DEVELOPMENT OF TUOLUMNE RIVER FLOW AND TEMPERATURE WITHOUT DAMS MODEL

Prepared For
Turlock Irrigation District
Modesto Irrigation District

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Executive Summary

The focus of the Tuolumne River Flow and Water Temperature Modeling "Without Dams" assessment was to develop a flow and water temperature model to simulate water temperatures in the Tuolumne River without the existing Hetch Hetchy reservoir, Don Pedro reservoir, or La Grange headpond. The model was created to complement detailed modeling for Don Pedro reservoir and La Grange headpond and the lower Tuolumne River. Supporting data included the development of long-term flow and meteorological conditions to assess flow and water temperature conditions over a multi-decade period – 1970 to 2012. Thus, with dams and without dams conditions could be examined for a variety of hydrologic and meteorological conditions. Such comparisons include flow and water temperature, including water temperature metrics such as daily mean, maximum and minimum, as well as 7DADM and MWAT. While assessment of potential water temperature objectives was a consideration in model development, this project element did not include the task of model comparisons. However, the model was developed to provide sub-daily flow and water temperature at a fine spatial scale to allow the development of sub-daily metrics.

The study area included the main stem of the Tuolumne River from above Hetch Hetchy Reservoir to the confluence with the San Joaquin River. Tributary flows include Cherry Creek, the South Fork Tuolumne River, Clavey River, and North Fork Tuolumne River, as well as minor tributaries. Located between Hetch Hetchy Reservoir and the San Joaquin River confluence are Don Pedro Reservoir and Don Pedro Dam. Two miles further downstream is La Grange Diversion Dam, which diverts flows to Turlock and Modesto Irrigation Districts. Below La Grange Diversion Dam, the Tuolumne River flows approximately 50 miles to the confluence with the San Joaquin River – a total of approximately 130 river miles.

The modeling study in its simplest form included four major components: development of a conceptual framework, model selection, model development, and model application. The development of the conceptual framework provided focus and direction of the modeling study comparing with and without dams conditions on Tuolumne River flows. During the model selection phase, a review of appropriate computer models occurred that resulted in the selection of RMA-2 and RMA-11 for analysis and comparison. An equilibrium analysis was applied to develop near-term and long-term tributary inflow water temperatures to augment the flow and meteorological data sets. An approach based on a shade model used by Oregon Department of Environmental Quality was employed for use with RMA-11 to assess effects of riparian shading, part of which required estimating pre-dam conditions in currently inundated reaches.

Model development was further divided into several major processes: data development and implementation, calibration, and sensitivity analysis. During the data development process, the flow, temperature, geometry, and meteorological data from 1970 to 2012 were reviewed and formatted for model use. Model implementation included developing the initial model conditions, modifying the software as needed, and specifying the model parameters. Once the data was developed and the model setup, the calibration phase began. During this phase, model parameters (e.g., Manning's channel roughness,

evaporation coefficients) were adjusted to reduce the difference between simulated and observed data for both flow and temperature. Model performance at the calibration locations was assessed both graphically and statistically. A general sensitivity analysis was performed to assess the models' response to changes in selected model parameters. The final study phase was model application.

Implementation and calibration produced the Tuolumne River flow and temperature (TRFT) model that reproduced flow and temperature through a range of inter-annual, seasonal, short duration, and diel conditions with overall low bias, mean absolute error, and root mean squared error. The subsequent application of the TFRT model to the long-term data set (1970 to 2012) provided a remarkably rich temporal and spatial representation of the Tuolumne River – simulated hourly water temperature at approximately 100-foot intervals throughout the study reach for 42 years. These data are now available to develop a range of statistical measures useful for assessing anadromous fish conditions in the system, including flow duration curves; daily minimum, mean, and maximum temperature; seven-day averages of the daily maximum and means; and examination of these metrics by hydrologic year type. Examples were provided to illustrate the application of simulated temperature in development of these metrics. A data library of electronic files accompanies the final report.

Development of Tuolumne River Flow and Temperature Without Dams Model

1. Introduction

Turlock Irrigation District and Modesto Irrigation District (TID/MID) own and operate the Don Pedro Project and La Grange Diversion Dam on the lower Tuolumne River. The Don Pedro Project is currently undergoing relicensing by the Federal Energy Regulatory Commission (FERC). As part of a wide range of ongoing studies for relicensing, the TID/MID Districts are developing reservoir and river temperature models (HDR 2012) to characterize the thermal regime of Don Pedro Reservoir and downstream reaches of the Tuolumne River. FERC has determined that Environmental Protection Agency (EPA) water temperature guidelines apply to the lower Tuolumne River, unless other empirical information can be developed to inform potential alternative water temperature criteria as allowed under EPA (2003) guidelines.

To assess the potential for alternative water temperature criteria, Watercourse Engineering, Inc. (Watercourse) developed a water temperature model to simulate water temperature in the mainstem Tuolumne River, from above Hetch Hetchy Reservoir to the confluence with the San Joaquin River, without the Don Pedro Project and the Hetch Hetchy reservoir and La Grange headpond. The "without dams" condition is intended to represent a river with no reservoirs or regulation within the project area, but not intended to be a "pre-development" representation. That is, efforts to recreate pre-development conditions were not explicitly considered (e.g., existing conditions were used to describe stream geometry in existing free flowing reaches). Simulated water temperatures will be used to develop specific metrics to compare "without dams" (WOD) conditions to "with project" (WP) conditions, as represented by TID/MID (2017) in the Tuolumne River below La Grange Diversion Dam.

While model development and application were completed by Watercourse, the project was largely a team effort with HDR, Inc. (HDR), which developed key data sets (i.e., meteorology, unimpaired hydrology, and geometric configurations of currently inundated stream reaches). Further, Watercourse and HDR communicated frequently regarding approaches, assumptions, and schedule.

2. Background

The purpose of this effort was to develop a water temperature tool that was capable of representing a "without dams" condition to compare with existing conditions. Developing a "without dams" condition required careful considerations because, unlike developing a model for an existing system, field data were unavailable to formulate and test aspects of the model. For this project, stream alignments, reach gradients, and cross-section morphologies under Don Pedro and Hetch Hetchy reservoirs were not readily available, nor were unregulated stream flows or associated water temperatures for headwater or tributary inputs. The development of these and other data, along with basic assumptions and approaches in model development, testing, and evaluation of outcomes, are based on available data, first principles based on theoretical concepts and representations, as well as experience in the Tuolumne River and other basins. First principles include using physically based flow and water temperature models founded in the fundamental laws of conservation of mass, momentum, and energy; developing basic data using best available information and techniques; and considering theoretical concepts of flow, heat transfer, and the fate and transport of heat energy in stream systems. Experience in other basins includes similar "without dams" simulations in the Klamath River and in the Middle Fork American River, where similar hydropower relicensing efforts were analyzed.

Outlined briefly herein are the study area and previous work in the study area.

2.1. Study Area

The Tuolumne River is the largest tributary watershed to the San Joaquin River system, with an area in excess of 1,900 square miles[1]. The range of elevations extends approximately 30 feet at the confluence with the San Joaquin River to 13,000 feet at Mt. Lyell in Yosemite National Park (Epke *et al.* 2010, Mount 1995). Mean annual runoff is 938 thousand acre-feet (TAF) at Modesto, 757 TAF below La Grange Diversion Dam, and 280 TAF below O'Shaughnessy Dam near Hetch Hetchy (Table 1). Summers are typically warm and dry, and winters cool and wet. Average annual watershed precipitation is 38 inches[2], the bulk of precipitation occurs in winter with rain at lower elevations and snow at the higher elevations.

Table 1. Tuolumne River mean annual flow at Modesto, La Grange, and Hetch Hetchy for the period 1971-2011[3].

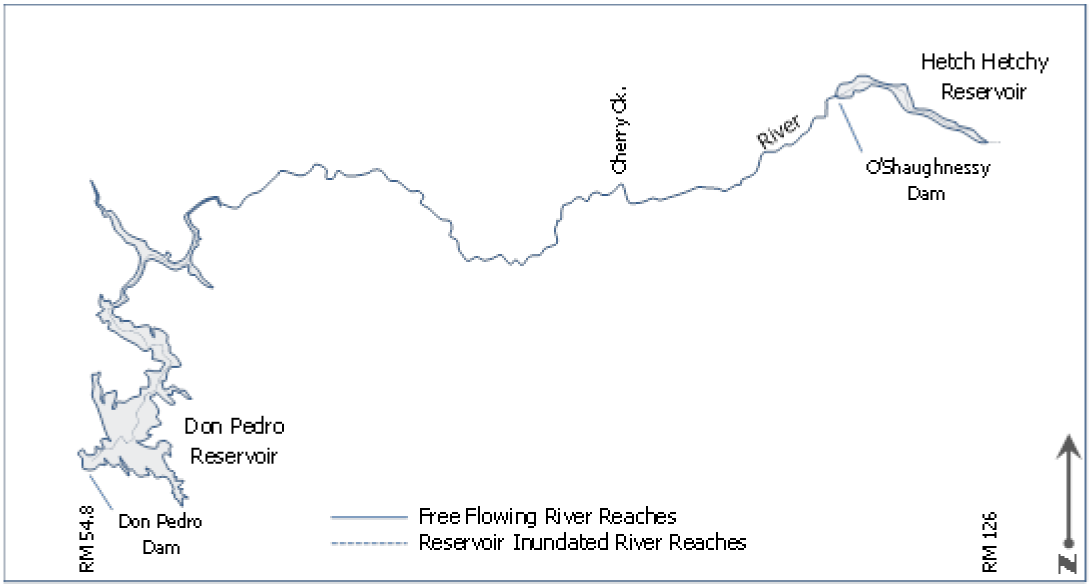
Name	Gage #	Mean annual flow (cfs)	Mean annual flow (TAF)
Tuolumne River at Modesto, CA	1129000 0	1,296	938
Tuolumne River below La Grange Diversion Dam near La Grange, CA	1128965 0	1,045	757
Tuolumne River Near Hetch Hetchy, CA	1127650 0	387	280

The project study area includes the mainstem Tuolumne River from above Hetch Hetchy Reservoir to its confluence with the San Joaquin River. Throughout this reach, the Tuolumne River receives notable tributary flow contributions from Cherry Creek, South Fork Tuolumne River, Clavey River, and North Fork Tuolumne River, as well as flow from numerous minor tributaries. About halfway between Hetch Hetchy Reservoir and the San Joaquin River confluence is Don Pedro Reservoir, formed by New Don Pedro Dam. Approximately two miles downstream of New Don Pedro Dam is La Grange Diversion Dam, which provides a means for diversion of irrigation and municipal and industrial water to Turlock and Modesto Irrigation Districts. Below La Grange Diversion

[1] http://streamstatsags.cr.usgs.gov
[2] http://streamstatsags.cr.usgs.gov
[3] http://waterdata.usgs.gov

Dam, the Tuolumne River flows approximately 50 miles to its confluence with the San Joaquin River.

For this project, the river is represented by two separate reaches: upper and lower Tuolumne River (Figure 1). The upper Tuolumne River reach extends from the present-day headwater of Hetch Hetchy Reservoir (River Mile (RM) 126) to the present-day headwater of Don Pedro Reservoir (RM 79). The lower Tuolumne River reach extends from the present-day headwater of Don Pedro Reservoir to the San Joaquin River confluence (RM 0). Dividing the model domain into two portions was, in part, necessitated by project schedule demands and the disproportionate amount of data in the two reaches. Modeling the two reaches discretely allowed project work to progress on the lower Tuolumne River, while data were being developed in the upper reach. For analysis, the model was run in two steps, with the upper reach output providing input to the lower reach.



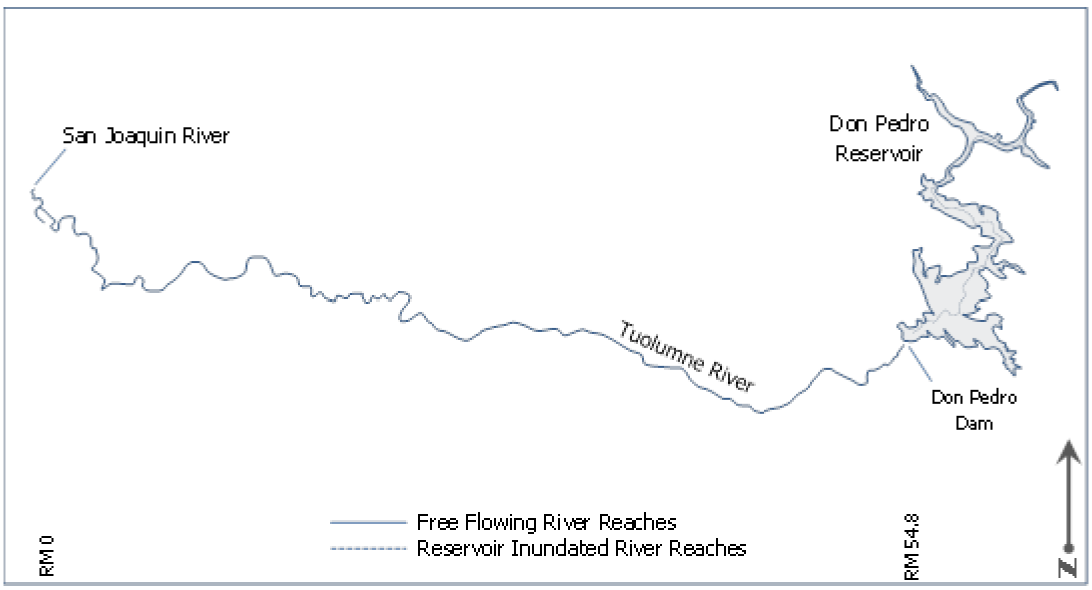


Figure 1. Project Area above Don Pedro Dam (top) and below Don Pedro Dam (bottom) (not to scale).

2.2. Previous Work

Recent water temperature modeling work in the study area includes studies in the reach between O'Shaughnessy Dam and Early Intake (Jayasundara *et al.* 2010) and studies of Don Pedro Reservoir and the lower Tuolumne River (TID/MID 2017, Dotan *et al*. 2013, Stillwater 2011, AD Consultants 2009, RMA 2007). For stream reaches, all of these efforts have focused on one-dimensional model representations of longitudinal temperature gradients with laterally and depth-averaged conditions. However, spatial and temporal resolution varied by study. Jayasundara *et al.* (2010) modeled the stream on a 25-meter spatial resolution with hourly time steps. TID/MID (2017) used a spatial resolution of approximately one-mile, with hourly time steps. Dotan *et al.* (2013), Stillwater Sciences (2011), AD Consultants (2009), and RMA (2007) all employed the

U.S. Army Corps of Engineers HEC-5Q model with a 6-hour time step and a spatial resolution of one-half to one-mile. All of these efforts modeled flow impaired conditions in the Tuolumne River.

The modeling effort for this project adopted a similar sub-daily time step (hourly) and directly built off of these previous efforts, through use of available field data, assumptions, and modeling parameters; or indirectly through review and interpretation of previous findings and results.

3. Modeling Approach

The modeling approach developed for this project includes a process of serial steps, or phases, to select an appropriate model, identify necessary data, implement and calibrate a model, and ultimately apply the selected model (Figure 2). Because the intent of this modeling study was to develop a model of a hypothetical river system without dams, a conceptual framework was also developed. This conceptual framework provided a means to cross-check the model's water temperature representations and model results with established theoretical understanding of river systems. Both the selection of the model and the development of the conceptual framework occur "pre-model" (i.e., before the development of the model begins). The information identified in the conceptual framework was considered throughout the modeling process.

Once the model was selected, the model development and calibration phase commenced. Within this phase, the necessary data was developed and the model was implemented, calibrated, and sensitivity analyses were completed. The completed model was then applied to assess the without dams condition. Each phase in the modeling approach is described below (Section 4 through Section 8).

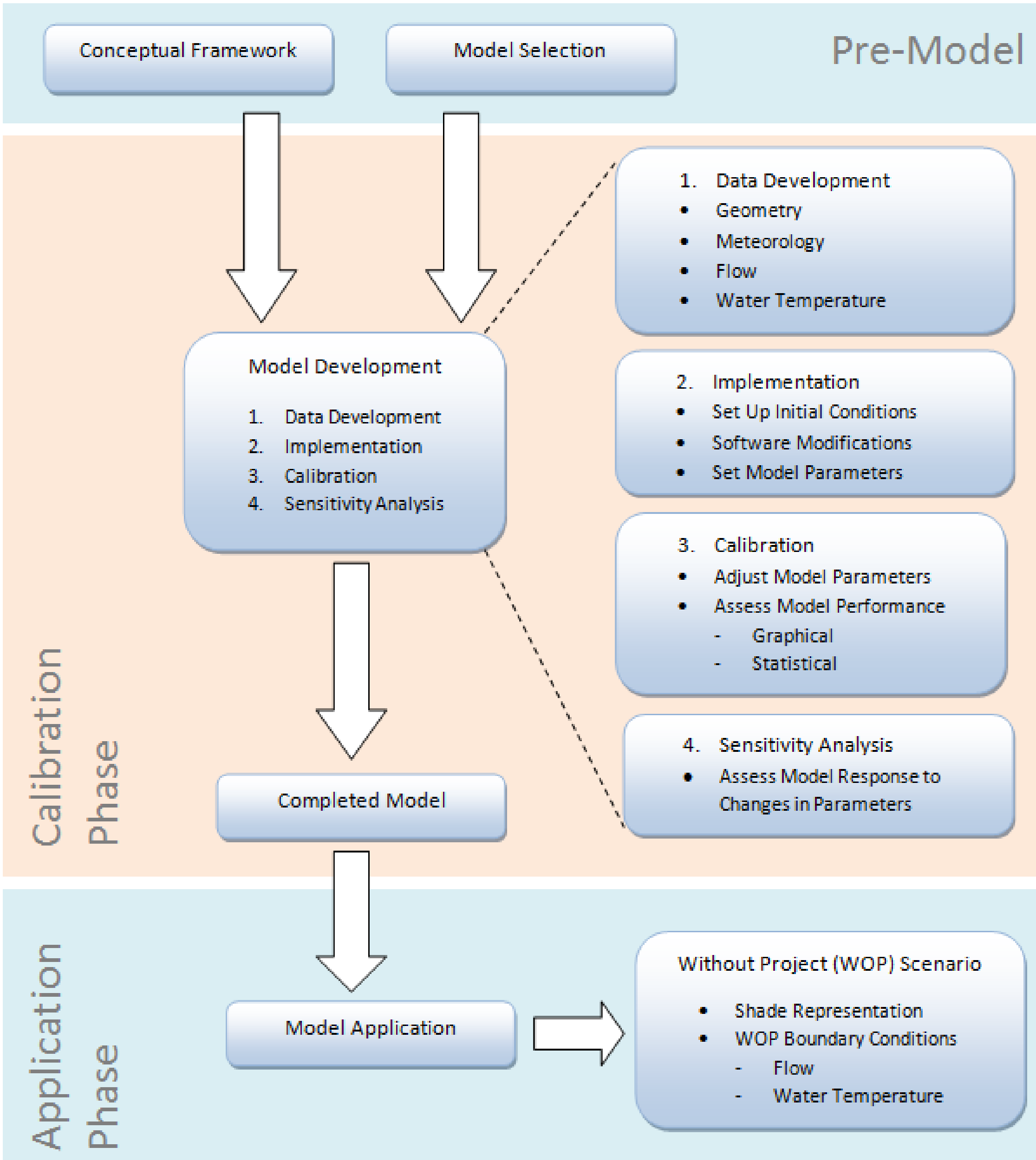


Figure 2. Modeling process flowchart.

4. Model Selection and Conceptual Framework Development (Pre-Model Phase)

The "pre-model" phase includes a review and selection of available models and the development of the conceptual framework.

4.1. Model Selection

Based on the project objective and fundamental attributes of the system, appropriate models were evaluated for use. A brief review of applicable riverine flow and temperature models are summarized in Table 2. Several attributes of the models were compared to assess the appropriateness of each model for the proposed project. In selecting a model, the following attributes were considered:

- Robust hydrodynamics. A model must be able to replicate variable flow conditions on a short time step (e.g., hourly) to assess potential implications of dynamic flow conditions in steep river reaches (i.e., robust hydrodynamics).
- Longitudinal temperature gradients. These are important in assessing temperature via the fate and transport of heat energy.
- Sub-daily temperatures. Sub-daily temperatures are desirable to identify not only mean daily conditions, but also minimum and maximum daily temperatures to develop metrics for anadromous fish assessment and regulatory considerations.
- Shade. Topographic and riparian shade may both be important factors in water temperature response.

Further, only models with open-source code (i.e., code that is accessible for user review and modification) that is actively supported by the model developer or sponsor were included in this evaluation. Neither this list, nor the criteria identified above are considered comprehensive; rather, this information is intended to provide general background information on potential models and the feasibility of applying a numerical model to the Tuolumne River.

The absence of a particular attribute is not considered a fatal flaw because certain processes can be added to the model (e.g., topographic or riparian shading). Nonetheless, as indicated by comparison of attributes, river models most suitable to this project include the Tennessee Valley Authority (TVA) set of models, Heat Source, HEC-RAS, and the RMA models.

Table 2. Comparison of model attributes.

	TVA	QUAL-2K	WASP	HSPF	Heat Source	SNTEMP	RMA2/ RMA11	CE-QUAL-RIV1	CE-QUAL-W2	HEC-RAS
Author/ Sponsor	Tennessee Valley Authority	EPA	EPA	USGS	Oregon Dept of Envir. Quality	USGS	RMA	U.S. Army Corps	U.S. Army Corps	U.S. Army Corps
System	River	River	River	River	River	River	River	River	River/ Reservoir	River
Dimension	1	1	1,2,3	1	1	1	1,2	1	1,2	1
Dynamic Flow Model	Yes	No	Yes*	No	Yes	No	Yes	Yes	Yes	Yes
Boundary Condition	P,NP	P,NP	P,NP	P,NP	P,NP	P	P,NP	P,NP	P,NP	P
Topographic Shade	No	No	No	Yes	Yes	Yes	Yes	No	Yes	No
Riparian Shade	Yes	No	No	Yes	Yes	Yes	Yes**	No	Yes	No
Time Step	Sub-daily	Sub-daily	Sub-daily	Sub-daily	Sub-daily	Daily	Sub-daily	Sub-daily	Sub-daily	Sub-daily
Actively Supported	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pre-Processor	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Post-Processor	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Open Source Code	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Documentation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

* Requires a hydrodynamic model (e.g. Dynhyd).
** There is a version of RMA-11 that includes riparian vegetation shading for the one-dimensional formulation.

While each of these models have strengths and weaknesses, the RMA-2 and RMA-11 suite of models was identified as the most robust system capable of meeting project needs and schedule. Further, these models have been applied successfully to the Tuolumne River in simulations below Hetch Hetchy over a wide range of flows (Jayasundara *et al*. 2010). The RMA models were chosen for this project because of their ability to model both flow and temperature in this extremely steep reach, the relatively short run times required, their capacity to report sub-daily water temperature, and the relatively minor modifications needed to represent the river system.

The RMA models, RMA-2 (v8.0) for hydrodynamics and RMA-11 (v8.0) for water temperature, represent the Tuolumne River in a one-dimensional, depth-averaged, finite element scheme. The utility application RMAGEN (v7.4) was used to create a geometry file of the Tuolumne River that was used by both the hydrodynamic and water temperature models. RMA-2 calculates velocity, water surface elevation, and depth at defined nodes of each grid element in the geometric network representing the river. In this project, the model was applied in one-dimensional, laterally and depth-averaged form. RMA-11 is a companion finite-element water quality model that uses depth and velocity results from RMA-2 to solve advection and diffusion equations of constituent transport. Details of each of these models are provided below.

4.1.1. RMAGEN

RMAGEN is a pre-processor program used to construct the numerical mesh used in RMA-2 and RMA-11. RMAGEN assigns spatial information to each node within a mesh (x-y location and elevation), or network, interpolating values from available topographic data. In a one-dimensional model, the mesh consists of linear elements of variable size. Each element consists of three nodes – one at each endpoint and one middle node. Cross-sectional information for each endpoint is specified in tabular form, representing a river cross section as layers of fixed thickness that vary with width. This format is depicted graphically in Figure 3.

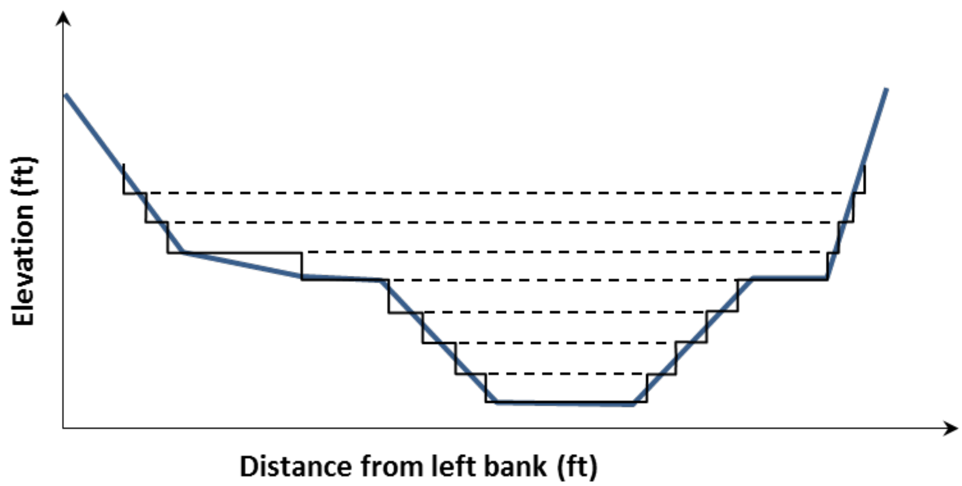


Figure 3. Example of a cross-sectional detail in model representation of channel geometry.

4.1.2. RMA-2 Model

RMA-2 is a finite-element hydrodynamic numerical model that can also be applied in either one (laterally and depth-averaged) or two (either laterally or depth-averaged) dimensions. The model computes water surface elevations and horizontal velocity components for free-surface flow fields. Model formulation is based on a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady (dynamic) flow problems can be analyzed with this model. RMA-2 is a general purpose model designed for far-field problems in which vertical accelerations are negligible and velocity vectors generally point in the same direction over the entire depth of the water column at any instant of time. For complete details about RMA-2, see King (2008).

4.1.3. RMA-11 Model

RMA-11 is a finite-element water quality model capable of simulating one- and two-dimensional approximations to systems either separately or in combined form. The model is designed to accept velocities and depths, either from an ASCII data file or from binary results files produced by RMA-2, and to use these values in solution of the advection-diffusion equations of constituent transport. The model can represent sources, sinks, growth, or decay, for a number of water quality constituents. Only water temperature, the dependent variable in heat transport, was simulated for this study. The heat budget approach employed in simulating water temperature in RMA-11 is consistent with QUAL2E (Brown and Barnwell 1987) and other literature and assumes that heat is transferred from various energy sources in a complete heat budget formulation (See Equation 1). Water temperature results are both laterally and depth-averaged and can be viewed in both graphic and tabular forms. For comprehensive details about RMA-11, see King (2008).

4.2. Conceptual Framework for Temperature Representation

Water temperature dynamics in riverine systems, such as the Tuolumne River, depend on several independent factors including meteorological conditions, flow and hydrodynamic conditions, riparian vegetation, topographic shading and sheltering, geomorphology of the system, and more. This section reviews general concepts of water temperature and heat transfer in a riverine environment.

Concepts of heat budget will be introduced, describing how heat energy enters the aquatic system across the air-water and bed-water interface and how these processes are driven by meteorological conditions and water and bed temperatures. The concept of dynamic equilibrium temperature is introduced to describe the fate of heat energy in a system and how geometric characteristics (surface area and volume) and flow play important roles in the thermal regime of aquatic systems. These topics will then be briefly discussed with regard to the thermal regime of the Tuolumne River. Because this study aims to model the Tuolumne River without Hetch Hetchy and Don Pedro reservoirs – where field data to validate the model are unavailable – the development and application of a conceptual framework is useful to ensure that interpreting model results is consistent with physical processes that typically affect the riverine thermal regimes.

4.2.1. Temperature and Heat Budget

Water temperature is a measure of heat energy of water and is often reported in degrees Celsius or Fahrenheit. Heat energy is expressed as the rate of energy flow or flux (e.g., Watts) into the water surface or bed (at a perpendicular angle). Energy entering the surface or bed is typically normalized for area so that the units of energy flux are a density (e.g., Watts per square meter (W m^{-2})).

Typically, water temperature calculations are based on the laws of conservation of energy. The exchange between water (e.g., a river) and its surroundings (e.g., the overlying atmosphere and channel bed) may be expressed in terms of the heat budget:

Change in Heat Storage = Net Heat Flux = ∑Heat Energy In - ∑Heat Energy Out

The heat budget is composed of multiple heat fluxes: net solar short-wave radiation (H_{sn}), atmospheric long-wave radiation (H_{at}), water surface long-wave or back radiation (H_{ws}), conduction and convection from the water surface (H_h), evaporation (H_{evap}), and ground or bed conduction (H_{bed}). The total heat flux (H_{net}) is shown below (Equation 1):

$$H_{net} = H_{sn} + H_{at} - H_{ws} - H_h - H_{evap} + H_{bed} \quad (1)$$

The calculation of each term varies among formulations; see Martin and McCutcheon (1999) for one formulation.

Net solar short-wave radiation (H_{sn}) is the only form of radiation that penetrates the surface of a water body. This parameter can be measured directly and depends on the sun's altitude, which varies by time of day and day of year. Cloud cover, fog, or other matter in the atmosphere (e.g., dust, smoke) can notably reduce incident solar radiation. Further, riparian vegetation and topography can directly reduce solar radiation loading to a water body via shading (blocking or reducing incident solar radiation to the water surface). All riparian vegetation is assumed "woody" for the rest of this document, except where noted. In the vicinity of the streams, riparian vegetation shade can play a dominant role in affecting water temperature.

Long-wave or atmospheric radiation (H_{at}) is created when solar radiation is absorbed by the atmosphere and clouds (as well as particles in the atmosphere), then emitted as atmospheric long-wave radiation. It is dependent upon empirical constants, air temperature, and cloud cover and, in theory, would only vary slightly between stream sites along the Tuolumne River (assuming meteorological conditions are generally uniform throughout the basin).

The remaining terms in the heat budget (H_{ws}, H_h, H_{evap}, H_{bed}) depend on water temperature, which can vary between various reaches along the Tuolumne River. Water bodies are assumed to lose heat as black-bodies, that is, heat is emitted as long-wave radiation (H_{ws}). Long-wave radiation from water bodies is calculated based on water surface temperature, emissivity, and an empirical constant. Conduction/convection, or sensible heat transfer (H_h), is generally a small term in the heat budget. This term characterizes the heat gain or loss from the water surface due largely to the air-water temperature gradient. Evaporative heat flux (H_{evap}) characterizes the heat lost from the water body due to evaporation and is dependent upon the density of the water at the known temperature, the latent heat of vaporization, and the net evaporation rate or gradient. Bed conduction (H_{bed}) occurs through the bed-water interface when there is difference in temperature between the water above and the substrate below and is a function of the temperature difference mentioned above and the thermal conductivity of the streambed material.

4.2.2. Dynamic Equilibrium Temperature

Another concept useful for interpreting thermal conditions in aquatic systems is dynamic equilibrium water temperature (T_{eq}). The heat flux can be determined from basic meteorological parameters and water temperature (and bed temperature and conduction) per Equation 1. Subsequently, this term can be converted to water temperature for a water body of volume (V) with an air-water interface area (A_s) (Equation 2)[4].

[4] For simplicity, bed conduction is left out of Equation 2. Further, Equation 2 does not include diffusion or advection in aquatic systems, but rather represents only the source term (S) in the advection-diffusion equation used in most water temperature models (i.e., $dT/dt = -u\,(dT/dx) + D\,(d^2T/dx^2) \pm S$).

$$\frac{dT_w}{dt} = S = \frac{H_{net} A_s}{C_p \rho V} \tag{2}$$

Where T_w is water temperature (°C), t is the time step(s), S refers to sources and sinks (°Cs^{-1}), H_{net} is the net heat flux (Wm^{-2}), A_s is the area of water body surface (m^2), C_p is the specific heat of water at 15°C (4185.5 Jkg^{-1}°C^{-1} where 1 J = 1 W-s), ρ is the calculated density of water (kg m^{-3}), and V is the volume of water body (m^3).

Examining Equation 2 for a range of surface area to volume (A_s:V) ratios quickly yields valuable insight. For bodies of water that have very large volumes compared to surface areas, that is a small A_s:V (e.g., a relatively narrow, deep river reach), the rate of heat change is reduced. In contrast, for water bodies with a larger A_s:V wide (e.g., wide, shallow streams), the rate of heat change increases.

This calculation can be repeated for a specified set of conditions until the average change in temperature over time is negligible (e.g., $\Delta(dT/dt)_{daily} \rightarrow 0$), as shown in Figure 4. Note, the diurnal variation in response to meteorological conditions (dashed line) suggests a dynamic condition, while, the daily mean (heavy, solid line) indicates a steady rise and asymptotic approach to an equilibrium state, T_{eq}.

This simple relationship forms the basis of equilibrium temperature calculations used in developing tributary inflow temperatures and headwater boundary conditions in the upper Tuolumne River for the 1970 to 2012 period when measured data were unavailable.

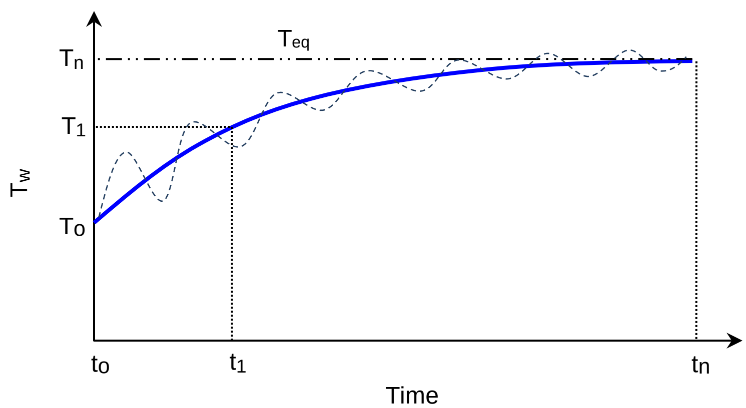


Figure 4. Theoretical rise to equilibrium water temperature from a parcel with an initial temperature less than equilibrium water temperature.

4.2.3. Tuolumne River Thermal Regime

The hydrology and meteorology largely drive water temperature conditions in the Tuolumne River. A useful concept in exploring thermal regimes of streams is to recognize that for much of the year, the river is in equilibrium with meteorological conditions. However, there are deviations from this equilibrium condition due to the imposition of warm and cold water flows on the mainstem. As noted previously, the hydrology of the system is driven by winter precipitation that yields rainfall runoff at lower elevations and accumulations of snow at higher elevations. Spring runoff associated with snowmelt yields increased flows during a period of increasing solar insolation and increasing heat loading. Through the summer period, flows diminish in response to depleted snowpack and lack of appreciable precipitation, while atmospheric thermal loading remains high. Flows continue to diminish through the fall, as do thermal loading rates. Water temperature responses to these conditions above Hetch Hetchy are shown in Figure 5. Modest to high flows occur in winter during a period termed winter storm/base flows and water temperatures are near equilibrium conditions. During spring, large flows associated with snowmelt water yield cold waters that are transported from higher elevation tributary headwaters to the mainstem in relatively short periods – periods sufficiently short that these tributary inflows reach the mainstem Tuolumne River prior to attaining equilibrium temperature (Figure 5). These contributions are often not only markedly colder than the mainstem, but can also be of considerable magnitude, and thus have a marked effect on downstream water temperatures. As the snowmelt hydrograph abates and summer sets in, lower flows lead to a notable increase in stream temperatures, in some cases exceeding 20^{o}C. During this period, certain tributaries may yield warm water inputs to the mainstem Tuolumne River, particularly in the lower reaches of the system. However, these smaller contributions probably have only minor, local effects on mainstem temperatures. As streamflows continue to decrease or stabilize into fall, water temperatures are reduced due to shorter day length, lower solar altitude, and overall meteorological conditions that favor cooler water temperatures.

In the lower reaches of the Tuolumne River, the system responds strongly to meteorological conditions, including potential shading from riparian vegetation. Currently, Don Pedro Reservoir resets the thermal regime in downstream river reaches (Ward and Stanford 1983). The storage of winter water in the reservoir and subsequent deep-water release maintains cool water temperatures in the river throughout the year. However, under a WOD condition, such storage would be absent and seasonal water temperature conditions would respond to upstream temperatures and local meteorological conditions. Milder winters and hot summers of the Central Valley, yield a T_{eq} in the lower Tuolumne River that is warmer than the upper river. Thus, WOD conditions are hypothesized to result in a temperature signal that follows the general seasonal trend of Figure 5, but would be warmer due to increased thermal loading en route to the San Joaquin River.

The concepts and hypotheses presented as part of the conceptual model framework will directly and indirectly play a role in model data development, calibration, and application.

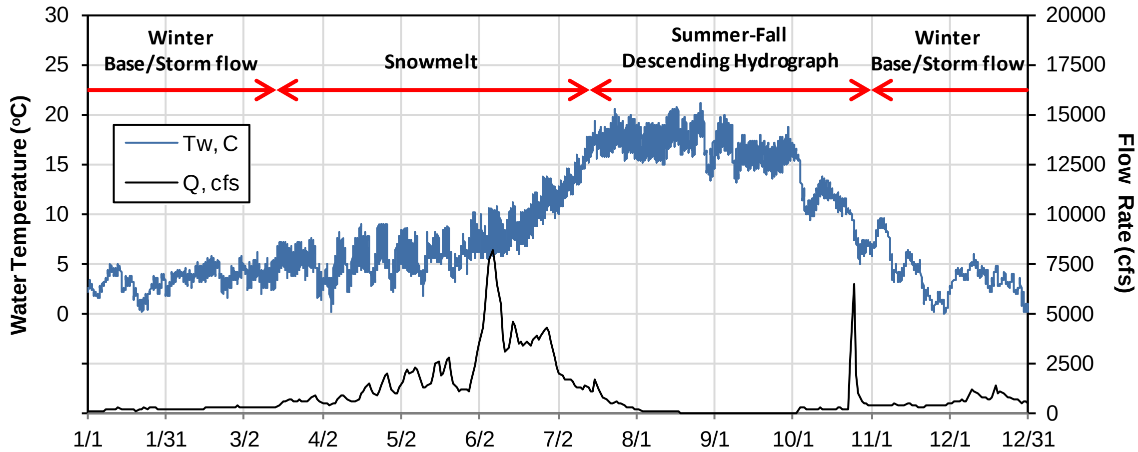


Figure 5. Flow and water temperature, Tuolumne River above Hetch Hetchy (2010) showing representative seasonal hydrograph elements. Flow data from HDR (2013), water temperature data from USGS 11274790 (http://waterdata.usgs.gov/ca/nwis).

5. The Modeling Development Process

Once the model was selected and the conceptual framework developed, the process of developing the model commenced. Model development included four elements: data development, model implementation, model calibration, and sensitivity analysis (Figure 2). These elements were, for the most part, carried out in that order to arrive at a complete, calibrated model. This completed model was subsequently used in the application phase to assess WOD conditions for a historic period.

5.1. Data Development

Data development included the process of aggregating all data necessary to implement a model. For a river temperature model, these data included geometric data, meteorological data, hydrologic data, and water temperatures. Geometric data were used to mathematically describe the river planform (e.g., UTM coordinates or latitude/longitude descriptions of the river) and gradient and local cross-section information describing the "shape" or morphology of the river. Meteorological data included solar radiation, air temperature, wet bulb or dew point temperature, wind speed (and in certain instances direction), cloud cover, and barometric pressure. Hydrologic data included headwater inflows, tributary inflows, and diversions or known outflows. Water temperature data included water temperature at inflow locations noted previously. In addition, there was a need for flow and water temperature data at locations within the model domain. These data were not used to run the model, but rather to calibrate the model.

Unique to this project was the development of separate model data for use in calibration and application periods. Data to calibrate a hypothetical WOD simulation did not exist. To calibrate the model, available field data were used to simulate two currently free-flowing reaches of the Tuolumne River – from below O'Shaughnessy Dam to the headwater of Don Pedro Reservoir and from below La Grange Diversion Dam to the San Joaquin River confluence. This calibration phase, extending from 2010 to 2012, was used to establish model parameters. Calibration results illustrated that the model effectively simulated existing conditions and provided a level of confidence that the model was appropriate for assessing WOD conditions. For simulating WOD conditions, the calibrated model was applied to the entire study reach for the period 1970 to 2012. Because certain data were limited or unavailable for the WOD conditions, meteorology, hydrology, and water temperature representations in the WOD model were not based on observed data. Instead, these data sets were estimated by HDR and Watercourse. The development of calibration and application period data sets will be presented in subsequent sections below (Section 6).

5.2. Model Implementation

Model implementation was a significant task, consisting of acquiring and testing the selected model; using available data to construct the appropriate geometric representation of the river (including shading characteristics); formulating boundary conditions for flow and temperature; formatting necessary meteorological data; and selecting representative model parameters. The outcome of this effort was a functional, but uncalibrated model. Additional detail on model implementation is presented in Section 6.4.

5.3. Model Calibration

Model calibration included modifying parameter values and appropriate information to ensure that the model replicated field observations over a range of hydrologic, thermal, and meteorological conditions. Therefore, this task required additional field data for flow and temperature in the study region (within the model domain) to sufficiently test the model. Appropriate statistical measures are included in this process to provide resource managers and decision makers the level of confidence necessary to make informed decisions based on model simulations. Additional detail on model calibration is presented in Section 7.

5.4. Model Sensitivity

Often included in the calibration phase is a sensitivity analysis to assess flow and temperature response to variations in selected parameters. Sensitivity analyses range from basic (single-parameter perturbation through fixed ranges) to complex (sophisticated statistical techniques and advanced variance-based methods).

6. Data Development and Model Implementation

The first stage in model development includes development of the necessary geometry, meteorology, flow, and water temperature data (Figure 2). Both the model calibration and application phase used the same river geometry data and meteorological data. However, for flow and temperature data, separate data sets were necessary for the calibration phase and the application phase. These data sets and the distinction between calibration and application are outlined below.

6.1. Geometry Data

Geometry was developed for discrete reaches based on available information and existing river and reservoir reaches (Table 3). For river reaches, there were planform, profile, and cross section data from previous HEC-RAS modeling efforts (McBain and Trush unpublished data, Jayasundara *et al.* 2010, TID/MID 2017). Available geometric data, cross section spacing of those data, electronic formats, and sources are included in Table 3.

Table 3. Tuolumne River reaches used in modeling.

Reach #	River section	Available data*	Cross-section spacing	Available file format	Source**
1	Hetch Hetchy and above	X,Y and Z	100 ft	Excel	SFPUC and HDR
2	O'Shaughnessy Dam to Early Intake	X,Y and x-sections	100 ft	GIS (.geo)/ RMA	M&T
3	Early Intake to Don Pedro	X,Y and x-sections	100 ft	HEC-RAS	M&T and HDR+
4	Don Pedro bathymetry	X,Y, Z, and x-sections	100 ft	Excel	HDR
5	Don Pedro to La Grange Diversion Dam	Estimated	0.5 – 2.0 mile	HEC-RAS	HDR
6	La Grange Diversion Dam to San Joaquin	X,Y, Z, and x-sections	0.3 – 0.8 mile	HEC-RAS	HDR

*X, Y data represent the planform description of the river, Z data represent the river elevation, x-section data represent cross section information.
**SFPUC is San Francisco Public Utilities Commission, HDR is HDR, Inc., M&T is McBain and Trush.
+Additional information provided for updating model geometry.

6.1.1. Planform Data

Planform river course data were available throughout the study reach. Coordinates used in the model for each discrete reach are shown in Figure 6. Spatial resolution of the model throughout the system was 100 feet. Lower river geometry spacing was notably longer than the desired spatial resolution (i.e., 100-feet) and the cross sections were interpolated approximately at 100-foot intervals using HEC-RAS. Further, several of the original lower river coordinates were not located on the river course (e.g., outside of the channel) and were updated with aerial photos (Google Earth) to be representative of the river course and assigned to the interpolated cross sections.

Planform data for the reservoir reaches (Don Pedro and Hetch Hetchy) were derived from detailed bathymetric surveys (HDR 2012, SFPUC 2002a). The river thalweg location in the reservoir reaches was identified based on minimum longitudinal elevations along the river course. These locations were smoothed with a running average because the thalweg does not necessarily represent that centerline of a stream (see HDR (2012) for additional details).

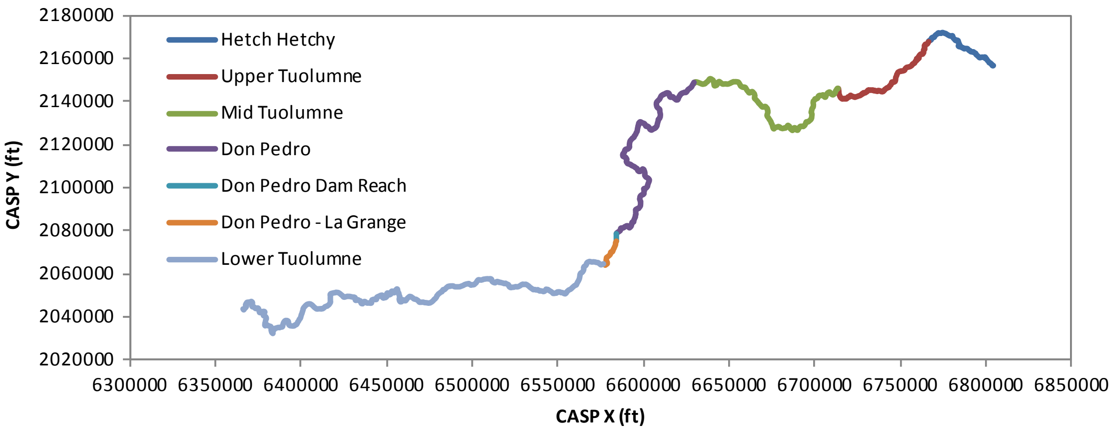


Figure 6. Tuolumne River planform coordinates by reach. (CASP refers to California State Plan, Zone 3.)

6.1.2. Profile Data

River profile data were available throughout the study reach. Profile data for each planform location (100-foot spacing) were used in the model for each discrete reach (Figure 7). In the upper reaches of the Tuolumne River, as well as near La Grange Diversion Dam, transitions between certain higher and lower gradient reaches were locally smoothed to avoid model instabilities.

Two locations were modified sufficiently to warrant discussion: O'Shaughnessy Dam and La Grange Diversion Dam. Available profile data at O'Shaughnessy Dam indicated a precipitous drop of approximately 30 feet and suggested that the upstream end of Tuolumne River reach below Hetch Hetchy had an elevation that was higher than the bottom of the O'Shaughnessy Dam elevation. Review of SFPUC (2002b) suggested that remnant modifications to the channel form during the construction of the dam may be responsible for this aberration. Namely, the remnants of a coffer dam that rises approximately 20 feet above the reservoir bottom may have caused this inconsistency. This profile section was modified as shown in Figure 8.

The other location at La Grange Diversion Dam required interpolation between Don Pedro Dam and the Tuolumne River below La Grange Diversion Dam. Existing profile data were unavailable for a WOD condition because sedimentation since the placement of La Grange Diversion Dam has filled in a notable fraction of the headpond volume. As a result, an approximate linear interpolation was used to fill this estimated 2-mile reach.

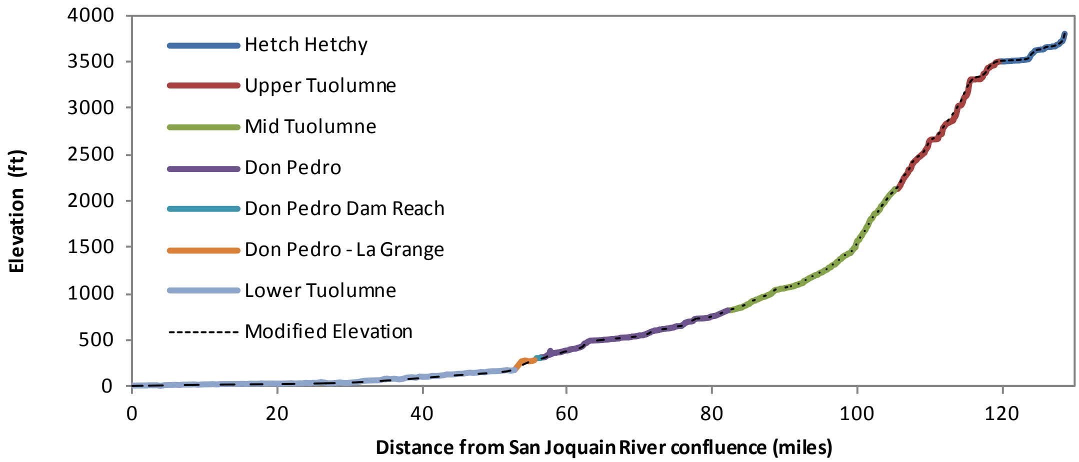


Figure 7. Tuolumne River profile data by reach.

6.1.3. Cross Section Data

Cross section data for much of the river was available at the planform locations. HEC-RAS format data and coordinates were combined and processed to represent cross-section form in RMA (Figure 3). Excel format data were pre-processed to HEC-RAS format and then processed for RMA format. For the upper river, this representation was refined with approximately 1.5 miles of detailed mapping at four discrete locations. For the lower river, cross section information at larger spatial resolution was interpolated to approximately 100-foot node spacing used in the RMA model representation. For the existing reservoir reaches, cross section estimates were made using the detailed bathymetric surveys (HDR 2012). A review of these GIS derived cross sections indicated that while they lacked details of typical surveyed cross sections, they reflected sufficient detail to incorporate them into the model. A global modification was made to the cross section information below La Grange Diversion Dam, wherein channel widths were all increased by 25 percent. Initial model testing indicated that low flow channel widths may not be representative of field conditions. Further examination of individual cross sections identified that the resolution cross sectional data were somewhat coarse (20-foot point-to-point distances along the channel bottom and 100-foot increments at higher elevations). The challenge with the original, narrower low flow channel was that travel times were reduced, depth increased, and a reduced air-water interface resulting in lower heating rates. This modest change largely resolved these issues.

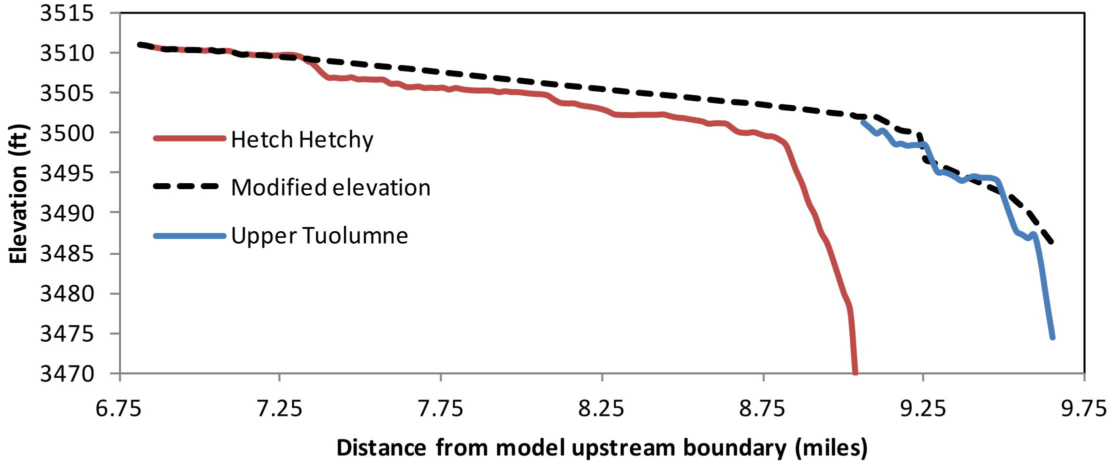


Figure 8. O'Shaughnessy Dam site bed elevation for the Hetch Hetchy and Upper Tuolumne River data and the final modified data used in the modeling geometry.

6.2. Meteorological Data

Meteorological data described above were applied throughout the model calibration phase. To represent sub-daily conditions, data were input as an hourly time series. These data sets were adjusted, as noted previously, for reach-specific elevations. Four meteorological data "zones" were assumed in the model to represent local conditions over the longitudinal and vertical ranges of the model domains. One zone was applied for the lower Tuolumne River reach and three zones were employed for the upper Tuolumne River reach. The lower Tuolumne River reach meteorological zone had a representative elevation of 500 feet. The upper Tuolumne River reach was divided into three meteorological zones: from above Don Pedro to above Lumsden Bridge (with a representative elevation of 1,205 feet), from above Lumsden Bridge to Early Intake (with a representative elevation 1,951 feet), and from Early Intake to above Hetch Hetchy Reservoir, with a representative elevation of 3,000 feet. These meteorological zones were specified in the model input files to automatically apply the appropriate meteorological conditions on a reach specific basis. All data were formatted for RMA-11 and the appropriate input files constructed.

Riparian and topographic shading was also implemented in the model. Shading itself is not a meteorological parameter, but shade affects heat exchange by reducing solar radiation (see Section 4.2 for more information on heat exchange). Shade-producing elements and transmittance values on an element-by-element basis were identified based on aerial photos and estimated woody riparian vegetation types.

Hourly meteorological data for the project area were developed by HDR. Data were acquired through the National Oceanic and Atmospheric Administration (NOAA 2013), National Renewal Energy Laboratory (NREL 2013), and Turlock Irrigation District/Modesto Irrigation District (TID/MID 2011). The data ranges from October 1970 to December 2012. Information of the three stations is presented in Table 4.

Table 4. Meteorological data stations, operating agency, period of record, parameters, and river zone. (Source: HDR)

Station Location	Operating Agency*	Period of Record	Parameters
Don Pedro	TID/MID	10/1/1970 to 12/31/2012	Wind Speed
Crocker Ranch (lower Tuolumne)	TID/MID	10/1/1970 to 12/31/2012	Wind Speed Solar Radiation
Stockton (Metropolitan Airport)	NOAA, NREL	10/1/1970 to 12/31/2012	Air Temperature Relative Humidity

* TID = Turlock Irrigation District; MID = Modesto Irrigation District, NOAA = National Oceanic and Atmospheric Administration, and NREL = National Renewable Energy Laboratory.

6.2.1. Meteorological Zone

The Tuolumne River was separated into the upper and lower reach for this modeling study, but there were four meteorological zones (Table 5). Meteorological data were unavailable for the upper reach (above Don Pedro Reservoir) for the entire period of analysis, but three stations were identified in the lower river reach: Don Pedro, Crocker Ranch, and Stockton Metropolitan Airport (Figure 9).

Different meteorological data parameters were available at the three data stations (e.g., only the Stockton Metropolitan Airport station recorded air temperature since the 1970's). Thus, certain parameters from the lower reach were used as surrogates for the upper reach and vice versa. Further, certain data were used in all four zones (e.g., solar radiation) without modification. The model parameters for the four meteorological zones are presented in Table 6.

Table 5. Meteorological zones by reach.

Reach	Representative elevation for reach (ft)
Don Pedro Reservoir to confluence with San Joaquin River	500 (max/min: 17 ft/832 ft)
Above Lumsden Bridge to Don Pedro Reservoir	1,205 (max/min: 832 ft/1,578 ft)
Early Intake to above Lumsden Bridge	1,951 (max/min: 1,578 ft/2,323 ft
Hetch Hetchy to Early Intake	3,000 (max/min: 3,793 ft/2,323 ft)*

* max/min represents the maximum and minimum elevation of the Tuolumne River in each reach.

Table 6. RMA model parameters and data source for each meteorological zone.

Model Parameters	Units	Meteorological Zones 500 ft	1,205 ft	1,951 ft	3,000 ft
Atmospheric Dust Attenuation[1]	n/a	Estimated	Estimated	Estimated	Estimated
Cloud Cover[2]	n/a	Calculated	Calculated	Calculated	Calculated
Air Temperature[3]	deg C	Stockton	Adjusted Stockton	Adjusted Stockton	Adjusted Stockton
Wet-Bulb Temperature[4]	deg C	Calculated	Calculated	Calculated	Calculated
Barometric Pressure[5]	mmHg	Calculated	Calculated	Calculated	Calculated
Wind Speed	m/s	Crocker	Don Pedro	Don Pedro	Don Pedro
Solar Radiation	w/m^2	Crocker	Crocker	Crocker	Crocker

[1] Atmospheric Dust Attenuation values are set to 0.06 for all meteorological zones.
[2] Cloud cover was estimated based on solar radiation.
[3] Air temperature was only available from the Stockton meteorological station. Air temperature for the 3,000 feet and 1,500 feet meteorological zones was calculated using a lapse rate (Section 6.2.2).
[4] Wet-bulb temperatures are calculated based on the air temperature or adjusted air temperature.
[5]Barometric pressure was calculated based on elevation of meteorological zone.

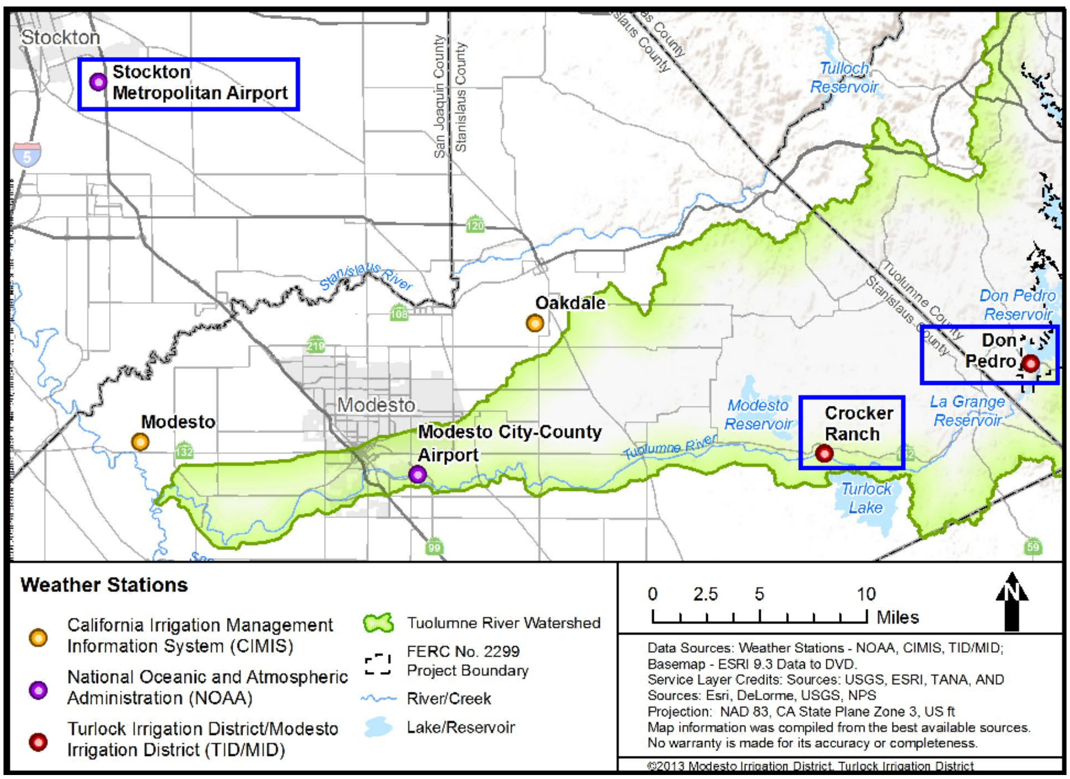


Figure 9. Map of meteorological stations in the area with those stations relevant for this RMA model shown in blue boxes. Figure was modified (courtesy of HDR).

6.2.2. Lapse Rate

Lapse rate describes air temperature changes with respect to elevation. The air temperature in higher elevations is generally lower than air temperature at lower elevations (Linacre 1992, Holman 1976). The Don Pedro meteorological data station does not record air temperature back to 1970. Thus, air temperature in the upper zones was estimated based on adjustments for the altitude change (lapse rate) between the lower zone (Stockton station, 500 ft) and upper zones (1,205 ft, 1,951 ft, and 3,000 ft). A lapse rate of 6°C per 3,128 ft of elevation change was applied (Linacre 1992), and air temperature adjusted according to the elevations identified in Table 5.

6.2.3. Wet Bulb and Dew Point Temperature

Wet bulb temperature (T_{wb}) is the temperature of the air if cooled to saturation (or 100 percent relative humidity) (Martin and McCutcheon 1999). With the assumed elevation and barometric pressure (P), air temperature (T_a), and relative humidity, the wet bulb temperature can be calculated through the iterative process presented in Equation 3. Dew point temperature is the temperature at which water condensation begins to form (Martin and McCutcheon 1999). Dew point temperature can be calculated using Equation 4 (when air temperature and relative humidity are known, or alternatively, if vapor pressure (e) is known). Wet bulb and dew point temperatures were calculated for each meteorological zone to accommodate changes in air temperature (based on the aforementioned lapse rate) and barometric pressure with elevation. Wet bulb temperature was used in the RMA models, while dew point temperature was used in the modeling approach when formulating boundary conditions in the upper Tuolumne River reach.

$$e(Twb, Ta, P) = \left(6.108 \exp\left(\begin{cases} \dfrac{17.27Twb}{Twb + 237.3} & Twb \geq 0 \\ \dfrac{21.875Twb}{Twb + 265.5} & Twb < 0 \end{cases} \right) \right) - 0.00066(1 + 0.00115Twb)(T_a - Twb)P \quad (3)$$

$$DP = \frac{\dfrac{237.3}{17.27} \ln\left(\dfrac{e}{6.108}\right)}{1 - \dfrac{1}{17.27} \ln\left(\dfrac{e}{6.108}\right)} \quad (4)$$

6.3. Flow and Temperature Data

Flow and temperature data were required for the calibration phase in the free flowing reaches between O'Shaughnessy Dam and Don Pedro and from La Grange Diversion Dam to the San Joaquin River confluence. These data consisted of field observations during the 2010 to 2012 period. Upon completion of model calibration, the calibrated model was applied to the WOD condition extending back to 1970. However, observed data for the WOD condition were not available. As such, flow and temperature conditions for the 1970 to 2012 water year period that were used in the application phase were not based solely on observed data. The flow and temperature data approach for both the calibration and application phase are presented below. Note that both the upper and lower Tuolumne River reaches included the same tributaries as the model used in the calibration phase.

6.3.1. Model Calibration Phase Data: Flow

The model calibration phase was performed from 2010 through 2012, and observed flow data were used as boundary conditions and for calibration where available. The Upper Tuolumne River reach was calibrated from O'Shaughnessy Dam to Don Pedro Reservoir.

Key boundary conditions included the Tuolumne River below Hetch Hetchy and the principal tributaries of Cherry Creek, South Fork Tuolumne River (SFTR), Clavey River, and North Fork Tuolumne River (NFTR). The Lower Tuolumne River reach was calibrated from below La Grange Diversion Dam to the San Joaquin River Confluence. This reach included Dry Creek as the sole tributary. Available USGS flow data used during the calibration phase for headwater boundary conditions, tributary boundary conditions, and calibration are summarized in Table 7.

In addition to these flows, tributary contributions were required for ungaged tributaries in the study reach. Historic flows in the project area for major tributaries and accretions were based on HDR proration analysis (HDR 2013), and were used in the upstream and downstream reaches. The proration analysis not only identified daily flows for the major tributaries, but also miscellaneous or ungaged accretions on a reach-by-reach basis. Ungaged accretions were assigned to the minor tributaries based on watershed areas above Don Pedro. Below La Grange, Dry Creek inflows and accretions were assigned flows consistent with the HEC-RAS model application (TID/MID 2017).

Table 7. Summary of available USGS flow data used in model calibration.

River Reach	Upstream Boundary	Tributaries	Calibration
O'Shaughnessy Dam to Don Pedro reservoir	Below Hetch Hetchy USGS 11276500	Canyon Power Tunnel Flow (USGS 11276600 - USGS 11276900)	Above and below Early Intake USGS 11276600
	n/a	Cherry Creek Below Dion R Holm Power House USGS 11278400	n/a
La Grange Diversion Dam to SJR	La Grange Diversion Dam USGS- 11289650		Modesto USGS 11290000

In addition to major tributary inflows, reach accretions were provided for the Tuolumne River above Hetch Hetchy to O'Shaughnessy Dam, from O'Shaughnessy Dam to Early Intake, on Cherry Creek from Eleanor and Cherry Dams to the mouth of Cherry Creek, from Early Intake to Don Pedro (Ward's Ferry), representing local inflow to Don Pedro below Ward's Ferry, and lower Tuolumne River accretions below La Grange, including Dry Creek. Inflow from Canyon Power Tunnel was determined by mass balance between the USGS gages above and below Early Intake. Accretions from La Grange to Modesto were added to the model at two evenly spaced locations within the reach. For the reach between Modesto and San Joaquin River confluence, accretion flows and Dry Creek flows were summed and located at the Dry Creek confluence. Major tributary and accretions assigned to local tributaries and their locations are summarized in Table 8.

Table 8. Location of flow accretions for the calibration period.

Appendix A. Location	Inflow Type	Approximate river mile*
Above Hetch Hetchy Reservoir to O'Shaughnessy Dam accretions	Accretion	124
Accretion O'Shaughnessy Dam to Early Intake (3 locations distributed through the reach) Accretion #1 Accretion #2 Accretion #3	Accretion	 116.9 114.8 113.0
Canyon Power Tunnel flow at Early Intake	Tributary	106
Cherry Creek	Tributary	104
Cherry Creek accretion: Cherry Creek from Eleanor and Cherry Dams to the confluence to the mouth of Cherry Creek (assigned at confluence)	Accretion	104
Jawbone Creek	Tributary	102
Corral Creek	Tributary	101
South Fork Tuolumne River	Tributary	98
Clavey River	Tributary	91
Grapevine Creek	Tributary	89
Indian Creek	Tributary	88
Big Humbug Creek	Tributary	83
Big Creek	Tributary	83
North Fork Tuolumne River	Tributary	81
Accretion La Grange Diversion Dam to Modesto Accretion 1 Accretion 2	Accretion	 25 19
Dry Creek	Tributary	16
Modesto to San Joaquin River (added to Dry Creek)	Accretion	16

* Source: http://streamstatsags.cr.usgs.gov

6.3.2. Model Calibration Phase Data: Temperature

Observed temperature data were available at several locations during the 2010 to 2012 model calibration period and were used as boundary conditions as well as during the calibration phase (Figure 10). In the upper Tuolumne River reach, the boundary condition below O'Shaughnessy Dam was represented by historical observations of temperature data at the USGS Gage (#11276500). This record was not complete for all years as both years (2010 and 2011) contained data gaps. The 2010 period had several data gaps and was filled with temperature averages from 2008 and 2009 (Figure 11). Similarly, the 2011 data gaps were filled based with temperature averages from 2008 to 2012 (Figure 12). There were no data gaps in 2012. The implications of these data gaps are discussed further below under calibration.

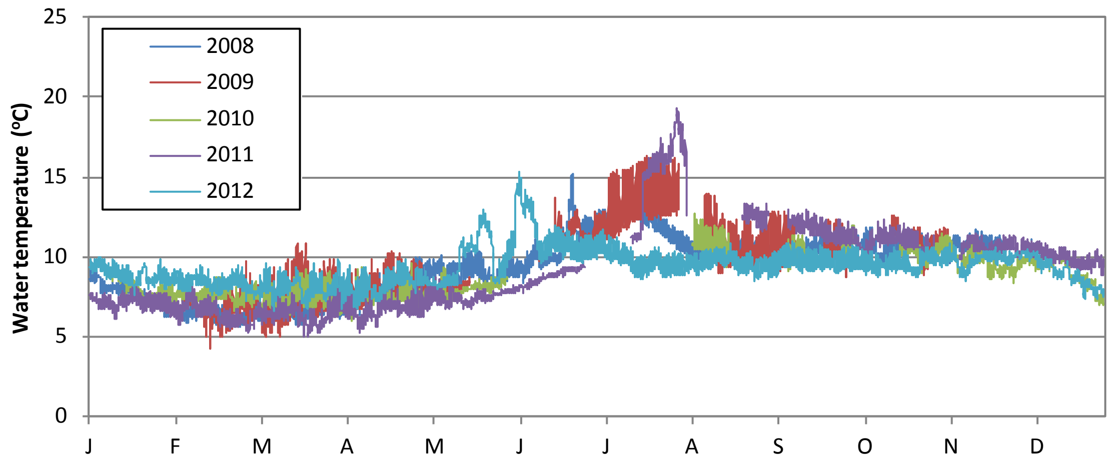


Figure 10. Observed water temperature boundary condition at Hetch Hetchy for 2008, 2009, 2011, and 2012.

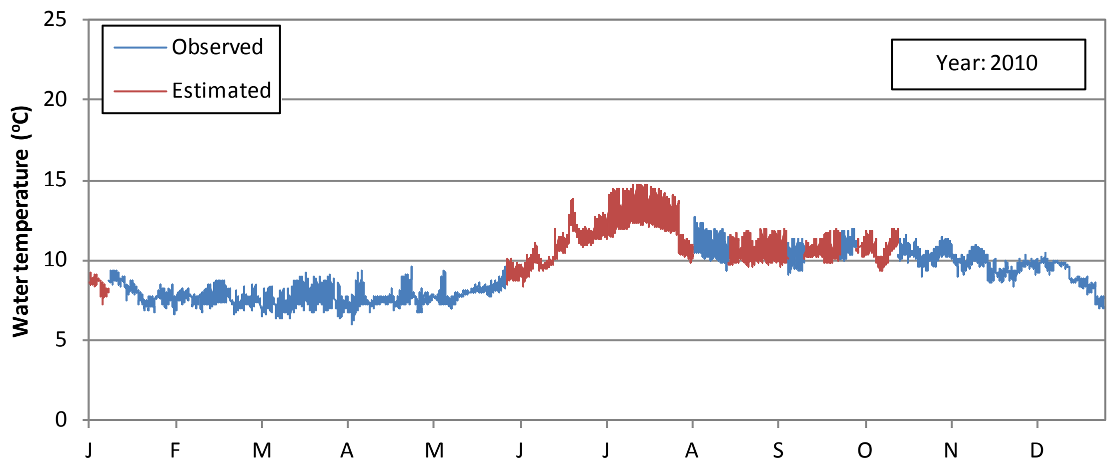


Figure 11. Water temperature boundary condition for below Hetch Hetchy, 2010.

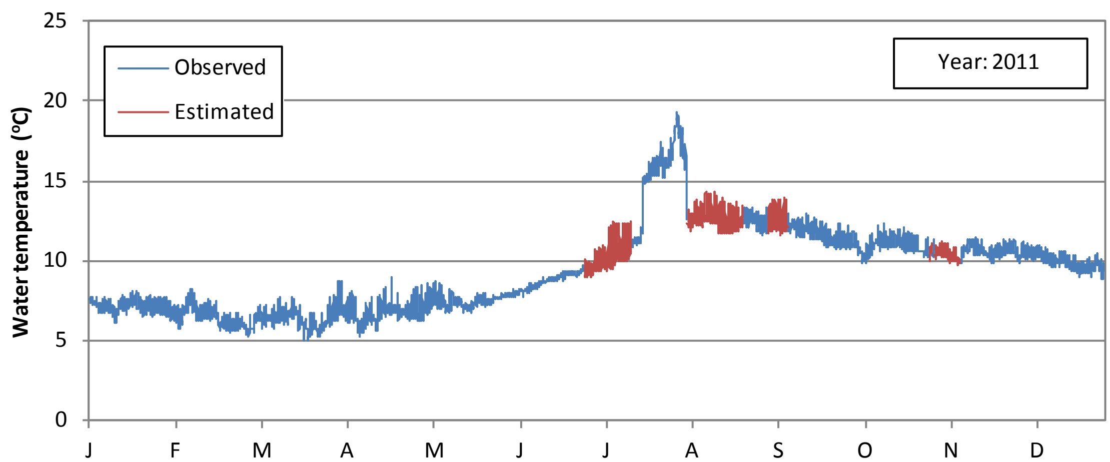


Figure 12. Water temperature boundary condition for below Hetch Hetchy, 2011.

Tributary temperatures for Cherry Creek were available, and Canyon Power Tunnel was assumed equal to the Tuolumne River below Hetch Hetchy. The South Fork Tuolumne, Clavey, and North Fork Tuolumne Rivers inflow boundary conditions were based on equilibrium water temperature (Section 4.2.2). Calibration data included three locations over the three calibration years: the USGS Gage (#11276600) Tuolumne River above Early Intake (2010, 2011, 2012), and above Don Pedro Reservoir near Ward's Ferry (2010, and partial 2011; data source: HDR) and near Indian Creek (2011 and 2012; data source: HDR).

The lower Tuolumne River headwater temperature boundary condition at La Grange for 2010, 2011, 2012 were input as hourly time series was developed from USGS gage #11289650. Unlike the boundary conditions below O'Shaughnessy Dam, this temperature record had no significant data gaps for the 2010 through 2012 calibration period. Minor accretions and Dry Creek were not assigned an inflow temperature, but rather entered the mainstem Tuolumne River at the local river temperature. Sensitivity testing around this assumption indicated that minor accretion temperature had a negligible effect on mainstem river temperatures. Calibration data included a single location downstream at the Modesto USGS gage (#11290000).

Table 9. Summary of temperature data used for model calibration.

River Reach	Upstream boundary	Tributaries	Calibration
O'Shaughnessy Dam to Don Pedro	Below Hetch Hetchy USGS 11276500	Canyon Power Tunnel Flow (USGS 11276600 - USGS 11276900)	[1]Above Early Intake USGS11276600
		Cherry Creek Below Dion R Holm Power House USGS 11278400	
			[2]Tuolumne near Indian Creek
			[2]Tuolumne near Ward's Ferry
La Grange to SJR	La Grange Diversion Dam USGS 11289650		[1]Modesto USGS 11290000

[1] USGS data, [2] HDR data

6.3.3. Model Application Phase Data: Flow

Unimpaired daily flows for the Tuolumne River and principal tributaries were derived via a flow proration method described in HDR (2013). These flows were further refined by HDR to provide a breakdown of each flow for principal tributaries and accretions by subreach. Accretions were subsequently assigned to minor tributaries based on watershed area similar to the calibration period (Table 8). In addition, local accretions to Hetch Hetchy were added to accommodate inflow between the headwaters of Hetch Hetchy and O'Shaughnessy Dam. A minimum flow of 7 cfs at the upper inflow point was applied in the model application phase (WOD scenario, 1970 to 2012) to avoid model instabilities for such low flows in the steep reaches of the upper Tuolumne River. Such conditions occurred infrequently: approximately 2.5 percent of simulation days.

6.3.4. Model Application Phase Data: Water Temperature

For the WOD condition, daily flow data was supplied by HDR for the entire 1970 to 2012 period; however, water temperature data for the Tuolumne River above Hetch Hetchy, Cherry Creek, and the South Fork Tuolumne, Clavey, and North Fork Tuolumne Rivers were largely unavailable for the majority of the desired analysis period. To calculate representative daily inflow temperatures for each of these flows, an equilibrium temperature (T_{eq}) model approach was applied. There was sufficient data available for the Tuolumne River above Hetch Hetchy, Cherry Creek, and the South Fork Tuolumne to develop these boundary conditions. Clavey and North Fork Tuolumne River water temperatures were estimated based on South Fork Tuolumne River temperatures. In the lower Tuolumne River, minor accretions and Dry Creek were not assigned an inflow temperature, but rather entered the mainstem Tuolumne River at the local river temperature.

The principal inputs for T_{eq} model include meteorological and flow data. Daily flow and hourly meteorological data were available from HDR for the period (1970-2012). The T_{eq} model estimates used the hourly data, but hourly values were averaged to daily average temperatures to form the boundary conditions. As with the mainstem reaches, meteorological data were adjusted for elevation within each sub-watershed when applying the T_{eq} model to the upper Tuolumne River above Hetch Hetchy, and the tributaries, Cherry Creek, South Fork Tuolumne River, Clavey River, and North Fork Tuolumne River, to form these water temperature boundary conditions.

6.4. Model Implementation

Model implementation consisted of assembling the aforementioned data into the proper format for RMA-2 and RMA-11, and selecting default model coefficients and parameters. Specific tasks included:

- Constructing the appropriate geometric representation of the river and creating a geometry input file with RMAGEN. Shading characteristics were also formulated for the river reaches.
- Formulating boundary conditions for flow and temperature for appropriate model inflows.
- Assigning representative meteorological data to the individual meteorological zones.

This process was initially completed for the calibration phase, with the outcome of this effort being a functional, but uncalibrated model. Once the model was calibrated (see below), a similar process of formulating boundary conditions and meteorological data set for the 1970-2012 period was completed. Model geometric representations were also updated to represent the river reaches for Hetch Hetchy and Don Pedro Reservoirs. However, model calibration coefficients and parameters were not changed for the WOD simulations.

7. Model Calibration

Following model implementation described above, adjustments were made to specific model coefficients and parameters to calibrate the model to observed data for the period 2010, 2011 and 2012. Four calibration locations were assessed based on available/provided data: above Early Intake, at Indian Creek, at Ward's Ferry and at Modesto (note that not all years were available for calibration at all locations).

Model results were assessed graphically and with summary statistics. Graphical assessment includes a visual comparison of simulated and observed time series to qualitatively examine temporal response of the model over a range of time scales ranging from seasonal to sub-daily. Summary statistics were calculated to quantitatively assess model performance and include mean bias, mean absolute error (MAE), and root mean squared error (RMSE) (Deas and Lowney 2000). Mean bias yields insight on systematic error and ideal values are near zero. MAE indicates overall model performance as a deviation from zero. Finally, RMSE can assist in identifying large deviations from observed data. Included herein are the results for 2011.

7.1. Flow Calibration

Flow calibration was performed for the 2010 through 2012 period at two locations where downstream flow data were available:

- Above Early Intake (USGS 11276600) for 2010 and 2011, and
- Tuolumne at Modesto (USGS 11290000) for 2010 to 2012.

Model parameters employed in the Tuolumne River flow calibration included reach slope factors and Manning's roughness coefficients. Eddy viscosity was generally insensitive to changes and was not used in flow calibration. Slope factors were employed to represent different stream morphology units, such as pools, runs, low and high gradient riffles, and steep rapids or cascades. These factors reduce the effective slope of the stream to more realistically represent water surface slopes in the hydrodynamic model, leading to more representative depths and travel times. In steep reaches, the slope factors play a larger role, while in low gradient reaches, they play a smaller role. Model calibration aimed at reducing the difference between simulated and observed data at the calibration locations based on graphical assessment and summary statistics. The final calibration values for each reach type are presented in Table 10. Graphical and statistical model performance for the Upper and Lower Tuolumne River calibrations are presented below.

Table 10. Model parameters used in Upper and Lower Tuolumne flow calibration.

Cross section type	Slope factor	Manning's *n*
Pool	0.60	0.045
Run	0.80	0.042
Low Gradient Riffle	0.90	0.040
High Gradient Riffle	0.90	0.037

Rapids (Cascade)	0.95	0.035

7.1.1. O'Shaughnessy to Don Pedro (Upper Tuolumne River)

For the Upper Tuolumne River reach from O'Shaughnessy to Don Pedro, the modeled stage and flow effectively reproduced field observations at the USGS monitoring site above Early Intake (USGS #11276600) (Figure 13 and Figure 14, respectively). Simulated flows exhibited a similar pattern to the observed data, reflecting both seasonal and short-term variability over a range of flow conditions. Deviations in simulated stage from observed data are most likely associated with geometric representation, i.e., channel form. Flow was well represented in model simulations, with deviations largely a function of boundary condition flow estimates and daily average values versus sub-daily estimates.

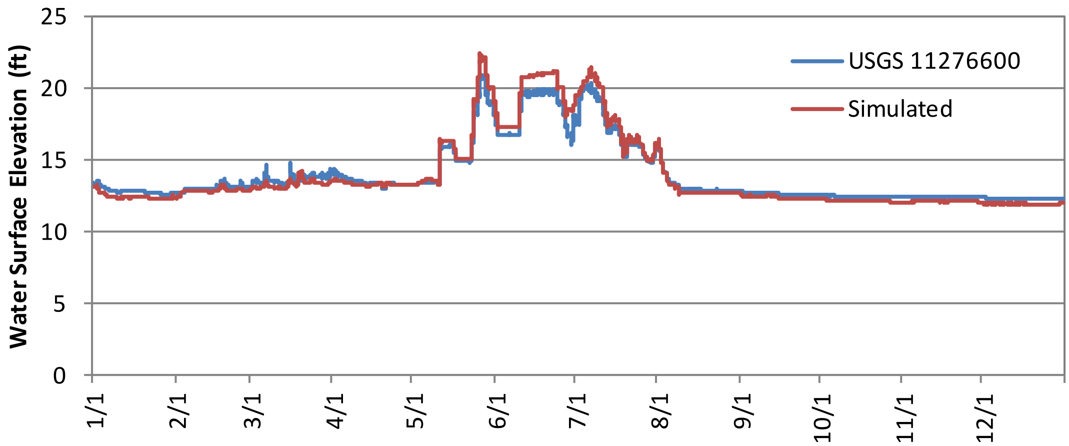


Figure 13. Stage comparison in the Tuolumne River above Early Intake, 2011.

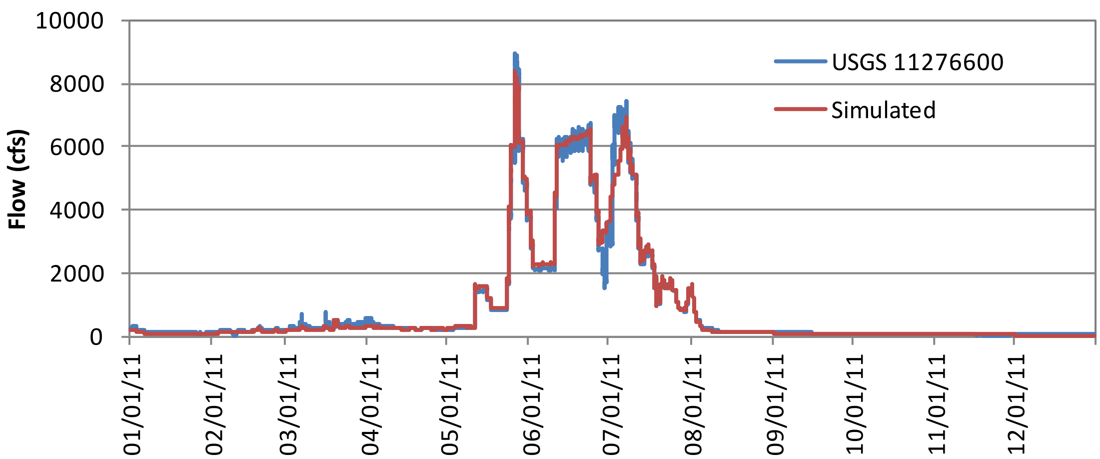


Figure 14. Flow calibration comparison for above Early Intake, 2011.

Table 11. Flow performance statistics for above Early Intake for 2010.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	cfs	100	103	105	104
Mean Absolute Error (MAE)	cfs	183	180	177	193
Root Mean Squared Error (RMAE)	cfs	280	272	277	292
Number of Data Points (*n*)	-	8,760	347	347	347

Table 12. Flow performance statistics for above Early Intake for 2011.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	cfs	-5	-8	20	-43
Mean Absolute Error (MAE)	cfs	81	72	85	85
Root Mean Squared Error (RMAE)	cfs	209	179	213	210
Number of Data Points (*n*)	-	8760	347	347	347

7.1.2. La Grange to San Joaquin (Lower Tuolumne River)

For the lower Tuolumne River reach from La Grange to the confluence with the San Joaquin River, modeled stage and flow effectively reproduced field observations at the USGS monitoring site near Modesto (USGS #11290000) (Figure 15 and Figure 16, respectively). Simulated flows exhibited a similar pattern to the observed data, reflecting both seasonal and short term variability over a range of flow conditions. Deviations in simulated stage from observed data are most likely associated with geometric representation, i.e., channel form. Flow was well represented in model simulations, with infrequent deviations that were largely a function of rapid flow changes during short duration flow events. Otherwise the model tracked observed flows closely.

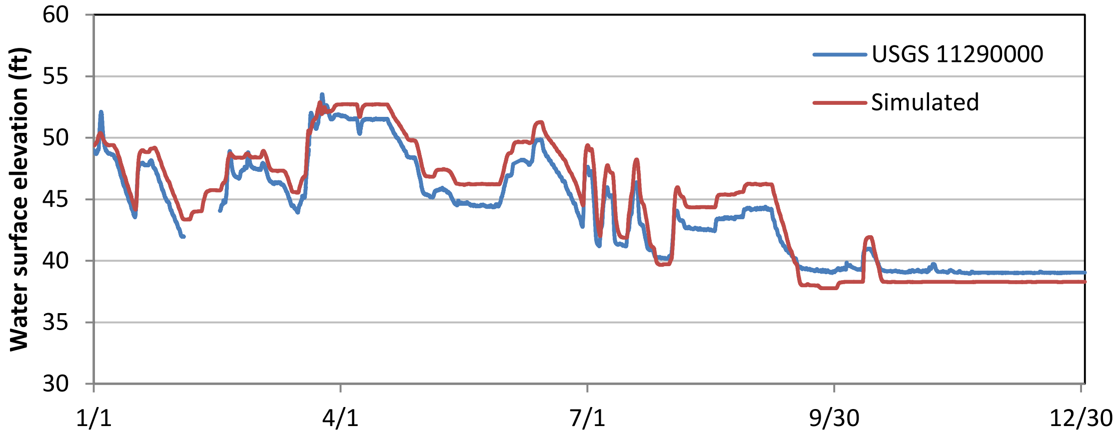


Figure 15. Stage in the Tuolumne River near Modesto, 2011.

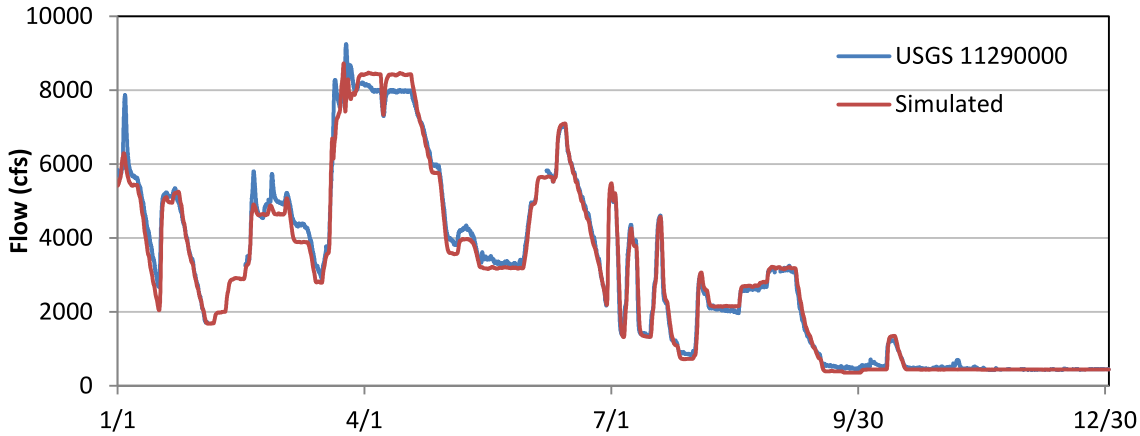


Figure 16. Flow in the Tuolumne River near Modesto, 2011.

Table 13. Flow performance statistics for Modesto for 2010.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	cfs	-57	-67	-51	-84
Mean Absolute Error (MAE)	cfs	123	115	103	131
Root Mean Squared Error (RMAE)	cfs	230	219	215	238
Number of Data Points (*n*)	-	6,983	286	286	286

Table 14. Flow performance statistics for Modesto for 2011.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	cfs	-69	-64	-46	-73
Mean Absolute Error (MAE)	cfs	173	172	154	194
Root Mean Squared Error (RMAE)	cfs	265	255	231	316
Number of Data Points (*n*)	-	8,187	347	347	347

Table 15. Flow performance statistics for Modesto for 2012.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	cfs	-8	-8	3	-20
Mean Absolute Error (MAE)	cfs	41	39	36	49
Root Mean Squared Error (RMAE)	cfs	77	73	68	89
Number of Data Points (*n*)	-	6,576	274	274	274

7.1.3. Travel Time for O'Shaughnessy to Early Intake

In addition to assessing flow volume, travel time calibration for O'Shaughnessy to Early Intake was also performed based on data available from Jayasundara *et al*. (2010). Overall, the simulated travel times (red dashed line) exhibited a similar pattern as the observed data (blue symbols) based on gage data identified in the aforementioned previous study (Figure 17). Similar information was not readily available for other reaches in the study area. However, the close match between the model and observations over a wide range of flows in this reach provides confidence in model performance.

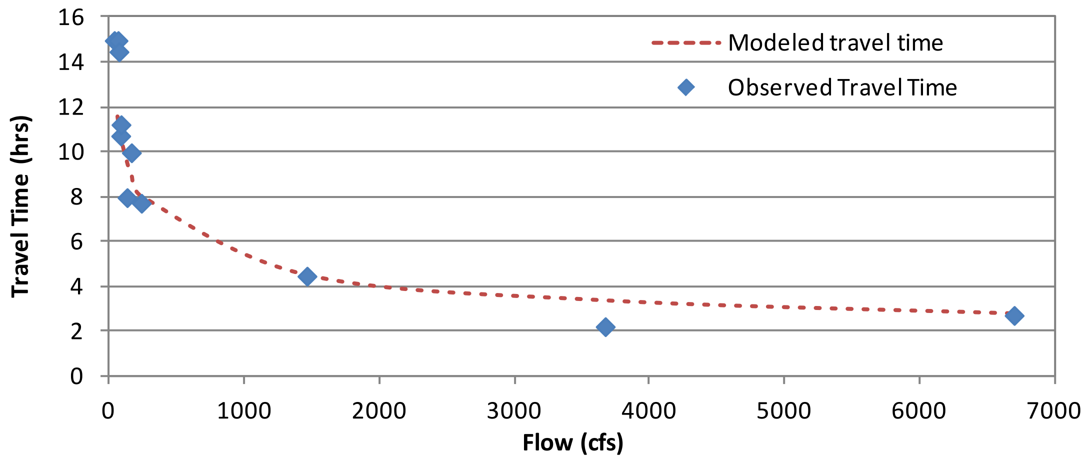


Figure 17. Observed (blue) and modeled (red dashed line) Upper Tuolumne River (O'Shaughnessy to Early Intake) travel time.

7.2. Temperature Calibration

Temperature calibration was performed at four calibration locations in study reach, three in the upper and one in the lower Tuolumne River.

- Tuolumne above Early Intake (USGS 11276600) for 2010 and 2011,
- Tuolumne at Indian Creek for 2011,
- Tuolumne at Ward's Ferry for November 2010 to June 2011 (HDR data), and
- Tuolumne at Modesto (USGS 11290000) for 2010 to 2012.

Selected model parameters were adjusted to reduce the difference between simulated and observed data at these calibration locations. Model parameters that were adjusted include:

- Evaporative heat flux coefficient *a* and *b*,
- Dead pool area (area below zero flow),
- Shade (vegetation), and
- Bed conduction.

Evaporative heat flux coefficients[5], *a* and *b*, were both set to 3.0×10^{-6} between above Early Intake and 5.0×10^{-6} below Early Intake. Dead pool area was applied in pools and

[5] The evaporative heat flux coefficients *a* and *b* have units of [pressure^{-1} L t^{-1}] and [pressure^{-1}], respectively.

riffles to represent the potential increased thermal mass associated with such features. Specifically, these features typically have storage below zero flow stage (see PCWA 2010). Pools had higher volumes than riffles, while higher gradient reach types were assigned a nominal value of 0.01 m^3 (an insignificant volume). Dead pool volumes were refined as a result of the updated cross section information. The dead pool volumes used in the modeling are listed in Table 17.

Bed conduction can affect water temperatures, particularly during low flow conditions (Jobson 1977). Because bed temperatures vary seasonally, a step-function was used to define bed temperatures in the model (Table 18), while the bed conduction coefficient was maintained constant at 28.7 ($W \cdot m^{-2} {}^{\circ}C^{-1}$). Bed conduction was found to be insensitive in the lower reaches of the river and was not employed in the calibration. However in the upper reaches of the system where the river is largely bedrock controlled (i.e., above Don Pedro), bed conduction was employed. As with flow, temperature calibration results for the 2011 year are presented herein.

Table 16. Evaporation coefficient used in Upper and Lower Tuolumne River water temperature calibration.

Meteorological Zone	*a* (m/hr/mbar)	*b* (m/hr/mbar per m/s)
Hetch Hetchy to Early Intake	$3x10^{-6}$	$3x10^{-6}$
Early Intake to above Lumsden Bridge	$5x10^{-6}$	$5x10^{-6}$
Above Lumsden Bridge to Don Pedro	$5x10^{-6}$	$5x10^{-6}$
Don Pedro to San Joaquin	$5x10^{-6}$	$5x10^{-6}$

Table 17. Dead pool area used in Upper Tuolumne River water temperature calibration.

Cross section type	Dead pool area[1]
Pool	Bottom width x 1.0 m^2
Run	Bottom width x 0.5 m^2
Low Gradient Riffle	0.01 m^2
High Gradient Riffle	0.01 m^2
Cascade	0.01 m^2

[1]Dead pool area were only used from O'Shaughnessy Dam to Don Pedro

Table 18. Step function defines assumed seasonal bed temperature in the model (°C).

Date	Hetch Hetchy to Early Intake	Early Intake to Don Pedro	Date	Hetch Hetchy to Early Intake	Early Intake to Don Pedro
1-Jan	8	8	15-Jul	30	24
1-Feb	8	8	1-Aug	30	24
1-Mar	13	13	1-Sep	30	24
1-Apr	13	13	1-Oct	20	18
1-May	21	21	15-Oct	12	12
1-Jun	24	24	1-Nov	4	4
1-Jul	24	24	31-Dec	4	4

7.2.1. Tuolumne River Near Early Intake

Comparing simulated and observed water temperature at Early Intake indicates that the model effectively responded to seasonal variations in flow, tributary contributions and upstream conditions, and meteorology (Figure 18). The months of January, April, July, and August are provided in Figure 19 through Figure 22 to provide insight into diel and short duration model performance (e.g., days, weeks). Overall, the model simulated seasonal variations in diel range and overall tracked observed data well. Deviations from observed data are most likely due to non-local meteorological data, as well as upstream water temperature boundary condition data gaps. Summary statistics for hourly, daily mean, maximum, and minimum temperatures indicate low bias, MAE less than 1°C and RMSE less than 1.34°C (Table 14). Summary statistics at Early Intake for other years were similar in performance. A brief exploration of the impact of water temperature data gaps for the headwater boundary (shaded areas in Figure 18) indicated that this data gap has a direct impact on model performance. Overall, RMAE and MAE were higher for the period when data were estimated. RMAE was 1.19°C for periods where data were available and 1.81°C when data were estimated. The MAE was 0.95°C for periods of available data, compared to 1.39°C with the estimated data.

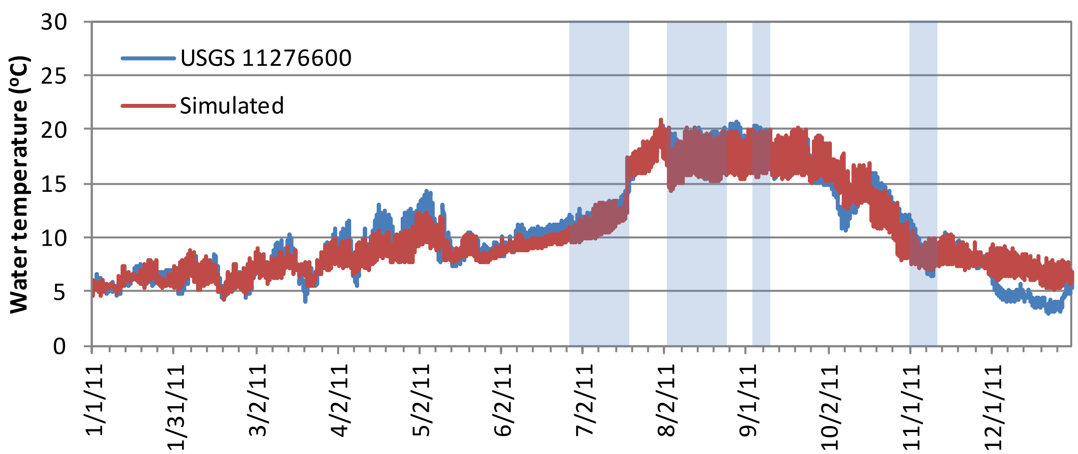


Figure 18. Water temperature calibration above Early Intake, 2011 (shaded areas denote times when boundary condition data is missing).

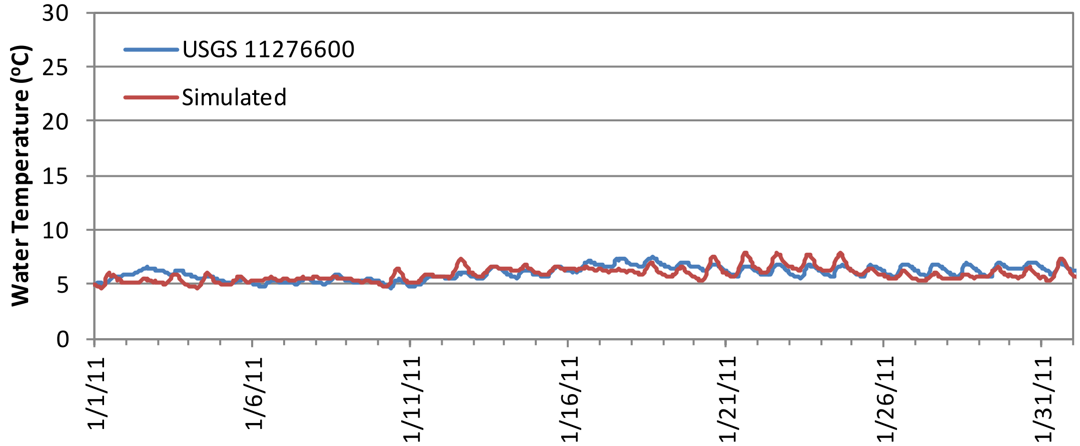


Figure 19. Water temperature calibration comparison above Early Intake, January 2011.

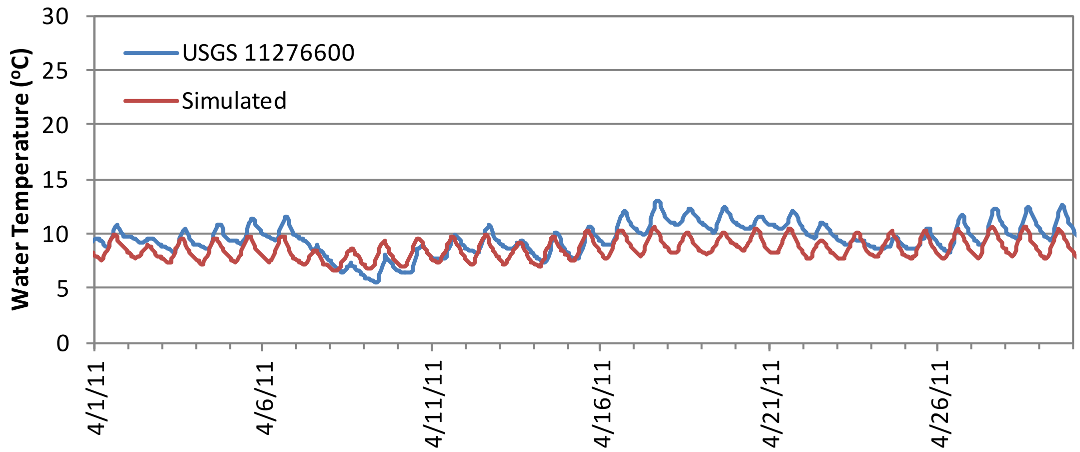


Figure 20. Water temperature calibration comparison above Early Intake, April 2011.

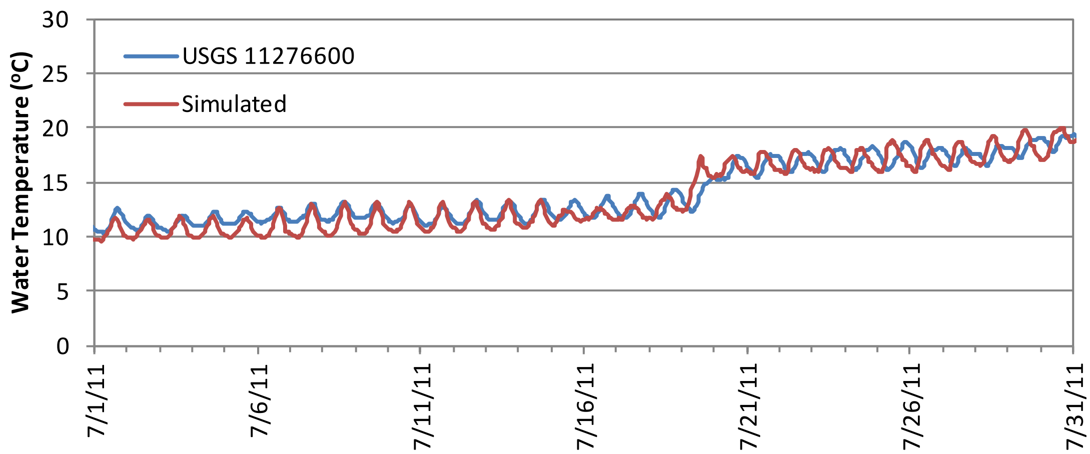


Figure 21. Water temperature calibration comparison above Early Intake, July 2011.

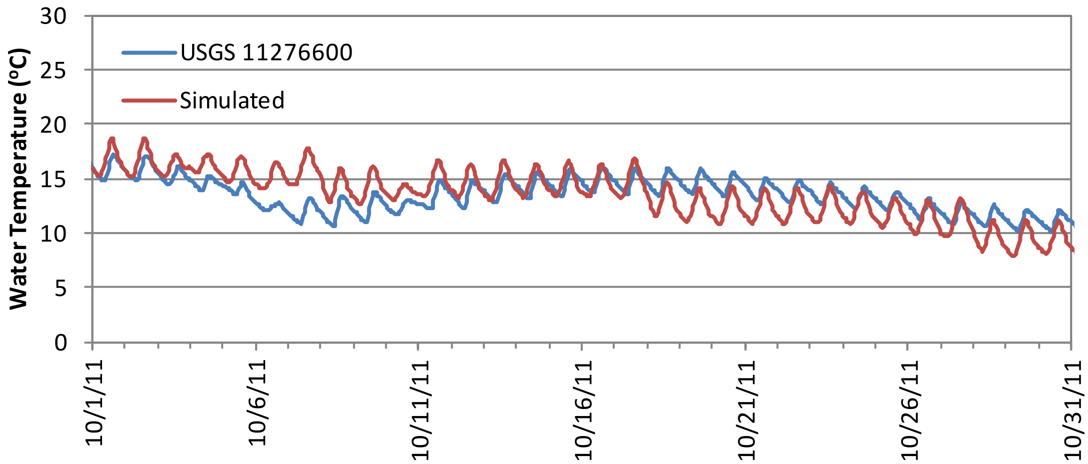


Figure 22. Water temperature calibration comparison above Early Intake, October 2011.

Table 19. Water temperature performance statistics for above Early Intake for 2010.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	ºC	-0.48	-0.48	-0.72	-0.17
Mean Absolute Error (MAE)	ºC	1.08	0.95	1.01	0.99
Root Mean Squared Error (RMAE)	ºC	1.40	1.24	1.37	1.24
Number of Data Points (*n*)	-	365	-0.48	365	365

Table 20. Water temperature performance statistics for above Early Intake for 2011.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	ºC	-0.07	-0.07	-0.27	0.21
Mean Absolute Error (MAE)	ºC	0.99	0.83	0.84	0.94
Root Mean Squared Error (RMAE)	ºC	1.11	1.12	1.11	1.34
Number of Data Points (*n*)	-	8760	365	365	365

7.2.2. Tuolumne River at Indian Creek

Comparing simulated and observed water temperature for the Tuolumne River at Indian Creek indicates that the model effectively responded to seasonal variations in flow, tributary contributions and upstream conditions, and meteorology (Figure 23). The months of January, April, July, and August are provided in Figure 24 through Figure 27 to provide insight into diel and short duration model performance (e.g., days, weeks). Overall, the model simulated seasonal variations in diel range and overall tracked observed data well. Simulated temperatures were slightly cooler in the winter. Deviations from observed are most likely due to non-local meteorological data, as well as upstream water temperature boundary condition data gaps; however, upstream boundary condition uncertainty is diminished with distance from O'Shaughnessy Dam. Summary statistics for hourly, daily mean, maximum, and minimum temperatures indicate low bias, MAE less than 1°C and RMSE less than 1.16°C (Table 15).

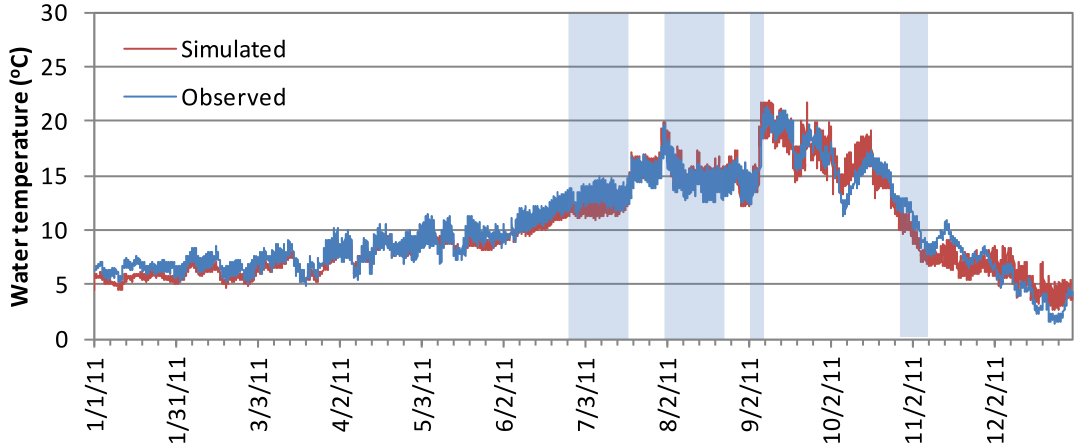


Figure 23. Water temperature calibration at Indian Creek, 2011 (shaded areas denote times when boundary condition data is missing).

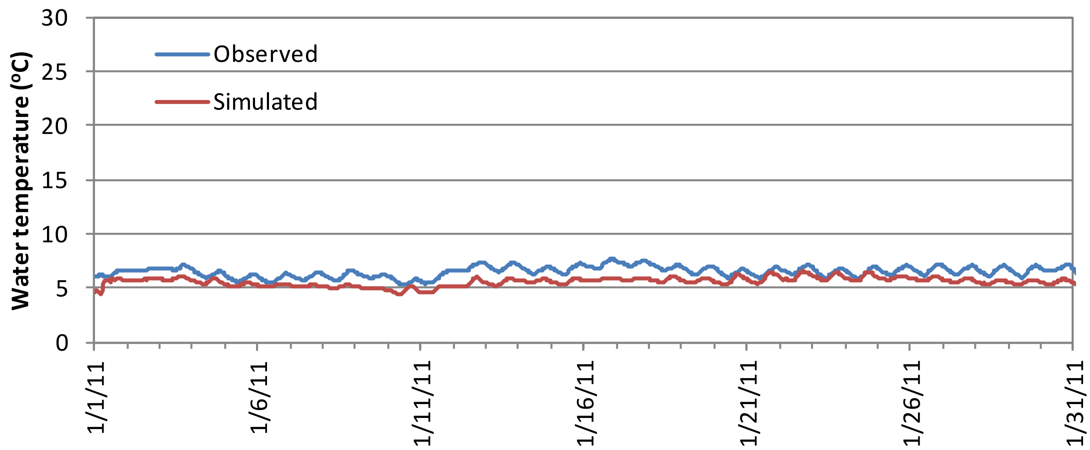


Figure 24. Water temperature calibration comparison at Indian Creek, January 2011.

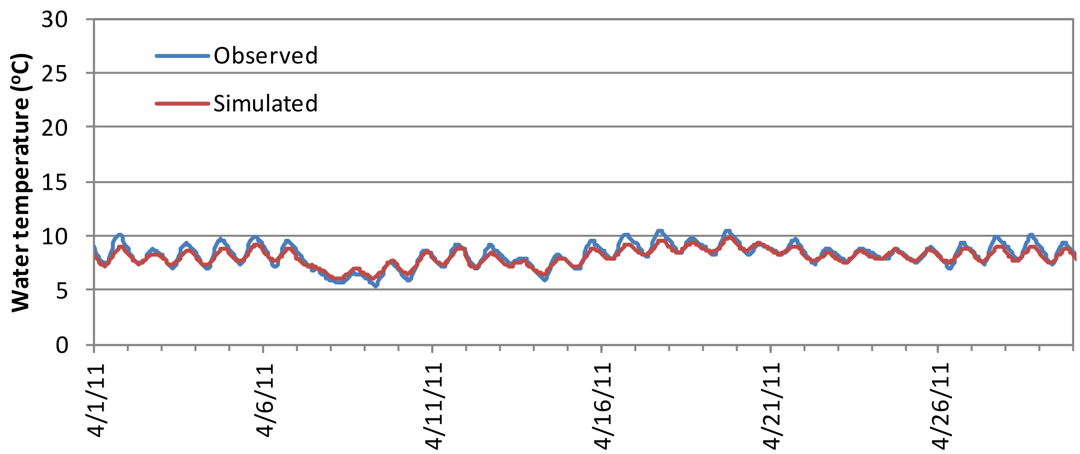


Figure 25. Water temperature calibration comparison at Indian Creek, April 2011.

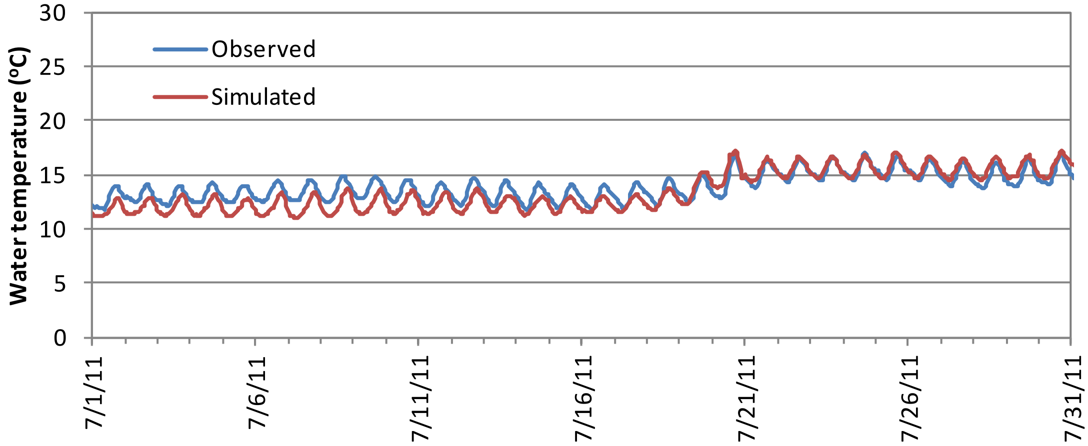


Figure 26. Water temperature calibration comparison at Indian Creek, July 2011.

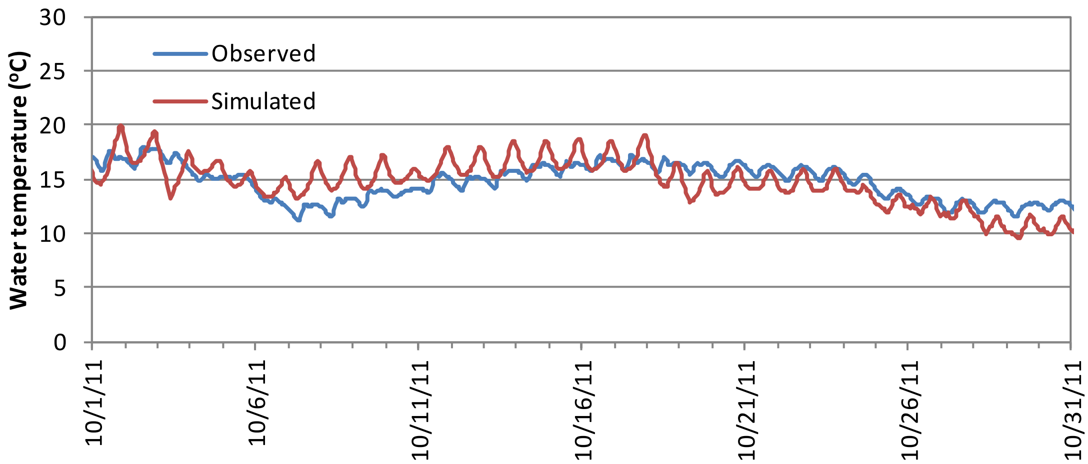


Figure 27. Water temperature calibration comparison at Indian Creek, October 2011.

Table 21. Water temperature performance statistics for at Indian Creek for 2011 and 2012.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	ºC	-0.36	-0.37	-0.32	-0.18
Mean Absolute Error (MAE)	ºC	0.82	0.74	0.72	0.95
Root Mean Squared Error (RMAE)	ºC	1.04	0.91	0.92	1.16
Number of Data Points (*n*)	-	7371	365	365	365

7.2.3. Tuolumne River at Ward's Ferry

Observed data was only available for mid-November of 2010 through mid-June of 2011 (Figure 28 and Table 22). In 2011, the RMAE at Indian Creek was 1.0°C, while the MAE was 1.1°C. In general, the simulated water temperatures had the same general pattern as the observed data, but tended to be cooler than what was observed. Water temperatures were also assessed graphically on a short-duration basis. In general, the simulated temperatures had a less diurnal variation than the observed (Figure 27 and Figure 29).

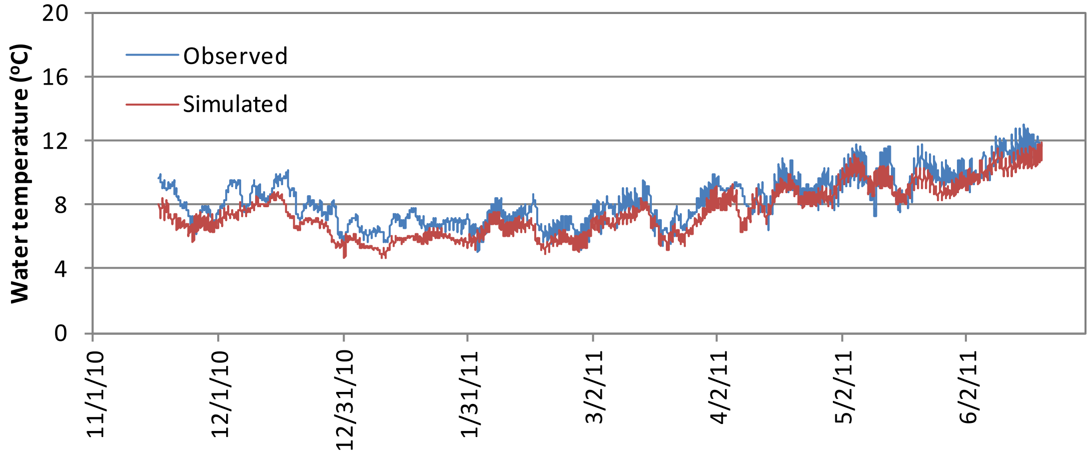


Figure 28. Water temperature calibration at Ward's Ferry, 2010/2011.

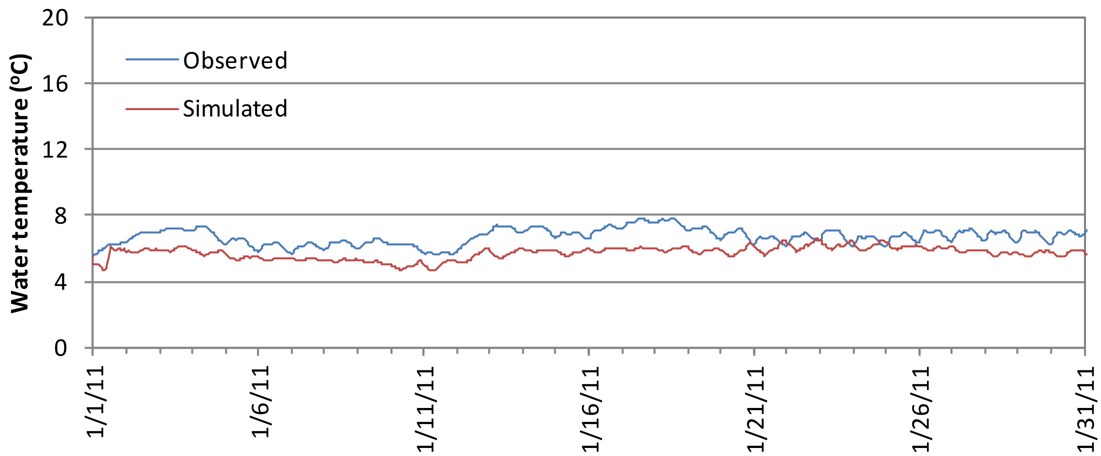


Figure 29. Water temperature calibration comparison at Ward's Ferry, January 2011.

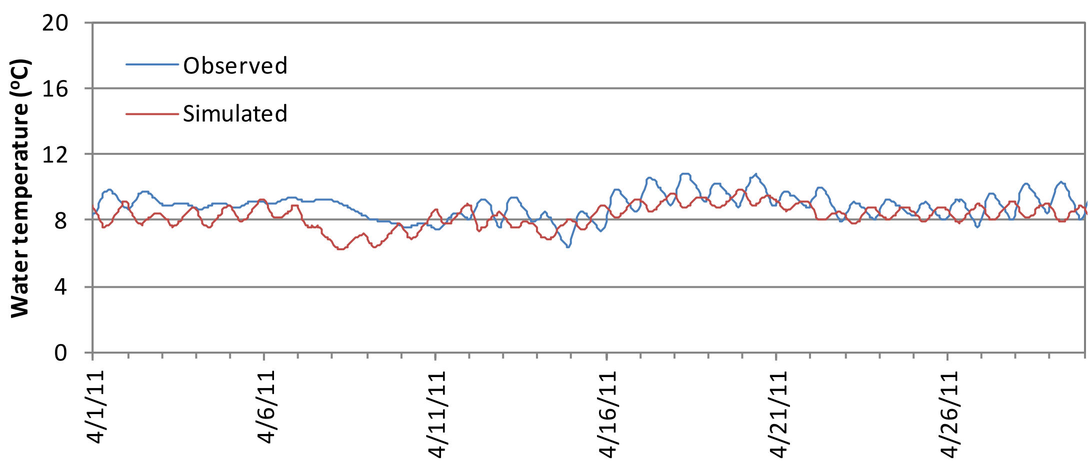


Figure 30. Water temperature calibration comparison at Ward's Ferry, April 2011.

Table 22. Water temperature performance statistics for at Ward's Ferry for 2010/2011.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	ºC	-0.76	-0.76	-0.52	-0.80
Mean Absolute Error (MAE)	ºC	0.96	0.80	0.62	0.86
Root Mean Squared Error (RMAE)	ºC	1.13	0.92	0.72	0.99
Number of Data Points (*n*)	-	5175	216	216	213

7.2.4. Tuolumne River at Modesto

Water temperature was calibrated at Modesto (Figure 31 and Table 13 through Table 15). In 2011, the RMAE at Modesto was 1.2°C, while the MAE was 0.9°C. For the three calibration years, the RMAE ranged from 1.0°C to 1.5°C, while the MAE ranged from 0.9°C to 1.1°C. In general, the simulated water temperatures had the same general pattern as the observed data, with cooler temperatures in the winter and early spring, rising temperatures in the late spring, warmer temperatures in the summer, and decreasing temperatures in the fall.

Water temperatures were also assessed graphically on a short-duration basis. In general, the simulated temperatures had a fairly similar pattern to the observed data but tended to be slightly warmer on a sub-daily basis (Figure 32 through Figure 35).

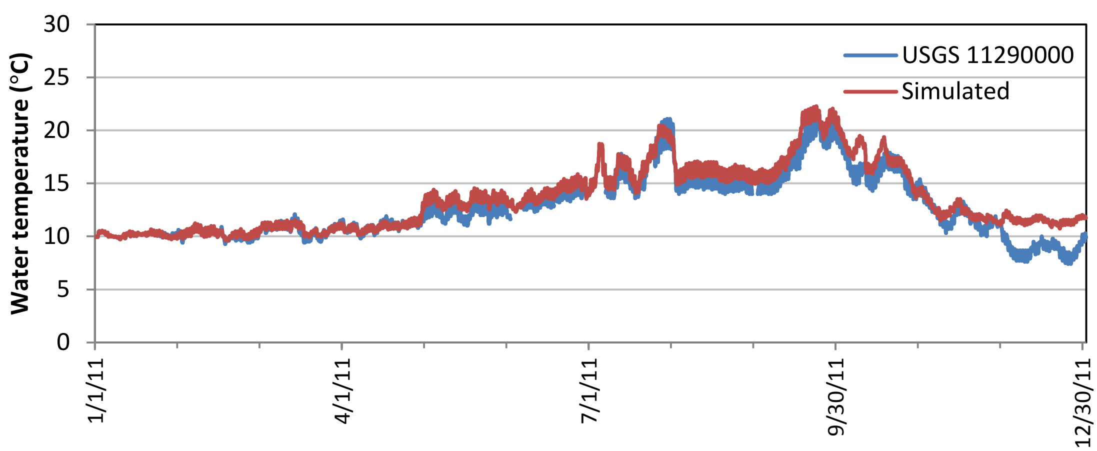


Figure 31. Water temperature calibration USGS station at Modesto, 2011.

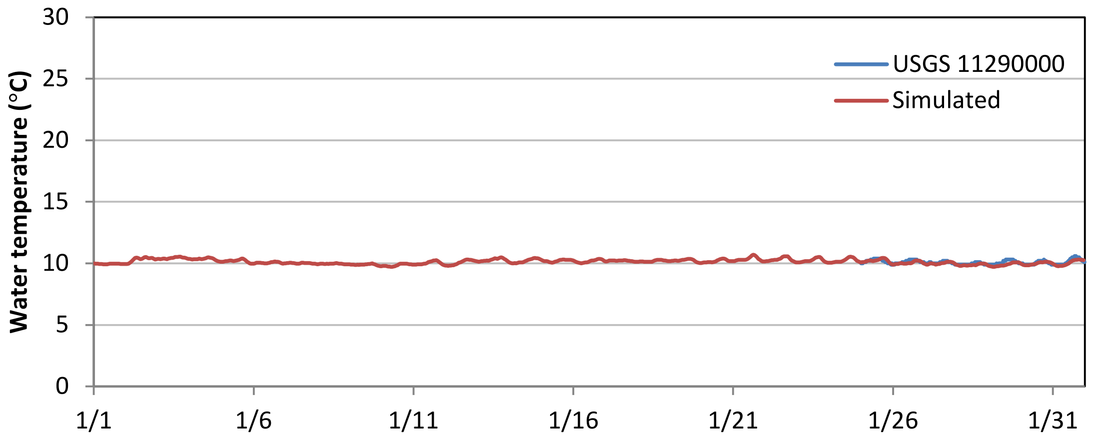


Figure 32. Water temperature calibration comparison at Modesto, January 2011.

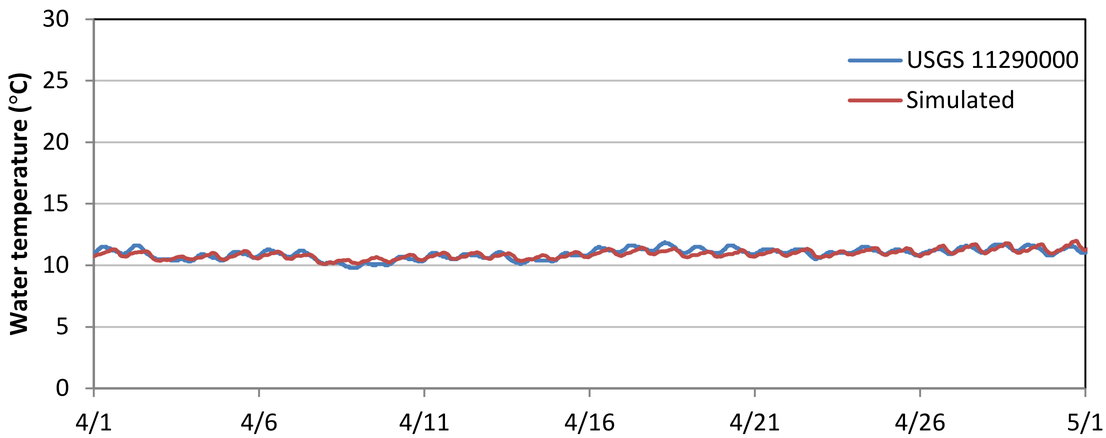


Figure 33. Water temperature calibration comparison at Modesto, April 2011.

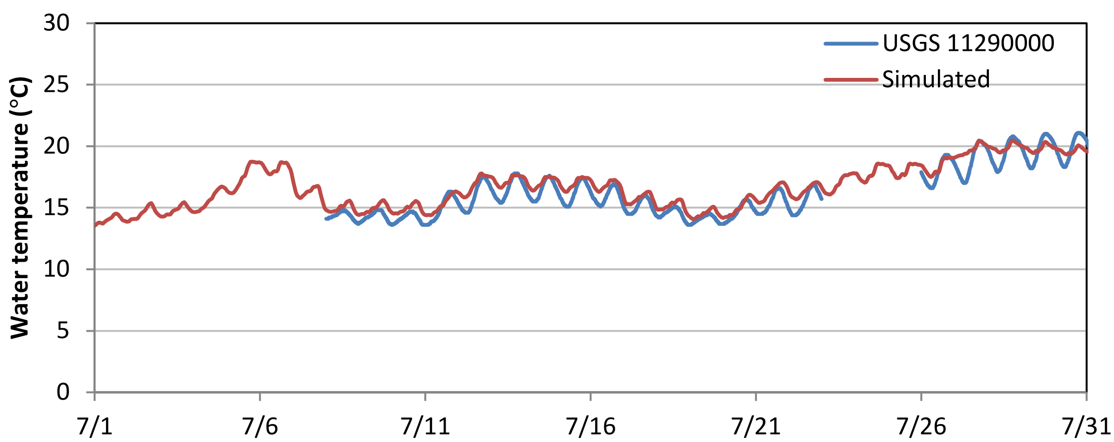


Figure 34. Water temperature calibration comparison at Modesto, July 2011.

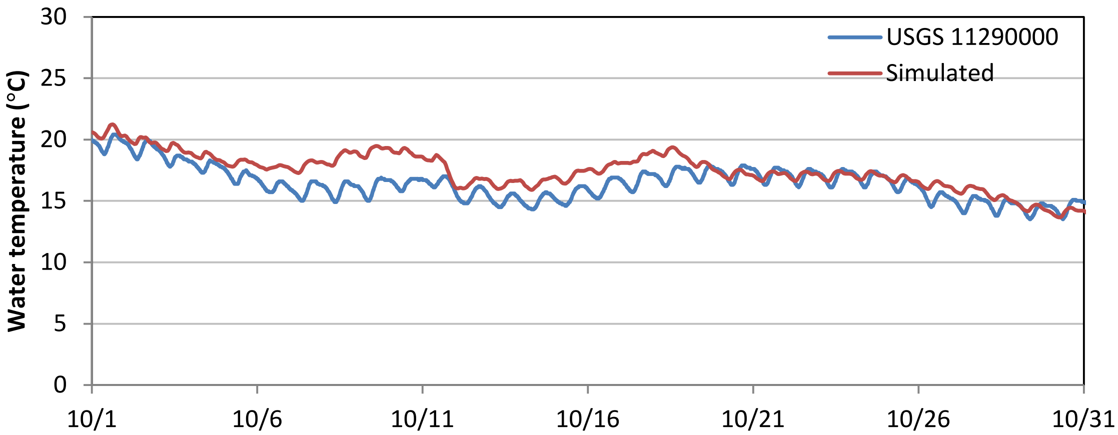


Figure 35. Water temperature calibration comparison at Modesto, October 2011.

Table 23. Water temperature performance statistics for Modesto for 2010.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	ºC	0.11	0.11	0.63	-0.30
Mean Absolute Error (MAE)	ºC	0.85	0.72	0.88	0.85
Root Mean Squared Error (RMAE)	ºC	1.01	0.86	1.06	0.97
Number of Data Points (*n*)	-	4585	191	191	191

Table 24. Water temperature performance statistics for Modesto for 2011.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	ºC	0.80	0.80	0.98	0.68
Mean Absolute Error (MAE)	ºC	0.88	0.85	1.01	0.78
Root Mean Squared Error (RMAE)	ºC	1.19	1.16	1.34	1.07
Number of Data Points (*n*)	-	7441	310	310	310

Table 25. Water temperature performance statistics for Modesto for 2012.

Statistic	Units	Hourly	Daily average	Daily minimum	Daily maximum
Mean Bias	ºC	-0.18	-0.18	0.52	-0.98
Mean Absolute Error (MAE)	ºC	1.09	0.91	1.00	1.41
Root Mean Squared Error (RMAE)	ºC	1.46	1.25	1.34	1.77
Number of Data Points (*n*)	-	6578	274	274	274

7.2.5. Water Temperature Calibration Summary

For all years, mean bias was typically low and near zero in several cases, MAE was almost always under 1ºC, and RMSE was consistent with few outlying (large) simulation values. Overall, given the level of available data, these results indicate that the model effectively captures a range of hydrologic and water temperature conditions in the

Tuolumne River system. Subsequently, the model was applied to WOD conditions for the 42-year period from 1970 to 2012.

7.3. Sensitivity Analysis

A sensitivity analysis is the test of a model in which parameter values are changed (typically while the others remain constant) and the impact of this change on the independent variable is observed. Such analyses can be used to identify the characteristics of importance in a system. Uses of sensitivity analysis include:

- Confirming that the model is consistent with theory,
- indicating the effects of errors in each of the variables and parameters, on the dependent variables,
- identifying sensitive parameters or variables that must be reliably estimated,
- indicating the relationship between control variables and decision variables to help ensure that a change in control variable can have a desirable effect on the decision variables, and
- identifying regions of "design invariance" where desirable levels of the decision variables are insensitive to possible errors of estimation in the model variables and parameters.

Other methods of quantifying uncertainty include first order analysis, Monte Carlo simulations and Kalman filtering, and are based on aggregate error terms and determine the total estimation (or prediction) error in a particular variable (Chapra and Reckhow, 1983). These multivariate methods are beyond the scope of this project.

Selected model parameters in both RMA-2 and RMA-11 were examined to determine relative sensitivity. Only those variables explored during calibration were examined. The input data sets, field observations or estimated values for flow and water temperature boundary conditions and meteorological parameters, were not altered. This qualitative assessment determined the general sensitivity of a particular parameter, (e.g., low, moderate, or high sensitivity, or insensitive), provided insight on model performance (e.g., was model consistent with theory), and indicated the effects of modifying said parameters on the dependent variables. Many of the changes were carried out over modest ranges in parameter value, i.e., testing the model over extreme ranges for each parameter was not considered and the findings are outlined below. Sensitivity identified herein for the Tuolumne River system may not represent responses encountered in other systems, i.e., these analysis may not translate to or from other river basins.

Table 26 presents parameters considered and the general findings of the sensitivity testing. Generally, individual parameters had a low to modest sensitivity in the tested range. Rather, when calibrating the models, particularly temperature, the effect of more than one parameter tended to have a cumulative effect. Overall, flow was sensitive to geometry (cross section and slope factor) and Manning's roughness. These parameters affect temperature because they impact travel time through stream reaches.

Water temperature was more sensitive to geometry (cross section), evaporation coefficients, and meteorology, and less sensitive to shading, tributary inflows, dead pool volumes, and bed heat conduction. A grid resolution test is often carried out as part of model development and calibration as well. Under these tests the spatial resolution of the grid is modified to determine if model results vary with different spatial representations. The 100-foot node spacing grid was tested in the previous Upper Tuolumne River work (Jayasundara *et al.* 2010) and found to be appropriate. This resolution was deemed acceptable and applied to the remainder of the stream reaches in the study area.

Table 26. Relative sensitivity of simulated flow and water temperature to selected parameters.

Parameter	Flow	Water temperature
Channel geometry	Low to moderate	Moderate to high
Manning's roughness	Moderate	Low to moderate
Slope factor	Moderate to high	Low to moderate
Evaporation coefficients: a and b	n/a	Moderate to high
Topographic shade	n/a	Low
Riparian shade	n/a	Low (locally moderate)
Downstream stage boundary condition	Moderate to high	Low
Tributary boundary conditions temperature	n/a	Low to moderate
Meteorology	n/a	Moderate to high
Dead pools	n/a	Low
Headwater boundary condition water temperature (hourly versus daily average)	n/a	Low
Bed heat conduction	n/a	Low

8. Model Application – Without Dams Condition

The final calibrated and tested Tuolumne River flow and temperature model (TRFT) was applied to the 1970 to 2012 period water year (while calendar years were simulated, the actual period of analysis was water year 1971 through water year 2012 – April 1971 to September 2012). Calibration parameters and coefficients remained unchanged from the calibration phase of the project. For the application phase, the Upper Tuolumne River reach commenced at what is currently the headwater of Hetch Hetchy Reservoir and extended to confluence with the San Joaquin River approximately 130 miles downstream. As noted previously, this WOD condition was modeled in two sections: from the headwaters of Hetch Hetchy to the headwater of Don Pedro Reservoir, and from the headwaters of Don Pedro Reservoir to the confluence with the San Joaquin River. Both the upper and lower Tuolumne River reaches include the same tributaries as represented in the calibration phase. The required flow and water temperature boundary conditions for the application phase have been described in the data development section above (Section 6). Stage discharge relationships were developed for each reach, forming the downstream boundary. For the upper reach, a fixed stage was applied due to model stability issues over the wide range of flows, and was deemed appropriate for this steeper portion of the river. For the lower reach, a stage-flow relationship was developed successfully for the calibration years (2010 to 2012). However, under high flow years (greater than approximately 10,000 cfs at La Grange Diversion Dam), this relationship led to model instability and a new relationship was developed. This relationship was tested for a variety of years (low and high runoff) and functioned effectively. Additional testing of the downstream boundary condition is recommended to provide a single relationship for all simulation years.

8.1. Shading Representation

Water temperatures in surface waters are often strongly influenced by external heat sources, and solar radiation is one of the most important of these external heat sources. Shade can greatly influence the amount of solar radiation that reaches the water surface. For this project, riparian and topographic shading were considered in the RMA-11 model. Shade on the Tuolumne River was represented in both calibration and WOD scenarios. Both riparian vegetation and topography were included in this representation but, in the vicinity of the Tuolumne River, basin topography generally results in little shading. Therefore, topographic shade was given a negligibly small value that was applied to all reaches for all simulation periods.

On the other hand, riparian vegetation shade can play a role of variable importance in water temperatures in the Tuolumne River Basin. In the upper canyon, where terrain adjacent to the river is rocky and can experience high flow scouring events, shade-producing vegetation appears to be relatively sparse. But in broad bottomlands of Hetch Hetchy and in the lower reach along the Central Valley floor, where the river gradient is flatter and where bottomlands provide relief from high velocity runoff events, corridors of trees may provide effective shade along the river. This riparian corridor tends to be denser along the Central Valley floor, where temperatures are warmer year-round, than in the Hetch Hetchy reach. In moderately graded reaches running through the foothills between the upper and lower Tuolumne, a different vegetation structure has developed. Here, a population of mixed hardwoods and conifers generally line the north-facing banks of the river where sunny, south-facing, banks support little vegetation. Overall, the lower Tuolumne is a relatively wide river and riparian vegetation can only shade a portion of the river's width, especially during the middle of the day when solar radiation is highest and shadows are short. The effect of river width on effective shade was accounted for by a shade factor applied during calibration.

Shade along the Tuolumne River was estimated using a separate shade model created for this project and based on Shade-a-lator from Oregon Department of Environmental Quality (http://www.deq.state.or.us/wq/trading/trading.htm#Too). The shade model produces an hourly transmittance factor that reduces atmospheric solar radiation depending upon the location of the sun in the sky and the height and density of riparian vegetation.

8.2. Results of the "Without Dams" Application

The simulation of the WOD case for 42 years over the approximately 130-mile Tuolumne River reach produces simulated flow (depth, velocity) and water temperature results every 100 feet at one-hour intervals – nearly five billion data points for flow and temperature. This remarkably rich data set represents flow and water temperature in response to a wide range of hydrologic and meteorological conditions. Outlined herein are sample results and an example statistical assessment.

8.2.1. Results

All TRFT model hourly flow and temperature results were tabulated for selected locations identified in discussions with HDR (Table 27). These data were summarized for daily mean, maximum, and minimum temperatures. Average daily flow and temperature data for selected locations from below Hetch Hetchy to the San Joaquin River are shown in Figure 36 and Figure 37, respectively. Variation among wet years and dry years, and general heating trends from the upstream to downstream locations are apparent.

Simulation results indicate that peak summer water temperatures in the Tuolumne River below Hetch Hetchy are at times warmer than those above Don Pedro Reservoir. Several factors may contribute to this condition, including: low flows in the Tuolumne River above Hetch Hetchy at this time of year; adverse heating conditions in the low gradient Hetch Hetchy Valley reach; model estimates of tributary inflows and associated temperatures of the major tributaries between Early Intake and Don Pedro Reservoir (Cherry Creek, South Fork Tuolumne River, Clavey River, North Fork Tuolumne River); and assumed channel forms in the Hetch Hetchy Valley reach.

Table 27. Initial assessment locations in the project area.

Tuolumne River Location	Approximate River Mile
1. USGS Gage above Hetch Hetchy	128.5
2. USGS Gage below O'Shaughnessy Dam	118.5
3. Cherry Creek – upstream	105.5
4. Cherry Creek – downstream	105.3
5. South Fork TR – upstream	97.5
6. South Fork TR – downstream	97.2
7. Clavey River – upstream	91.5
8. Clavey River– downstream	91.2
9. North Fork TR – upstream	82.8
10. North Fork TR – downstream	82.5
11. Indian Creek – Upstream	90.9
12. Indian Creek – Downstream	90.6
13. Inflow To Don Pedro	82.3
14. Outflow From Don Pedro	55.6
15. Below La Grange	51.5
16. Tuolumne River at RM 46	46
17. Tuolumne River at RM 40	40
18. Tuolumne River at RM 34	34
19. Tuolumne River at RM 24	24
20. Tuolumne River R at RM 10	10
21. Tuolumne River (2) – above confluence with San Joaquin River	2

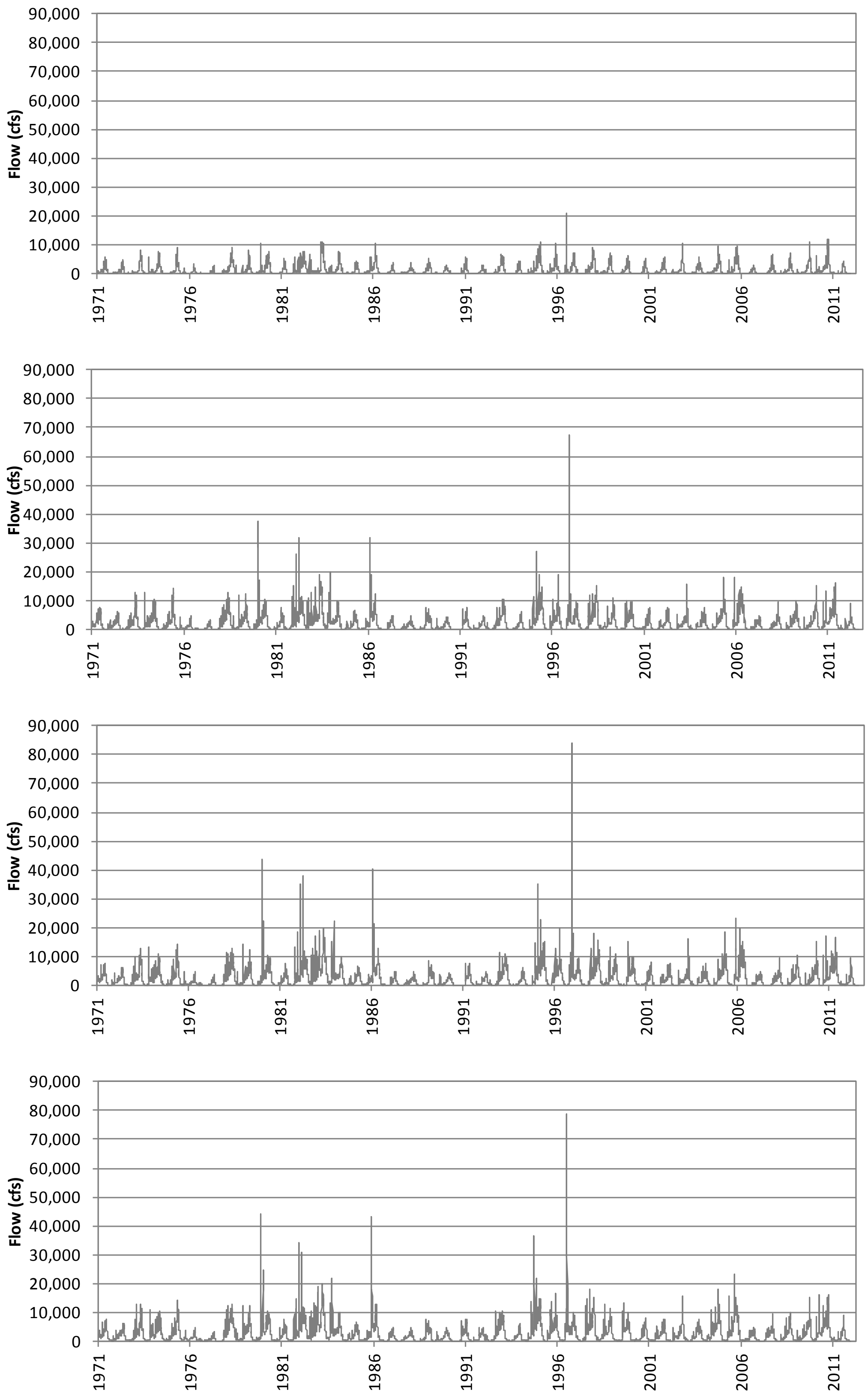


Figure 36. Simulated daily average flow for the without dams condition for the (top to bottom) Tuolumne River below Hetch Hetchy, above Don Pedro, below La Grange, above the San Joaquin River: 1971-2012.

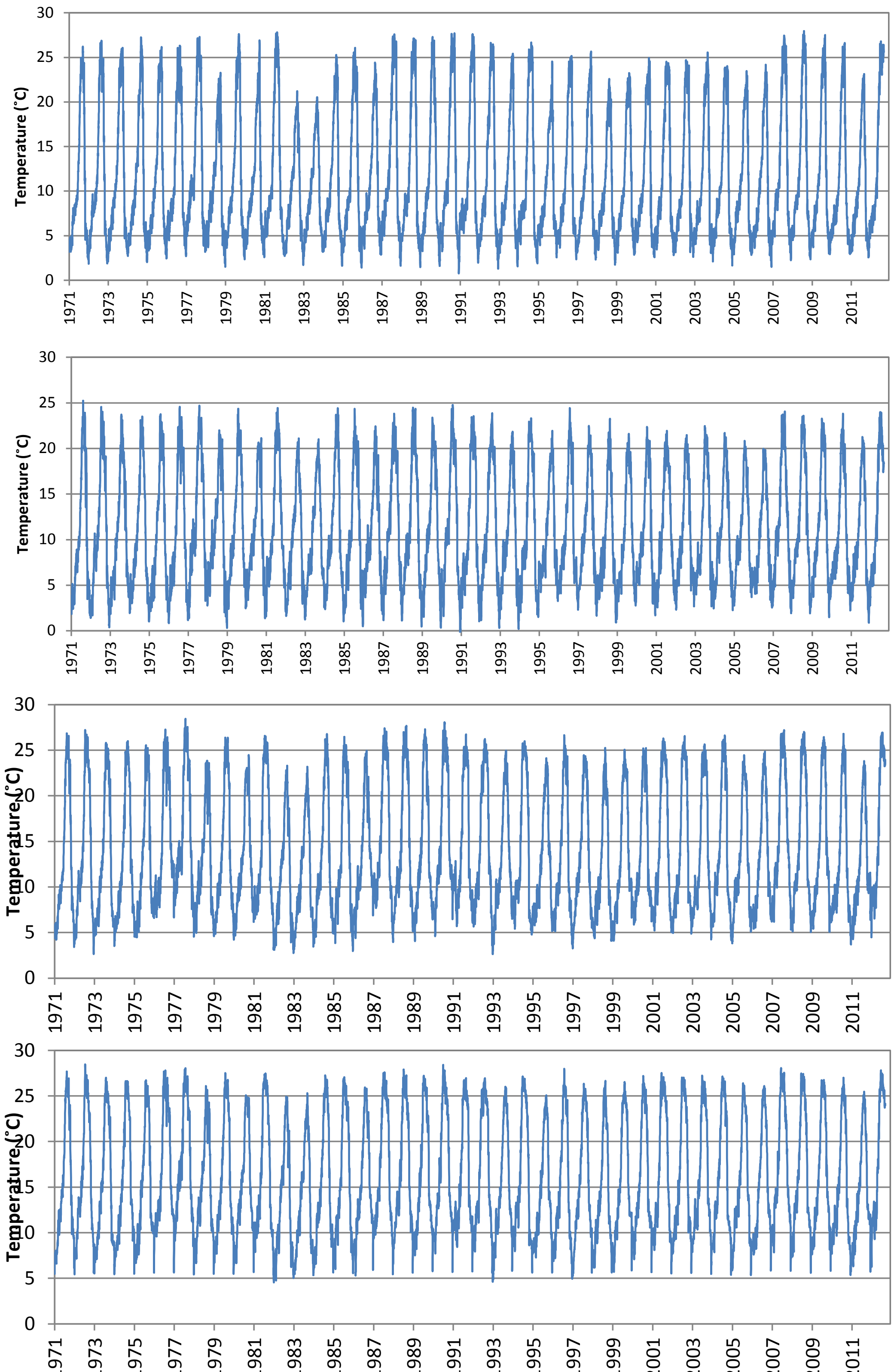


Figure 37. Simulated daily average water temperature for the without dams condition for the (top to bottom) Tuolumne River below Hetch Hetchy, above Don Pedro, below La Grange, above the San Joaquin River: 1971-2012.

8.2.2. Statistical Assessment

Water temperature information can be assessed in many ways. As part of an initial investigation, several specific statistics were identified, including hourly; daily maximum, mean, and minimum; seven-day average of the maximum daily temperature (7DADM), and seven-day average of the mean daily temperature (sometimes referred to as MWAT – mean weekly average temperature). Selected examples of these are presented below to illustrate the development of these metrics based on TRFT model output.

8.2.2.1. Daily Mean, Maximum, and Minimum Water Temperature

Daily mean, maximum, and minimum water temperature data, and the associated flow for dry, normal, and wet hydrologic conditions are presented herein for two locations on the Tuolumne River: above Early Intake and below La Grange (Figure 38, Figure 39, and Figure 40; and Figure 41, Figure 42, and Figure 43, respectively). Simulated water temperatures respond to seasonal flow, headwater and tributary inflow temperatures, and meteorological conditions. Diel temperatures are moderated in the fall, winter, and during spring snowmelt, and are maximum in summer. Differences between the hydrologic year types are apparent, with drier years experiencing lower flows and higher water temperatures during summer periods than wetter higher flow years.

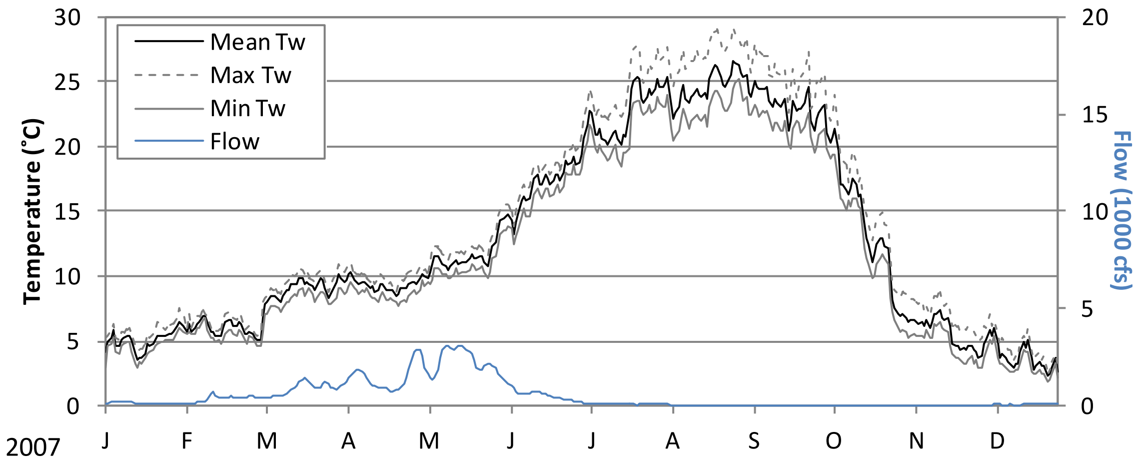


Figure 38. WOD average (mean), maximum, and minimum water temperatures and flow in the Tuolumne River above Early Intake for a representative Dry year (2007).

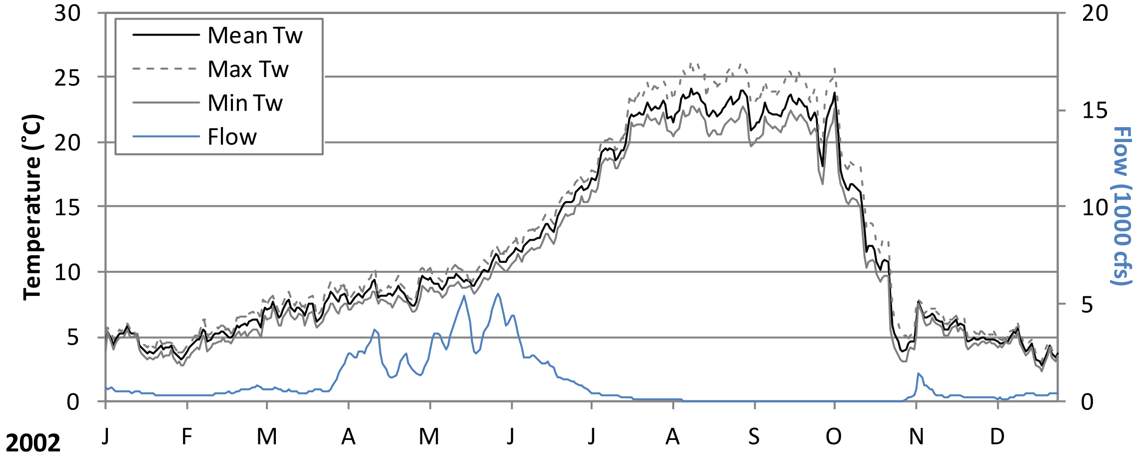


Figure 39. WOD average (mean), maximum, and minimum water temperatures and flow in the Tuolumne River above Early Intake for a representative Normal year (2002).

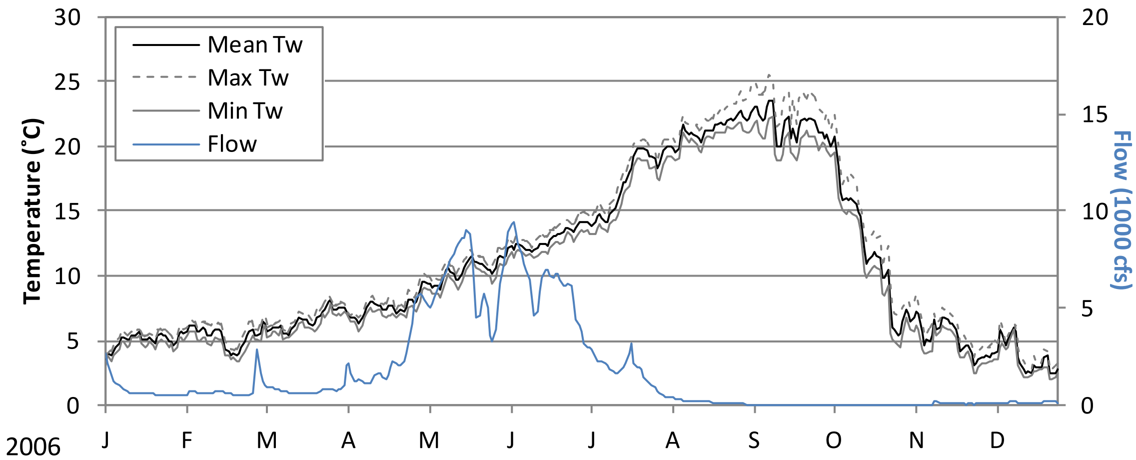


Figure 40. WOD average (mean), maximum, and minimum water temperatures and flow in the Tuolumne River above Early Intake for a representative Wet year (2006).

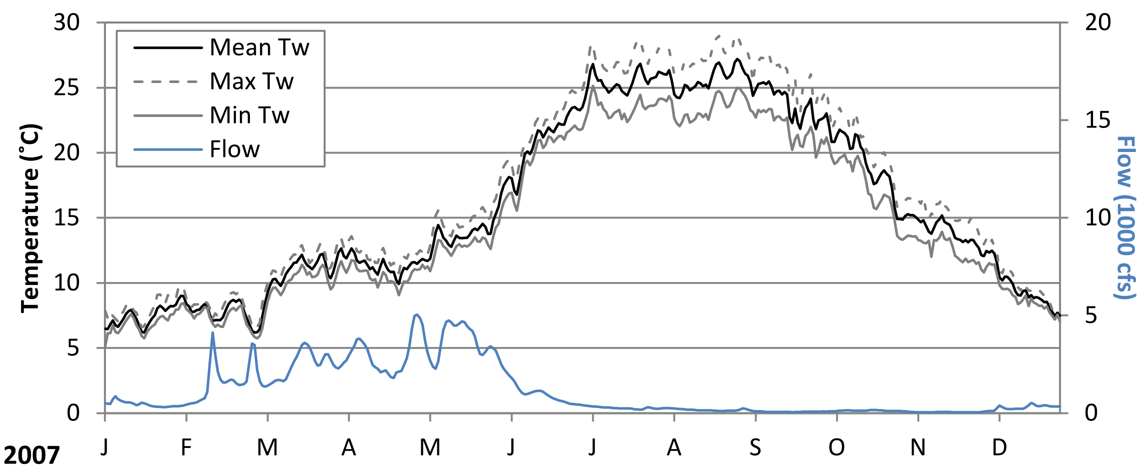


Figure 41. WOD average (mean), maximum, and minimum water temperatures and flow in the Tuolumne River below La Grange Diversion Dam for a representative Dry year (2007).

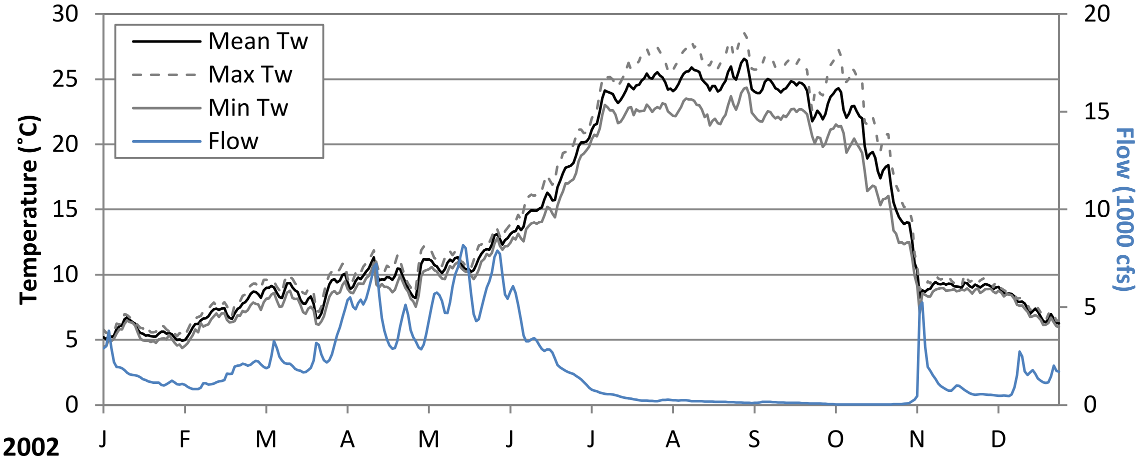


Figure 42. WOD average (mean), maximum, and minimum water temperatures and flow in the Tuolumne River below La Grange Diversion Dam for a representative Normal year (2002).

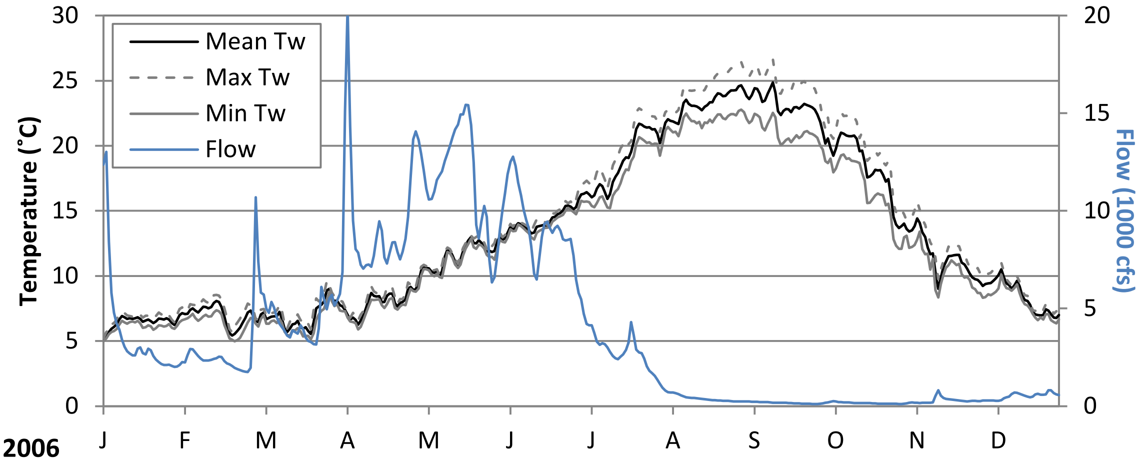


Figure 43. WOD average (mean), maximum, and minimum water temperatures and flow in the Tuolumne River below La Grange Diversion Dam for a representative Wet year (2006).

8.2.2.2. Seven Day Average of the Daily Maximum (7DADM) and Mean Weekly Average Temperature (MWAT)

Examples of 7DADM and MWAT based on simulated sub-daily TRFT model water temperature were calculated for the Tuolumne River below La Grange for the entire 42-year period (Figure 44 and Figure 45, respectively). While these results are presented for extended periods herein, subsets of these results for individual years, or months can also be examined in graphical or tabular form. The 7DADM illustrate more variability than MWAT temperatures because of accounting for maximum daily values versus mean daily values.

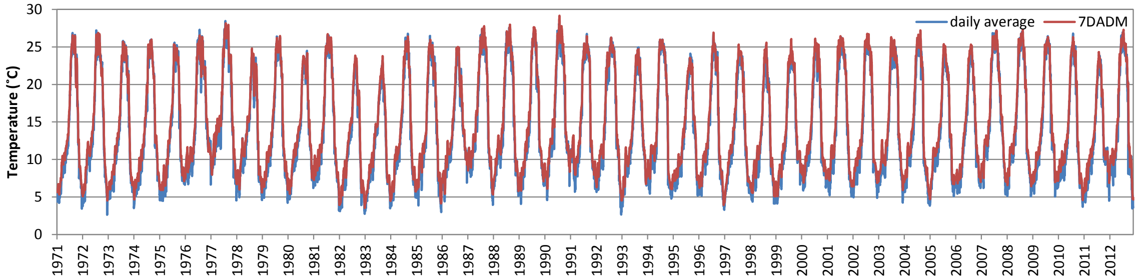


Figure 44. 7DADM water temperatures in the Tuolumne River below La Grange Diversion Dam for the WOD condition: 1970-2012.

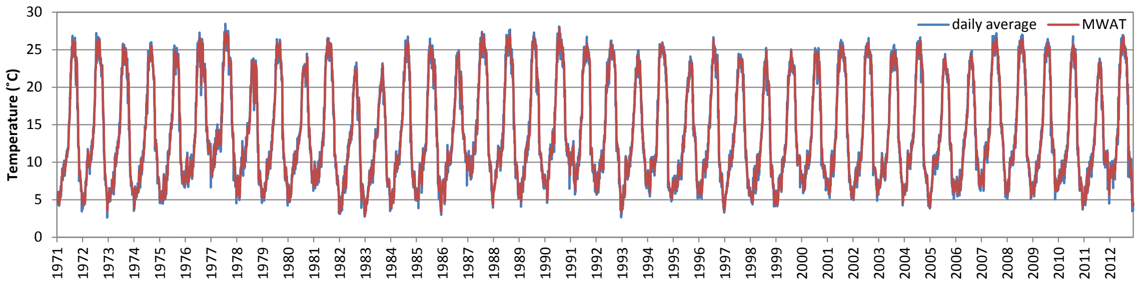


Figure 45. MWAT water temperatures in the Tuolumne River below La Grange Diversion Dam for the WOD condition: 1970-2012.

8.2.2.3. Initial Assessment and Electronic File Library

Initial assessment of TRFT simulated flow and temperature includes a specific list of statistical metrics and locations for examining simulated WOD conditions, as outlined in Table 28. In addition, there are three locations where without dams simulated water temperatures were compared to available observed data: Tuolumne River near Early Intake, Indian Creek, and Ward's Ferry.

All data were catalogued in a data library and made available in electronic format for assessment. The file format, structure, and contents were provided to ease navigation through the extensive data sets.

Table 28. Statistical metrics at assessment locations in the project area.

Statistic	Location (from Assessment Locations Table (above))																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Plot of mean, daily minimum, and daily maximum temperatures for the period of record				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Plot of hour temperatures and mean daily flows for a wet year (2006), dry year (2007), and normal year (2002)													x	x	x	x	x	x	x	x	x
Plot of hourly temperatures and mean daily flows for '87 to '92													x	x	x	x	x	x	x	x	x
Graphs of monthly flow duration curves using mean daily flows and temperatures using hourly temperatures from the period of record													x	x	x	x	x	x	x	x	x
Plot of 7DADM (7-day moving average of the daily maximum temperature) for the period record				x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x
Plot of the MWAT (used by Stillwater in its March 2011 filing with FERC). Described as the maximum weekly average temperature (interpeted as the 7-day moving average of mean daily temperatures for each year of the record)															x	x	x	x	x	x	x
MWAT's for the period October 15 through November 30; March 20 to May 31; October 15 to February 15															x	x	x	x	x	x	x
Daily min, max and mean for the period 2000 to 2009	x	x	x												x	x	x	x	x	x	x

9. Summary

The focus of the TRFT model study was to develop a flow and water temperature model to simulate temperatures in the Tuolumne River from above Hetch Hetchy Reservoir to the confluence with the San Joaquin River in the absence of reservoirs (i.e., without the existing Hetch Hetchy reservoir, Don Pedro reservoir, or La Grange headpond). The model was developed to allow the comparison of such a without dams condition with existing conditions where the three reservoirs are in place. This comparison includes flow and water temperature, as well as water temperature metrics such as daily mean, maximum and minimum, and seven-day average of the daily maximum temperatures and seven-day average of the daily mean temperatures.

The study area included the main stem of the Tuolumne River from above Hetch Hetchy Reservoir to the confluence with the San Joaquin River. Tributary flows include Cherry Creek, the South Fork Tuolumne River, Clavey River, North Fork Tuolumne River, Dry Creek, as well as other minor tributaries.

This modeling study included four major components: development of a conceptual framework, model selection, model development and testing, and model application. The development of the conceptual framework identified key river and tributary features, and hydrology, water temperature, and meteorology conditions to consider in a without dams representation. Examples include representation of the river course and morphology in the currently inundated reservoir reaches of the system; tributary hydrology and temperature conditions for the simulation period where data were limited; and the potential implications of without dams riparian shading on water temperatures. The conceptualization of these and other system elements provided focus and direction of the modeling study, and assisted in model selection. During the model selection phase, a review of appropriate computer models was completed that resulted in the selection of RMA-2 and RMA-11. These models have an ability to effectively represent high gradient stream reaches under a wide range of hydrologic and meteorological conditions. Other sub-models selected in this stage included an equilibrium temperature model to determine tributary inflow water temperatures and a shade model to assess effects of riparian vegetation shading on incoming solar radiation. This latter model was based on a shade model used by Oregon Department of Environmental Quality.

The subsequent stage of model development consisted of four processes: data development, model implementation, model calibration, and sensitivity analysis. During the data development process, flow, temperature, and meteorological data from 1970 to 2012 was reviewed and compiled in the format needed by the models. A geometric representation of the system was developed cooperatively with HDR based on available cross section data and detailed bathymetry of Hetch Hetchy and Don Pedro Reservoirs. Flow data were developed by HDR, and ungaged tributaries were represented using a unique proration method. Meteorological information was also provided by HDR. Reach specific meteorology was developed to accommodate elevation change through the project area. Water temperature data were based on available records and through the application of the aforementioned equilibrium temperature model and meteorology.

Implementation included populating the model with the geometric river representation, specifying appropriate model coefficients and parameters, defining all headwater and tributary flow and water temperature conditions, and constructing reach specific meteorological files. The model time step throughout the simulation was one-hour, effectively capturing sub-daily temperature response to system conditions. The result of model implementation was a functional, but uncalibrated model.

Model calibration included comparing available measured field data to simulated flow and temperature conditions, and adjusting model parameters (e.g., Manning's channel roughness, evaporation coefficients) to minimize the difference between simulated and observed data. Model performance at the calibration locations was assessed both graphically and statistically. Calibration indicated that the TRFT model reproduced flow and temperature through a range of inter-annual, seasonal, short duration, and diel conditions with overall low mean bias, mean absolute error, and root mean squared error. Subsequently, a sensitivity analysis was performed to assess the TRFT model response to changes in selected model parameters.

The final phase in the study was model application. Specifically, the subsequent application of the TRFT model to the long-term data set (1970 to 2012) provided an extensive and detailed temporal and spatial representation of the Tuolumne River – simulated hourly flow and water temperature at approximately 100-foot intervals throughout the study reach for 42 years. These data are available to develop a range of statistical measures useful for assessing anadromous fish conditions in the system, including flow duration curves; daily minimum, mean, and maximum temperature; seven-day averages of the daily maximum and means; and examination of these metrics by hydrologic year type.

9.1. Concluding Comment

The development of the TRFT model has produced a set of mathematical flow and water temperature models, calibrated and tested for the investigation of without dams condition from above Hetch Hetchy Reservoir to the confluence with the Tuolumne River. The careful development of geometric, flow, temperature, and meteorological data sets, through a highly collaborative team approach, was an important aspect of the project. The TRFT model was calibrated using historic observations for currently free- flowing reaches of the river and reproduced observed conditions over a wide range of conditions throughout the study reach. This effort has resulted in a powerful, physically-based model capable of long simulations at fine spatial and temporal resolution. Subsequently, the model was applied to an assumed Tuolumne River without the presence of O'Shaughnessy Dam, Don Pedro Dam, and La Grange Diversion Dam for the period 1970 to 2012. Simulated hourly flow and water temperature output were used to demonstrate the utility of this extensive data set in current and future analyses.

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