaries may not contribute to the cold water pool.



Summer: High thermal loading rates result in more pronounced and persistent stratified conditions in the reservoir.



Fall: During fall, the rate of heat exchange decreases as day length and solar altitude decrease. Heat leaves the reservoir faster than it enters. Tributary inflows, if any, are often colder than reservoir surface waters and contribute to deepening the epilimnion. These processes ultimately lead to destratification and a return to isothermal conditions, effectively resetting the reservoir cold water pool for the subsequent winter.



Rivers

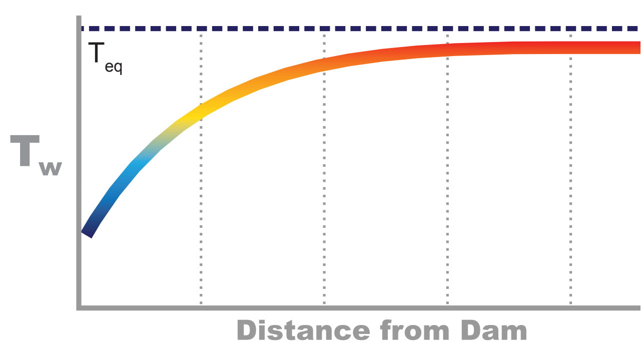
Seasonal thermal loading in rivers occurs in much the same manner as in reservoirs. The principal difference is that rivers continually mix as they flow through different topographies.

Unlike reservoirs, rivers have flowing waters with notable velocities and relatively shallower depths and smaller volumes. Travel time for a parcel of water flowing through a particular reach of river is typically short – hours or days – compared to residence time in reservoirs, which can be months or years. River environments typically are well-mixed and prevent the development of vertical stratification. If stratification does occur in slow, deep rivers, vertical temperature differences are usually minor and intermittent.

As such, riverine thermal regimes are strongly correlated to flow rates, meteorological conditions, tributary inflows and temperatures, and release temperatures from dams (regulated rivers only). In reaches where groundwater contributions to river flows are substantial, riverine thermal regimes can reflect groundwater temperatures.

Equilibrium Water Temperature

Equilibrium water temperature (T_{eq}) is the unique water temperature at which net heat flux (H_n) is zero, given a particular set of meteorological conditions (e.g., daily average conditions). Summer cold water releases from a reservoir are often well below T_{eq}, and water temperature (T_w) increases as water travels downstream due to local meteorological conditions.



Key Aspects of Natural Heating in Rivers

Upstream release conditions ((e.g., flow and temperature) from reservoirs, along with tributary inflows, groundwater contributions, diversions, and meteorological conditions can all play important roles in river temperatures below the dam.

Presented below are several key aspects of natural heating in rivers. Variables use herein are defined in the Table of Contents under Abbreviations and Acronyms.

Aspect 1: Shallow depths allow rivers to respond rapidly to local meteorological conditions.

Changes in river temperature over time for a unit volume of water under a unit thermal load (i.e., heat exchange at the air-water interface) are a function of the ratio of surface area to volume:

$$dT/dt = f(S) = (H_{net} A_S(\rho C_p V))$$

Typically, lower river flows lead to greater heating rates than higher river flows (all other factors being constant).

Aspect 2: Heat energy can also be advected downstream with the water; an important aspect of temperature management below a dam.

$$dT/dt = f\ (velocity, S)$$

Flow rate also plays a role in the thermal regime of rivers. With distance, a river reach tends towards a temperature that is in balance with meteorological conditions (termed "equilibrium temperature"). Below large reservoirs with cold water releases, the upstream water temperature and meteorology often dominate conditions in downstream reaches.

Aspect 3: Tributary contributions to mainstem waters can directly affect water temperatures if tributary flows and temperatures are sufficiently high.

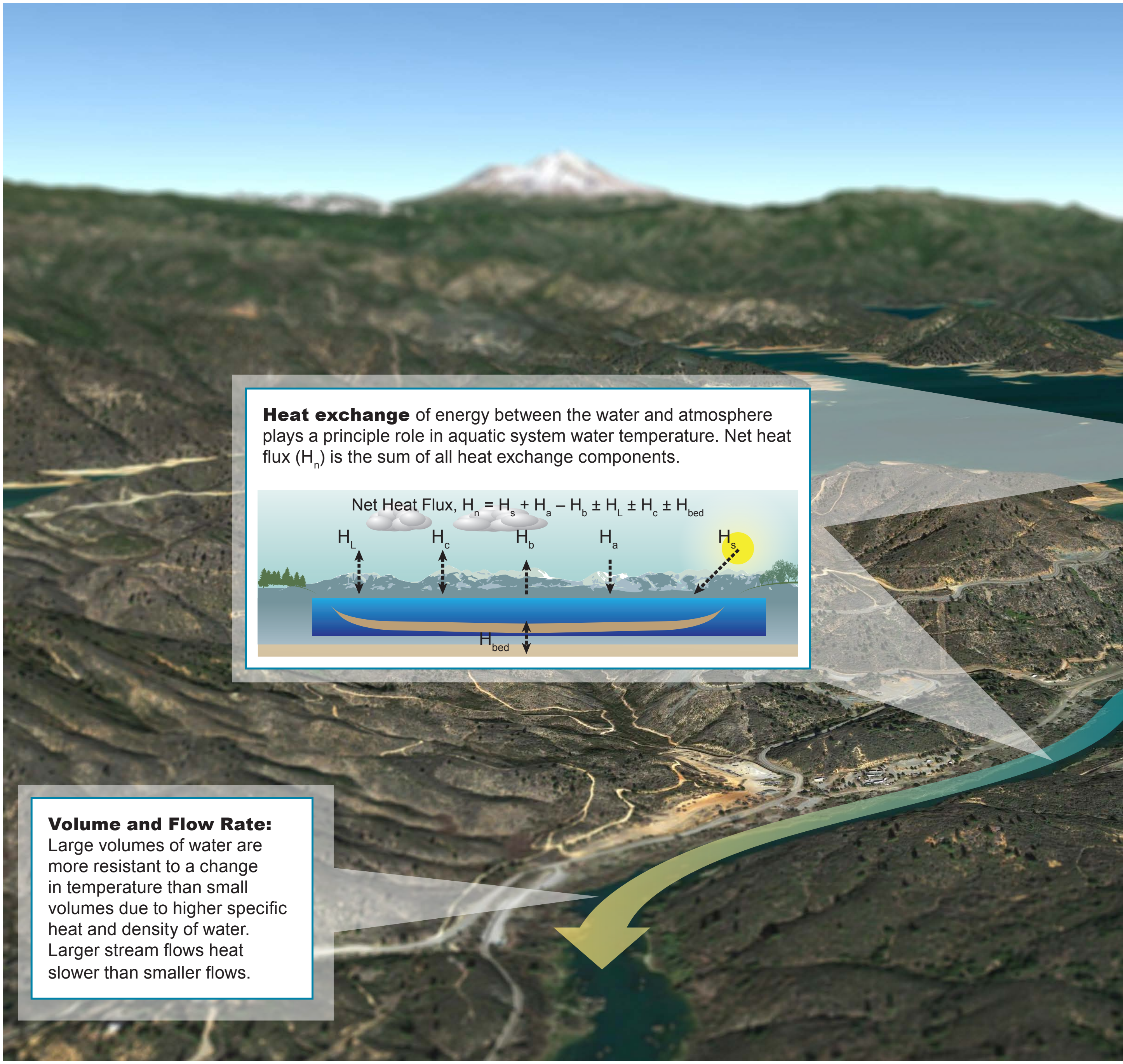
A tributary delivers a thermal load to a river that is a function of both temperature and flow ($T_{trib}Q_{trib}$), with high temperature and high flow potentially yielding a large thermal load.

Water temperature downstream of a tributary confluence can be estimated by a simple mass balance:

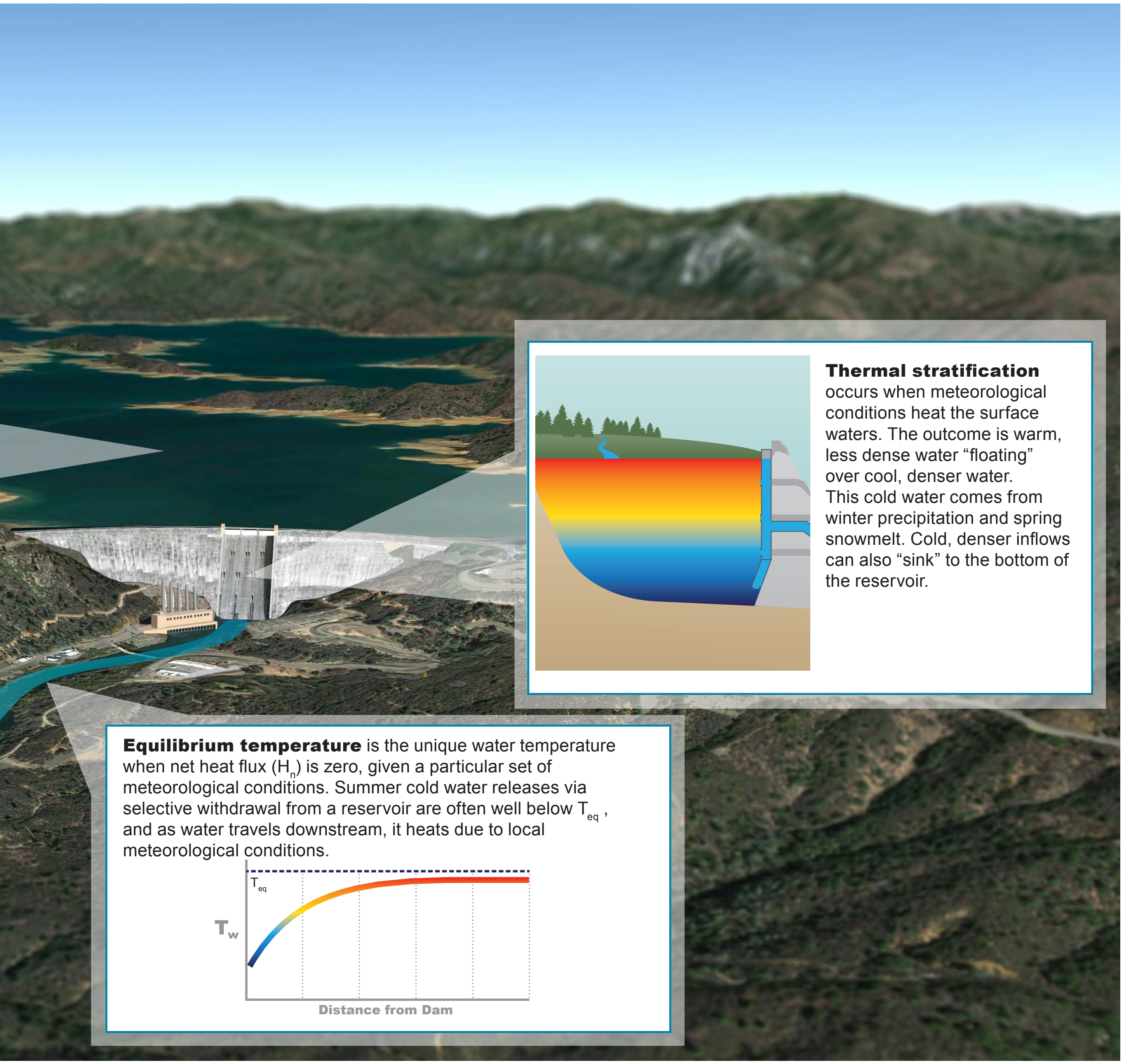
$$T_{downstream} = (T_{river}Q_{river} + T_{trib}Q_{trib})/(Q_{river} + Q_{trib})$$

Concept of Temperature Management in a Reservoir-River System

Operation of a typical multipurpose reservoir includes storing and regulating flows for hydropower generation, water supply reliability, navigation and recreation, downstream flood risk reduction, and riparian biological and environmental needs downstream of the reservoir, or supporting other beneficial uses. Each reservoir-river system has unique hydrology, watershed conditions, and resource management challenges. To provide temperature management, resource managers must contend with natural heating of reservoirs, associated stratification,



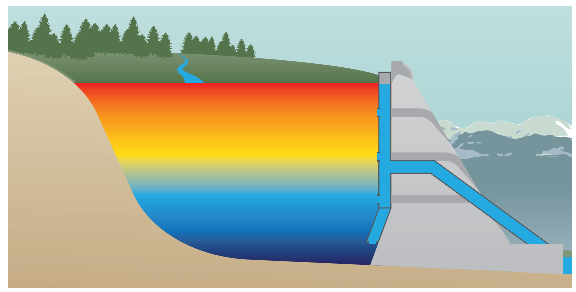
and downstream river heating considerations. As a result, resource managers may install selective withdrawal facilities capable of accessing different water depths in the reservoir. These facilities allow water managers to blend waters of different temperatures and effectively use limited cold water resources for downstream temperature management. The concept of selective withdrawal and its importance in temperature management are introduced in the illustration below and in the subsequent discussion.



Selective Withdrawal's Critical Role in Temperature Management

Efficient management of cold water resources is needed to meet downstream environmental and instream biological needs. Management of the cold water pool in reservoir-river systems requires selective withdrawal structures or facilities that allow water from different depths and temperatures to be released from upstream reservoirs to achieve downstream river temperatures over the summer and fall months.

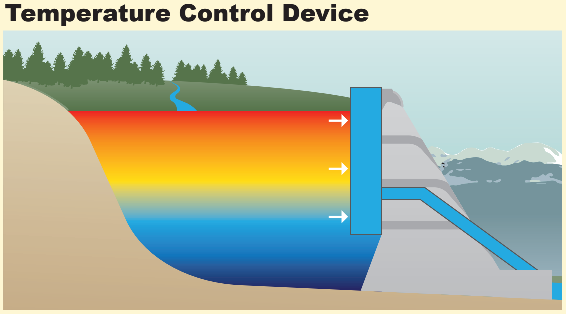
Reservoirs without selective withdrawal capabilities, as illustrated below, lack the ability to efficiently use cold water resources. Without selective withdrawal capabilities, resource managers have limited ability in managing downstream water temperatures and, in certain circumstances, temperature management becomes infeasible. In contrast, reservoirs with selective withdrawal capabilities provide a higher level of temperature management. Selective withdrawal can be accomplished with a variety of types of structures or facilities, as shown below. The goal is similar in all cases – to access water of a desired temperature under stratified reservoir conditions.



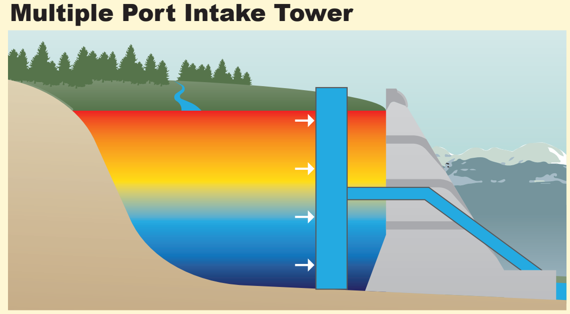
Reservoir Without Selective Withdrawal Capability

Types of Facilities for Selective Withdrawal

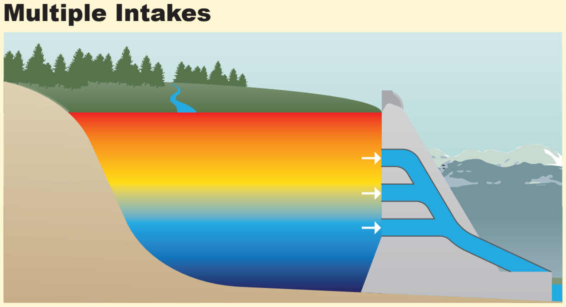
Temperature Control Device



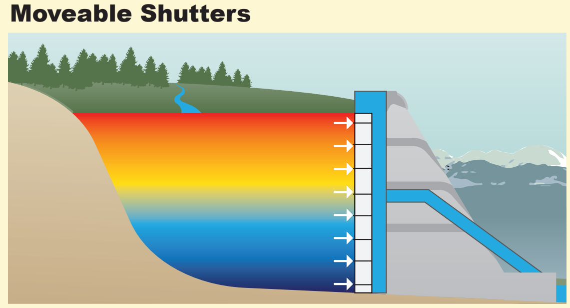
Multiple Port Intake Tower



Multiple Intakes



Moveable Shutters

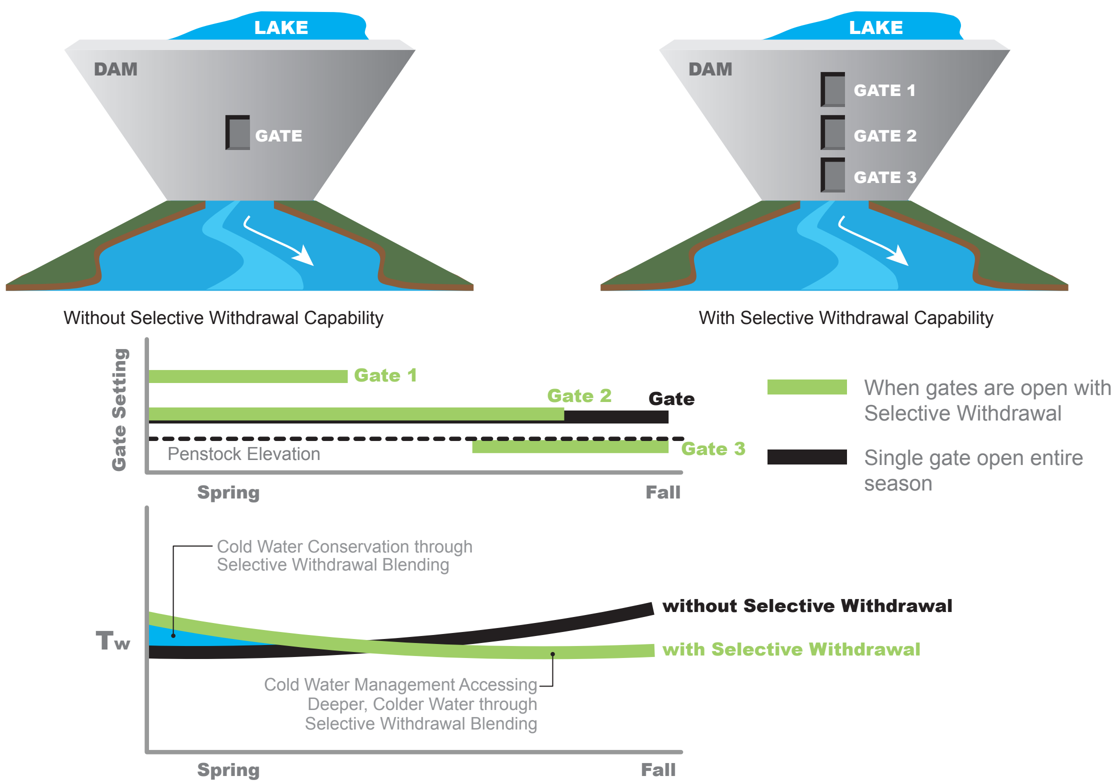


Annual Temperature Management Strategy

Managing water temperature in reservoir-river systems through selective withdrawal is challenging for many reasons, including inter- and intra-annual variability in hydrology and meteorology, variable operations and demands, and other unforeseen events and circumstances throughout the year (e.g., unexpected weather changes and fishery needs). A management strategy is usually developed on an annual basis, leveraging the typical reservoir temperature turnover phenomenon in the winter and refill in the spring.

Selective Withdrawal Progression

Employing selective withdrawal in water temperature management is a dynamic conservation action because the temperature management season is long, the cold water resource is limited, and downstream environmental objectives change from season to season. Determining timing or progression of specific selective withdrawal operations in response to reservoir conditions, river conditions, meteorology, and other relevant factors is critical throughout the temperature management season. The graphic below illustrates the essential flexibility that a reservoir with selective withdrawal capability can contribute to the effectiveness of downstream temperature management.



More details on selective withdrawal and how it may be deployed for better temperature management are discussed in the remaining sections of this technical memorandum. However, **without selective withdrawal capabilities, resource managers have limited ability in managing downstream water temperatures—and under certain circumstances, temperature management becomes infeasible without selective withdrawal.**

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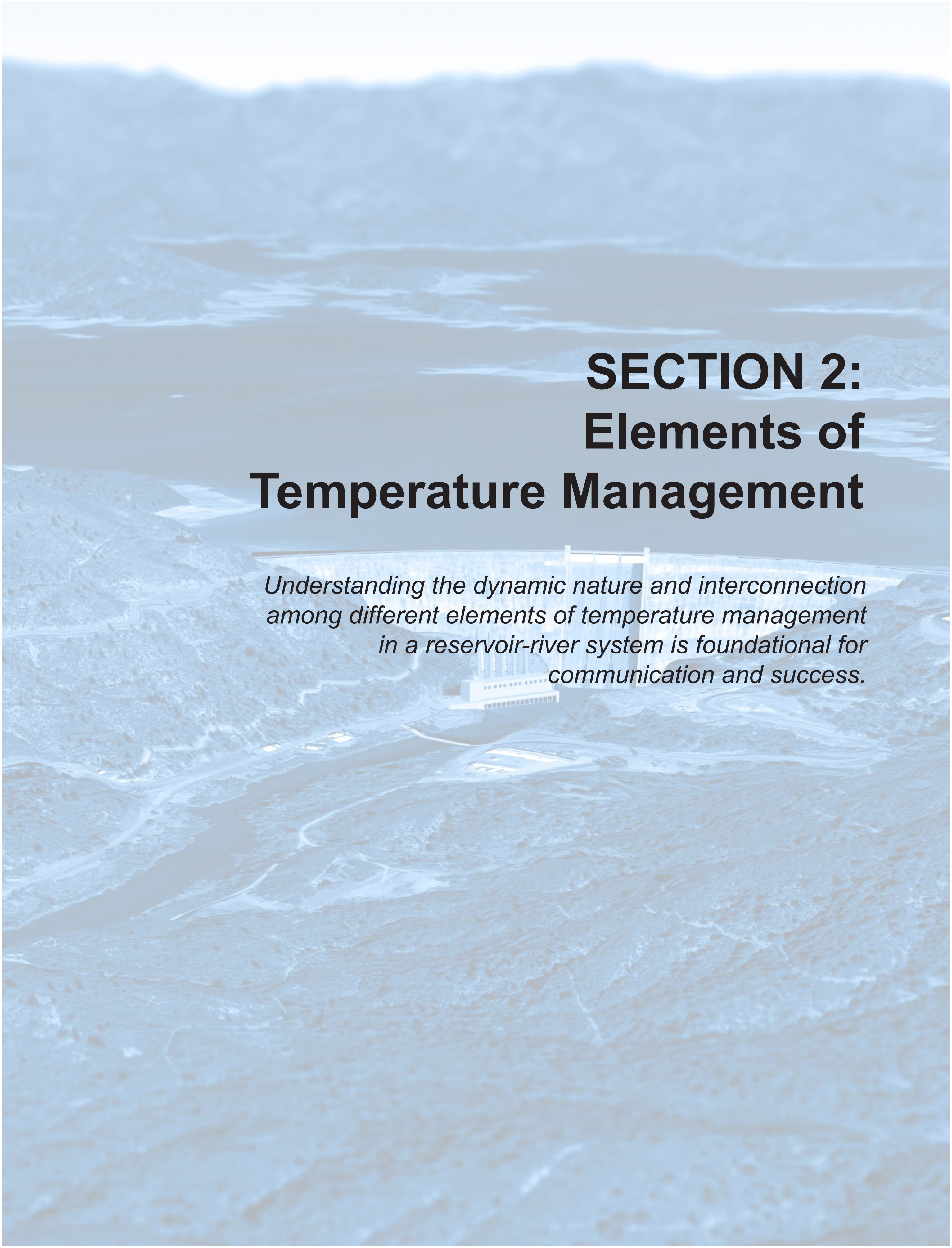

SECTION 2: Elements of Temperature Management

Understanding the dynamic nature and interconnection among different elements of temperature management in a reservoir-river system is foundational for communication and success.

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SECTION 2: Elements of Temperature Management

Water temperature management in a reservoir-river system is challenging for many reasons, including inter- and intra-annual variability in hydrology and meteorology, year-specific demands and constraints, and unforeseen events and circumstances throughout the year. Water temperature management typically consists of ten inter-related elements in five groupings:

The "Why": Environmental objectives, typically specified as target water temperatures at a downstream location, provide the basis for water temperature management.

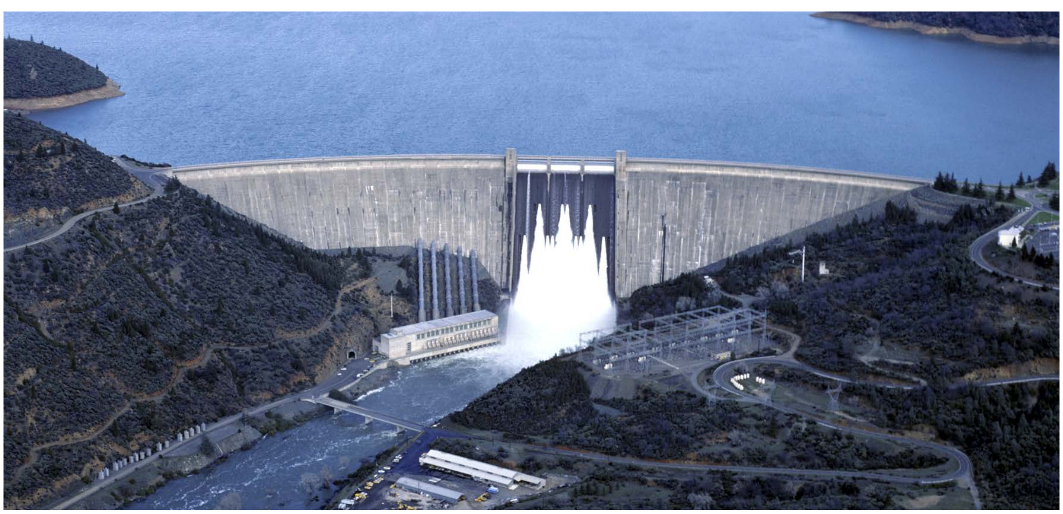
The "Resources": Resources, including total reservoir storage and reservoir water temperature profiles, constrain the management options available to resource managers.

The "Means": Water temperature management is achieved through selective withdrawal and tail bay water temperature management.

The "Factors": Meteorological conditions, re-regulating reservoirs, major tributary inflows, and the river flow heat gain relationship affect reservoir and river water temperatures.

The "Methods": Monitoring data provide supplemental information for developing a temperature management strategy and feedback on temperature management performance.

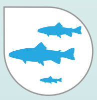
Each element is relevant to temperature management in its own unique way; the elements are illustrated on the next page and described in detail in this section.



High storage condition in Shasta Lake.

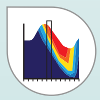
Elements of Temperature Management

The Why

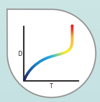


1. Environmental Objectives: Defining management criteria (e.g., target species' seasonal temperature requirements and their distribution in downstream river reaches).

The Resources

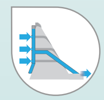


2. Total Reservoir Storage: Defining cold water volume through reservoir storage.

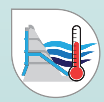


3. Reservoir Water Temperature Profile: Defining cold water volume through thermal profile characterization.

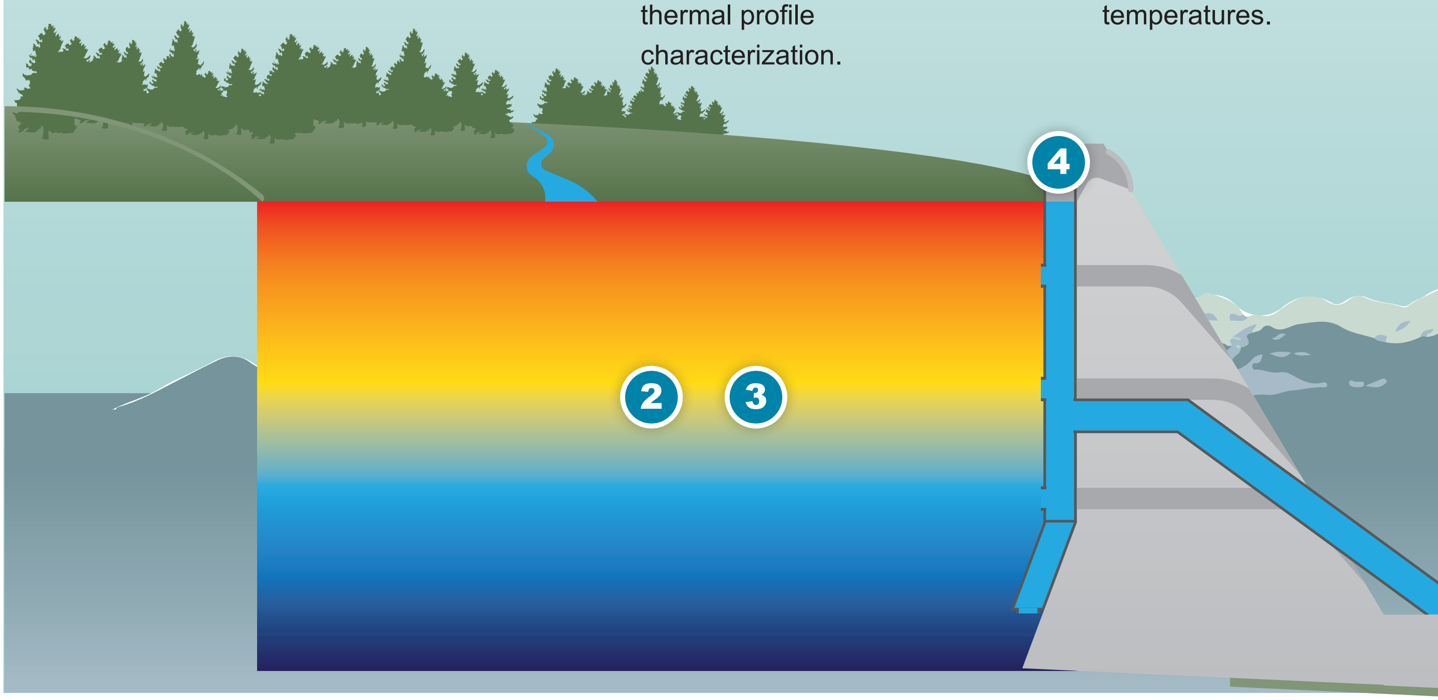
The Means



4. Selective Withdrawal: Assessing selective withdrawal facilities and strategies.



5. Tail Bay Water Temperature Management: Determining reservoir tail bay temperatures.



Cross sectional representation of a reservoir with selective withdrawal capability and downstream river. Graphic represents the Elements of Temperature Management where icons are highlighting the specific features.

The Factors

6. Meteorological Conditions: Determining heat gain from the reservoir to downstream river management locations to inform decision-making processes.

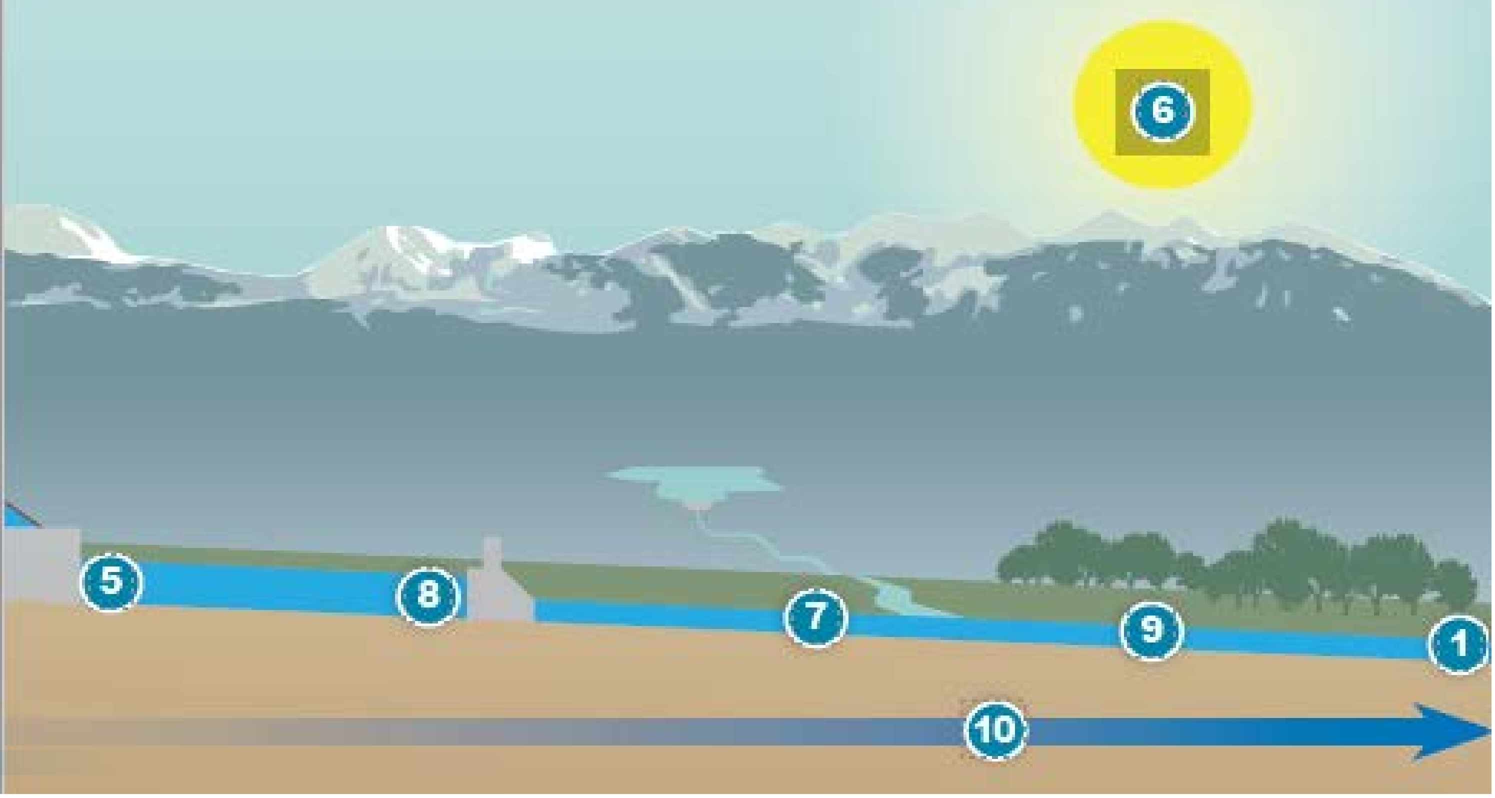
7. Major Tributary Inflow: Determining thermal conditions of tributaries.

8. Regulating Reservoirs: Characterizing re-regulating reservoir conditions and river release temperatures.

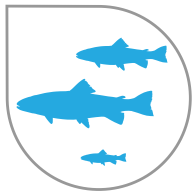
9. River Flow Heat Gain Relationship: Employing river flow and heat gain relationships.

The Methods

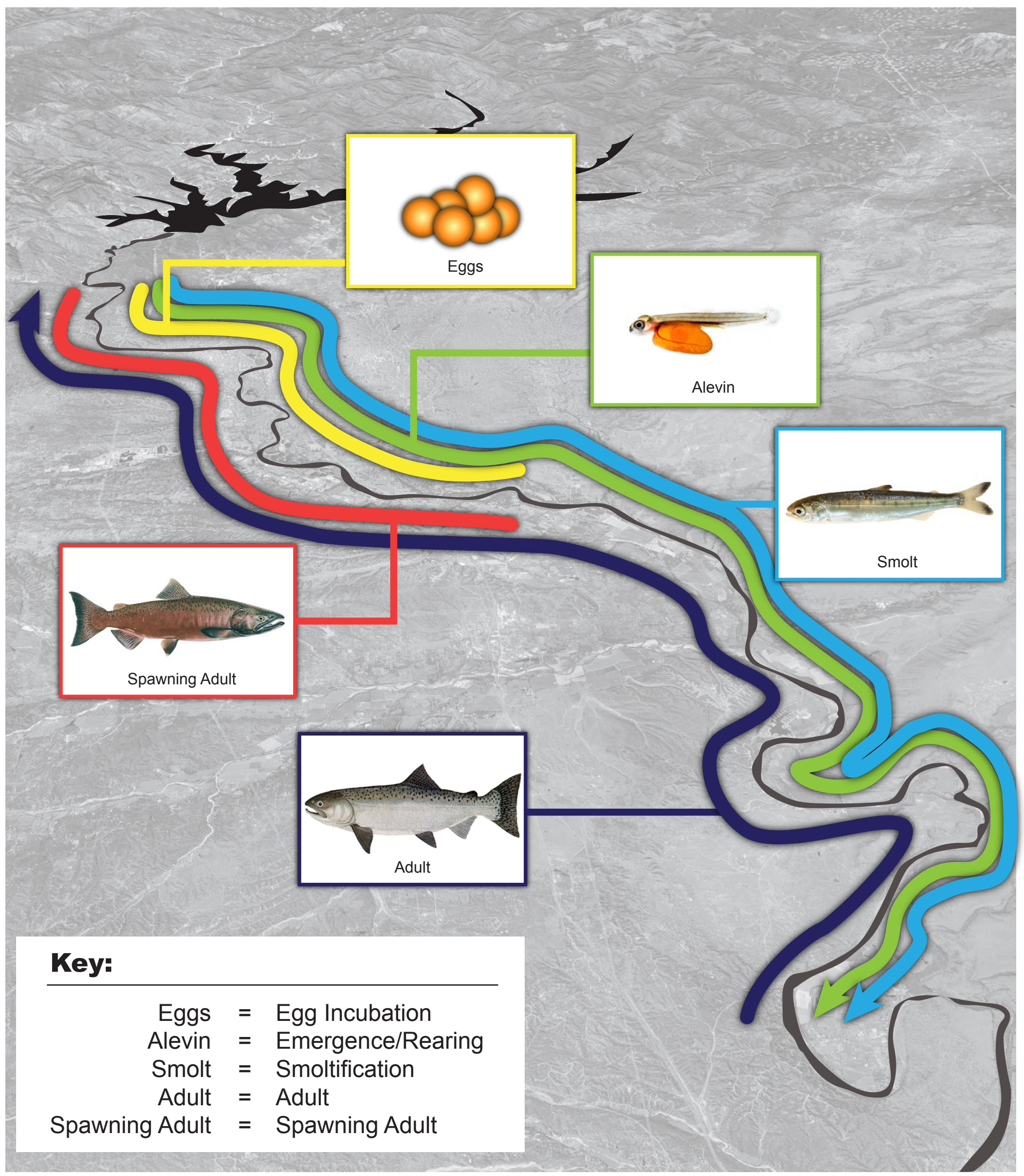
10. Monitoring: Using system-wide monitoring network information to assess conditions and adapt the selective withdrawal strategy.



Environmental Objectives

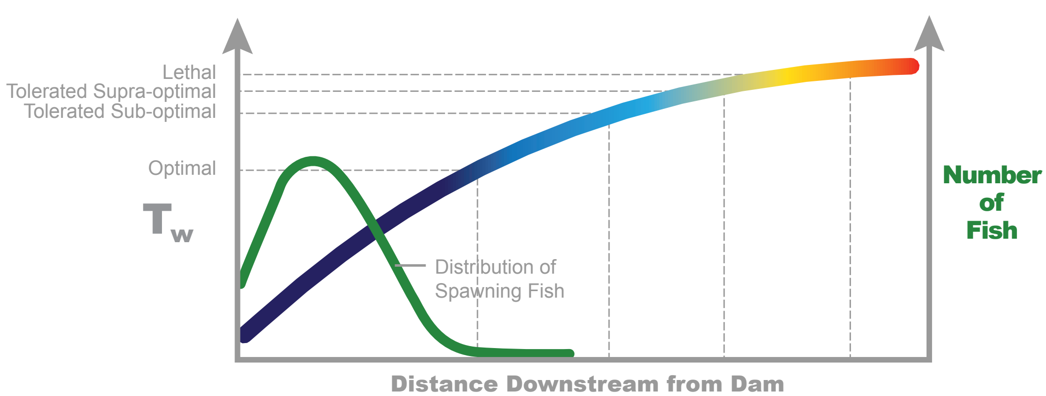


Selecting environmental objectives (e.g., temperature targets) for downstream river reaches takes into consideration the thermal requirements, spatial distribution, and timing of various life stages of the target species. Temperature management is needed to achieve the environmental objectives given the available resources.

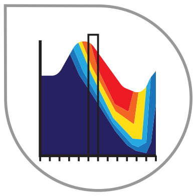


Target species in a given reservoir-river system often have distinct needs that present challenges to resource managers. For illustrative purposes, the following graphic below provides examples of the temporal distribution of life-cycle stages for two species of fish. The temperature management season typically begins in spring (April or May) and ends in fall (October or November), and temperature preferences for each stage can be different.

Long-term trends and real-time data for river reaches where target fish species are inhabiting, spawning, and rearing provide resource managers with information as they develop temperature management strategies and determine how to operate facilities for selective withdrawal for efficient and effective use of limited available cold water resources.



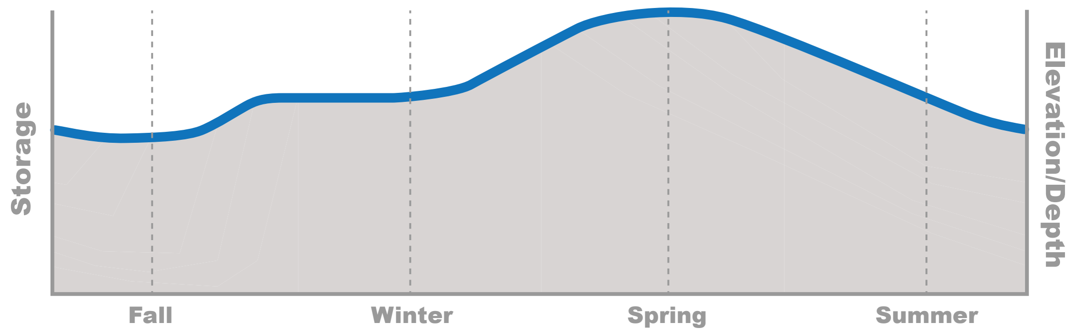
Total Reservoir Storage



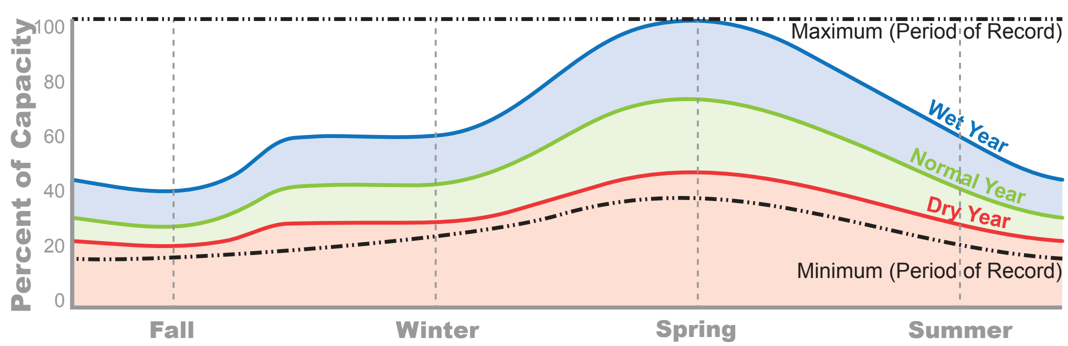
Reservoir storage characterizes total water availability at any given time. Coupled with temperature profile information, storage defines both the cold water volume at the beginning of the temperature management season, and the subsequent overall storage and cold water volume throughout the season. This information relates available cold water to reservoir outlet elevations and is used to develop selective withdrawal strategies for temperature management based on known and forecasted conditions. Reservoir storage varies from year to year based on hydrologic conditions, timing of precipitation and snowmelt runoff, and operations for flood risk reduction, water supply, environmental requirements, and other purposes. Storage can also reflect extended hydrologic conditions spanning multiple years, as shown in the November 2015 photograph of Folsom Lake during the historic drought from 2013 through 2016 (below, left). However, as shown in the subsequent picture, flood control spills were made in March 2016 as lake storage in Folsom Lake recovered after several major winter storms (below, right).

Folsom Lake storage was at an extremely low stage after three years of drought with the temperature control shutter system exposed (above; taken on November 14, 2015). Four months later, Folsom Lake storage recovered and flood control spills occurred after several intensive winter storms (right; taken on March 8, 2016). Photo credit: Yung-Hsin Sun; used with permission.

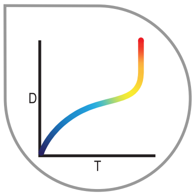
As previously mentioned, reservoir storage varies throughout the year in response to hydrology (timing of precipitation and snowmelt runoff), and operational constraints (e.g., flood control releases). The plot below illustrates how reservoir storage can vary throughout the year. In this example, storage increases in winter/spring due to precipitation and snowmelt, and decreases the rest of the year to meet operational requirements such as water supply or environmental demands.



Reservoir storage varies not only intra-annually, but also from year to year. In general, reservoir storage is higher in wet years than in drier years, as shown in the plot below. Note the depicted conditions are generalized for conceptual discussion purposes to show that inter-annual seasonal variation in storage can vary significantly.



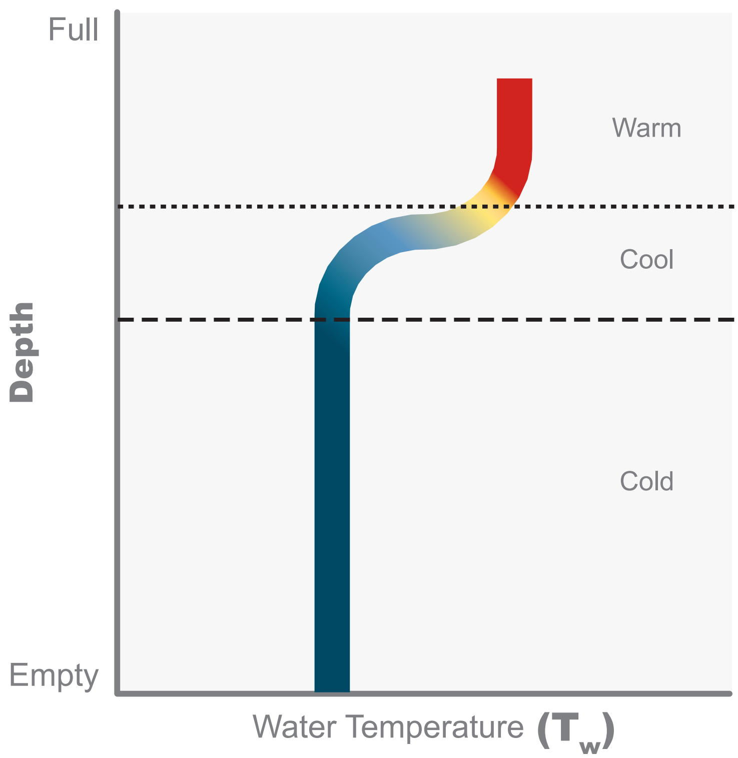
Reservoir Water Temperature Profile



Water temperature profiles characterize how water temperature changes in a vertical column in a reservoir. With a collection of water temperature profiles at different locations, resource managers can define:

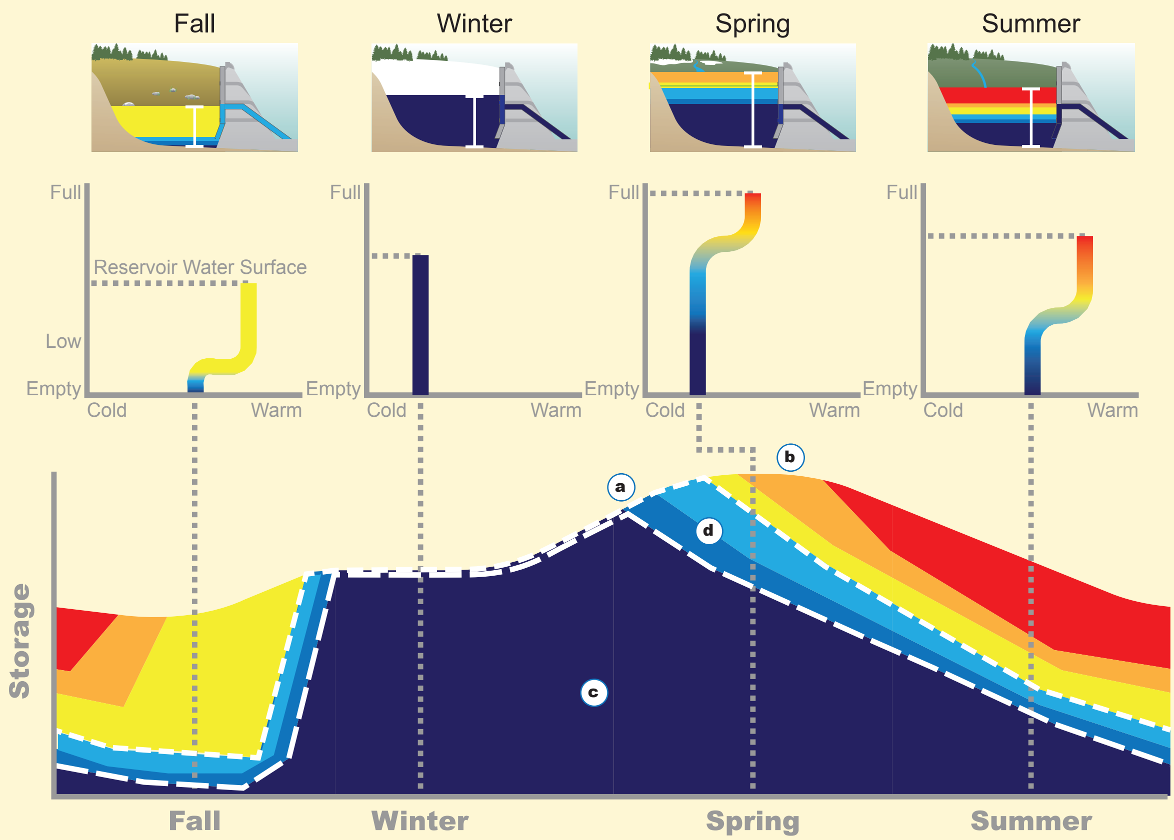
- Available cold water volume of a specific temperature
- Available volumes of cold water with different temperatures that can be used for blending purposes during the temperature management season.

Both of these pieces of information allow resource managers to effectively develop strategies for selective withdrawal to meet downstream temperature objectives. A typical water temperature profile, identifying warm, cool, and cold water pools in a reservoir, is shown below. .



As seasons change, reservoir water temperature profiles change accordingly. The graphic on the next page illustrates typical seasonal changes of reservoir water temperature profiles and corresponding cold water volumes.

Volumetric Progression of the Cold Water Resource in a Reservoir



Key:

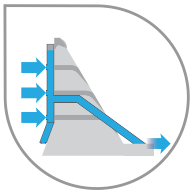
a **Maximum Cold Water Storage** is the maximum annual cold water volume and characterizes available volume for the subsequent temperature management season. The onset of seasonal stratification defines this volume.

Maximum Storage refers to the maximum total reservoir storage. This volume usually occurs after maximum cold water storage is attained, typically at the end of flood control season.

Cold Water Storage varies both intra- and inter-annually. Selective withdrawal is necessary to manage these dynamic cold water conditions.

Zone of Conservation Management is the volume of cool water (between fine and heavy dashed lines) that is effectively managed using selective withdrawal to blend cold and cool waters from late spring through fall to meet downstream environmental objectives.

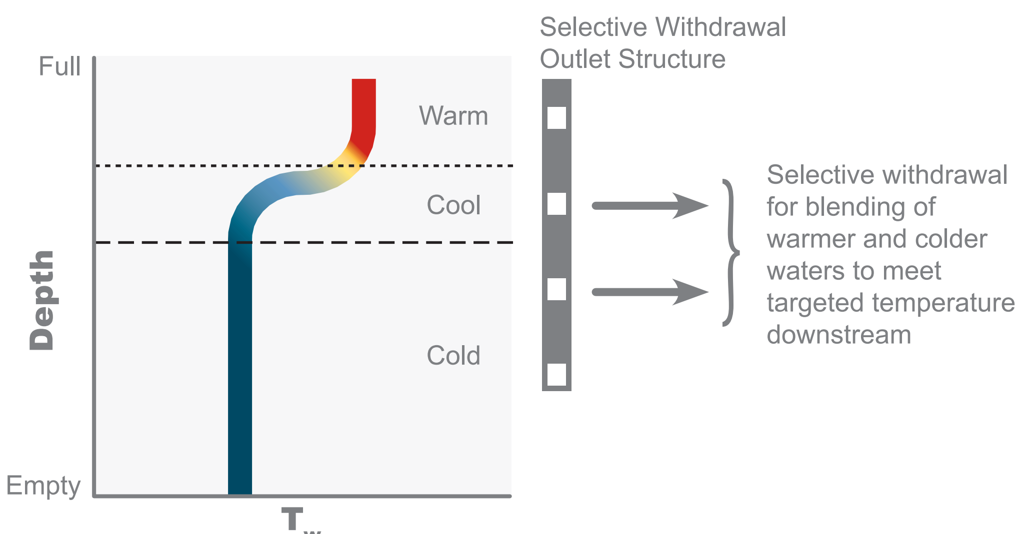
Selective Withdrawal



Selective withdrawal provides the means to preferentially access water of specific temperatures in a stratified reservoir to attain desired release (tail bay) temperatures. For a given flow rate, a release temperature can be achieved either by selecting reservoir water from an individual depth or by blending waters from multiple depths. Selective withdrawal operations are dynamic through time, responding to the many factors that influence water temperature from early spring to late fall.

With selective withdrawal, resource managers can accomplish dual purposes of conservation and temperature management. By blending warmer and colder waters as needed, limited cold water resources can be used more effectively and their effectiveness for meeting downstream environmental objectives can be extended. This blending allows resource managers to avoid engaging other, less effective means (e.g., excess flow) for temperature management purposes that may adversely affect other purposes and needs in the reservoir-river system. Given the same storage and flow conditions, different selective withdrawal strategies yield distinct outcomes for progressions of cold water storage volumes, tail bay temperatures, and downstream river temperatures during the remaining temperature management season.

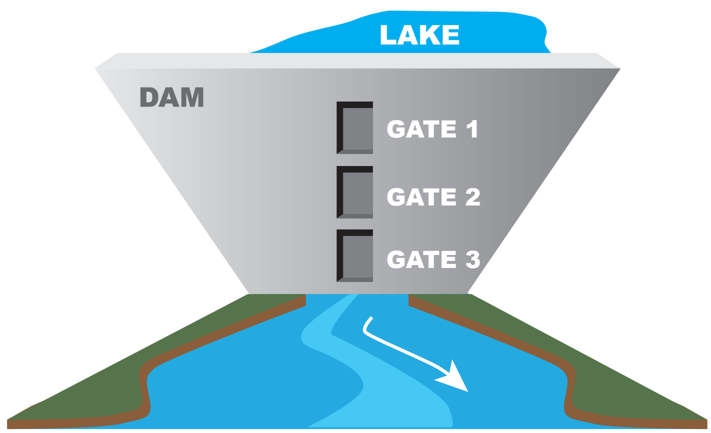
The profile below depicts of how a facility with outlets at different depths can facilitate selective withdrawal strategies that improve the efficiency of temperature management and better use the limited cold water resource.

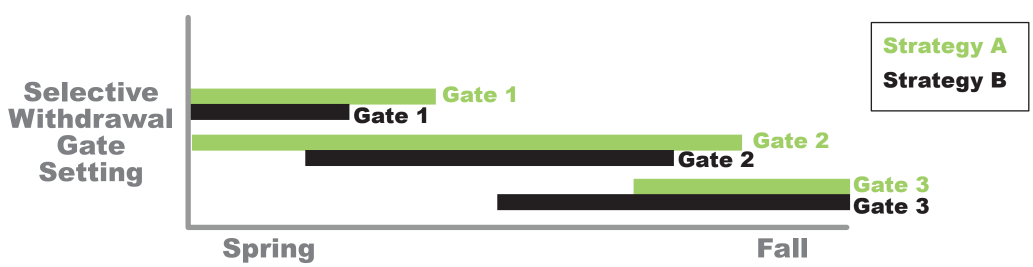


A hypothetical example is used herein to further illustrate the functions and effects of using selective withdrawal for temperature management. Shown below is a representative dam with three gate outlets to facilitate flow releases via selective withdrawal to manage downstream temperatures.

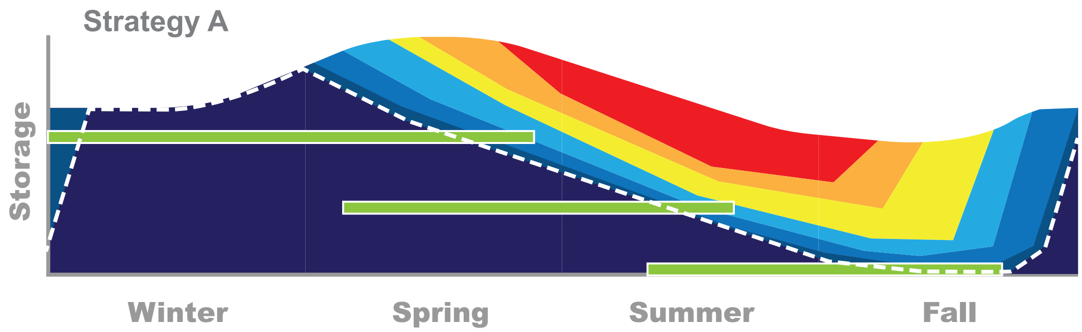
Two strategies are considered by resource managers in this example:

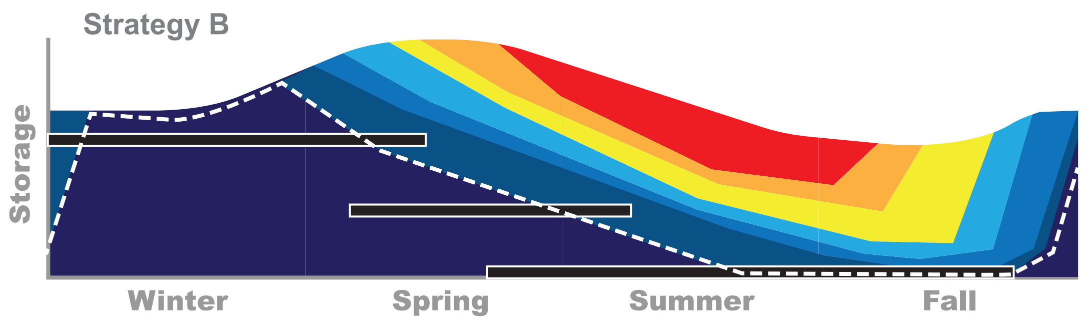
- In **Strategy A**, releases are made from Gate 1 starting in early spring and continuing through early summer. Releases from Gate 2 also begin in early spring and continue through late summer. Releases are not made from the lowest gate – Gate 3 – until late summer which preserves the coldest water until late in the season.
- In **Strategy B**, releases are made from Gate 1 in the spring only and from Gate 2 starting in late spring and continuing until late summer. Releases from Gate 3 start mid-summer and extend through late in the season.





The different strategies of gate use, or selective withdrawal, tap into different layers of water in the reservoir at different time periods. As a result, release water temperatures (and subsequent temperatures realized at downstream locations) differ in these two scenarios. This concept can be further illustrated by superimposing the gate opening information on the annual reservoir temperature profile figure, as shown on the following page.

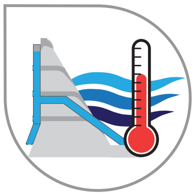




As shown in the typical reservoir water temperature profile throughout a year (page 2-9), gate elevations correspond to water with different temperatures. Early use of lower gates increases the potential to provide water that is colder than needed for downstream environmental objectives and/or to deplete cold water resources prematurely. The typical water temperature profile used in this section is a hypothetical example and for illustrative purposes only. In reality, different selective withdrawal progressions will lead to different progressions of reservoir temperature profiles.

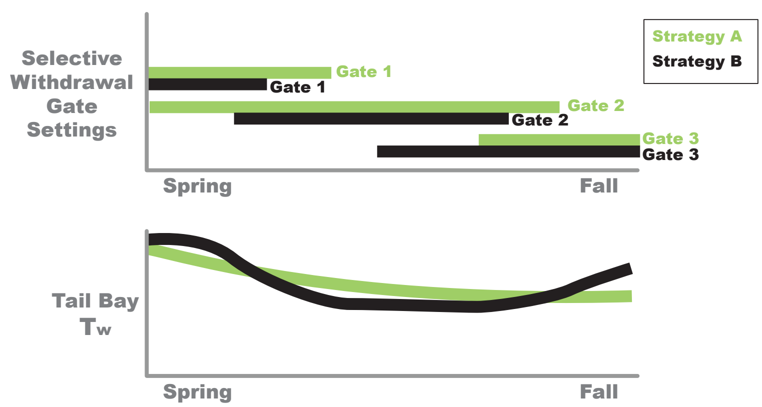
The discussion of selective withdrawal strategies cannot be complete without discussion of tail bay water temperature management. The tail bay is immediately downstream from the main dam, and different progressions of gate use for selective withdrawal result in different tail bay water temperatures. The next subsection provides additional details on tail bay temperature management.

Tail Bay Water Temperature Management



The tail bay is the point of operational control immediately downstream from the reservoir and is the last point of operational temperature control. As reservoir releases flow downstream from the tail bay, they are subject to meteorological conditions, tributary inflows, and other factors beyond the control of resource managers through managing cold water resources behind the dam. Downstream river temperatures are often related to targeted tail bay temperatures for management considerations (through the use of empirical relationships, estimated heating, and estimated effects from tributary inflows that are discussed later). The targeted tail bay water temperature is then used in the development of selective withdrawal strategies.

Continuing with the example from the previous subsection, different selective withdrawal strategies result in different tail bay water temperatures, as shown below. In Strategy A, Gate 2 is used earlier, resulting in lower early season water temperatures compared to Strategy B. Strategy B employs Gate 2 later and Gate 3 earlier, resulting in lower summer water temperatures than Strategy A. As the cold water pool is exhausted in Strategy B, water temperatures begin to increase and the temperature management season ends with a higher water temperature.

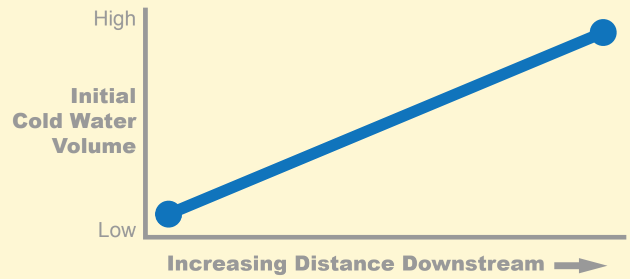


A selective withdrawal strategy combines the use of selective withdrawal facilities with tail bay water temperature management to meet downstream environmental objectives. In wetter years when a larger cold water storage volume is available, a properly formulated selective withdrawal strategy may provide temperature management to locations farther downstream than in drier years, when cold water storage volumes may be smaller.

Benefits of Available Empirical Relationships

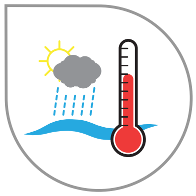
Empirical relationships that build on experience of operating the existing selective withdrawal infrastructure, available studies, and expert knowledge are valuable tools for resource managers. These relationships can help resource managers quickly assess likely thermal conditions and identify temperature management strategies early in the annual temperature management season.

A representation of the empirical relationship between initial cold water volume and likely extent or distance downstream from the dam where active management of river temperature is feasible is shown here. Other beneficial empirical relationships, when available, may provide guidance on approximate dates (or more precisely, periods of time) for different gate uses to achieve more efficient use of available cold water pool. Like all empirical relationships, they can be system- or infrastructure-specific.



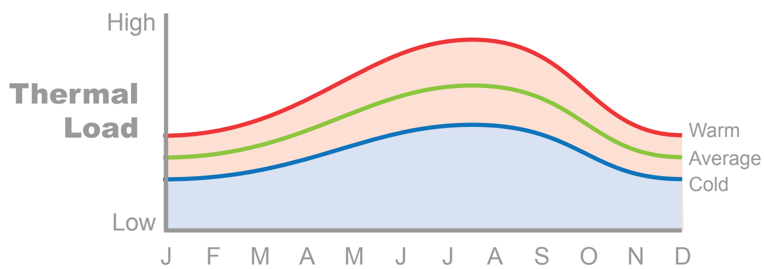
American River below Nimbus Dam. *Photo Credit: Reclamation*

Meteorological Conditions



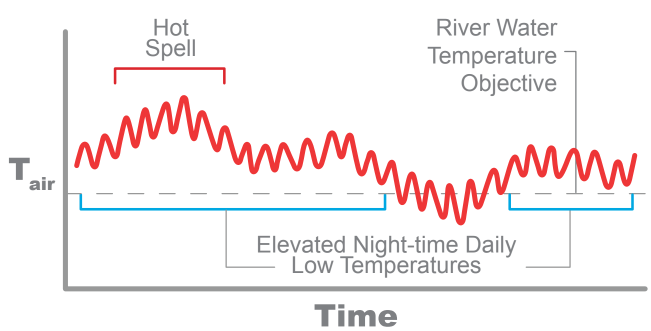
Along with tail bay water temperatures, meteorological conditions are the principal seasonal and short-term factors affecting water temperature. Heat exchange at the air-water interface during the long days of late spring and summer can impart considerable energy into relatively shallow river reaches, leading to notable increases in water temperature.

Conceptually, seasonal thermal loading from meteorological conditions is greatest during warm months (as illustrated to the right). Significant natural variations can occur from year to year.



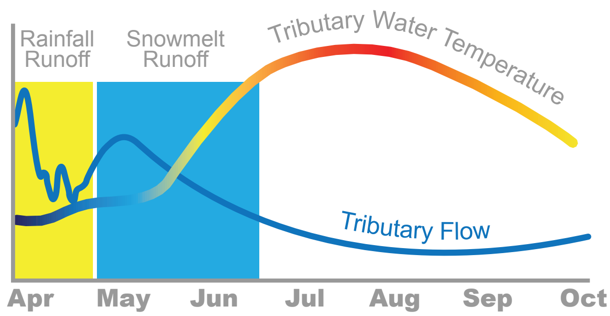
Theoretically, during the temperature management season from late spring to fall, water temperature increases as the released waters travel farther away from the dam and thermal loading continues (as illustrated to the right).

Short-term meteorological conditions can also have a significant effect on river temperature and are important considerations in developing temperature management strategies. In particular, short-term warm weather events (e.g., hot spells) and periods when night time air temperature remains elevated (as illustrated above) have the most significant effect on river water temperature.

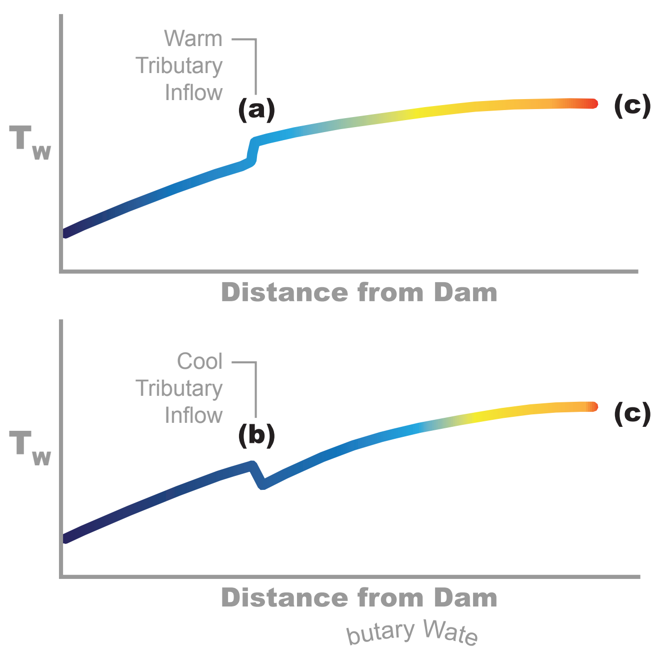


Major Tributary Inflows

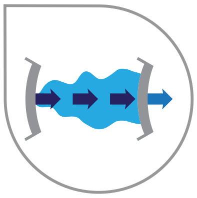
In addition to thermal loading from meteorological conditions, if tributary inflows are sufficiently large, they can affect river temperatures below the confluence. Tributary flows are subject to the natural heating process and may also be influenced by snowmelt or other factors. Generally, tributary flows are substantially lower in late spring through fall with correspondingly warmer water temperatures during this same period. A general depiction of the seasonal variation of tributary flow and its associated temperature range is shown below.



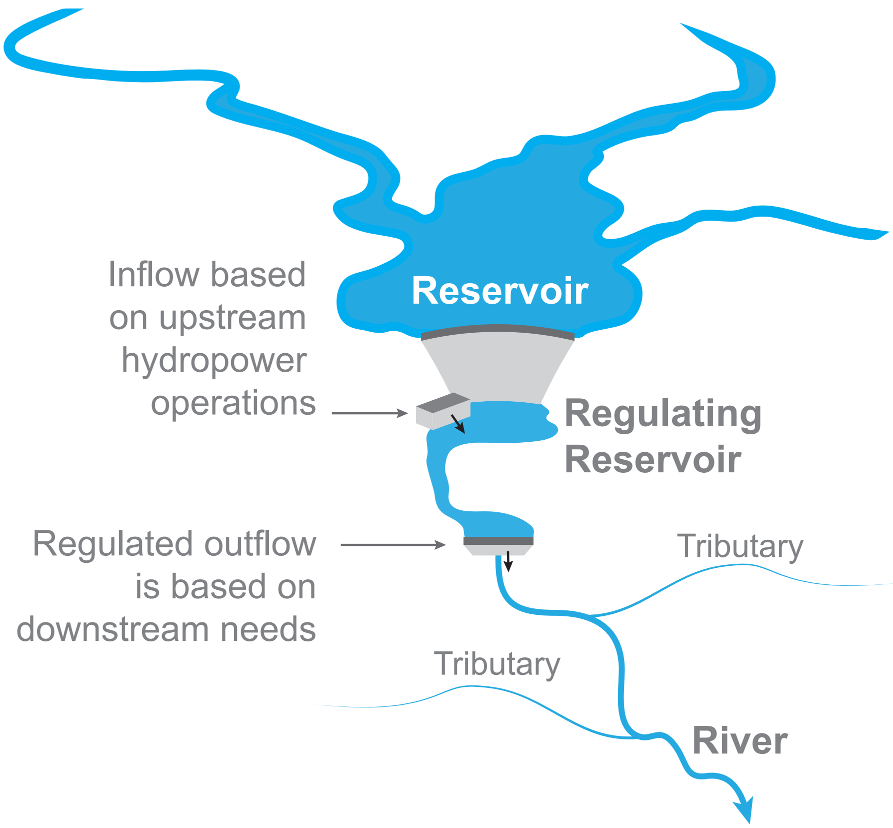
As illustrated below, if the tributary inflow is warmer than the river, a net increase in river temperature occurs downstream from the confluence **(a)**. Conversely, if the tributary inflow is cooler, the resulting river temperature downstream is reduced **(b)**. However, given sufficient distance below the confluence, the river temperature could reach its equilibrium temperature in both situations **(c)**. In other words, the different impacts of tributary inflows on river temperatures typically diminish gradually downstream.



Regulating Reservoirs



Located below the tail bay of a large dam, a regulating reservoir, is typically constructed to regulate flow releases from the dam for power generation as well as to regulate any inflows to and/or diversions from the river that occur in this reach. The purpose of flow regulation is to produce a desired flow regime in downstream river reaches. A conceptual illustration of a regulating reservoir and its functions is shown below.



Residence Time

Residence time (Θ_R) is defined as the amount of time it takes for a parcel of water to pass through a reservoir. Large reservoirs may have residence times of months or years, while regulating reservoirs often have residence times of days or weeks.

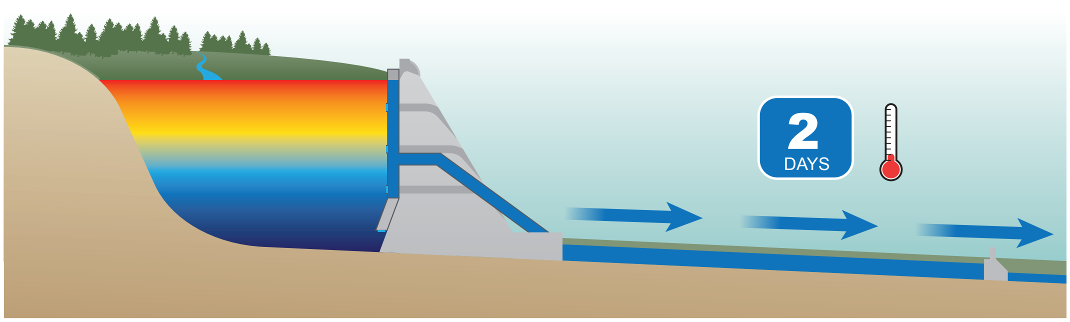
$$\Theta_R = \frac{\text{Reservoir Volume}}{\text{Outflow Rate}}$$

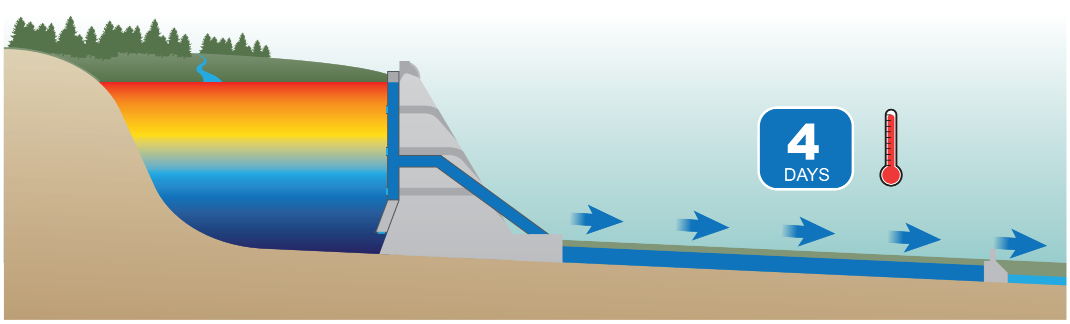
For example, for a regulating reservoir with a 10,000 acre-foot (AF) capacity, residence times are 10.1 days and 5.0 days, at flowrates at 500 cubic feet per second (cfs) and 1,000 cfs, respectively.

$$\Theta_{R,\,500} = 10{,}000 \text{ AF (0.5042 cfs/AF/day)/500 cfs} = 10.1 \text{ days}$$

$$\Theta_{R,\,1000} = 10{,}000 \text{ AF (0.5042 cfs/AF/day)/1000 cfs} = 5.0 \text{ days}$$

Regulating reservoir storage volume is often significantly smaller than that of the upstream reservoir. The relatively shallower depth means more rapid warming compared to conditions in the large reservoir. Therefore, the longer water stays in the regulating reservoir, the greater the opportunity for heat gain. From a temperature management viewpoint, a higher flow rate through a regulating reservoir leads to a shorter residence time, less heat gain, and more efficient use of limited cold water resources for downstream environmental objectives.





River Flow Heat Gain Relationship

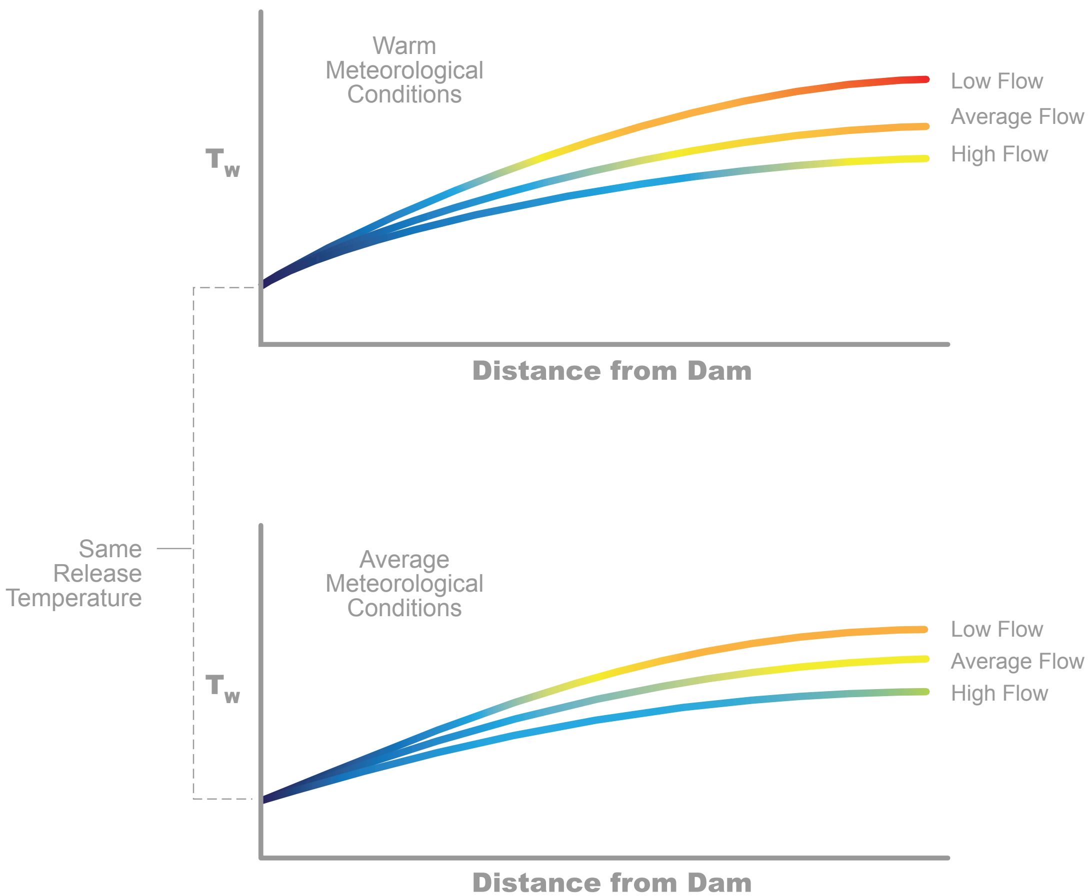
Flow and meteorological conditions, as well as tributary inflows, characterize the unique flow-heat gain relationship from the river release point to downstream water temperature control point(s). Cool reservoir waters released to a river warm towards equilibrium temperature. The goal is to manage flow and temperature to achieve desired conditions at a downstream location. Travel times through river reaches are also short (on the order of hours or days) compared to the residence times in upstream reservoirs. There is a limit to reliable downstream temperature management, beyond which meteorological conditions overcome upstream temperature management measures.

Natural variations in flow, temperature, and meteorological conditions can influence selective withdrawal strategies during the season, resulting in slightly different progressions than identified in the initial annual temperature management strategy.

The photos below show two different flow conditions. A river reach with higher flows generally resists heat gain and loss more effectively than a reach under low flow conditions.

Variations in flow conditions impact river flow-heat gain relationships. Low flow conditions (left) have a higher potential for heat gain compared to high flow conditions (below).
Photo credit: Watercourse Engineering, Inc.; used with permission.

More specifically, for cold water management considerations, a low river release rate leads to a longer travel time, shallower depths, and a higher potential for heat gain to a downstream control point. Conversely, a high river release rate leads to a shorter travel time, deeper depths, and a lower potential for heat gain to a downstream control point. Likewise, water released during warm meteorological conditions is likely to experience more heat gain as it travels downstream.

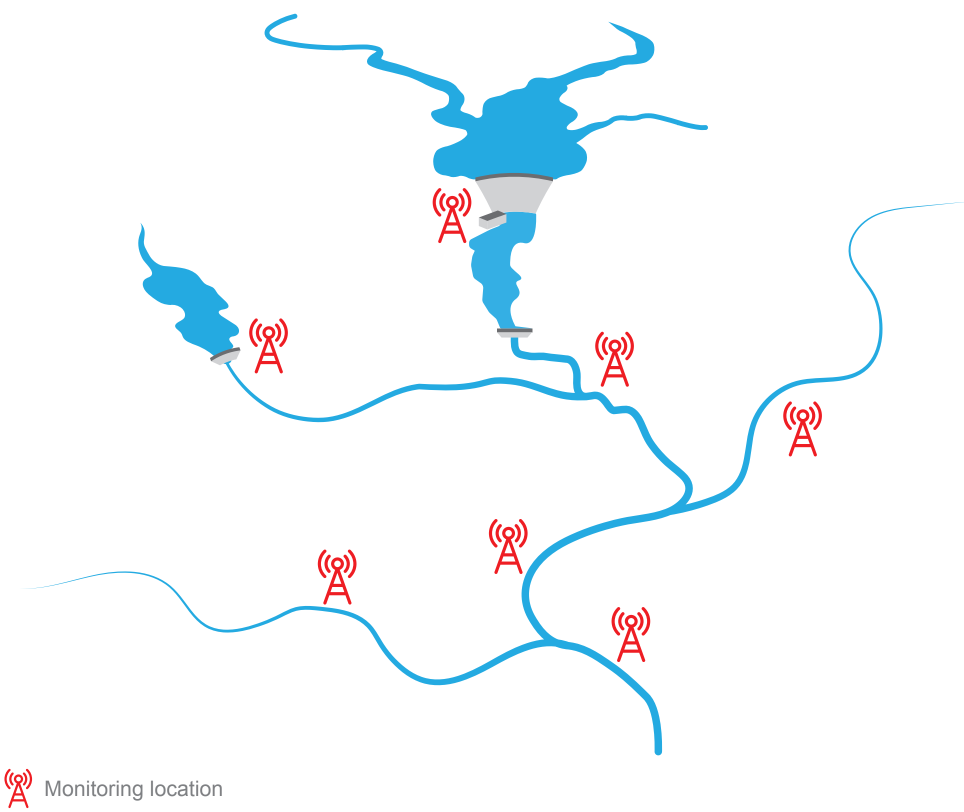


Monitoring

Monitoring data are used to provide a consistent body of information to assess performance, develop strategies, and formulate adaptation actions to mitigate for unexpected conditions (e.g., a extreme and/or extended heat wave).

Data generally consist of the following:

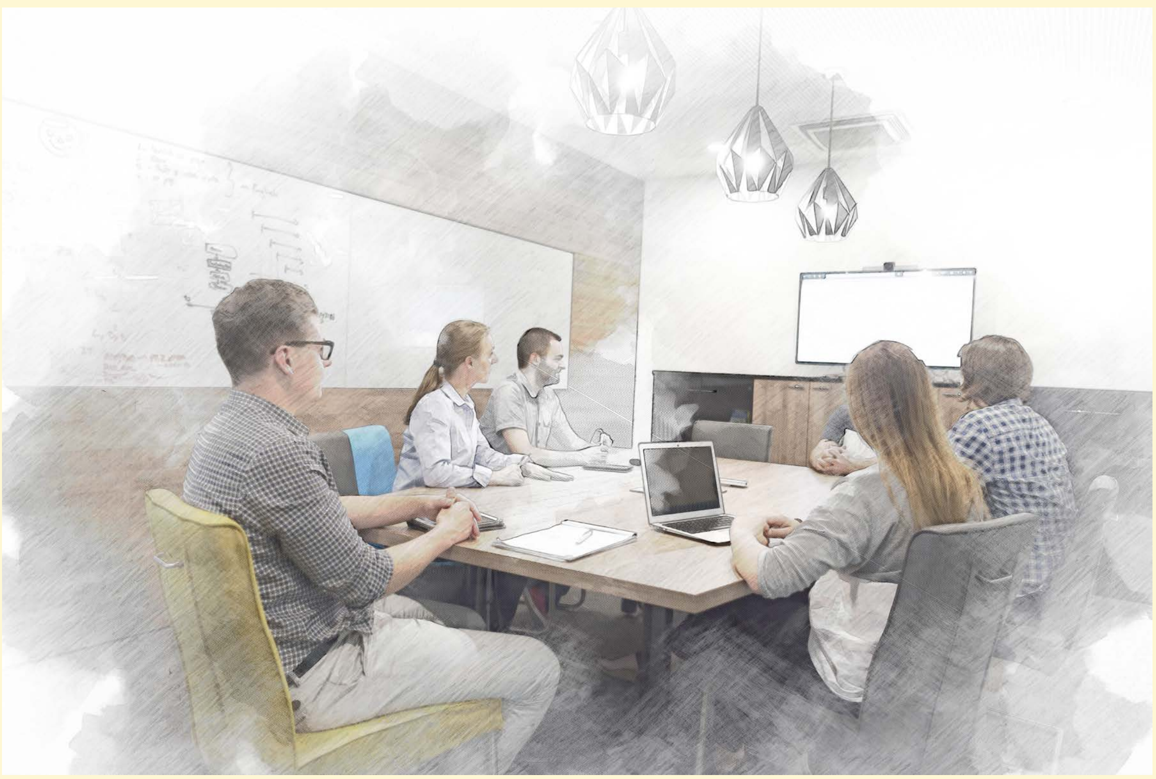
- Real-time and seasonal progressions of reservoir storage
- Real-time and seasonal progressions of reservoir water temperature profiles
- Real-time and seasonal water temperature management strategy performance and tail bay water temperature progressions
- Real-time and seasonal regulating reservoir and river release water temperature progressions
- Real-time and seasonal flow rates at critical monitoring locations
- Real-time and seasonal meteorological conditions and forecasts
- Annual fish distribution estimate
- Near real-time fish occurrence and habitat use

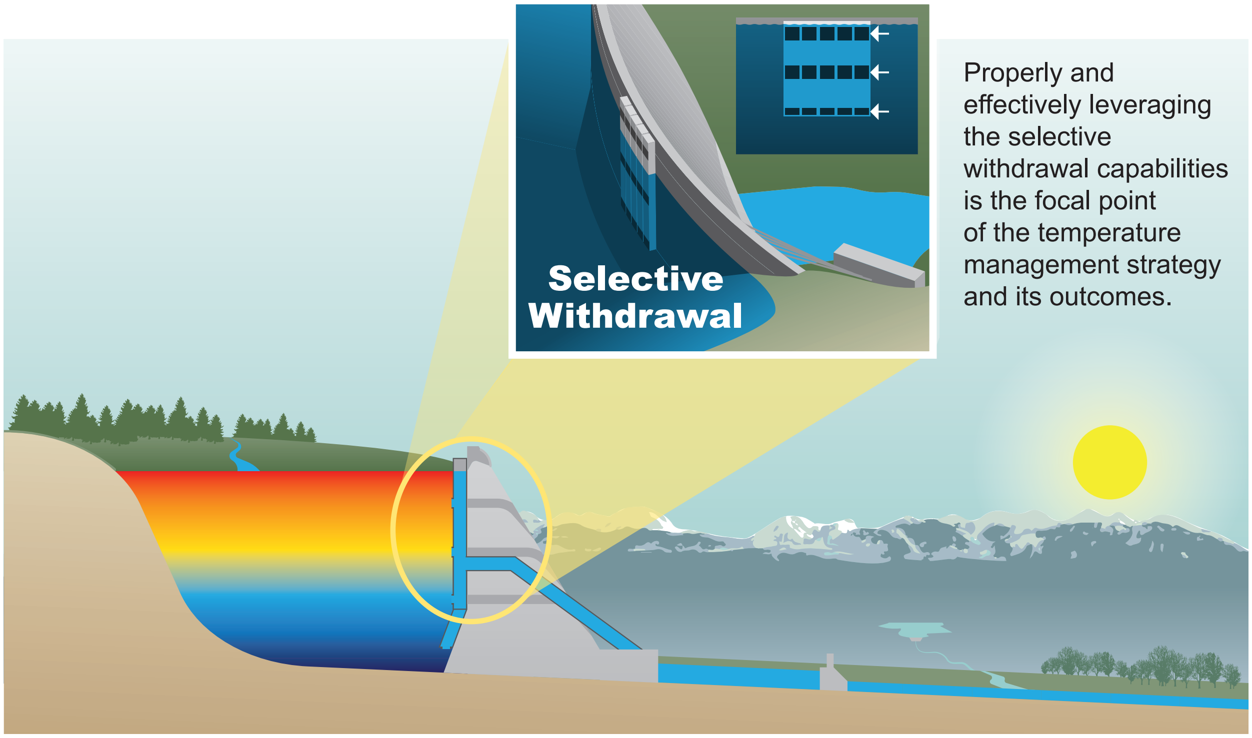


The Role of Computer Models in Water Temperature Management through Selective Withdrawal

Interactions of reservoir conditions, reservoir operations, river conditions, meteorology, and other factors as they relate to a selective withdrawal strategy are complex. Computer models contain mathematical representations of the reservoir-river systems, and they calculate flow and temperature based on physical thermodynamic principles, field data, and applicable assumptions and empirical relationships. While models have limitations and they reflect an approximation of the real world system, they are useful tools for the following purposes:

- To aid in understanding the complex interactions present in reservoir-river systems
- To organize and integrate large amounts of data and information for needed analyses
- To quickly and efficiently perform numerous, complex computations necessary to compare different selective withdrawal strategies for achieving downstream environmental objectives





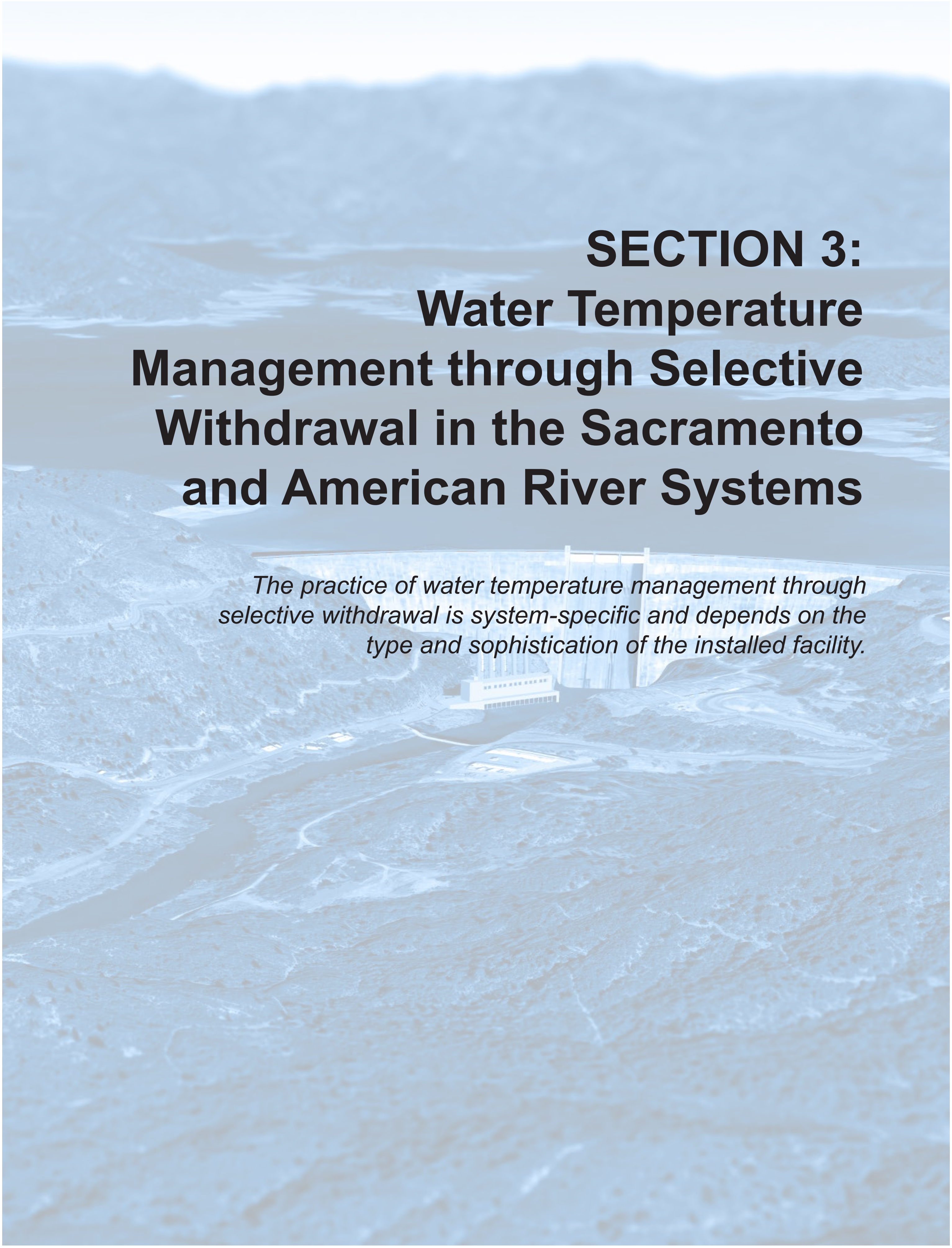
Summary

Ten different inter-related elements associated with temperature management in a reservoir-river system were introduced and discussed in detail in this section. With various examples, the information presented herein provides important concepts from the viewpoint of active temperature management: the ability of resource managers to properly and effectively leverage selective withdrawal capabilities provided by installed facilities directly results in the ability to manage river temperatures for environmental objectives. Only through consideration of all influencing factors and their natural variabilities can selective withdrawal strategies and associated gate operations be developed to achieve all intended benefits.

To further tie all elements together and illustrate the above point, the example used throughout this section is summarized and presented on the following page with a brief narrative on temperature management through selective withdrawal.

Temperature Management through Selective Withdrawal

Given equivalent storage conditions (a), and equivalent flow regimes (b), different selective withdrawal strategies progressions can yield different tail bay temperatures (c), and produce different cold water pool utilization rates (d). Alternative strategies subsequently lead to different downstream water temperatures (e) to meet environmental goals (f).



SECTION 3: Water Temperature Management through Selective Withdrawal in the Sacramento and American River Systems

The practice of water temperature management through selective withdrawal is system-specific and depends on the type and sophistication of the installed facility.

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Section 3: Water Temperature Management through Selective Withdrawal in the Sacramento and American River Systems

The Sacramento River is the largest river in California, with headwaters in northern California. The American River originates in the Sierra Nevada near Lake Tahoe and flows west to join the Sacramento River near the City of Sacramento. Annual temperature management strategies are used on both rivers to most efficiently utilize stored winter and spring cold water to meet downstream environmental objectives (e.g., fishery life stage needs) from late-spring to early-fall.

Facilities that enable selective withdrawal capabilities are requisite to manage water temperature in the Sacramento and American River systems. At Shasta Dam on the Sacramento River, a Temperature Control Device (TCD) was installed for this purpose. At Folsom Dam on the American River, a shutter system is available. Selective withdrawal strategies and the associated progressions of TCD gates and shutters at Shasta and Folsom Dams, respectively, throughout the temperature management season are developed considering the ten inter-related elements discussed in Section 2. This section provides a system-specific discussion of these elements and their associated temperature management-related topics.

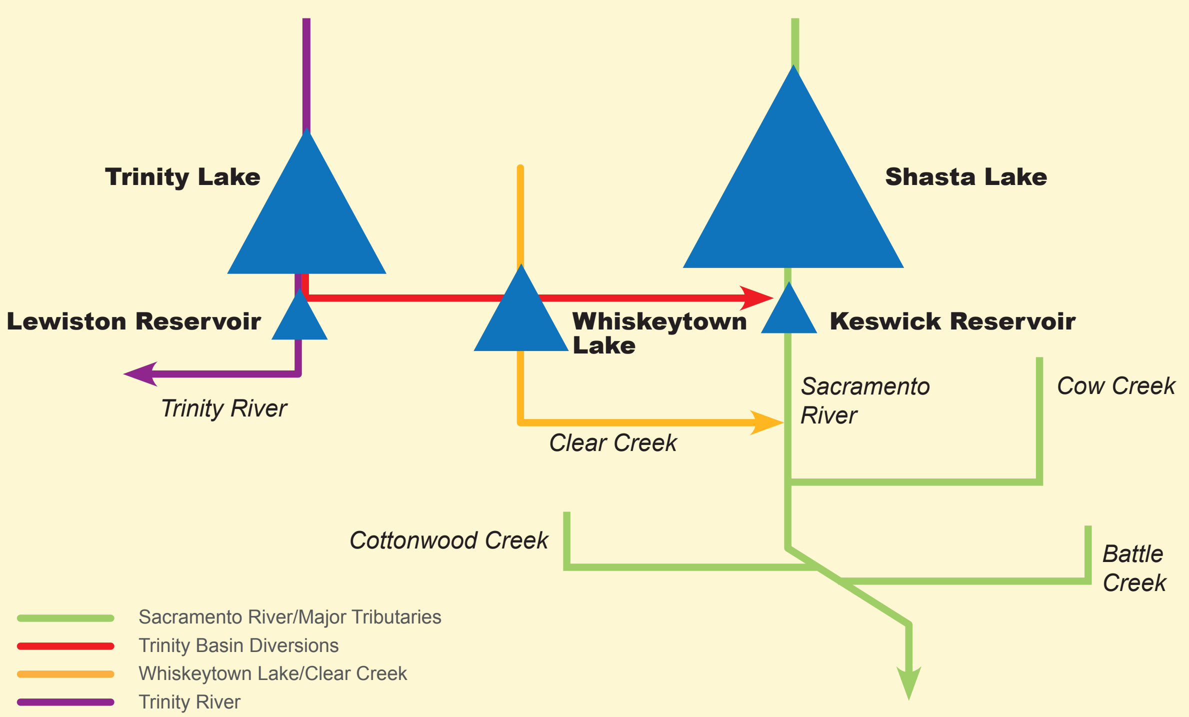
Water Temperature Management through Selective Withdrawal in the Sacramento River System

The Sacramento River system includes several major features and facilities that are relevant to temperature management:

- Shasta Dam and Lake, and the installed TCD.
- Interbasin transfers from the Trinity River basin—Waters from Trinity Lake are conveyed through Lewiston Reservoir and releases to the Trinity River are diverted to Whiskeytown Lake through the Clear Creek Tunnel and Carr Powerhouse. Outflows from Whiskeytown Lake include releases to Clear Creek and diversions to Keswick Reservoir via the Spring Creek Tunnel.
- Keswick Reservoir—Keswick Reservoir regulates releases from Shasta Dam and Spring Creek Powerhouses, resulting in a stable flow regime for release from Keswick Dam.
- Major tributaries to the Sacramento River in the temperature management reach include Clear, Cow, Cottonwood, and Battle Creeks.

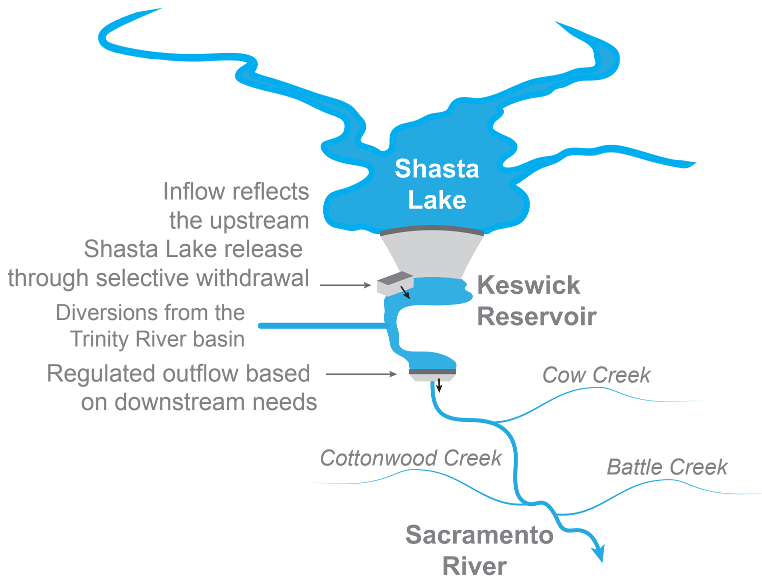
The following schematic shows the major movement of water in the Shasta-Trinity Division. Actual flows are governed by many legal, regulatory, and physical constraints not detailed in the schematic.

Movement of Water through the Shasta-Trinity Division



Cold water management through selective withdrawal to meet water temperature goals in downstream Sacramento River reaches is largely consistent with concepts presented in Section 2. However, to further understand temperature management in the Sacramento River system, the following four unique system attributes are presented below to provide additional context and detail.

- **Environmental objectives**—Reclamation operates Shasta Dam and Lake for specific environmental objectives related to downstream temperature management.
- **Trinity River Basin Diversions**—Trinity River basin diversions from Whiskeytown Lake via the Spring Creek Tunnel deliver both flow and a thermal load to Keswick Reservoir.

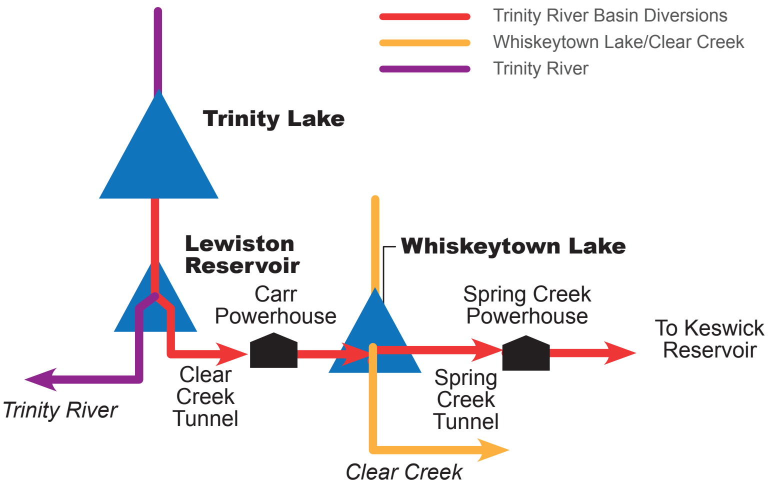


- **Natural variability**—In the Sacramento River system, meteorology and tributary inflows are factors that introduce uncertainty into forecasts, which need to be reflected in selective withdrawal strategies.
- **Temperature Control Device**—This facility for selective withdrawal was installed on Shasta Dam to conserve and efficiently manage cold water resource for downstream temperature management.

Environmental Objectives

In a given year, Sacramento River water temperatures are managed to a prescribed temperature at a downstream control point. This control point defines how far downstream protective water temperature will be maintained throughout the temperature management season (typically May through October) using all available cold water resources. Control point designation varies according to the initial cold water storage in Shasta Lake. High initial cold water volumes translate to a control point that is farther downstream, and low cold water volumes result in a control point closer to Keswick Dam. Occasionally, the control point may be adjusted during the temperature management season to take into account changes in cold water storage, updated forecasts, and other factors that influence downstream temperature management.

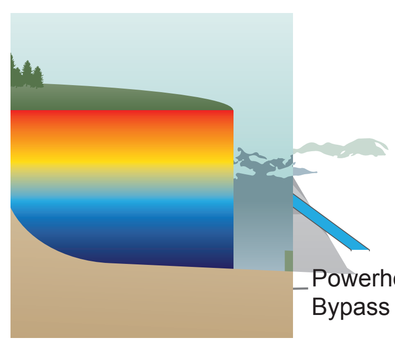
Trinity River Basin Diversions



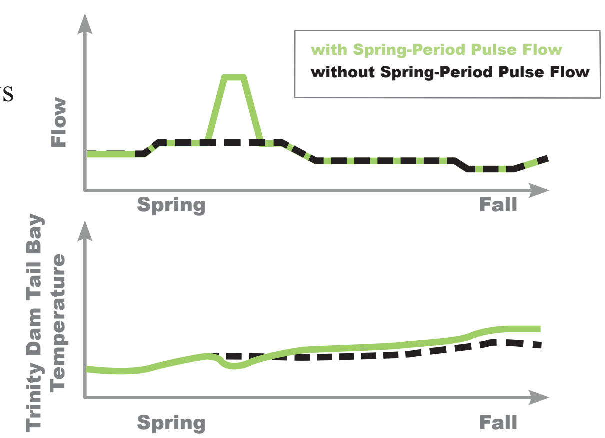
The second unique attribute of the Sacramento River System relates to Trinity River basin diversions. Temperature management in the Sacramento River system must consider conditions in the Trinity River basin because water is conveyed from Lewiston Reservoir, through Whiskeytown Lake, and into Keswick Reservoir (as shown in the above schematic). Trinity Lake and Lewiston Reservoir are operated principally to meet Trinity River objectives.

Temperature considerations for flow diverted to the Sacramento River through Whiskeytown and Keswick Reservoirs are subsidiary to Trinity River temperature objectives. Outlined below are the facilities, in sequence, that facilitate diversions from the Trinity River basin to the Sacramento River: Trinity Lake, Lewiston Reservoir, and Whiskeytown Lake.

Trinity Lake



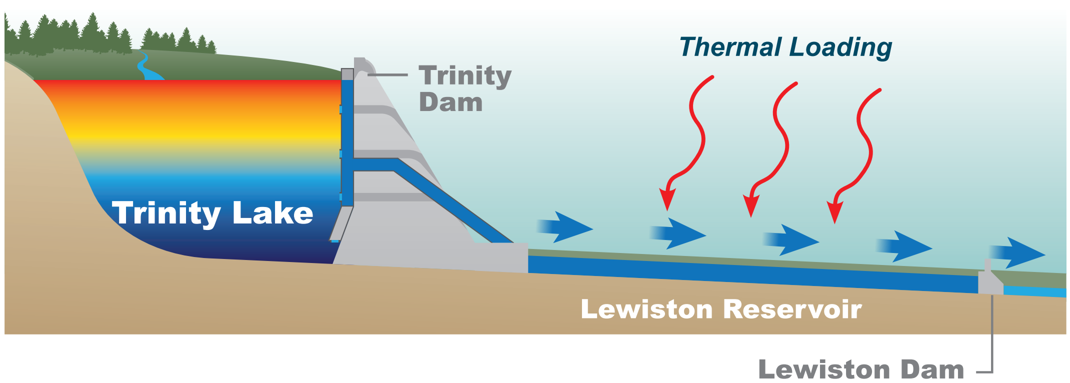
Trinity Lake, the largest reservoir in the Trinity River basin, experiences seasonal stratification, and deeper cold waters are used for temperature management in the Trinity River below Lewiston Dam. There is no facility installed for selective withdrawal at Trinity Dam. If reservoir storage is low or colder water is needed for downstream temperature management in the Trinity River, flows may be released through the powerhouse bypass.



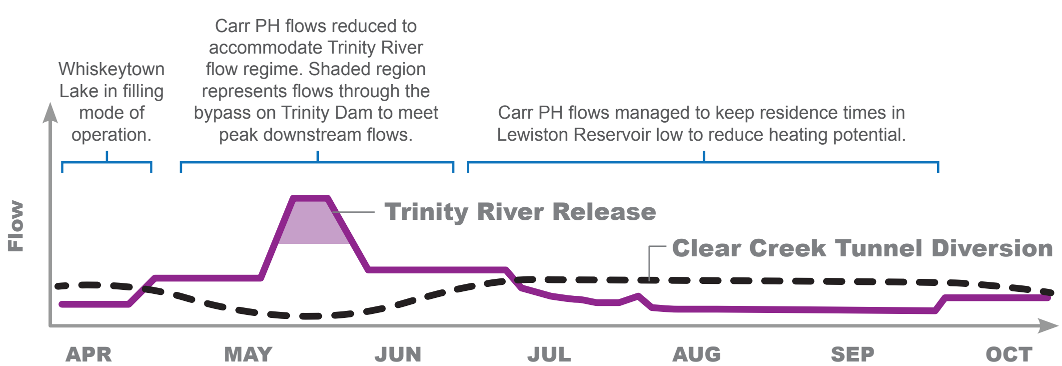
As illustrated to the right, in wetter year types, spring-period pulse flows for the Trinity River exceed Trinity Dam Powerhouse capacity, and the low level powerhouse bypass is used to augment the powerhouse flows. As a result, the coldest and deepest waters in the lake are used in spring, when downstream temperature management is not yet a concern. This early use of cold water pool can result in higher Trinity Dam tail bay temperatures later in the year, compared to conditions without spring-period pulse flows. Such increases in Trinity Dam tail bay temperatures add to the thermal load to Lewiston Reservoir.

Lewiston Reservoir

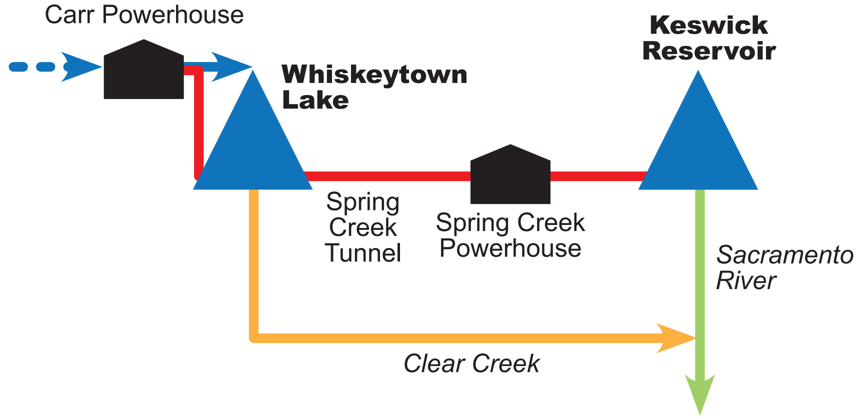
Lewiston Reservoir regulates hydropower releases from Trinity Dam to the Trinity River below Lewiston Dam and diversions to the Sacramento River basin via Clear Creek Tunnel, Carr Powerhouse, and Whiskeytown Lake. To meet downstream Trinity River objectives, sufficient flow is necessary to keep residence times low in Lewiston Reservoir and avoid excessive heating during summer and fall. Residence time in Lewiston Reservoir is typically on the order of 2 weeks. Furthermore, a temperature control curtain is used in Lewiston Reservoir as a measure to support fish hatchery needs below Lewiston Dam.



Different operations and conditions at Trinity Dam result in different temperature and flow conditions in Lewiston Reservoir, which impacts Whiskeytown Reservoir via Clear Creek Tunnel diversion flows and temperatures (see the figure below).



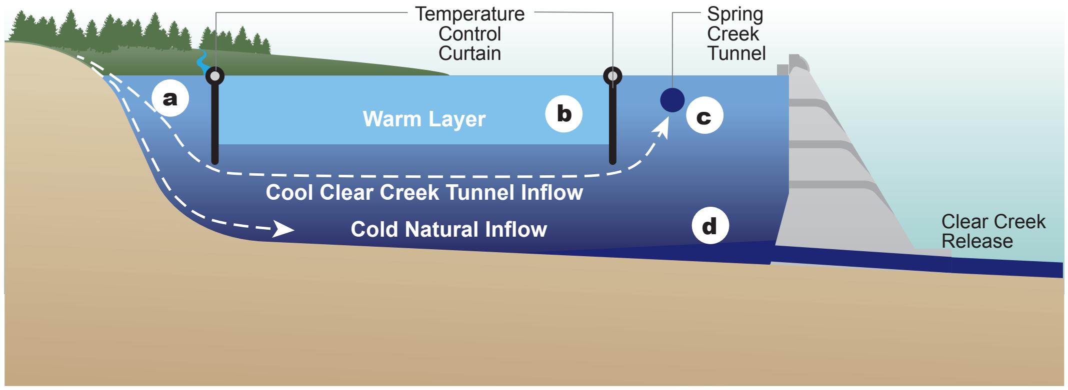
Whiskeytown Lake



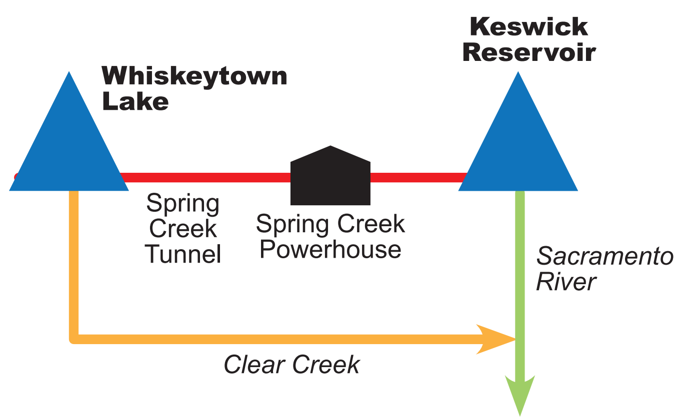
Whiskeytown Lake, located on Clear Creek, serves as a storage reservoir as well as an afterbay to Carr Powerhouse and a forebay to Spring Creek Powerhouse located at Keswick Reservoir. Whiskeytown Lake also receives local natural inflows and releases flows to Clear Creek for instream needs downstream of the dam. Clear Creek eventually joins the Sacramento River downstream of Keswick Dam.

As mentioned previously, the temperature of Carr Powerhouse discharge to Whiskeytown Lake is a byproduct of, and ancillary to, operations to meet Trinity River flow and temperature objectives in reaches downstream of Lewiston Dam.

Whiskeytown Lake stratifies seasonally due to natural heating. As illustrated in the graphic above and the reservoir profile on the next page, temperature control curtains are installed below the Carr Powerhouse (upstream) and near the Spring Creek tunnel intake (downstream) to reduce heat gain on waters conveyed through the lake. During the summer, the curtains act to guide cooler, denser waters from Clear Creek Tunnel via Carr Powerhouse ((a)) to flow below the warm surface waters ((b)) as they move through the reservoir to the Spring Creek Powerhouse tunnel intake ((c)). Winter runoff from the local watershed contributes to the coldest portion of the cold water pool ((d)). Typical summer residence time through Whiskeytown Lake is on the order of 6 to 8 weeks, depending on flow rates. Even with the temperature control curtains, notable heating can occur as waters traverse the lake.

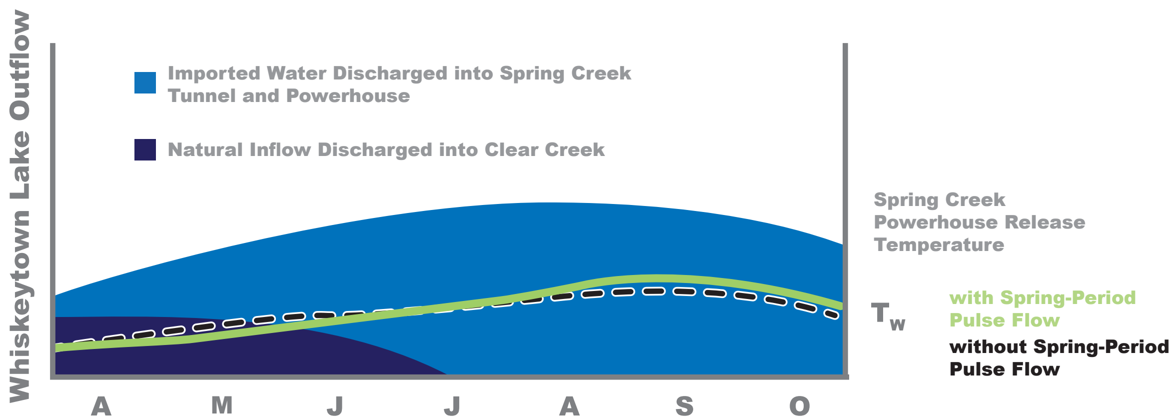


There is no selective withdrawal facility at Whiskeytown Dam to manage temperature releases to downstream Clear Creek; however, two low-level river outlets access near-bottom waters (Pool ⓓ, in the graphic above). Pool ⓓ has limited volume and varies naturally depending on hydrology and meteorology. Releases to Clear Creek can ultimately exhaust Pool ⓓ, at which time Pool ⓒ waters occupy the lower portion of Whiskeytown Lake. This interaction influences release water temperatures to Clear Creek, which become downstream tributary inflows to the Sacramento River.

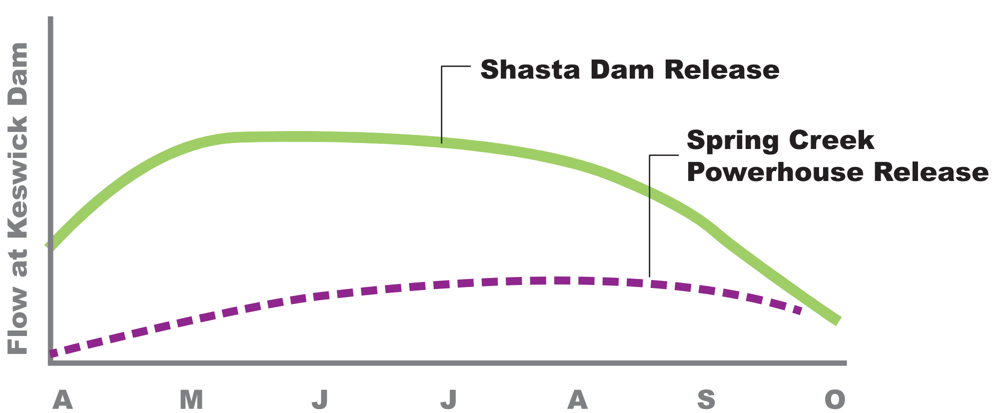


Diversions from Whiskeytown Lake to the Sacramento River are made through Spring Creek Tunnel and Powerhouse. Temperatures of Spring Creek Powerhouse releases to Keswick Reservoir represent the culmination of multiple factors, reflecting conditions at Trinity Lake, Lewiston Reservoir, and Whiskeytown Lake. These factors include natural variability flows and temperatures at Trinity Dam tail bay and Lewiston Dam, Clear Creek Tunnel and Carr Powerhouse flows and temperatures, heating and residence times in Whiskeytown Lake, release rates to Clear Creek, and diversion rates to Spring Creek Powerhouse. Combinations of these factors lead to different outcomes in flow and temperature contributions to Keswick Reservoir and Sacramento River reaches.

As illustrated below, the culmination of multiple factors from the distant Trinity River basin, in the form of spring-period pulse flows, may impact temperatures of releases from Spring Creek Powerhouse to Keswick Reservoir in the late summer.



Shasta Dam selective withdrawal strategies must accommodate the range of potential temperatures of Spring Creek Powerhouse discharge into Keswick Reservoir by targeting appropriate Shasta Dam tail bay temperatures to manage water temperatures in Sacramento River reaches below Keswick Dam. Water temperature variations in Spring Creek Powerhouse flows typically have a relatively modest impact on Keswick Dam release temperatures because Shasta Dam discharges are much larger than Spring Creek Powerhouse flows into Keswick Reservoir.

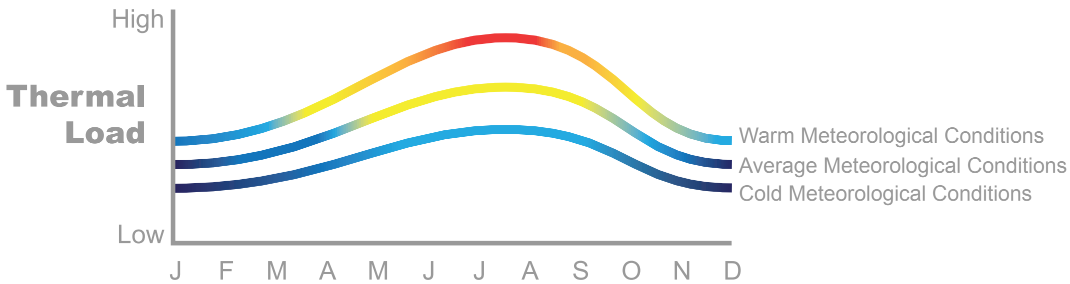


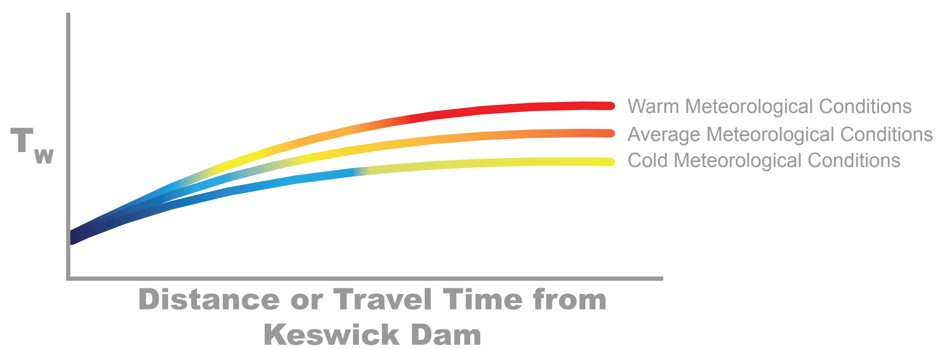
Natural Variation of Other Influencing Factors

The third unique attribute of the Sacramento River system is natural variation. Among the factors influencing water temperature discussed in Section 2, meteorology and tributary contributions are factors that experience natural variation and can be important when considering selective withdrawal strategies.

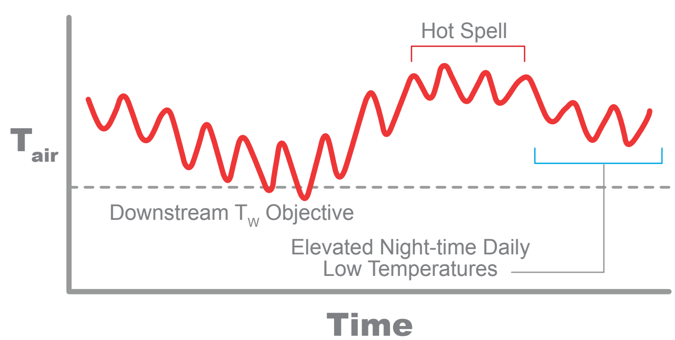
Meteorology

Intra-annual variations in meteorological conditions (e.g., warm or cool summers) impact reservoir and river temperature dynamics on longer (months) and shorter term (days/weeks) time scales. Late spring, summer, and fall meteorological conditions can lead to notable increases in release water temperature from Shasta Dam, particularly below Keswick Dam.

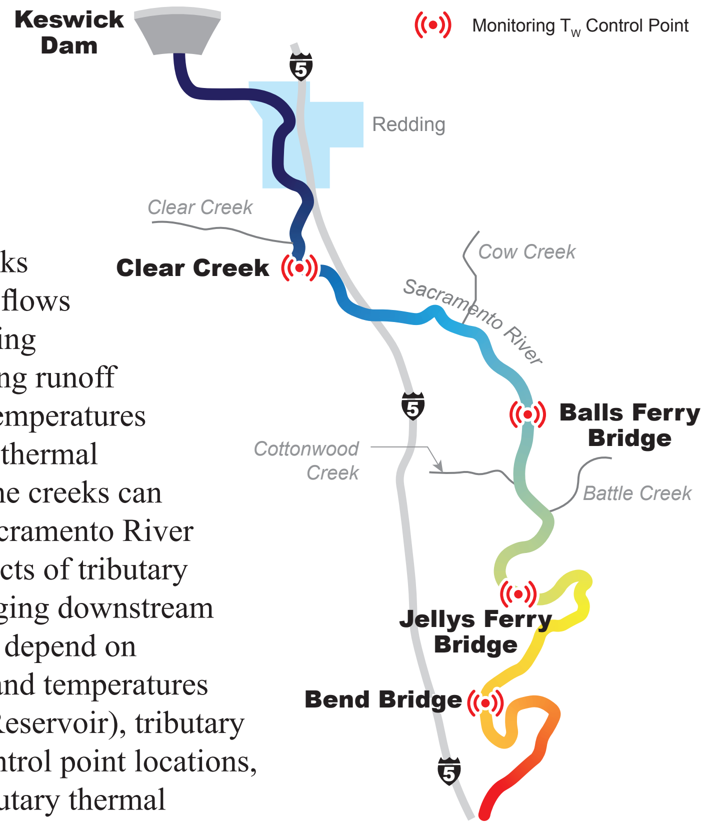




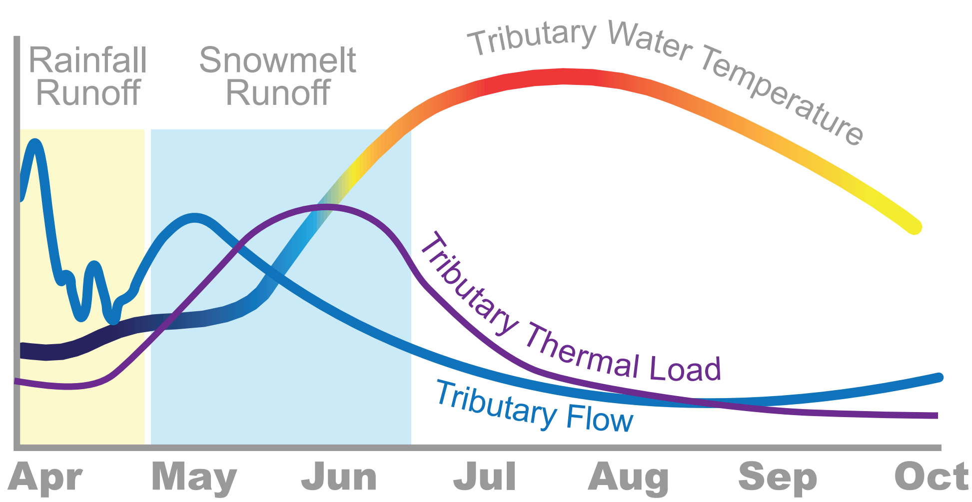
In addition to seasonally variable conditions, temperature management strategies need to be adapted in response to warm weather events ("hot spells") and periods when night time air temperatures remain elevated.



Tributary Thermal Load



Major tributaries that enter the Sacramento River below Keswick Dam and above Red Bluff include Clear, Cow, Cottonwood, and Battle Creeks. These creeks can provide considerable flows during the winter and spring months. During high spring runoff periods, tributary water temperatures can also be elevated, and thermal loads of one or more of the creeks can influence downstream Sacramento River water temperatures. Impacts of tributary thermal loading on managing downstream environmental objectives depend on Sacramento River flows and temperatures (releases from Keswick Reservoir), tributary flow and temperature, control point locations, and timing. If a large tributary thermal load enters the river above a control point, selective withdrawal may be used to offset potentially deleterious effects. As tributary flows decrease in late spring and early summer, this natural variation no longer plays a significant role in temperature management.

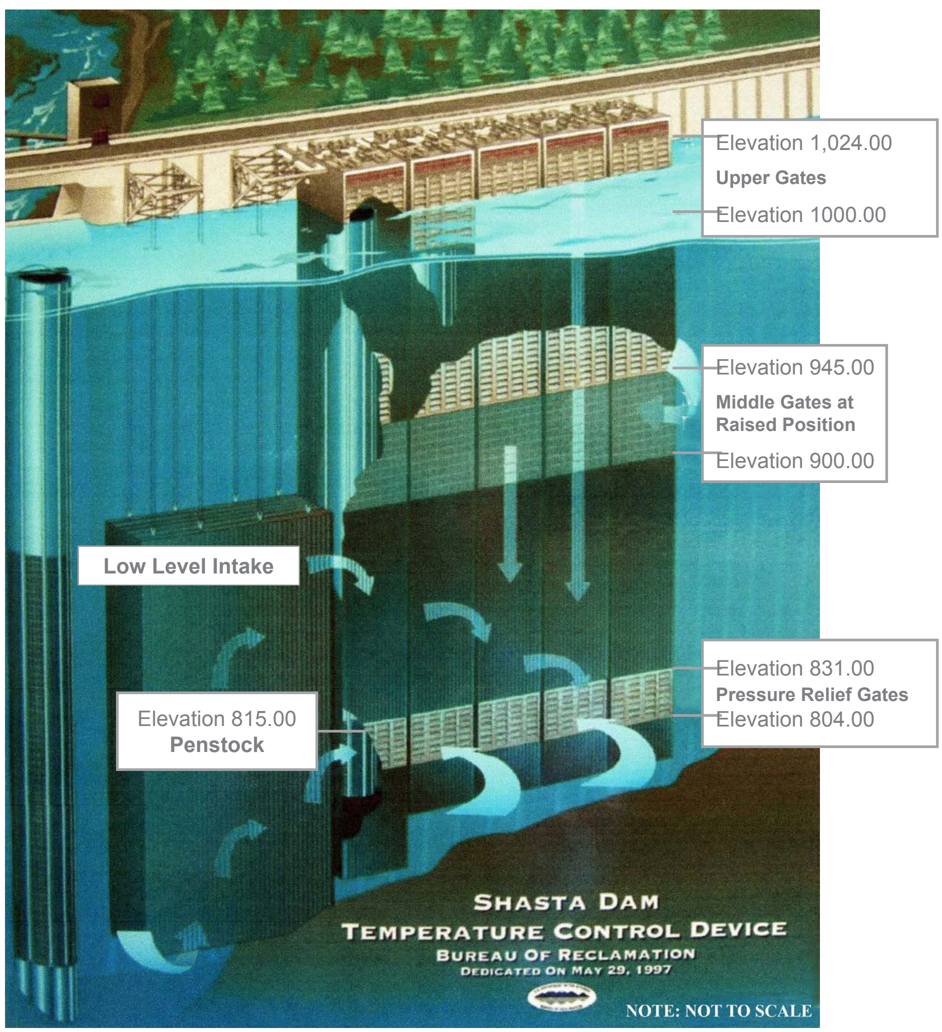


Temperature Control Device

The fourth unique attribute of the Sacramento River system is the TCD, which was constructed in 1997 to provide flexibility and improve efficiency in managing cold water resources in Shasta Lake. The TCD enables selective withdrawal of water from varying lake depths for release through the hydropower plant, while maintaining adequate water temperatures to support environmental objectives in the Sacramento River downstream of Keswick Dam.

TCD Physical Configurations

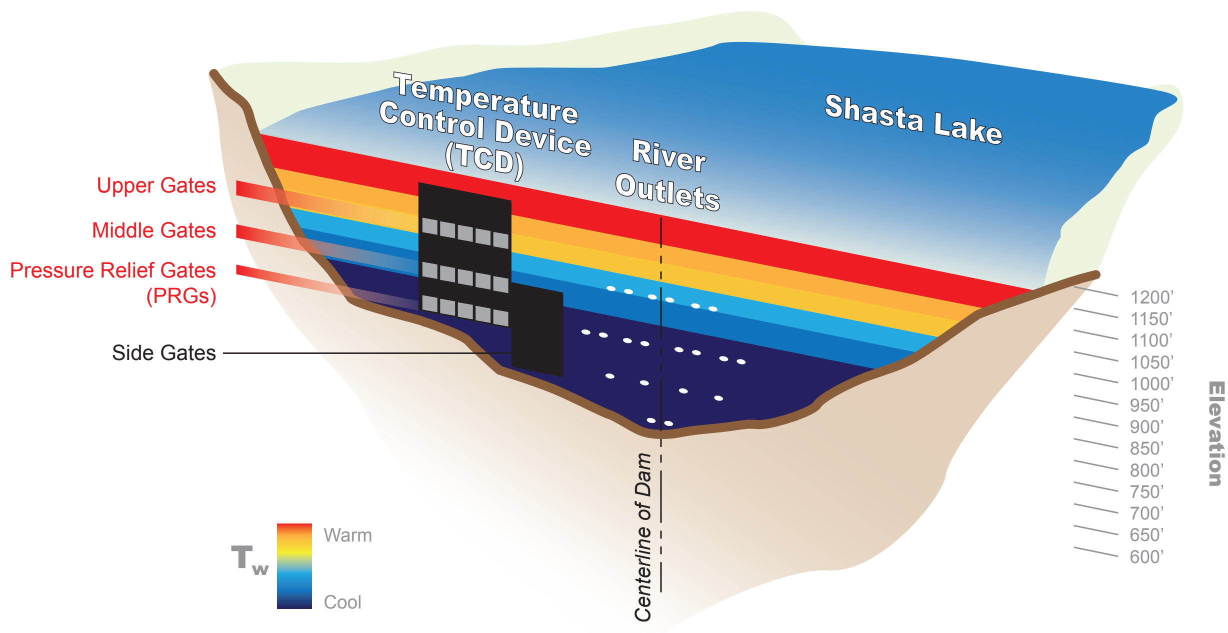
The TCD is located on the upstream face of Shasta Dam and includes four sets of gates: the upper, middle, lower (also termed Pressure Relief Gates, or PRGs), and side gates. The TCD is also open at the top, allowing releases through this ungated section when reservoir storage levels are high. The side gates, located adjacent to middle and lower gates access to Low Level Intake (LLI). Reservoir waters enters the LLI vertically through the bottom of that structure.



The TCD was constructed specifically for Shasta Lake thermal conditions, hydropower operations, and other physical attributes of Shasta Dam. Reservoir size, stratification dynamics, progression of gate use through the temperature management season, and downstream conditions and objectives were all considered in facility design.

Waters entering the TCD from any of the gates can flow to all five powerhouse penstocks. Although waters are often drawn into the TCD at different elevations with different temperatures, resulting tail bay temperatures vary minimally, indicating that waters are well mixed within the TCD prior to release through the penstocks. (See also discussions on the non-baffled system related to hydraulic constraints, page 3-15.)

The TCD was not designed to be water tight; hence, there are areas where leakage can be considerable and may affect overall performance of the TCD. Reservoir storage and stratification; the timing and order of gate opening and closing, both laterally (left to right within a gate level) and vertically (among the four gate levels); flow rate; and leakage can all play a role in TCD performance.

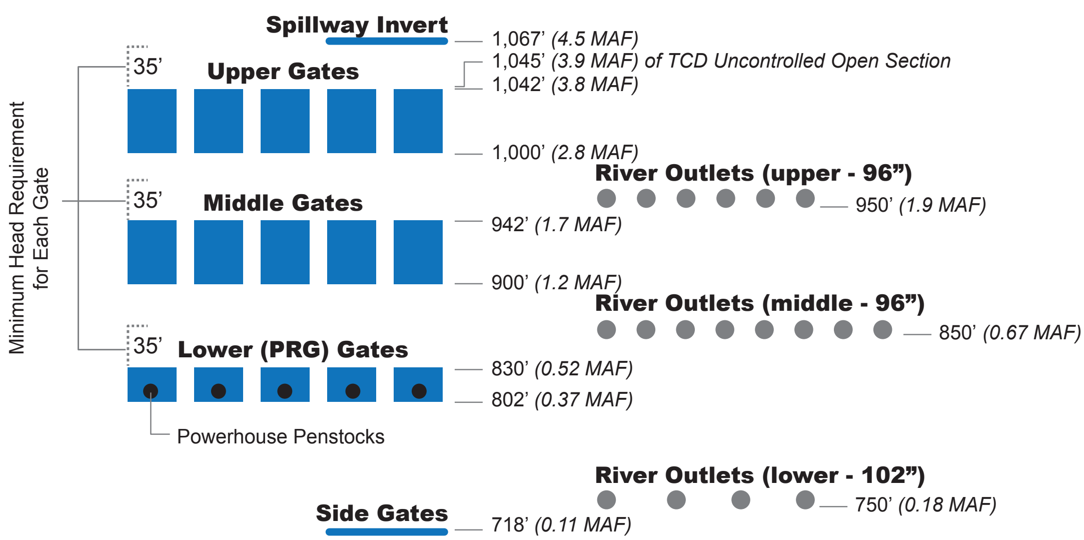


Hydraulic Constraints of TCD Gate Use

Hydraulic constraints include minimum head requirements for hydropower production and gate access. Minimum head requirements for each set of gates are 35 feet. The illustration below shows the outlet facilities on Shasta Dam with their corresponding elevation and storage information. The 35-foot hydraulic buffer required for gate operation was also indicated in the illustration.

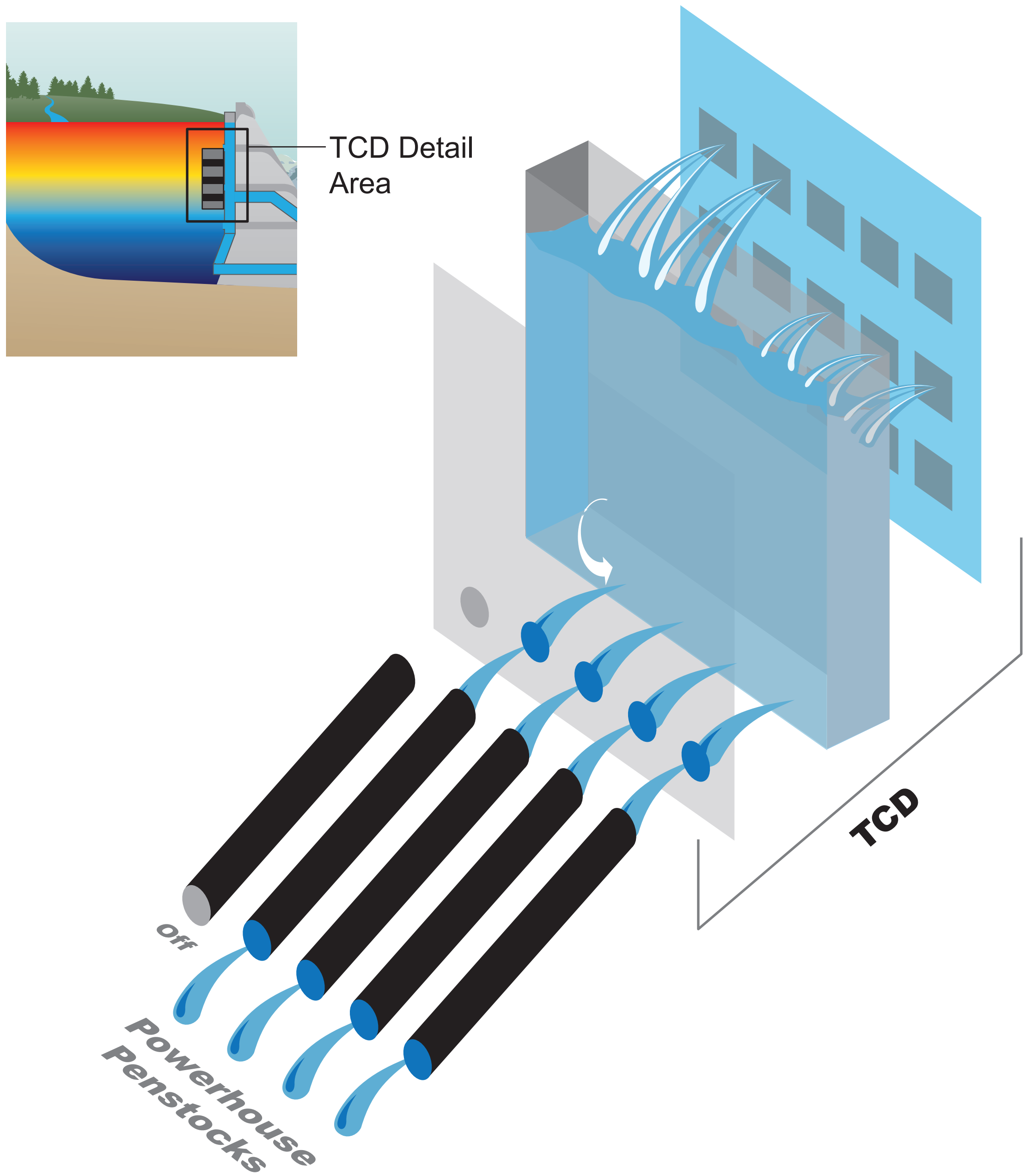
Access to the upper gates early in the temperature management season is critical for overall cold water pool conservation and downstream temperature management thorough the season. If the upper gates are limited by hydraulic constraints and are inaccessible in the spring period, temperature management challenges can be significant.

Shasta Dam and Outlet Facilities with Corresponding Elevation and Storage Information



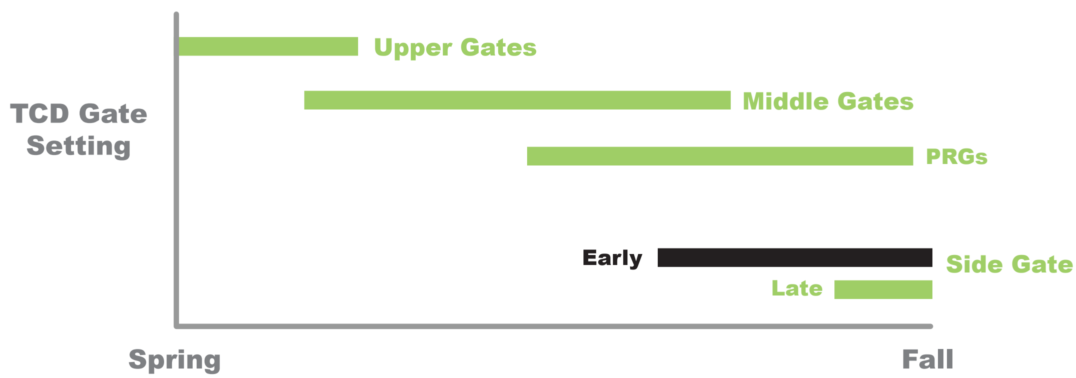
Note: Not to Scale. All elevations and corresponding storage in feet above mean sea level and million acre-feet (MAF).

Water entering gates is mixed in the TCD. Subsequently, water from the TCD is discharged to all active penstocks. The TCD is termed non-baffled because water cannot be preferentially delivered from any particular gate or gates to specific powerhouse units. At the same time, not all gates on the same level perform exactly the same. The outcome is a complex hydrodynamic and thermal mixing regime that can present challenges to accurately use gate combinations to meet tail bay temperatures.



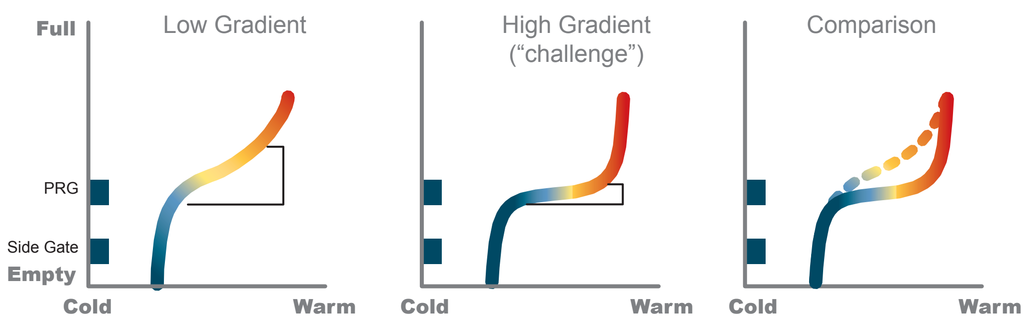
Hydraulic Constraints of TCD Side Gate and Low Level Intake

The TCD is used to respond to the seasonal progression of thermal conditions in Shasta Lake, which in turn are the result of seasonal thermal loading and releases from the dam to meet downstream objectives. Critical to annual temperature management and efficient use of cold water resource is the progression of TCD gate settings throughout the temperature management season, particularly the timing of side gate operations. The LLI is the lowest elevation that water can be drawn from the lake, and once transition to the side gate commences, the LLI is used throughout the remainder of the temperature management season. Thus, timing of transition to the side gate (i.e., schedule) is an important aspect of a temperature management strategy because this gate accesses the last manageable cold water volume in the lake. Transitioning to the side gate too early can lead to over-utilization of the cold water pool, resulting in further challenges later in the temperature management season.



In drier hydrologic year types, the progression of thermal conditions in the lake can present operational challenges for temperature management using the lower gates (PRGs) and side gate operations. Under these conditions, mid- to late-summer temperature profiles can exhibit locally high temperature gradients. A temperature gradient is defined as the ratio between change in water temperature and change in elevation. A high temperature gradient translates to a large change in temperature within a small vertical elevation change. A high temperature gradient yields a high density gradient, which can result in complex hydrodynamics and thermal conditions.

When these high temperature gradients occur in the vicinity of the PRG, small changes in the seasonal thermal structure progression in the reservoir can lead to rapid and considerable changes in tail bay temperatures as shown below. Side gate operations are particularly sensitive to these conditions, as waters enter the structure vertically, pulling water upwards to access the last remaining cold water supplies. The patterns of vertical inflow of water via the side gates into the TCD are a function of local water density conditions. Consequently, TCD performance characteristics are sensitive to late season high temperature gradients, and associated water density differentials in the vicinity of the PRGs in the later season.

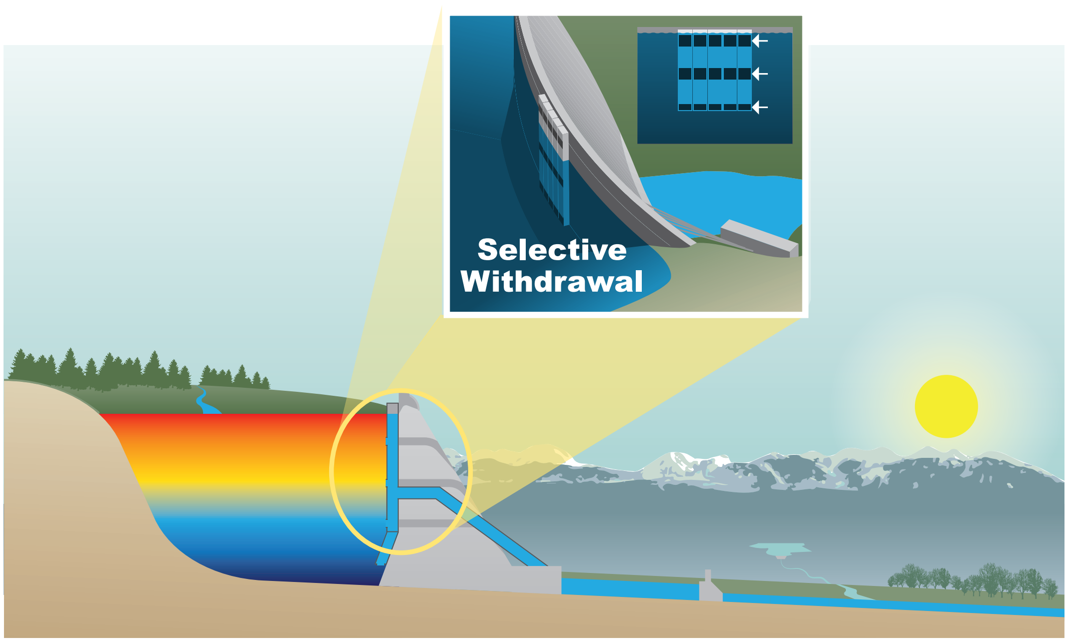


The high temperature gradient condition in the vicinity of the PRG often occurs in years when initial storage is low and access to the upper gates is limited. It can diminish the effectiveness of the TCD for remainder of the temperature management season.

Upstream face of Shasta Dam in 2017, showing the top of the TCD. *Photo credit: Watercourse Engineering, Inc; used with permission.*

Summary for the Sacramento River System

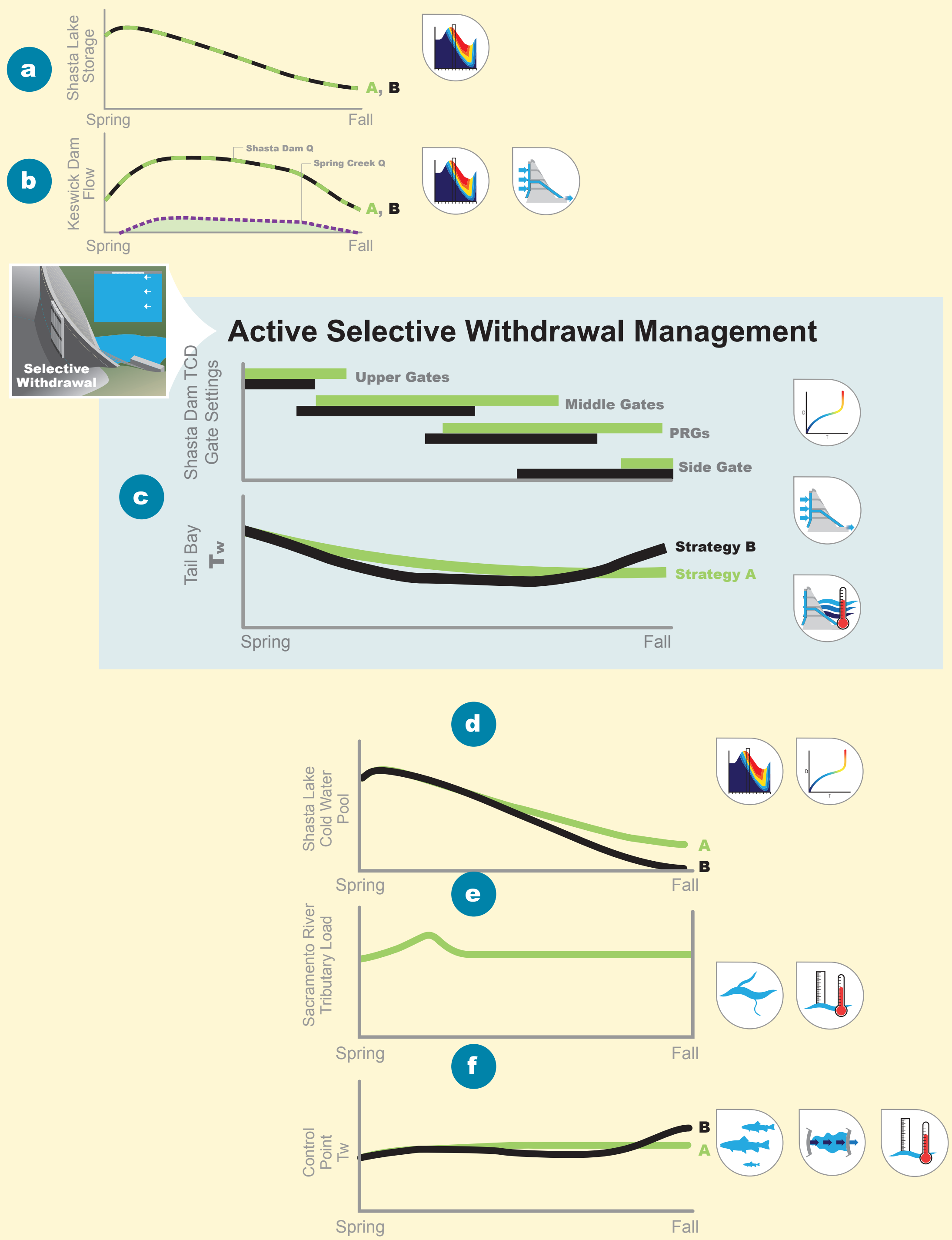
The TCD is the pivotal facility to manage water temperature in downstream reaches of the Sacramento River. TCD selective withdrawal strategies and the associated gate progression through the temperature management season consider multiple factors and temperature related elements as well as natural system variability, as described in Section 2.



Alternative TCD selective withdrawal strategies, as well as response to natural variability, result in different temperature management outcomes. TCD operations (i.e., gate progression, water blending) that are made early in the temperature management season have direct ramifications on tail bay temperatures late in the season. Similarly, TCD operations made in response to natural variations have a cumulative direct effect on tail bay temperature as the season progresses. TCD flexibility in the late summer and fall may be limited due to a seasonal low cold water storage (limited available supply) and reduced access (limited number of gates) to the remaining cold water volume. Similar to the summary in Section 2 for a generic system, a simple narrative with illustrations is presented on the next page and summarizes temperature management in the Sacramento River system for different selective withdrawal management strategies.

Temperature Management through Selective Withdrawal in the Sacramento River System

Given equivalent storage conditions in Shasta Lake (a) and equivalent flow regimes from Keswick Dam (b), alternative TCD selective withdrawal strategies (gate progressions) result in alternative tail bay temperatures (c), and different cold water pool utilization rates (d) to account for natural system variability and tributary thermal loads (e) to meet downstream environmental objectives (f).



Water Temperature Management through Selective Withdrawal in the American River System

The American River system includes Folsom Lake, Lake Natoma, and the American River downstream to the confluence with the Sacramento River. Hydropower releases from Folsom Dam to Lake Natoma are regulated at Nimbus Dam. Waters are subsequently released from Nimbus Dam to the American River to meet downstream objectives.

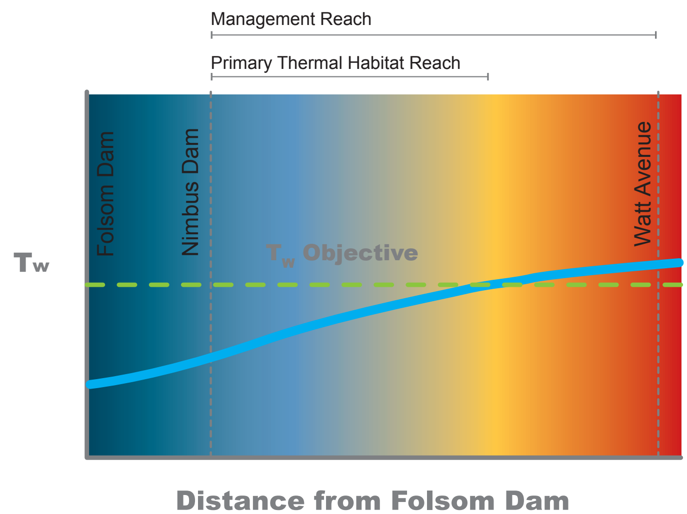
Cold water management through selective withdrawal to meet water temperature goals in the American River below Nimbus Dam is largely consistent with the concepts presented in Section 2, with the exception that there are no major tributaries along the American River between Nimbus Dam and the confluence with the Sacramento River. To further understand temperature management in the American River system, the following three unique system attributes are discussed below to provide additional context and detail:

- Environmental objectives
- Natural variability
- Shutter system at Folsom Dam to provide selective withdrawal capabilities

Environmental Objectives

American River water temperatures are managed to a fixed downstream river reach from Nimbus Dam to Watt Avenue Bridge, and the temperature goal at Watt Avenue Bridge may vary throughout the temperature management season based on cold water availability.

The relatively small size of Folsom Lake, in comparison with other major reservoirs, further limits cold water availability for downstream temperature management purposes. As shown below, the environmental objectives essentially allow for establishment of a primary thermal habitat reach in the management reach from Nimbus Dam to Watt Avenue Bridge. A target water temperature is set at Watt Avenue Bridge to extend the thermal habitat as far downstream as possible from Nimbus Dam based on cold water availability and other factors.



Natural Variability

Natural variability in the American River system is largely related to meteorology because there are no major tributaries below Nimbus Dam. In particular, meteorology in spring can be highly unpredictable and have direct impacts on snowmelt runoff, cold water pool, and resulting reservoir operations because of the modest size of Folsom Reservoir. These factors introduce uncertainty into forecasts, which subsequently are considered when developing selective withdrawal strategies.

Shutter System for Selective Withdrawal

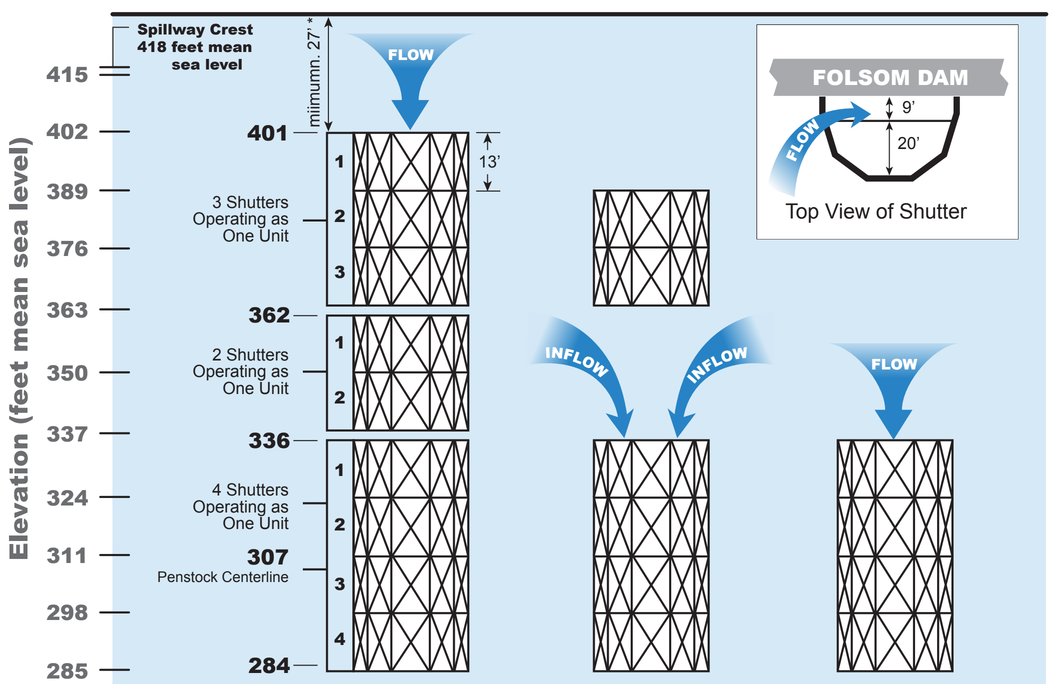
Selective withdrawal operations at Folsom Dam are accomplished using a system of shutters at each powerhouse intake. The shutter system provides flexibility and improves efficiency in managing cold water resources in Folsom Lake. The shutter system enables selective withdrawal of water from varying depths to maintain adequate water temperatures to support environmental objectives in the American River downstream of Nimbus Dam.

The shutter system is located on the upstream face of Folsom Dam and consists

Upstream face of Folsom Dam in 2015 under low storage conditions. *Photo credit: Yung-Hsin Sun; used with permission.*

of three discrete sets of shutters – one associated with each powerplant penstock. In this manner, the shutter system differs from the TCD at Shasta Dam, which is a non-baffled system.

Each set of shutters has nine levels of shutters (each 13 feet tall); individual shutters are connected into units (or ganged) with a configuration of 3, 2, and 4 shutters, respectively, from top to bottom. Temperature management through selective withdrawal is managed by removing different shutter units from different powerplants to access different temperature water as the season progresses. The timing of removing the last (bottom-most) shutter unit is a key consideration in temperature management in the American River. The graphic below shows shows the physical configuration of a set of shutters and some possible use conditions. A minimum of 27 feet of water above the top shutter is required for hydropower production. If this minimum head is not available, the powerhouses cannot be



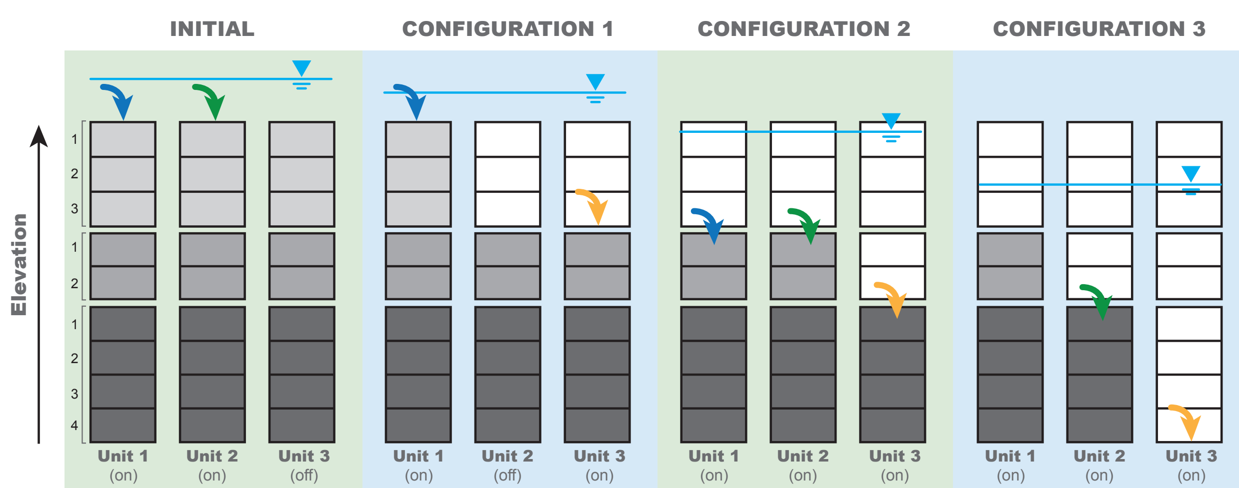
*Minimum 27' hydropower head requirements on shutter configurations.

used and that set of shutters becomes unusable for temperature management.

Shutter System Operational Considerations

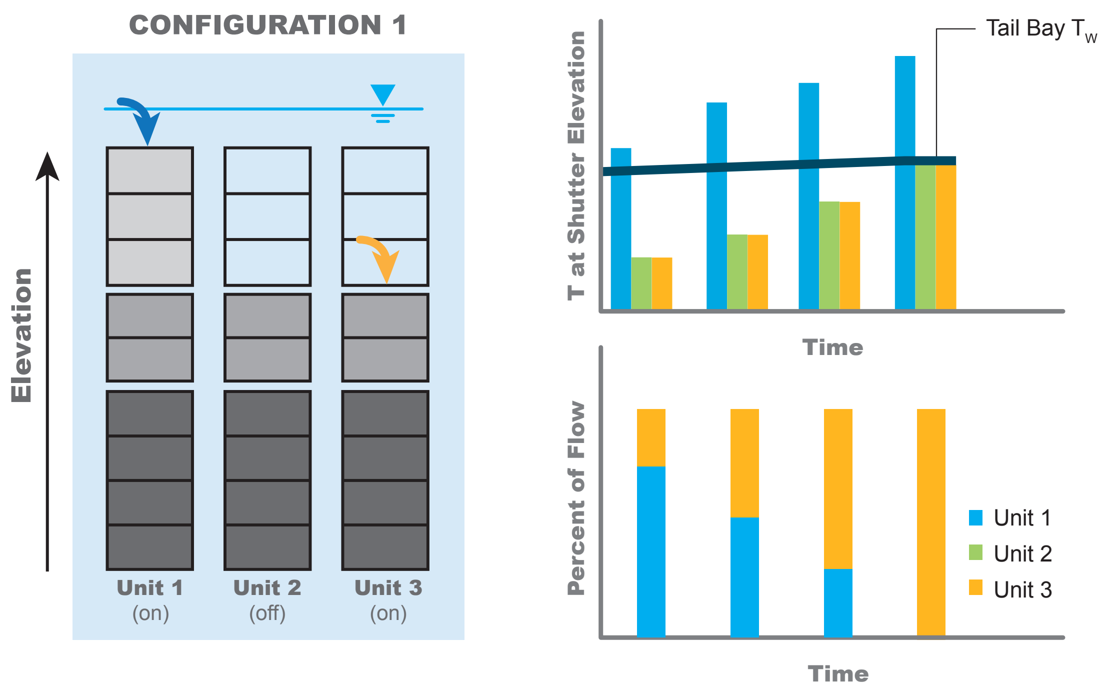
Water temperatures in the lower American River are affected by available cold water resources in Folsom Lake, Nimbus Dam release schedules, annual hydrology, water supply demands, and powerhouse availability. There are areas in the shutter system where leakage occurs. Coupled with reservoir storage and stratification, timing and order of shutter operations, and head requirements for each shutter configuration, these factors play a role in developing and implementing temperature management strategies. Shutter configuration during the temperature control season, shutter management, and low storage conditions are other important aspects of temperature management in the American River system.

Seasonal Configuration Progression: Critical elements of temperature management at Folsom Dam are shutter configurations and individual powerhouse operations. Temperature control is achieved through blending waters from different depths in Folsom Lake. To access water at different depths (i.e., water of different temperature), the shutter configuration must vary among powerhouse units in a "stepped configuration," as shown below. Temperature management is provided by using different shutter configurations to achieve the necessary blended tail bay temperatures to meet downstream temperature targets. Constraints on shutter configurations include hydraulic constraints for minimum head, in-reservoir thermal structure, powerhouse availability (e.g., outages), and shutter management requirements.



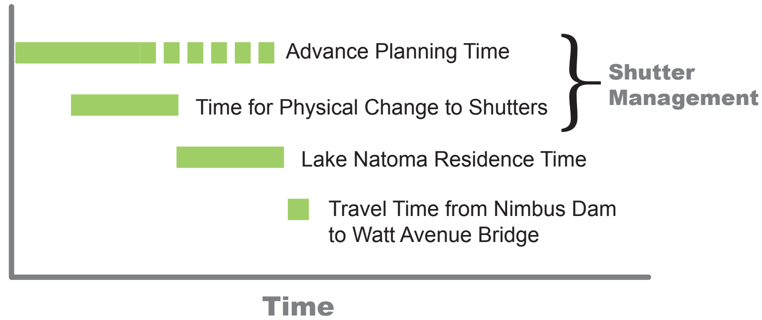
Configuration Blending: In any particular stepped shutter configuration, waters from different elevations released through powerhouse units are blended to achieve a desired tail bay temperature.

This blending operation considers needed tail bay water temperature, total release requirements from Folsom Dam, and water temperature at each shutter elevation. The fraction of water passing through each hydropower unit may change through time, even with the same shutter configuration, in response to the progression of water temperatures at each elevation. The outcome is a managed and relatively consistent tail bay water temperature. For example, using Configuration 1 from the previous page, Unit 2 is off and releases only through Units 1 and 3. Unit 1 has a higher shutter elevation, accessing warmer water in the blending operation. However, as the water temperature at Unit 1 increases through time, the percentage of total flow passing through Unit 1 is reduced, and the percentage of total flow passing through Unit 3 is increased to maintain a consistent tail bay water temperature (see below).



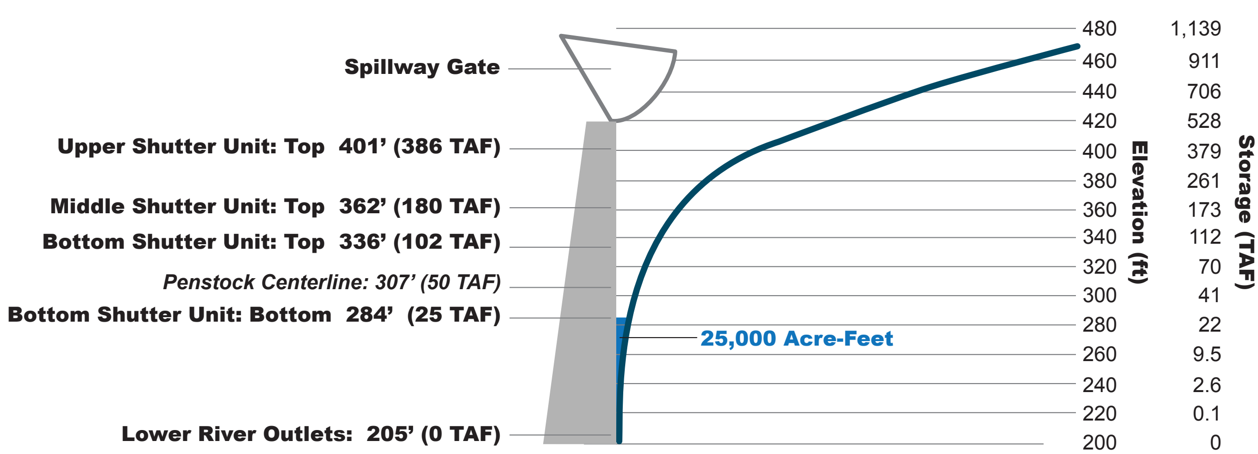
The rate at which blending proceeds for a specific configuration is a function of withdrawal rate of cold water from the reservoir, rate of reservoir heating, overall reservoir storage and thermal structure, head requirements over a particular shutter setting, and powerhouse availability. While the uppermost unit of shutters may have sufficiently cold water to meet the targeted tail bay temperature, head constraints may limit use of this unit. Inability to fully utilize the upper units can impact efficient use of cold water and create more challenges later in the temperature management season.

Shutter Management: Shutter removal is a one-way operation during a temperature management season. Specifically, shutters that are removed for temperature management purposes are not replaced until the next winter or spring. Unlike the Shasta Dam TCD, operating the shutter system on Folsom Dam requires considerable resources. The process of removing shutters is an intensive effort that involves use of heavy machinery, significant labor, and time. Therefore, coordinated, advanced planning is imperative. In temperature management strategy development, resource managers consider the advanced planning time, time required for physical change to shutters, residence time through Lake Natoma, and travel time between Nimbus Dam and Watt Avenue Bridge.



Lower River Outlet Use

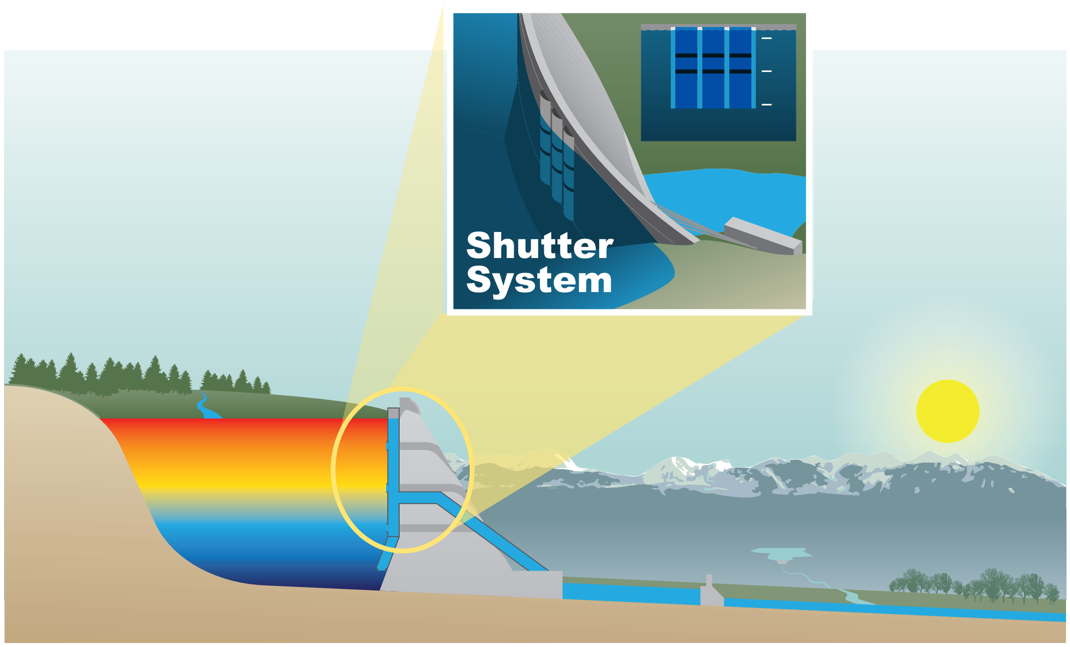
Under low storage or late season storage conditions, the lower river outlets can be used to bypass the powerhouses and release waters directly to Lake Natoma. This operation is used when available cold water in storage falls below the invert elevation of the shutter system (elevation 284 ft). Use of the low level river outlet can access a small amount of water (approximately 25,000 AF). Once a decision is made to utilize this lowest outlet, there are no additional temperature control measures available. Utilizing the river outlets translates to a limited period of cold water release, followed by loss of ability for temperature management. Late season forecasts of meteorological conditions are an important consideration to properly assess risks associated with initiating use of the river outlets to support a cold water bypass.



Note: All elevations and corresponding storage are in feet above mean sea level and thousand acre-feet (TAF).

Summary for the American River System

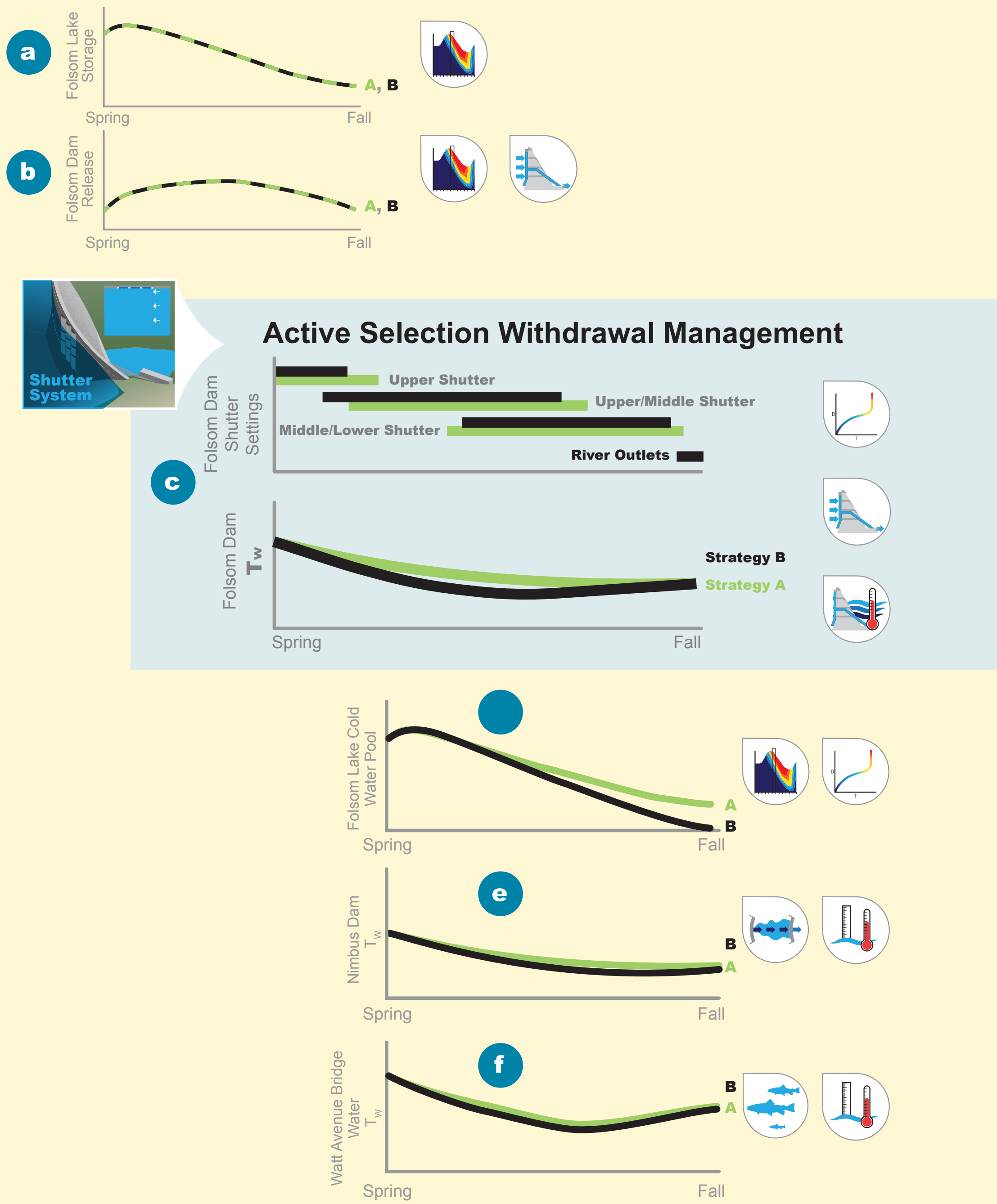
The shutter system is the essential facility to manage water temperature in downstream reaches of the American River. Shutter strategies and the associated progression of shutter settings (for temperature blending) through the temperature management season considers multiple factors and temperature related elements as well as natural variability.

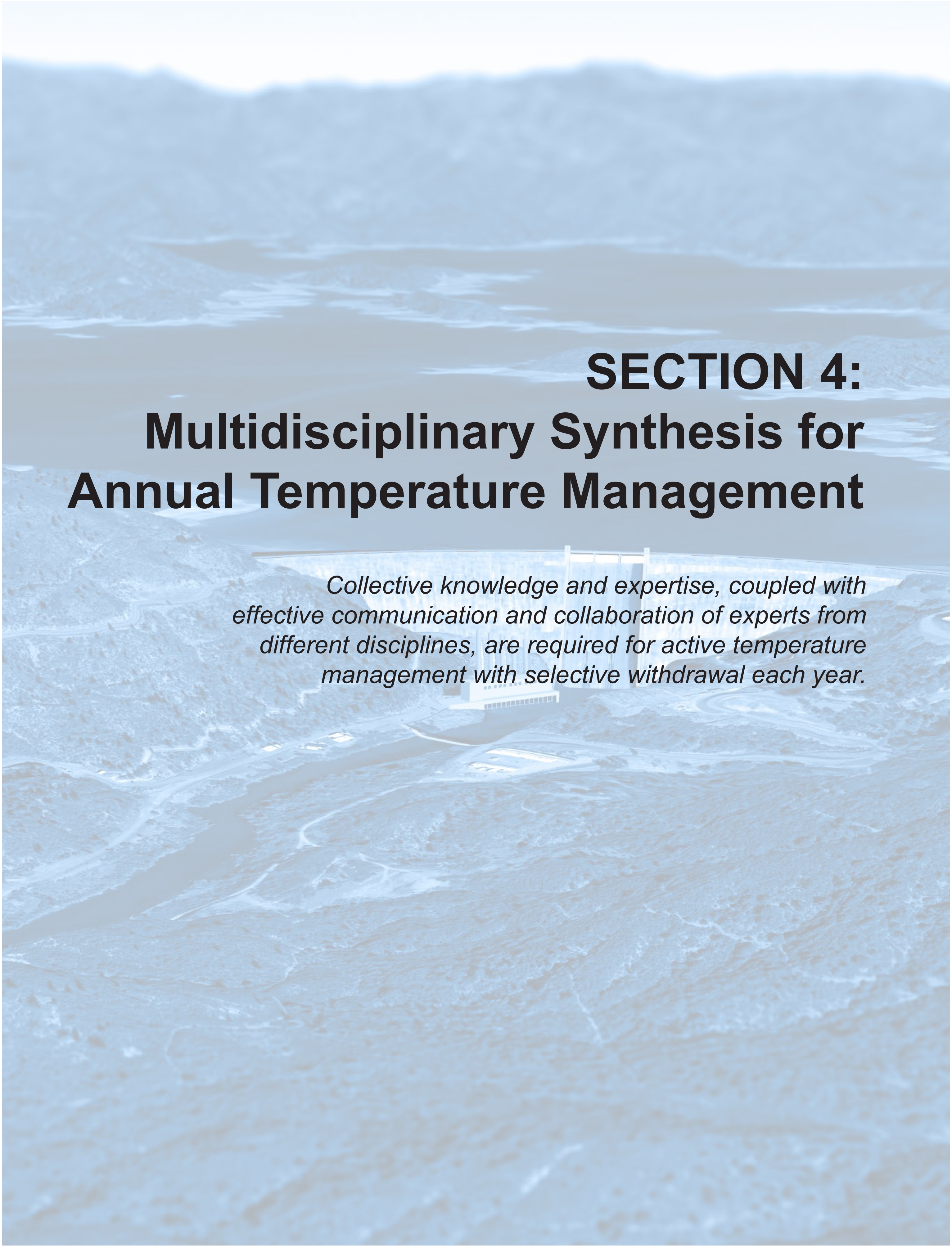


Alternative shutter system operational strategies result in different temperature management outcomes. Shutter system operational decisions that are made earlier in the temperature management season have direct ramifications on tail bay temperatures late in the season. Similarly, shutter system operations made in response to natural variations as the temperature management season progresses have a cumulative direct effect on tail bay temperature later in the season. Shutter options in late summer and fall, coupled with seasonal low cold water storage, can reduce the capability to manage the remaining available cold water volume. Similar to the summary in Section 2 for a generic system, a simple narrative with illustrations is presented on the next page, summarizing temperature management in the American River system for different selective withdrawal management strategies.

Temperature Management through Selective Withdrawal in the American River

Given equivalent storage conditions in Folsom Lake (a) and equivalent flow regimes from Folsom Dam (b), different shutter strategies yield alternative tail bay water temperatures (c). Different shutter strategies, coupled with natural variability, also result in different cold water pool utilization rates (d), Nimbus Dam tail bay water temperature (e), and downstream water temperatures in the American River at Watt Avenue Bridge (f).





SECTION 4: Multidisciplinary Synthesis for Annual Temperature Management

Collective knowledge and expertise, coupled with effective communication and collaboration of experts from different disciplines, are required for active temperature management with selective withdrawal each year.

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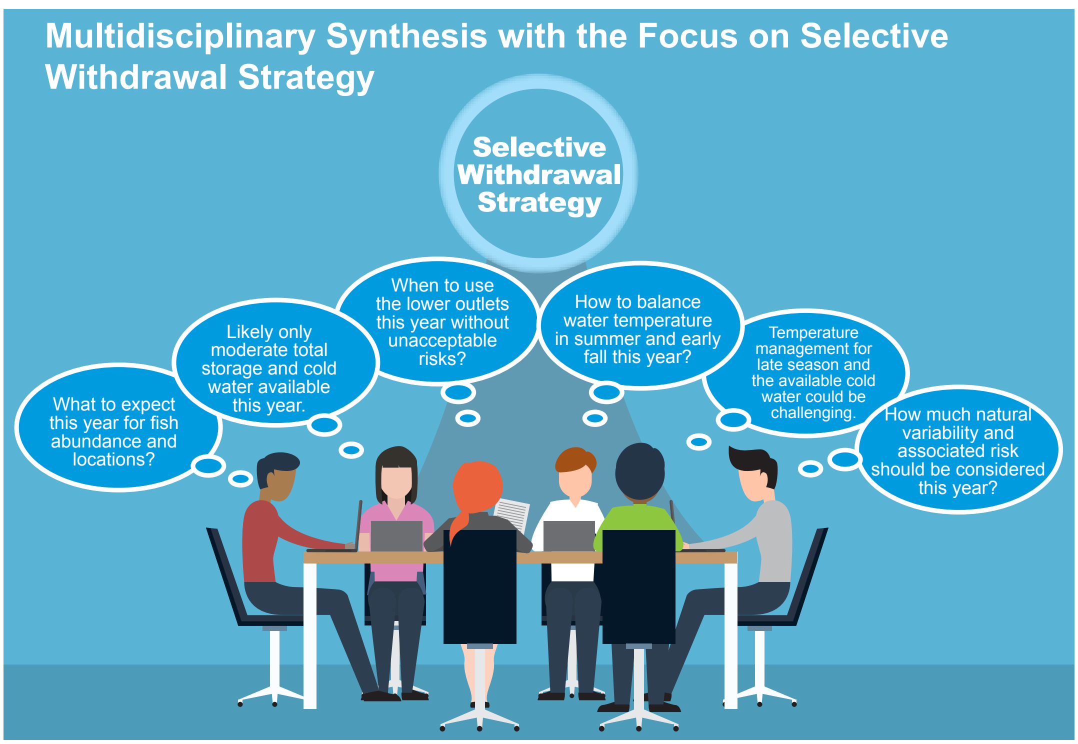
SECTION 4:Multidisciplinary Synthesis for Annual Temperature Management

A multipurpose reservoir equipped with selective withdrawal capability can provide a higher level of temperature management to meet downstream environmental objectives than reservoirs without such infrastructure. However, managing water temperature in reservoir-river systems through selective withdrawal can still be challenging due to intra-annual variabilities in hydrology and meteorology, variable operations and demands, and unforeseen events and circumstances throughout the year. A principal challenge is leveraging limited cold water resources to provide downstream temperature management for fishery species and their associated life-cycle stages, while considering other reservoir demands. Therefore, developing an effective annual temperature management strategy requires a broad range of experts that have common understanding of both basic physical and biological conditions of the system, and the potential functions and limitations of available selective withdrawal facilities. These experts must synthesize available information prior to and throughout temperature management season to update and refine temperature management strategies as conditions in the reservoir-river system change. This section presents a multidisciplinary synthesis by experts for annual temperature management.



The Critical Function of Multidisciplinary Synthesis

Multidisciplinary synthesis brings together a diverse group of people from various disciplines with specialized expertise to address challenging resource management problems. For multifaceted complicated reservoir-river systems like the Sacramento and American Rivers, a multidisciplinary approach is needed to effectively manage water temperatures in river reaches below the reservoirs.

As presented in previous sections, water temperature processes in reservoir-river systems are wide-ranging and multifaceted, and successful management requires collaboration and cooperation of experts from different disciplines. Development, implementation, and communication of selective withdrawal strategies that effectively use a limited cold water supply require:

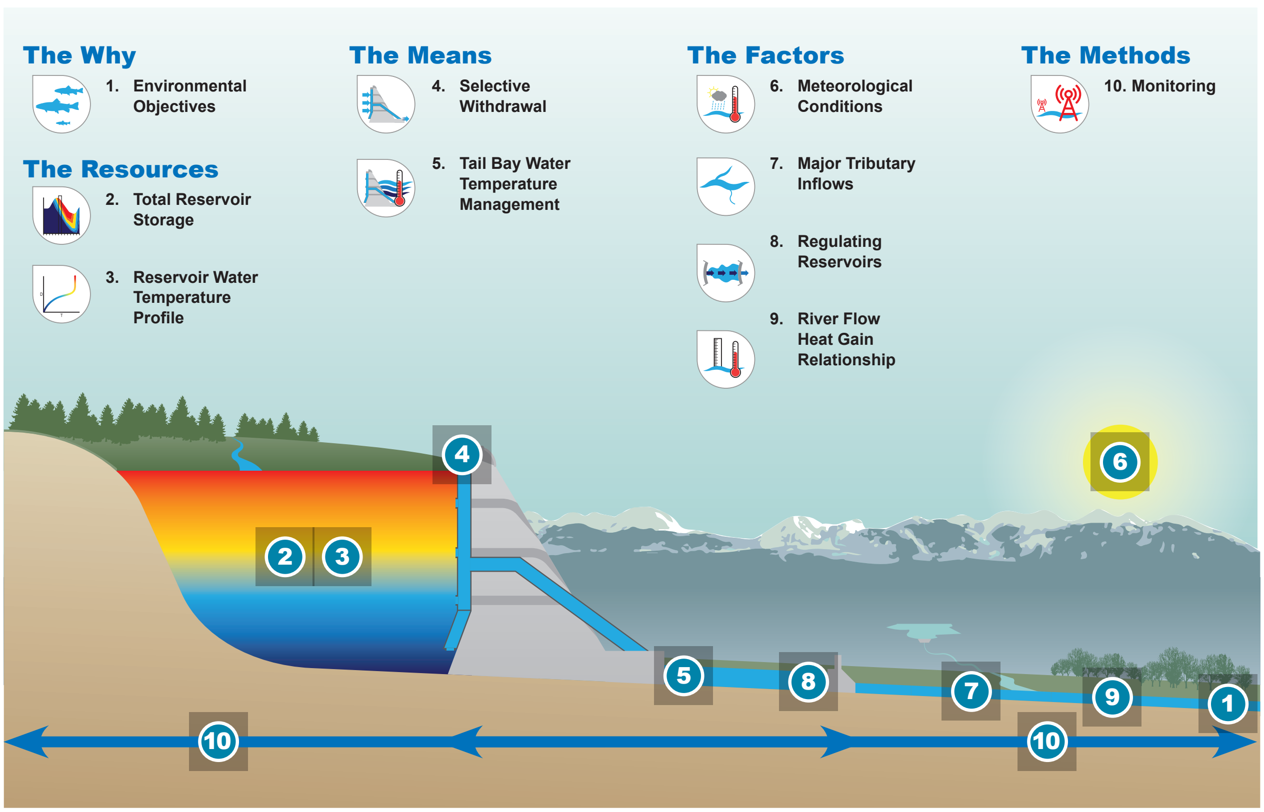
- A consistent group of experts with different backgrounds and subject-matter knowledge to collaboratively and cooperatively synthesize specific hydrology, meteorology, water temperature, fishery, and other information (both known and forecast) for the coming year.
- Synthesis of this information to develop an initial annual selective withdrawal strategy early in the temperature management season (i.e., April or May).
- Continued refinement of the initial selective withdrawal strategy based on newly available information and forecasted conditions throughout the remaining temperature management season (i.e., through October or November).

Shasta Dam and Lake. *Photo credit: Reclamation.*

Disciplinary Expertise and Knowledge in the Synthesis Process

Temperature management in reservoir-river systems contains many elements and an abbreviated overview of the graphic presented in Section 2 is shown below to highlight multidisciplinary expertise and knowledge necessary to synthesize these elements each year.

This expertise and knowledge can be separated into two major categories: (1) “Why,” representing environmental objectives (Element 1 in the illustration below), and (2) “How,” encompassing the other elements that potentially affect temperature management at downstream locations throughout the late-spring, summer, and fall (Elements 2 through 10 in the illustration below). The former category represents fish biology expertise and knowledge; the latter category represents physical science expertise and knowledge.

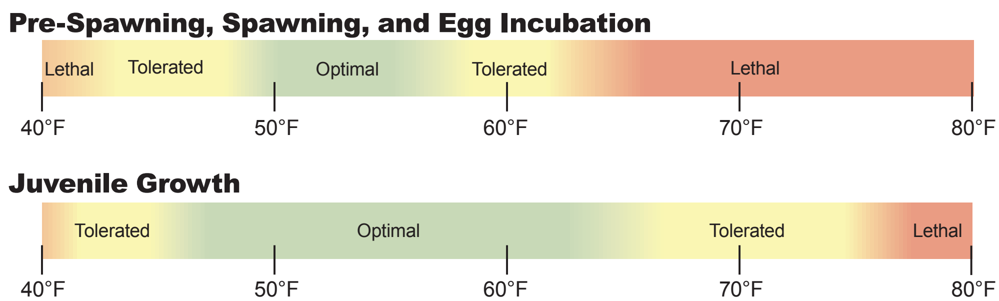


Fishery Biological Expertise and Knowledge

Fish biology expertise and knowledge necessary for temperature management in the Sacramento and American Rivers include consideration of thermal habitat management goals, seasonal timing of thermal management for key salmonids, and fish species abundance, and distribution. A discussion of representative types of information used by resource managers is presented below.

Thermal Habitat Management Goals

Management of aquatic habitat conditions recognizes that water temperature is one of the most important factors determining the geographic distributions, productivity, and survival of many aquatic species. Physiological, behavioral, and ecological responses of cold water fish, such as trout and salmon, to their thermal environment are commonly classified into “optimal,” “tolerated,” and “lethal” temperature ranges, are generalized below for many anadromous salmonids.

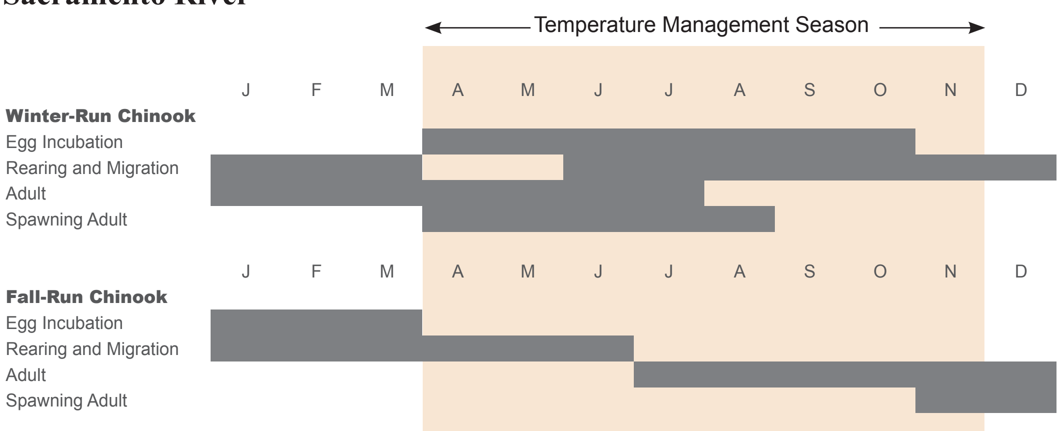


The “tolerated” and “optimal” temperature ranges for growth and survival vary over a species’ life cycles and are also partially dependent on accumulated thermal exposure history, nutrition, and health status of individual fish. However, these ranges are generally bounded by ultimate lethal temperature maxima and minima. Water temperature management must protect the most sensitive aquatic life use from short-term, acute exposure to lethal temperatures (i.e., lethal maxima and/or minima). These conditions must also protect against any deleterious effects of chronic exposure to stressful, but sub-lethal, temperatures outside the optimal range. Effective management maintains thermal regimes that promote overall health and productivity of populations, including suitable conditions for all life stages and requirements for growth and reproduction. **In this way, the management of water temperature in reservoir-river systems may be thought of as purposefully managing seasonal and spatial thermal gradients of aquatic habitats to achieve environmental objectives.**

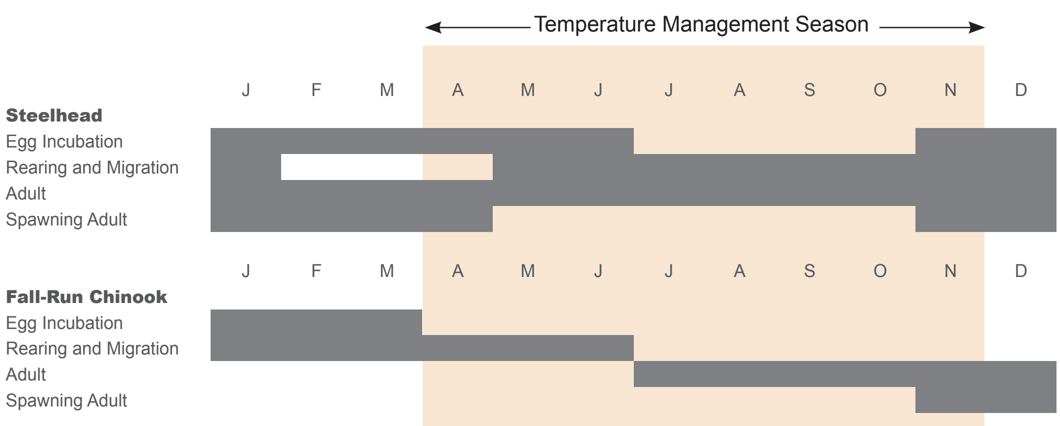
Seasonal Timing of Thermal Management for Key Salmonids

Freshwater life histories of fish are closely tied to the temperature regimes of the water bodies they inhabit. Salmonids are adapted to seasonal and spatial thermal heterogeneity and gradients of their environments. For cold water fish, such as salmonids, timing of reproductive cycles is closely correlated with seasonal water temperature patterns. In general, fishery managers identify the biologically-relevant temperature ranges or thresholds related directly to the most sensitive aquatic life stage during specific seasons and in specific stream segments of concern for temperature management purposes. Several fish species are present in the Sacramento and American River systems, and each species has its own unique lifestage and thermal preference. For illustrative purposes, the seasonal distribution of lifestages for two representative species in the Sacramento River (winter-run and fall-run Chinook salmon) and American River (steelhead and fall-run Chinook salmon) are shown below.

Sacramento River



American River



Population Abundance and Distribution

Selective withdrawal facilities are used to manage dynamic seasonal and spatial thermal gradients in reservoir-river systems to provide suitable habitat conditions for cold water fish populations in these altered river ecosystems.

Annual salmon and steelhead runs in the Sacramento and American Rivers can vary greatly from year to year, depending on a wide range of freshwater and oceanic conditions. Run timing and distribution of spawning in each river also vary each year, but are less variable than returning fish abundances. The spawning distribution in a river is affected by overall abundance of the returning adults and thermal conditions of the river as they migrate to the spawning grounds. In other words, spawning adults generally migrate to, congregate, and spawn in reaches with suitable cold temperatures, if available, at the time of spawning migration.

Adult and juvenile salmonids can and will respond to thermal gradients by moving to reaches exhibiting preferred temperature conditions, depending on life stage. In contrast, salmonid eggs and pre-emergent fry in riverbed gravel nests are not mobile, and their well-being and survival depend on the spawning location remaining in a suitable temperature range throughout the required egg and larval incubation period. These life history attributes, along with constraints and real-time information on each year's fish run timing and progression of freshwater life stage development, are important considerations for resource managers when developing initial annual selective withdrawal strategies and refining these strategies throughout the temperature management season.

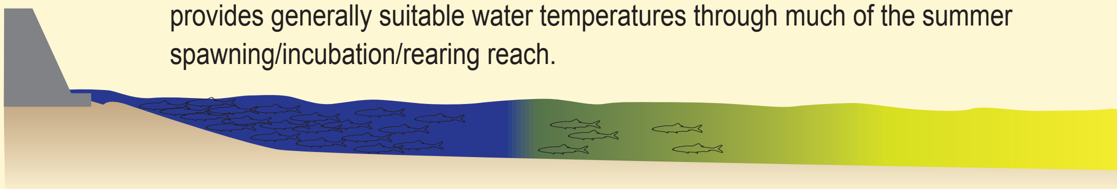
Sacramento River below Keswick Dam. *Photo credit: Reclamation.*

Dynamic Balance in Temperature Management for Fishery Needs

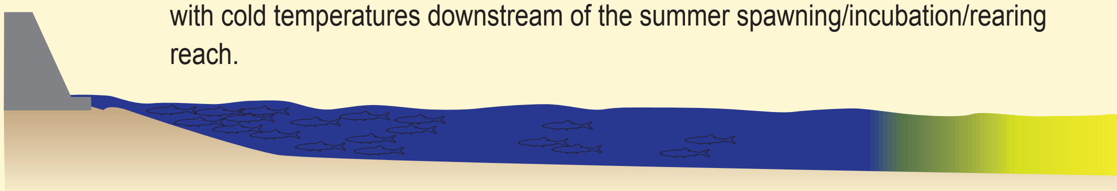
Managing downstream water temperatures with selective withdrawal to provide suitable thermal habitat conditions for one or more fish species or life stages may require dynamic balancing of available cold water supply in the reservoir throughout summer and into early-fall. Two scenarios with different strategies are presented below for illustrative purposes. The sequential choices in each strategy and their potential consequences are discussed by season.

Summer

Strategy A: Selective withdrawal is used to create a thermal gradient that provides generally suitable water temperatures through much of the summer spawning/incubation/rearing reach.

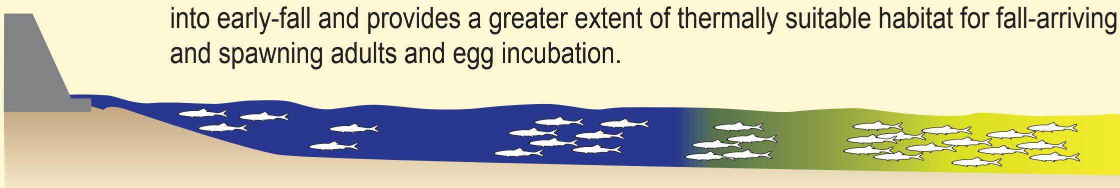


Strategy B: Selective withdrawal is used to provide a thermal habitat gradient with cold temperatures downstream of the summer spawning/incubation/rearing reach.



Fall

Strategy A: The conserved cold water from summer is available for release into early-fall and provides a greater extent of thermally suitable habitat for fall-arriving and spawning adults and egg incubation.



Strategy B: In early-fall, when ambient temperatures are still warm, there may be insufficient cold water supply remaining in the reservoir to provide cold temperatures throughout the spawning reach for fall-arriving and spawning adults and egg incubation.

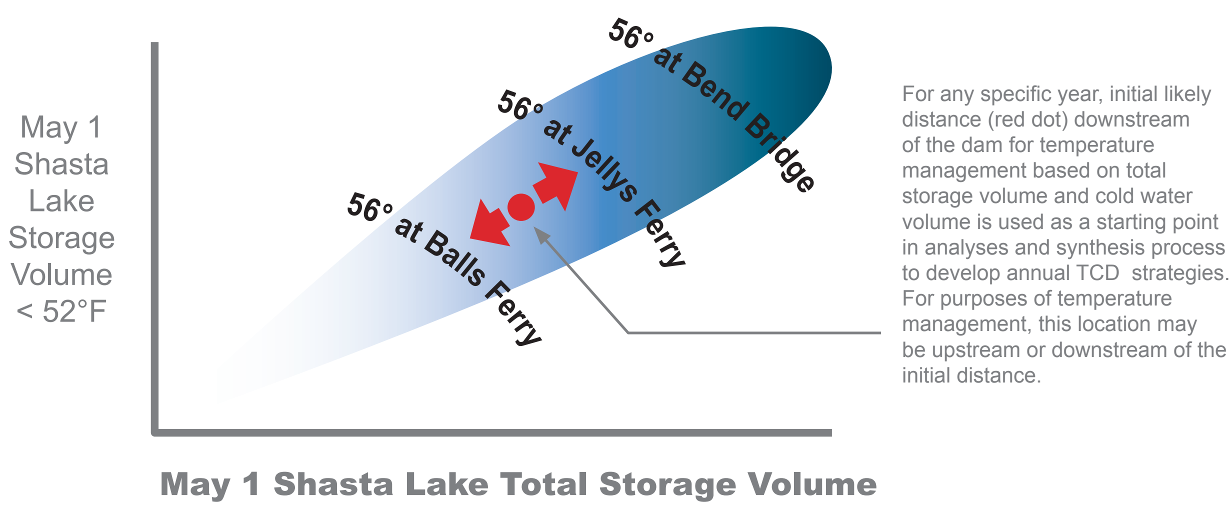
Physical Science Expertise and Knowledge

For temperature management throughout the season, fishery biological expertise and knowledge must be coupled with physical science expertise and knowledge on the "How" (i.e., how to address the resources, means, factors, and methods in managing water temperature for downstream environmental objectives). These theoretical and practical conditions were introduced in Section 2 and again in Section 3 where unique features and conditions for the Sacramento and American River systems were discussed in detail. For temperature management, several experts with specialized knowledge, along with additional tools, are needed. Herein, empirical relationships, mathematical models, and system-specific selective withdrawal facilities are presented as examples of how multiple disciplines bring physical science expertise and knowledge to bear on temperature management in the Sacramento and American River systems.

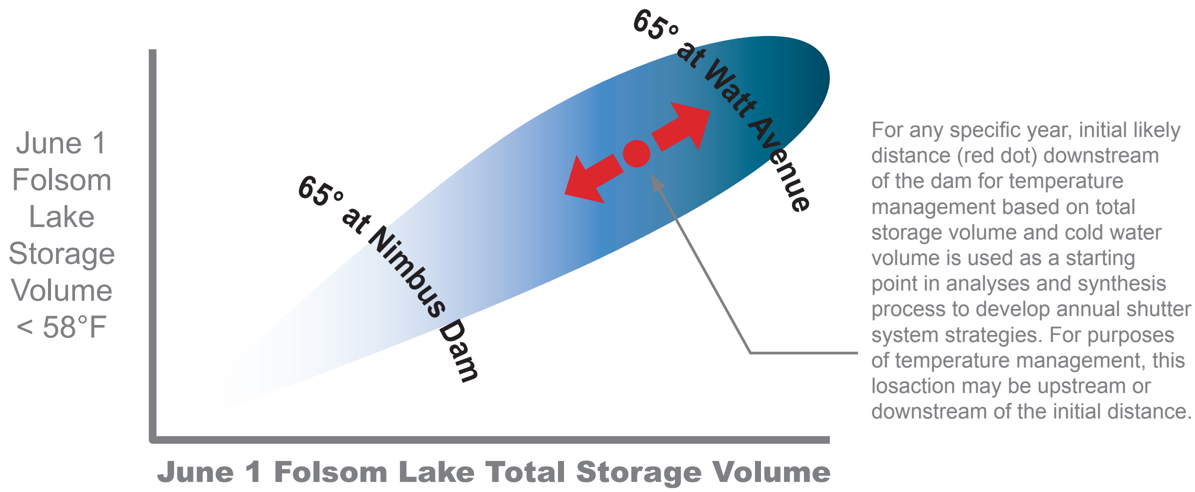
Empirical Relationships

Empirical relationships, sometimes termed "rules of thumb," are generally developed based on working knowledge of a particular reservoir and river, and are typically system and facility dependent. For example, an empirical relationship for a reservoir-river system might relate early season cold water storage to the distance downstream of the dam for temperature management. These initial assessments, combined with other information, are used in subsequent synthesis and analysis for developing an annual temperature management strategy.

Sacramento River: One rule of thumb used in the Sacramento River system relates May 1 Shasta Lake total storage volume and corresponding cold water volume (shown graphically below) to the likely distance downstream of the dam where temperatures can be managed throughout the season. Based on this initial assessment, resource managers conduct further analyses and synthesis to select the annual TCD strategy (e.g., Strategy A or Strategy B discussed in previous sections).



American River: A rule of thumb used in the American River system relates June 1 Folsom Lake total storage volume and corresponding cold water volume (shown graphically below) to the likely distance downstream of the dam where temperatures can be managed throughout the season. Based on this initial assessment, resource managers conduct further analyses and synthesis to select the annual shutter system strategy (e.g., Strategy A or Strategy B discussed in previous sections).



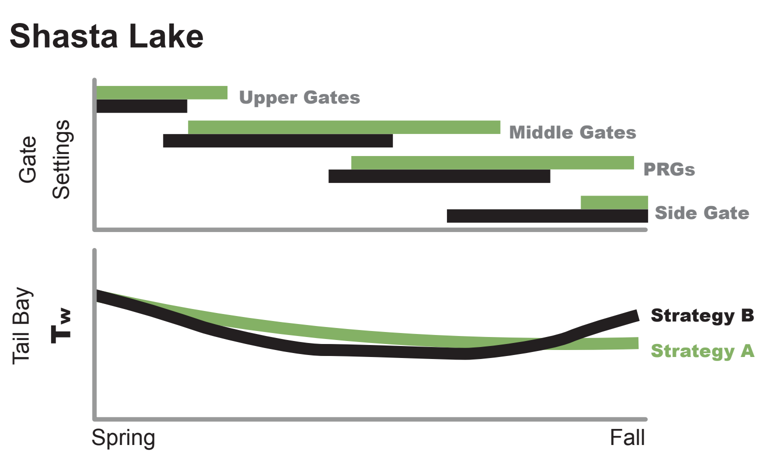
Mathematical Models and Computer Technology

Mathematical models are constructed to approximate the whole or parts of the actual reservoir-river system. Assembling the necessary information and applying models of large scale reservoir-river systems require making assumptions, estimates, and considerable data management. Continued advancements in computer technology (i.e., computer hardware and software) allow resource managers to utilize these powerful tools to analyze a wide range of temperature management strategies quickly and efficiently, and facilitate the communication of these strategies and their potential consequences more effectively. Mathematical models are used on both the Sacramento and American River systems to assist in developing alternative temperature management strategies. Modeling tools assist in communication and syntheses of information, but do not replace the expertise and knowledge of a multidisciplinary group of experts.

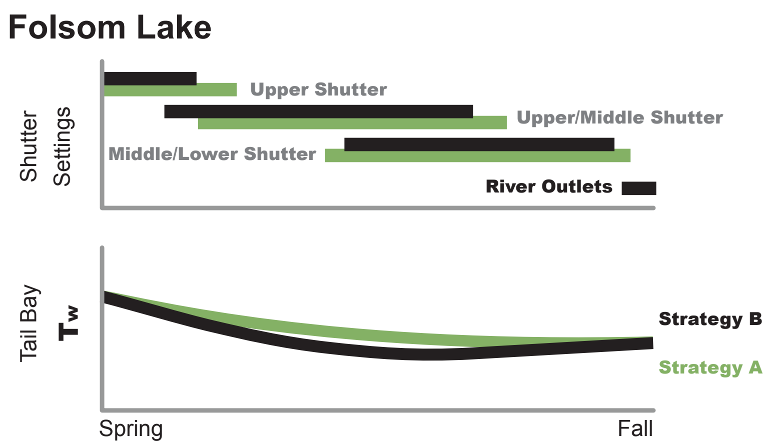
Temperature Management Strategy through Selective Withdrawal

The initial step in annual temperature management is to evaluate how, given early season conditions and information, alternative selective withdrawal strategies may impact water temperature throughout the season. As previously discussed in Section 3, different selective withdrawal facilities in the Sacramento River and American River systems provide different approaches and options for corresponding downstream temperature management. Outlined below are selected important considerations by multidisciplinary groups for initial strategy development.

Sacramento River System: Selective withdrawal strategy development on the Sacramento River system includes unique environmental objectives, Trinity River basin diversions, natural variability (e.g., seasonal tributary inflow and meteorology), and the TCD installed on Shasta Dam. Compared to other selective withdrawal facilities, the TCD provides considerable flexibility, including many possible alternative gate progressions and a side gate at a low elevation for accessing the deepest, coldest water in the reservoir. A specific additional consideration associated with the TCD in initial strategy development is the overall seasonal gate progression, including timing of side gate initiation and access to the upper gates early in the water temperature management season (see Section 3 for details). These particular elements have direct impacts on strategy development, overall TCD performance, and season-long temperature management (see figure below).



American River System: Selective withdrawal strategy development on the American River system includes unique environmental objectives, natural variability (e.g., meteorology), and the shutter system installed at Folsom Dam. The shutter system installed on Folsom Dam to facilitate selective withdrawal is different than the TCD at Shasta Dam, with operational considerations and fewer selective withdrawal options due to Folsom Lake having a substantially smaller volume than Shasta Lake. The shutter system has additional hydraulic constraints in requiring sufficient excess water above the shutter intake level (see Section 3). Unlike the TCD side gate, Folsom Dam has a low level river outlet for tapping into the coldest water behind the dam as a last resort. These system-specific considerations, coupled with the generic temperature control elements, illustrate the need for multidisciplinary synthesis of a broad range of information to effectively develop an initial annual temperature management plan, and implement and update that plan through the temperature control season.



Synthesis for Annual Temperature Management Strategy through Selective Withdrawal

A multidisciplinary group of experts that understands the critical utility of selective withdrawal capabilities in the reservoir-river system of interest are the heart of the synthesis to produce an annual temperature management strategy. This synthesis includes development of an initial annual strategy and subsequent updates and refinements throughout the temperature management season.

Initial Annual Strategy

In April or May of a given year, the multidisciplinary group of experts collaborates to synthesize available data, information, analyses, and forecasts to develop an initial temperature management strategy for the entire temperature management season. Different strategies are outlined in an annual temperature management plan, including the location, targeted temperature, selective withdrawal strategy (e.g., Strategy A or B), and associated gate progression. The annual temperature management plan also includes the timing and sequence of seasonal planning process for data, tools, and strategy updates, as needed.

Strategy Updates and Refinements

A well-developed initial annual strategy is the cornerstone for purposeful management of temperature in downstream river reaches throughout the season. However, as time progresses, the multidisciplinary group of experts has access to updated information, including actual downstream flow, temperature and fishery conditions, updated hydrologic and meteorological forecasts, and the remaining cold water pool volume and other reservoir conditions. Experts periodically review the continued validity of the initial annual strategy and provide refinements for the remaining season. This process uses the same level of collaboration in synthesizing new and updated data, information, analyses, and forecasts. More frequent reviews may be necessary later in the season, as cold water resources are depleted and temperature management options are reduced. The experience from collaboration and synthesis in formulating the initial strategy and ongoing refinements is cumulative, contributing to annual temperature management efforts in future years.

High storage condition in Folsom Lake in February 2017. *Photo credit: Yung-Hsin Sun; used with permission.*

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Bureau of Reclamation
Mid-Pacific Region