DEVELOPMENT OF A FLOW AND TEMPERATURE MODEL FOR THE HETCH HETCHY REACH OF THE UPPER TUOLUMNE RIVER

Prepared for the Natural Resources Division of the San Francisco Public Utilities Commission

Prepared By

Nimal Jayasundara

Mike Deas

Stacy Tanaka

Ann Willis

Watercourse Engineering, Inc.

424 Second Street, Suite B

Davis, California 95616

(530) 750 – 3072

December 12, 2010

Table of Contents

Table of Figures

Table of Tables

Upper Tuolumne River Flow and Temperature Modeling

1. Introduction

The Tuolumne River flows from its headwaters in Yosemite National Park into Hetch Hetchy Reservoir where it enters part of the water supply system managed by the San Francisco Public Utility Commission (SFPUC). Completed in 1923 and raised in 1938, O'Shaughnessy Dam creates the Hetch Hetchy Reservoir, which has a storage capacity of 360,360 acre feet (af). Water managers operate O'Shaughnessy Dam based on three water year classes: Schedule A (wettest 60 percent of all water years), Schedule B (32 percent of all water years) and Schedule C (driest 8 percent of all water years). The type of water year is determined based on rain gauge data and does not include snow pillow estimates or run-off forecasts. The 1987 flow stipulation currently drives daily base flow releases for each of these three water year types. The SFPUC is refining flow prescriptions in the 1987 flow stipulation to better incorporate ecological benefits during various water years. That is, the SFPUC would like to operate the dam in such a way as to provide ecologically beneficial flow during wet periods when water managers have increased flexibility (RMC-M&T 2007). As part of this effort, the SFPUC proposes to revise the water year classification to include five water years; extremely wet (15 percent), wet (20 percent), normal (30 percent), dry (20 percent) and extremely dry (15 percent). The ecological benefits would be derived from the relationship between reservoir releases and downstream water temperature. To better understand this relationship, as well as develop alternative reservoir operation prescriptions, Watercourse Engineering, Inc. (Watercourse) developed a flow and water temperature model. The flow and water temperature model was then used to inform a gaming tool that helps evaluate flow release management options based on the ecological benefit to target species. The flow prescriptions made by this gaming tool are based on a suite of model simulations that produce flow and temperature data given specified inputs. This report describes the development of the Upper Tuolumne River flow and temperature model to help evaluate ecological tradeoffs of different flow management scenarios.

2. Purpose

The purpose of the Upper Tuolumne River flow and temperature model is to simulate stream flows and water temperatures under a range of flow and meteorological conditions. The predictions generated by this model will then be used to populate the data matrix of the gaming tool, which managers can use to evaluate potential expected ecological benefit from their operational decisions.

3. Study Area

The Upper Tuolumne River study reach (known as the Hetch Hetchy reach) extends from O'Shaughnessy Dam to Early Intake – approximately 13 river miles (Figure 1). No major natural tributaries are in this reach; however, several smaller intermittent streams enter the river. Tuolumne River elevations range from approximately 3,600 feet to 2,400 feet through the study reach, while headwaters of tributary watersheds exceed 6,000 feet. The principal source of water is Hetch Hetchy Reservoir, where flows are regulated at O'Shaughnessy Dam. The stream is characterized by high gradient reaches passing through a steep walled, narrow canyon. The channel is dominated by bedrock and boulder features with limited alluvium. The region experiences cool wet winters and warm dry summer. Access to the reach is limited due to the remoteness and rugged terrain.

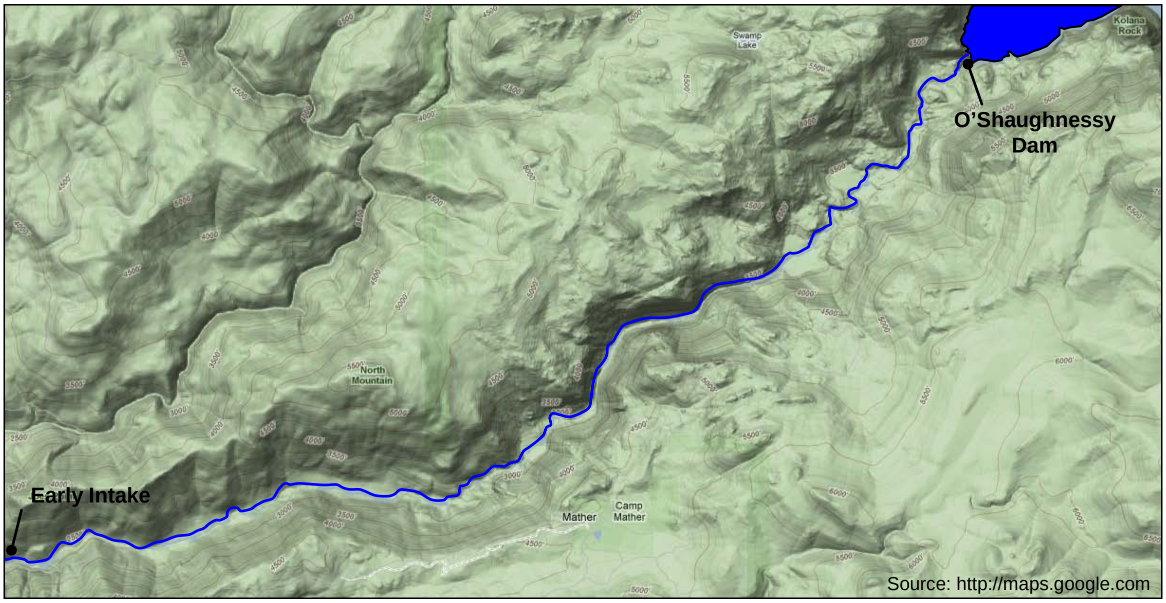

Figure 1. A map of the study reach, which begins at O'Shaughnessy Dam and ends at Early Intake.

4. Methods

The steps to develop a model that accurately predicted water temperature on the Hetch Hetchy reach were as follows:

- System conceptualization,
- Data assembly and organization,
- Model implementation,
- Model calibration, and
- Model application.

Conceptualization helped identify what kind of model would best represent the system. Data assembly and organization helped refine the conceptualization and define instream conditions over a period of several months. Implementation involved creating a running model of the system. After a running model was created, it was calibrated by using field data to test its accuracy. Finally, once the model was adjusted to accurately simulate observed baseline conditions, assessment of alternative flow regimes was completed.

5. System Conceptualization

Prior to model construction, a conceptual understanding of the Hetch Hetchy reach of the Upper Tuolumne River was developed to identify the type of model that would best represent the system. The conceptual understanding was achieved by analyzing data of the geometry, hydrology, water temperature, and meteorological conditions of the Hetch Hetchy reach. Understanding the general characteristics of the river helped determine that a one-dimensional model would simulate thermal complexity appropriately. Previous work (MSC, 2008) identified available data to support flow and temperature modeling.

5.1. Model Selection

A suite of modeling software, RMA-2 (v8) for hydrodynamics and RMA-11 (v8) for water temperature, was selected to represent the Upper Tuolumne River as a one-dimensional, depth-averaged, finite element model. RMAGEN (v74) was used to create a geometry file of the Hetch Hetchy reach that was used by both the hydrodynamic and water temperature models. RMA-2 is a finite element hydrodynamic model that calculates velocity, water surface elevation, and depth at defined nodes of each grid element in the geometric representation of the river – in this project, the model was applied in one-dimensional form with laterally and depth-averaged results. RMA-11 is a finite element water quality model that uses the depth and velocity results from RMA-2 to solve advection diffusion constituent transport equations. Details of each of these applications are provided below.

5.1.1. RMAGEN

RMAGEN is a preprocessor program used to construct the numerical mesh used in RMA-2 and RMA-11. RMAGEN assigns spatial information to each node within the mesh (x-y location and elevation), interpolating values from the topographic description. The mesh consists of linear elements of variable size. These elements consist of three nodes – one at each endpoint and one middle node.

5.1.2. RMA-2 Model

RMA-2 is a two-dimensional and depth-averaged, finite element hydrodynamic numerical model, that can also be applied in one-dimension (laterally and depth averaged). The model computes water surface elevations and horizontal velocity components for free-surface, one-dimensional 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) problems can be analyzed. 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).

5.1.3. RMA-11 Model

RMA-11 is a three-dimensional finite element water quality model capable of simulating one and two-dimensional approximations to systems either separately or in combined form. It is designed to accept input of velocities and depths, either from an ASCII data file or from binary results files produced by the one-dimensional hydrodynamic model, RMA-2. Results in the form of velocities and depth from the hydrodynamic model are used in the solution of the advection-diffusion constituent transport equations. Additional terms for each constituent represent sources, sinks, growth, or decay.

In RMA-11, the dependent variable modeled when simulating heat transport is temperature, T (^{o}C). The approach used in RMA-11 is consistent with QUAL2E (Brown and Barnwell 1987) and other literature, and assumes that heat is transferred from various energy sources, so that:

$$H_N = H_{SN} + H_{AN} + H_{SB} - (H_B + H_E + H_C)$$

Where H_N = Total net heat flux, (kJ/m^2/hr),

H_{SN} = Net short-wave influx, (kJ/m^2/hr), H_{AN} = Net long-wave influx, (kJ/m^2/hr),

H_{SB} = Bed heat influx, (kJ/m^2/hr),

H_B = Long-wave back radiation, (kJ/m^2/hr),

H_E = Conductive flux, (kJ/m^2/hr), and

H_C = Evaporative flux, (kJ/m^2/hr).

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).

6. Data Assembly and Implementation

Field data describing the Hetch Hetchy reach geometry, hydrology, water temperature, and meteorology were required to implement the conceptual and one-dimensional numerical models, as well as provide a measure of accuracy with which to test the model. Data were available from various sources including the United States Geologic Service (USGS), the San Francisco Public Utility Commission (SFPUC), the California Data Exchange Center (CDEC), and California Irrigation Management Information System (CIMIS). Details about data-gathering methods are provided below.

6.1. Geometry

Stream geometry data describing both the longitudinal and cross-sectional characteristics of the Hetch Hetchy reach were used to implement the water temperature model. Longitudinal characteristics included the planform profile of the river, as well as the longitudinal profile. Cross-sectional surveys were used to define habitat types. Some refinement of both longitudinal and cross-sectional data was required to increase the stability of the model. Details of both the original data sets and subsequent refinement are presented below.

6.1.1. Planform profile

Topographic data collected by the SFPUC in 2006 was used to construct a planform profile of the Upper Tuolumne River water temperature model (Figure 2). The Hetch Hetchy reach began immediately below O'Shaughnessy Dam and ended 12.97 miles downstream at the Early Intake diversion.

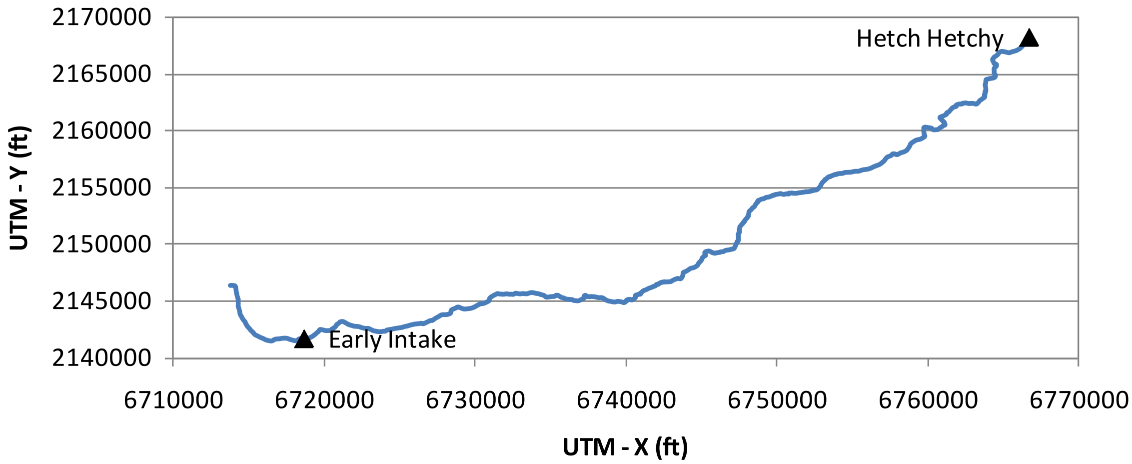

Figure 2. The planform view of the Hetch Hetchy reach water temperature model based on topographic data provided by SFPUC.

6.1.2. Longitudinal profile

The bed slope profile was also constructed using topographic data collected by the SFPUC in 2006 (1-ft contour data from photogrammetry). The stream bed was surveyed to the water surface when the river conveyed 87 cfs, a low flow in this channel. Generally, the overall profile illustrated by the topographic data was maintained in the water temperature model (Figure 3). However, local changes were made in reaches that contained abrupt transitions between steep and shallow bed slopes (e.g. cascades), causing instability in RMA-2 model. These abrupt transitions were smoothed for the numerical stability of the RMA-2 model (Figure 4 through Figure 7).

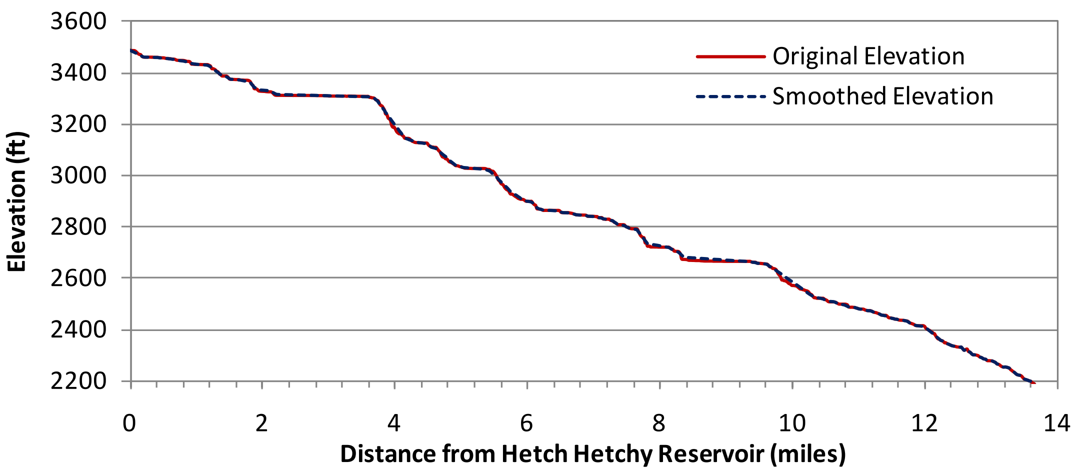

Figure 3. Comparison of the original longitudinal profile data; the profile was smoothed at abrupt transitions for use in the water temperature model.

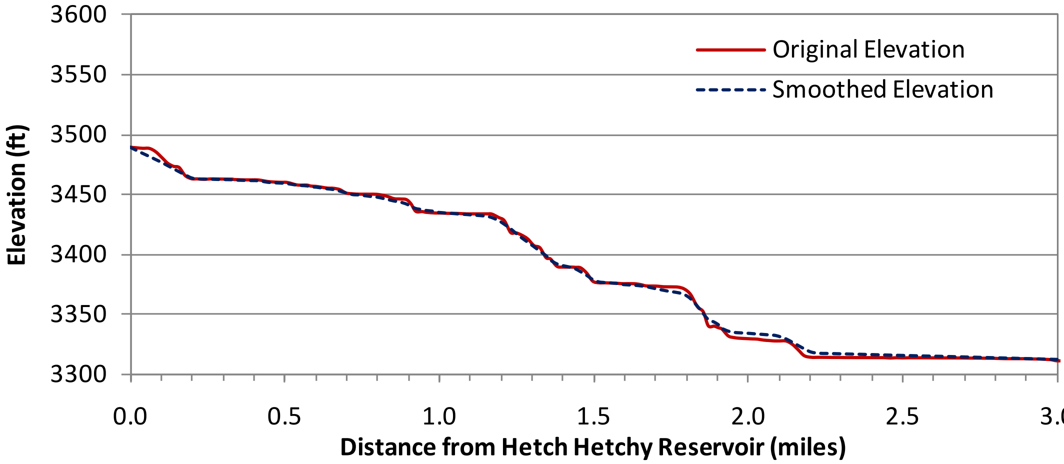

Figure 4. An illustration of the original and locally smoothed longitudinal profiles represented in the water temperature model from 0.0 mi to 3.0 mi below O'Shaughnessy Dam.

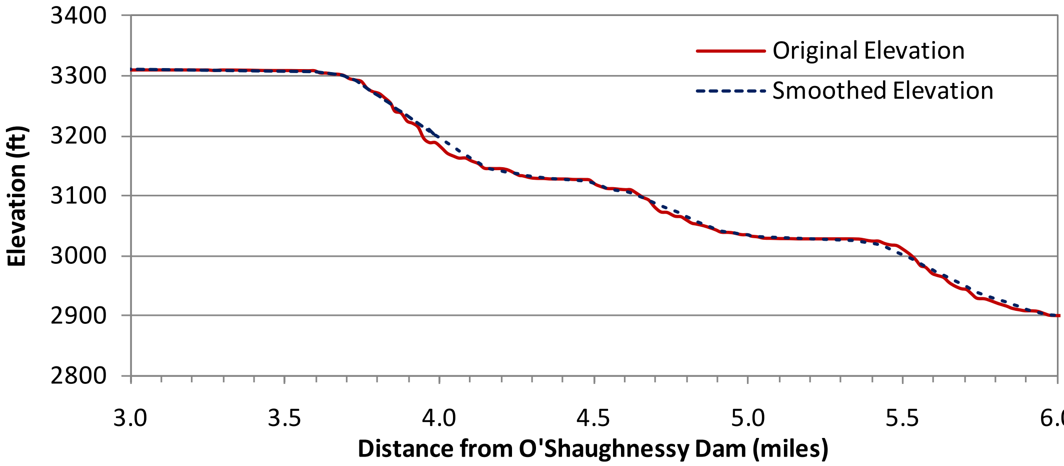

Figure 5. An illustration of the original and locally smoothed longitudinal profiles represented in the water temperature model from 3.0 mi to 6.0 mi below O'Shaughnessy Dam.

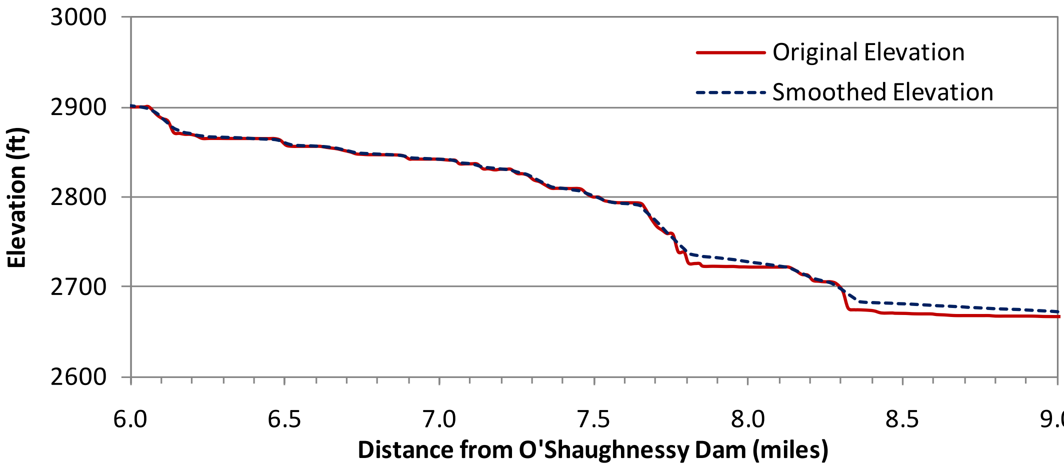

Figure 6. An illustration of the original and locally smoothed longitudinal profiles represented in the water temperature model from 6.0 mi to 9.0 mi below O'Shaughnessy Dam.

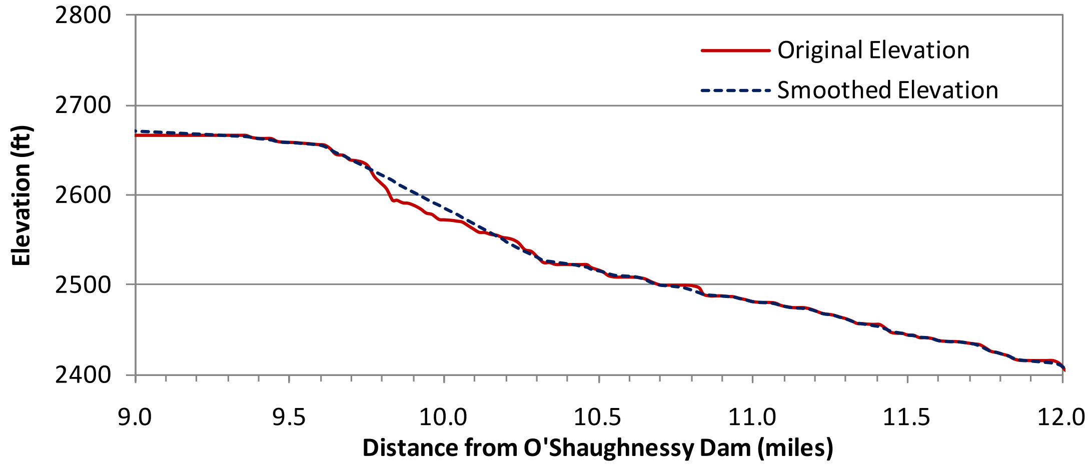

Figure 7. An illustration of the original and locally smoothed longitudinal profiles represented in the water temperature model from 9.0 mi to 12.0 mi below O'Shaughnessy Dam.

6.1.3. Cross-sections

Though the water temperature model is one-dimensional, tabular data describing cross-sectional widths and transect profiles were included to accurately simulate water velocities. The 1-ft contour interval digital terrain model developed by McBain & Trush from the 2006 photogrammetry was used to generate 758 cross-sections above the water surface on the day of the air photo (87 cfs) for the Hetch Hetchy reach. Below the 87 cfs water surface, no channel geometry data was provided. For reference, 87 cfs is a typical summer base flow that also represents approximately 64 percent of the 2000-2009 average flow observed in the channel. In some reaches, where cross-section widths lead to abrupt transitions between wide and narrow geometries, transitions were smoothed using a 20-cross-section moving average (Figure 7) to ensure model stability. Similarly, certain complex cross section geometries were also smoothed (Figure 9).

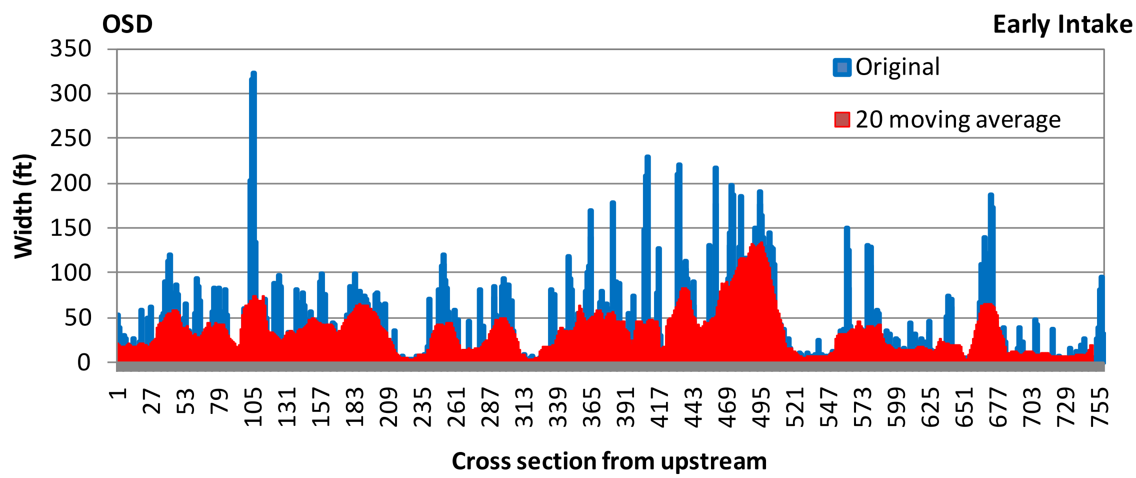

Figure 8. An illustration of the 20-cross-section moving average of the surveyed stream width data used to improve the numerical model's stability. OSD is O'Shaughnessy Dam.

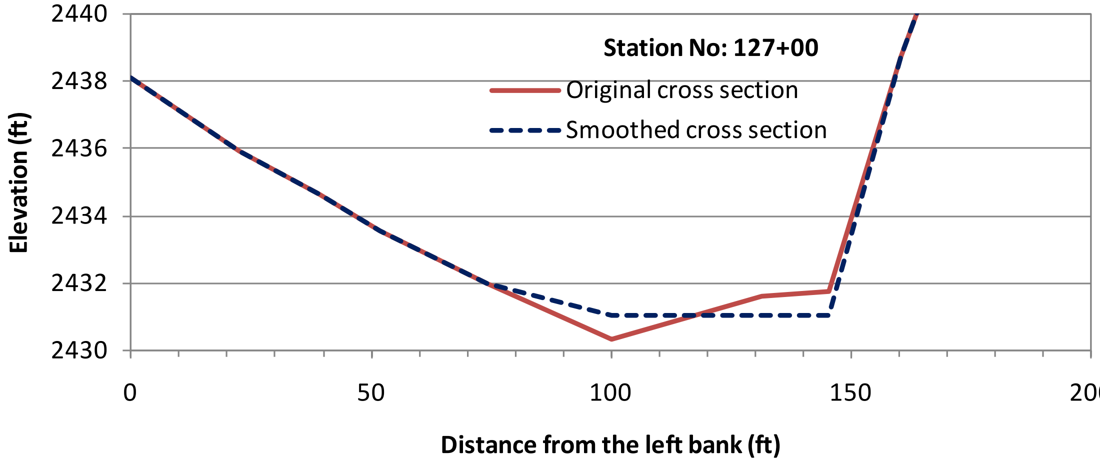

Figure 9. Sharp points in cross-section profiles were smoothed to improve the numerical model's stability.

A small number of cross-sections were surveyed by McBain & Trush that provided channel geometry below the 87 cfs water surface; however they were insufficient to provide the needed bathymetry for the model. Therefore to define the channel geometry below the water surface, the wetted area of the channel (when it contains 87 cfs) was calculated and added as five 0.1-m (0.33 ft) thick layers (Figure 10). The total area below 87 cfs was calculated using estimated velocity by Manning's equation. The average slope of each habitat type and roughness data were used. This minimal depth was assumed to maintain model stability. The width of each layer was calculated as a fraction of the original bottom width (Table 1). Overall, layer widths ranged from less than 1 ft to 300 ft. Additional refinement was made to the layers based on the cross-section's designated habitat type, which is discussed in the following section.

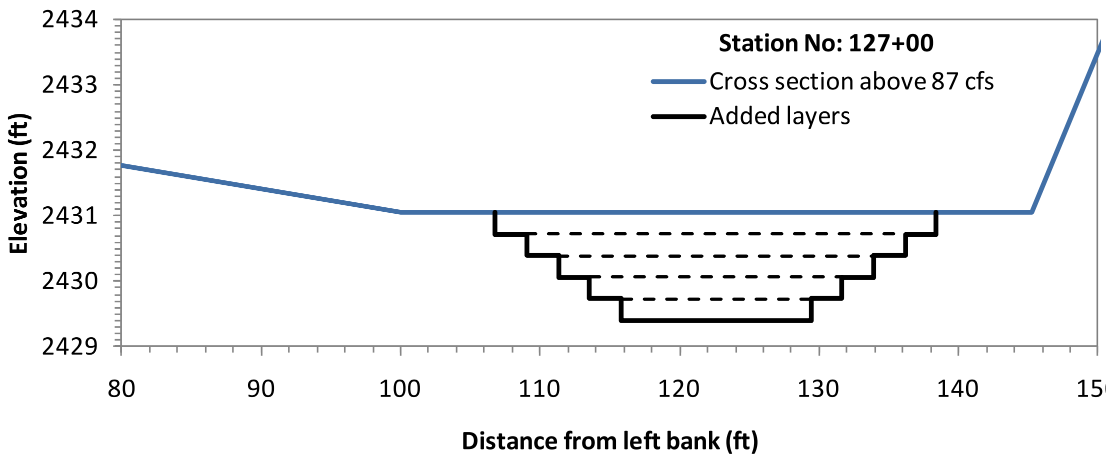

Figure 10. An example of the cross-sectional detail added to define channel geometry below the 87 cfs water surface when the channel conveys 87 cfs for a pool.

Table 1. The width of each layer (defined as a percentage of the water surface width at 87 cfs) added below the water surface elevation of the original cross-sectional survey data.

	Percent of Water Surface Width Used to Determine Layer Width				
Layer No:	**Pool**	**Run**	**LGR***	**HGR***	**Cascade**
1	70	70	70	70	70
2	60	50	50	50	50
3	40	30	30	30	30
4	30	20	20	20	20
5	20	10	10	10	10

*LGR = low gradient riffle, HGR = high gradient riffle

6.1.4. Habitat types

The 758 cross sections were further categorized into five habitat types. These habitat types included pools, runs, low-gradient riffles (LGR), high-gradient riffles (HGR), and cascades/waterfalls. Refining assumed cross section geometry below the 87 cfs water surface via habitat type improved model performance, specifically with regard to travel time. Habitat types were categorized based on a range of slopes obtained by the longitudinal profile shown in Figure 3 (Table 2). The locations of these habitat types were identified based on aerial photographs and slopes.

Table 2. Habitat type slope values and frequency.

Habitat type	Minimum slope	Maximum slope	Number of cross sections
Pool	0.0002	0.0505	281
Run	0.0004	0.0384	114
LGR	0.0032	0.0646	135
HGR	0.0140	0.0741	69
Cascade	0.0124	0.0903	159
			Σ = 758

6.2. Hydrology

Daily flow data in the Tuolumne River near Hetch Hetchy, as well as daily data describing accretion/depletion and tributary inflows, was needed. Flow data was obtained from USGS for the Tuolumne River near Hetch Hetchy gauge (USGS gauge #11276500, the approximate upstream model boundary) and Tuolumne River above Early Intake gauge (USGS gauge #11276600, the downstream model boundary). Accretion between two gauges was computed by subtracting flows at Hetch Hetchy from those at Early Intake. Two years of flow data (2002 and 2006) that would encompass a wide range of flows were selected for model implementation and calibration. Flow accretion was proportioned to sub-reaches based on drainage area. For modeling purposes, each year is simulated over the calendar year (January through December) rather than the water year (October through September).

6.2.1. Flow data

Computed unimpaired flow data for 1952-2007 period was provided by the SFPUC, and examined for representative wet and dry years to ensure that the model was calibrated using a range of flows for this system (Figure 11). A dry year, 2002, and a wet year, 2006, were selected based on their annual yield percent exceedence for model implementation and calibration (Figure 12). Though other years also represented wet and dry water years, additional factors, such as availability of meteorological and water temperature data, were considered when selecting these two years for calibration.

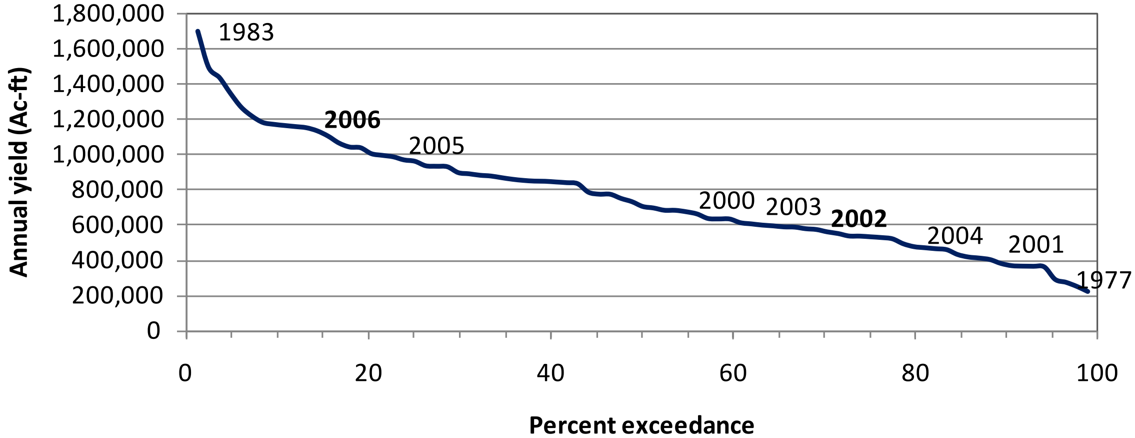

Figure 11. Exceedence ranking of the unimpaired annual flow yields of the Tuolumne River near Hetch Hetchy. Years 2002 and 2006 were selected to calibrate the Hetch Hetchy reach model.

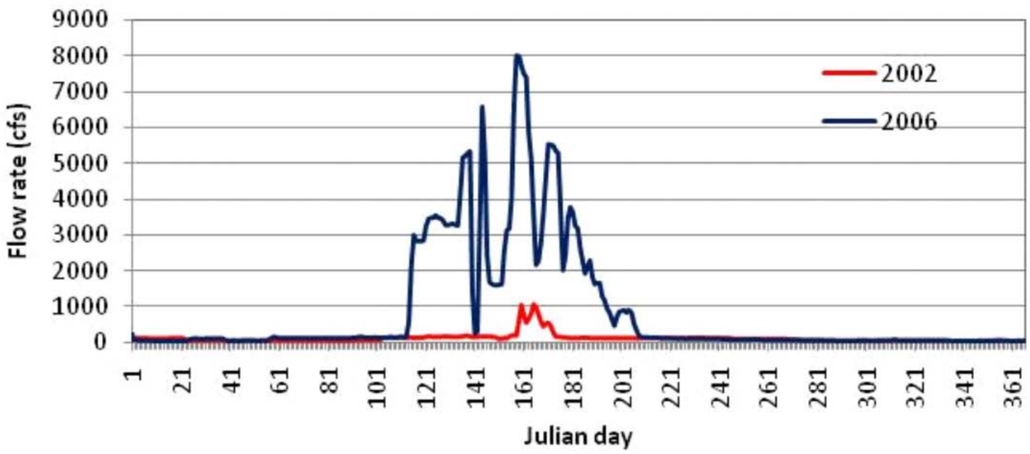

Figure 12. Annual flows of the Tuolumne River near Hetch Hetchy, by Julian Day, during 2002 and 2006.

6.2.2. Tributary accretion flow data

Tributary accretion/depletion data, provided by McBain & Trush, was calculated by subtracting flow data gathered at the top and bottom of the study reach for both 2002 (Figure 13) and 2006 (Figure 14). The computed difference between the flow at the top and the bottom of the study reach was assumed to be the tributary accretion/depletion. A negative value indicated a depletion (flow at the top was greater than flow at the bottom) and a positive value indicated an accretion. The Hetch Hetchy reach was divided into three sub-reaches (Figure 15). Each sub-basin's drainage area was used to determine weighting factors used to partition out the accretion/depletion (Table 3). As the exact locations of accretion/depletion were unknown, each sub-basin was divided into ten segments and the accretion/depletion was evenly distributed among the segments. Accretions and depletions were typically small, except during winter storm periods and during the spring snowmelt runoff.

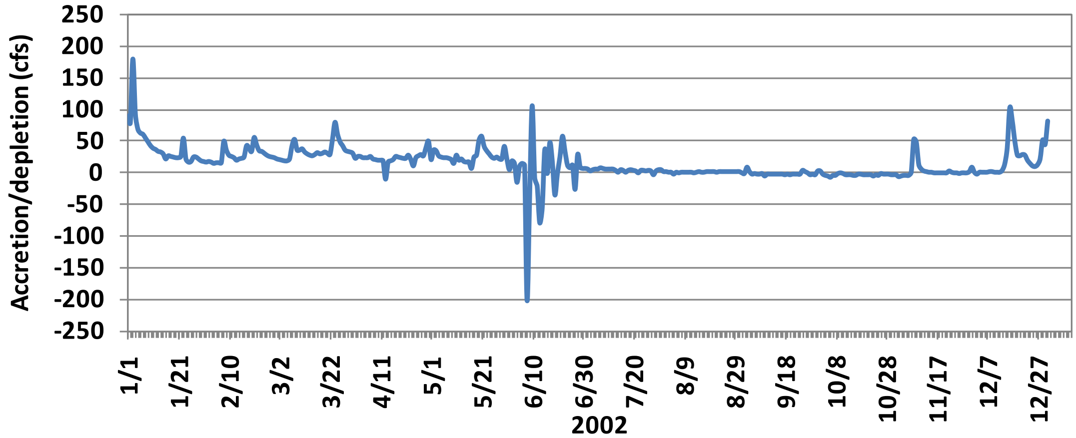

Figure 13. Daily average accretion/depletion flows in the Hetch Hetchy reach during the 2002 calibration year.

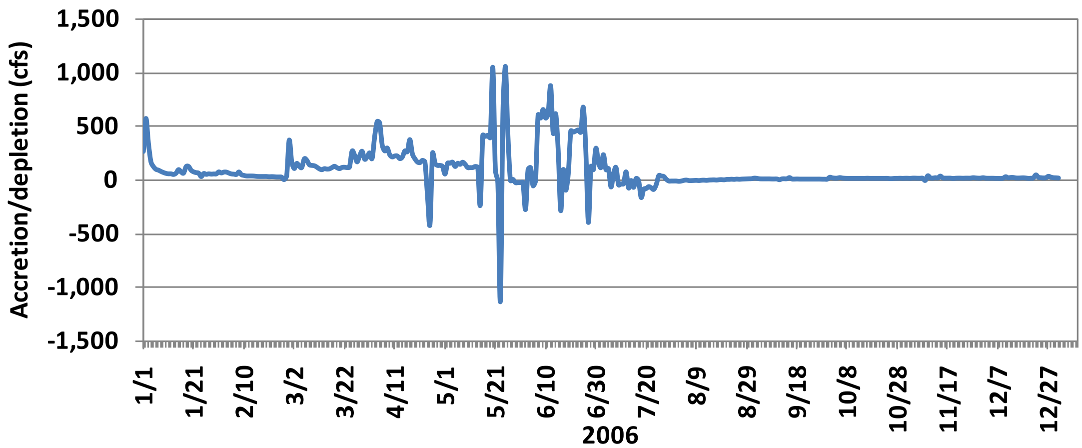

Figure 14. Total Daily average accretion/depletion flows in the Hetch Hetchy reach during the 2006 calibration year.

Table 3. The three sub-reaches of the Hetch Hetchy reach and their respective drainage areas. River stations refer to locations mapped using GPS and are measured from the Tuolumne River-Cherry Creek confluence; a pair of river stations defines the boundaries of each sub-reach.

Section	River station (ft)	Total drainage area (mi^2)	Sub-reach drainage area (mi^2)	Accretion/depletion in each sub-reach (percent)
O'Shaughnessy Dam	699+50	457	NA	NA
Upper	699+50 to 532+00	469.7	12.7	47
Middle	532+00 to 346+50	478.6	8.9	33
Lower	346+50 to 120+00	484	5.6	21

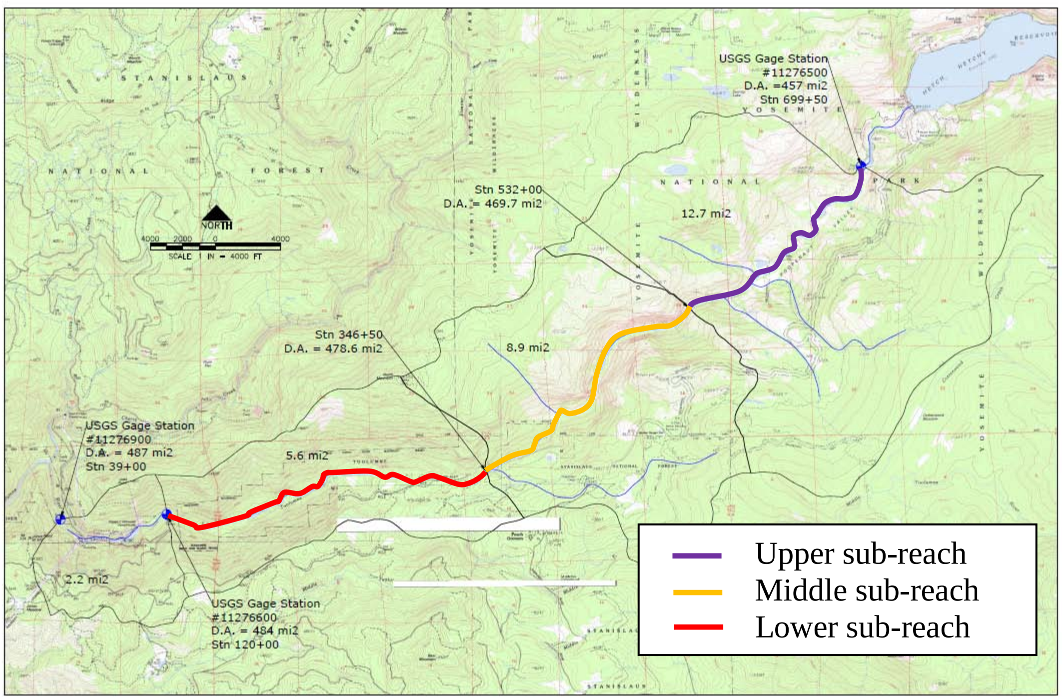

Figure 15. Three sub-reaches of the Hetch Hetchy reach; sub-reach drainage areas for the accretion/depletion are indicated.

6.3. Water Temperature

Water temperature data, provided by USGS, were also required to implement the water temperature model. Water temperatures were defined for both the upstream boundary condition of mainstream flow and for distributed accretions. Mainstream flow water temperatures were defined using USGS measured data at the Tuolumne River near Hetch Hetchy gauging station (USGS 11276500). Tributary flow and accretion water temperatures were assumed using measured data from the Tuolumne River above Hetch Hetchy gauging station (USGS 11274790), as well as short-term water temperature data in three tributaries.

6.3.1. Tuolumne River water temperatures

Hourly water temperature data from the USGS gauge near Hetch Hetchy was used to define water temperature boundary conditions in the Hetch Hetchy reach model. Water temperature data from 2002 and 2006 were used in model implementation and calibration (Figure 16).

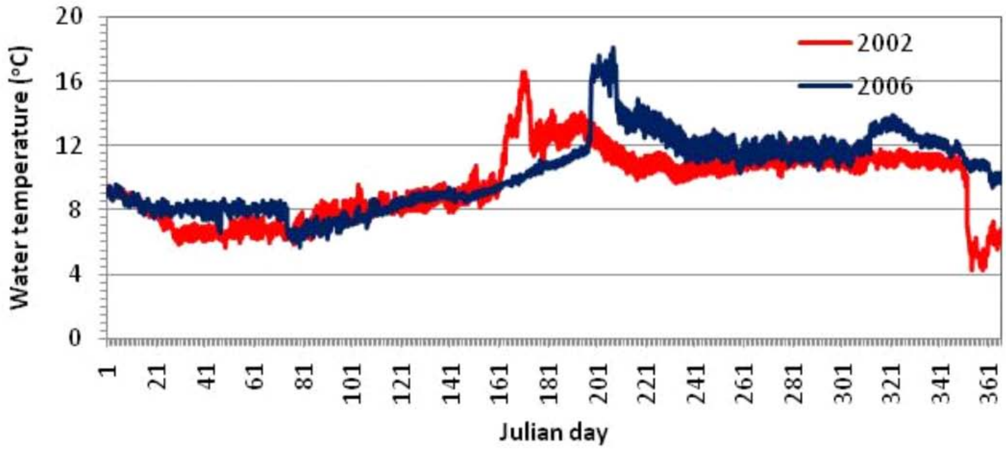

Figure 16. Hourly water temperature data for 2002 and 2006, by Julian Day, gathered at USGS gauge #11276500, in the Tuolumne River near Hetch Hetchy.

6.3.2. Tributary/Accretion water temperatures

Tributary and accretion water temperatures were represented using water temperature data gathered from USGS gauge above Hetch Hetchy, as well as NPS gauges placed in three tributaries located in Poopenaut Valley, approximately 3 miles downstream from O'Shaughnessy Dam (Figure 17). Water temperature data gathered at the USGS gauge located in Tuolumne River above Hetch Hetchy were available for parts of 2006, 2007, and 2008. As partial data sets existed for these three years, the three data sets were averaged to provide a full data set and were used in the sensitivity analysis of accretion/depletion water temperatures (Figure 18).

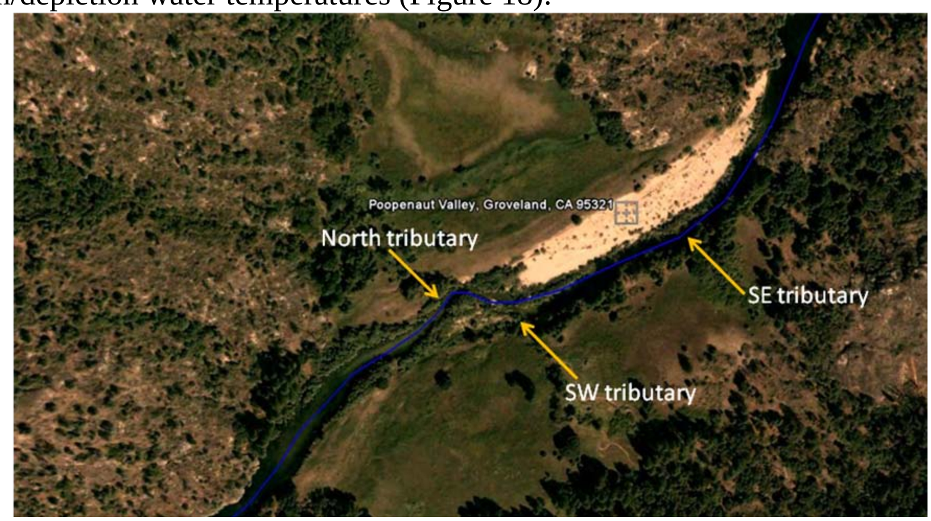

Figure 17. The location of three tributaries in which water temperatures were monitored in the Poopenaut Valley, which were used to assume tributary accretion temperature.

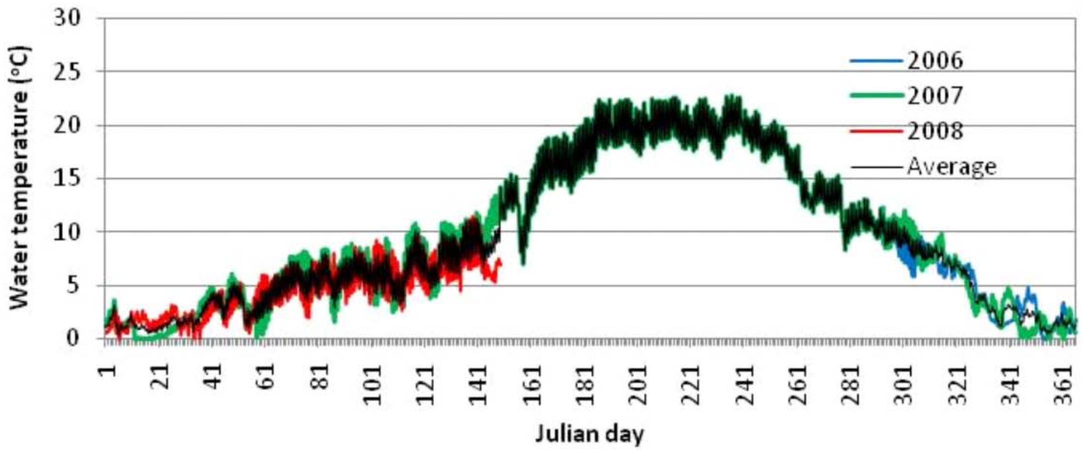

Figure 18. Water temperature data for 2006-2008, by Julian Day, gathered at USGS gauge #11247900, in the Tuolumne River above Hetch Hetchy.

As accretion water temperature data were not available for the calibrated years, data gathered in a tributary from 1 November 2008 through 31 March 2009 were used with the USGS data. Tributary data gathered in the SE tributary provided the most reliable data set during the winter months; however, elevated summer temperatures suggested that the gauge was out of water. During the summer months, three-year average (2006-2008) water temperature Tuolumne River above Hetch Hetchy were used.

6.4. Meteorology

To model water temperatures in the Hetch Hetchy reach, RMA-11 required information about local meteorological conditions for the following categories:

- Atmospheric dust attenuation,
- Cloudiness (percent),
- Dry bulb temperature (°C),
- Dewpoint temperature (°C),
- Atmospheric pressure (mb),
- Wind speed (m/s),
- Wind direction (radians from x-axis), and
- Solar radiation (W/m^2).

Data from several meteorological stations were used to construct a complete meteorological data set for each element. Most stations were located near the Hetch Hetchy reach (Figure 19 and Table 4), and available data from Buck Meadows were used. Missing data and unreliable data were filled using data records from adjacent stations.

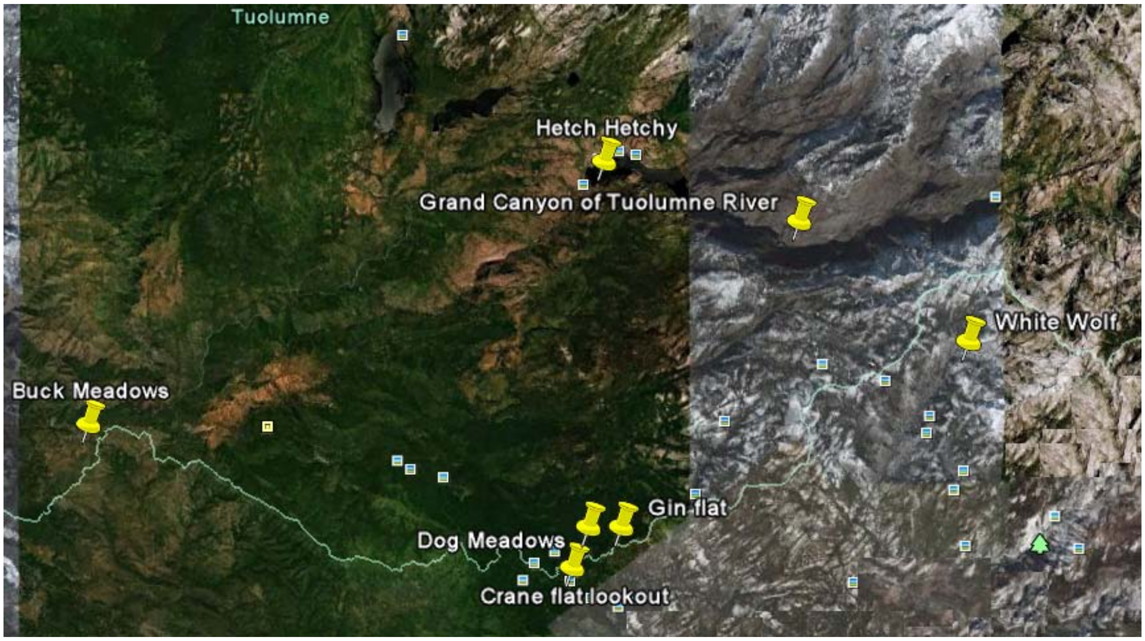

Figure 19. The location of the seven meteorological stations from which data was used to construct a meteorological file for the Hetch Hetchy reach model.

Table 4. The name and locations of the seven meteorological stations from which the meteorological data set was compiled for the Hetch Hetchy reach model.

Description	Latitude	Longitude	Elevation (ft)	Distance (mi)[a]	Data Type
Hetchy Hetchy Reservoir	37.9500°N	119.7830°W	3,870	-	Daily
Buck Meadows	37.8233°N	120.0975°W	3,200	19.3	Hourly
Crane Flat Lookout	37.7500°N	119.8000°W	5,957	13.9	Hourly
Gin Flat	37.7670°N	119.7730°W	7,050	12.7	Hourly
Dog Meadows	37.7626°N	119.7852°W	6,100	12.9	Hourly
Grand Canyon of the Tuolumne River	37.9167°N	119.6589°W	3,830	7.2	15-Minute
White Wolf	37.8595°N	119.5616°W	7,900	9.5	Hourly
Modesto #71	37°38'43"N	121°11'16"W	35	~80	Hourly

[a] Distance from O'Shaughnessy Dam to each site is measured by a straight line between the points.

Data sets were constructed for each meteorological element from using data from these stations except for solar radiation. Data records from the meteorological station in the study did not provide a reliable solar radiation data set from January 2006 through May 2006. Therefore, other regional stations were considered. Solar radiation data gathered at the Modesto site (CIMIS) were used to supplement the 2006 data records (Figure 20).

Topographic shading was also included in the model formulation. Using a 10-meter USGS digital elevation model and the river course, deviations in sunrise and sunset due to local topography were identified for a calendar year. Information was determined for each node in the river geometry, providing site-specific information throughout the model domain. This information was subsequently compiled in an input file to provide a topography-corrected sunrise and sunset for the water temperature model. Sunrise and sunset were rounded to the nearest whole hour to be consistent with the time step of the flow and temperature models.

6.5. Summary

Field data describing the geometry, hydrology, water temperature, and meteorology of the Hetch Hetchy reach were required to implement the conceptual and one-dimensional numerical models, as well as provide a measure of accuracy with which to test the model. Data were available from various sources including the United States Geologic Service (USGS), the San Francisco Public Utility Commission (SFPUC), the California Data Exchange Center (CDEC), and California Irrigation Management Information System (CIMIS). Geometry data was minimally refined to maintain numerical model stability. Hydrology data were selected to reflect a range of high to low flow conditions. Potential study periods were limited to years with available flow, water temperature, and meteorological data.

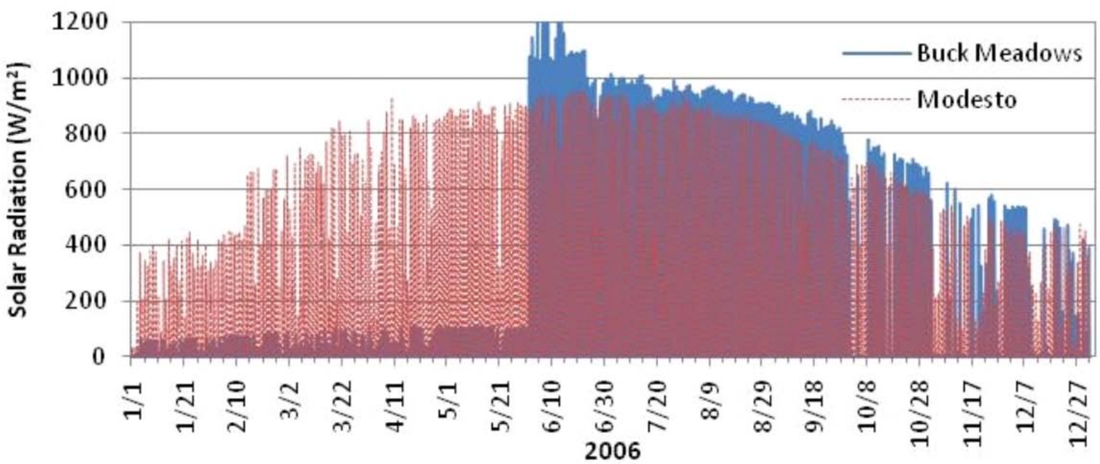

Figure 20. Solar radiation data used in the 2006 simulation was from both Modesto and Buck Meadows. Solar radiation data from the Modesto meteorological station was used to supplement data gathered at the Buck Meadows meteorological station.

7. Model Calibration

The flow and temperature model for the Hetch Hetchy reach was calibrated and tested for sensitivity to several parameters. The hydrodynamic model was calibrated for travel time. Water temperatures were calibrated using 2002 and 2006 observed water temperatures at the gauging station located above Early Intake. Because accretion temperatures and the meteorological data was compiled using several meteorological data sources, a sensitivity analysis was performed for both those elements.

7.1. Hydrodynamic model calibration

The Hetch Hetchy reach model was calibrated for travel time using the slope factor (i.e. gradient) and Manning's *n* of each habitat type (Table 5 and Table 6). Because the exact location and volume of accretions were unknown, travel times were calibrated without using the computed accretion/depletion data. Therefore some difference between the observed and simulated travel times may be due to the actual location of flow accretion in the model reach. The model routes flow through the centerline coordinates of the stream channel. However, at low flows, the flow may be only in the deepest part of the cross-section; which may or may not coincide with the channel centerline and would account for differences between the simulated and observed travel times during low flows.

Table 5. Calibrated slope factors and roughness values for each habitat type given observed travel times.

Habitat type	Slope factor	Manning's *n*
Pool	0.80	0.045
Run	0.75	0.042
LGR	0.75	0.040
HGR	0.65	0.037
Cascade	0.80	0.035

Table 6. Travel time between the gauge below Hetch Hetchy to the gauge above Early Intake.

Flow below Hetch Hetchy (cfs)	Observed (hrs)	Simulated (hrs)	Error (percent)
32	15.00	14.30	-0.05
60	17.50	12.20	-0.30
60	15.00	12.20	-0.19
67	14.50	11.90	-0.18
80	10.75	11.30	0.05
82	11.25	11.20	0.00
127	8.00	9.80	0.23
159	10.00	9.10	-0.09
233	7.75	7.90	0.02
1,460	4.50	4.20	-0.07
3,670	2.25	3.10	0.38
6,700	2.75	2.60	-0.05

To model steep river reaches more accurately, Deas and Orlob (1997) developed a method for iterative calibration wherein hydrodynamic and water temperature models were used jointly. Application of this method requires modeling on a sub-daily time step (e.g., hourly) and availability of associated sub-daily water temperature data. Both criteria were filled for this project.

Local bed slope over much of the length of steep rivers is generally significantly less than the overall gross slope of a river reach. This is because steep rivers are typically not uniform in slope, but consist of short cascades, or riffles, combined with intermediate pools and runs. RMA-2 includes a slope factor and associated logic that is designed to account for these changes in slope. The RMA-2 slope factor reduces effective bed slope and assumes that travel time through the short cascade sections is negligible compared to the transit time through runs or pools. Manning *n* values were consistent with Jarrett (1977) representing high gradient streams.

7.2. Water temperature calibration

Hetch Hetchy reach model calibration focused on mainstream water temperatures. Because no accretion water temperature was available during the 2002 and 2006 calibration periods, accretion temperatures were tested for three different water temperature data records during the calibration period to identify the best data set for assumed accretion temperature.

7.2.1. Water temperature model calibration parameters

Water temperatures were calibrated using several parameters, including:

- Evaporation coefficients *a* and *b*,
- Bed temperature (bed conduction)
  - Seasonal bed heat,
  - Heat exchange coefficient,
- Dead pool area,
- Terrestrial long-wave radiation, and
- Accretion water temperature.

These values were varied through a representative range and model performance was assessed statistically and graphically. Evaporation coefficients, *a* and *b*, governing mass transfer across the air-water interface were assigned constant values of 0.00001 m $mbar^{-1}hr^{-1}$ and 0.00001 sec $mbar^{-1}hr^{-1}$, respectively. 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 Hetch Hetchy reach model (Figure 21).

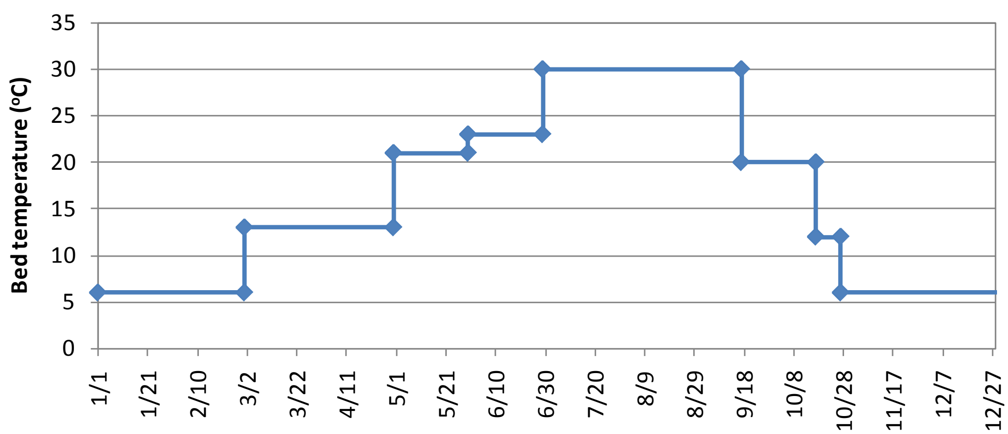

Figure 21. Step function defines assumed seasonal bed temperature in the Hetch Hetchy reach model.

During low flow periods, dead pool areas (the area below the stage of zero flow) can affect water temperatures in the channel due to the relatively large volume in the pool.

Dead pool areas were defined for each habitat type and ranged from 0.025 m^2 to 327.5 m^2 (Table 7). Finally, due to the canyon environment of the Tuolumne River below O'Shaughnessy Dam, terrestrial long-wave radiation was included in the model to reflect contributions from canyon walls. Final calibration parameter values are summarized in Table 8.

Table 7. Dead pool areas defined for each habitat type and applied during zero-flow conditions.

Habitat type	Dead pool area
Pool	Bottom width x 2.5 m
Run	Bottom width x 1.25 m
LGR	0.025 m^2
HGR	0.025 m^2
Cascade/Fall	0.025 m^2

Table 8. Parameter values used in the Tuolumne River temperature model

Parameter	Parameter Value
Evaporation coefficient, *a* (m $mbar^{-1}hr^{-1}$)	0.00001
Evaporation coefficient, *b* (sec $mbar^{-1}hr^{-1}$)	0.00001
Heat exchange coefficient ($Wm^{-2}\ {}^{o}C^{-1}$)	28.7
Terrestrial long-wave radiation	
a. Emissivity (dimensionless)	0.98
b. Topographic radiation contribution fraction	0.50

7.2.1.1. Accretion water temperatures

Because accretion water temperatures were unknown, three different water temperature data records were tested to define accretion water temperatures. These water temperature data records included:

1. Tuolumne River near Hetch Hetchy water temperature (USGS 11276500)
2. Tuolumne River above Hetch Hetchy water temperature (USGS 11274790)
3. Southeast (SE) tributary measured temperature for 2008 and 2009

The first and second data records generally resulted in simulated water temperatures that were higher and lower than observed water temperatures, respectively. The third data record best represented the study area's thermal conditions, thus water temperature data from the SE tributary were used in the final calibration. As discussed in section 5.3.2, only a partial data set for the SE tributary was available. Water temperature data observed in the Tuolumne River above Hetch Hetchy was used to complete the data set. Simulated water temperature results given this boundary condition are shown in Figure 22 and Table 9 for the 2002 simulation and in Table 10 and Figure 23 for the 2006 simulation.

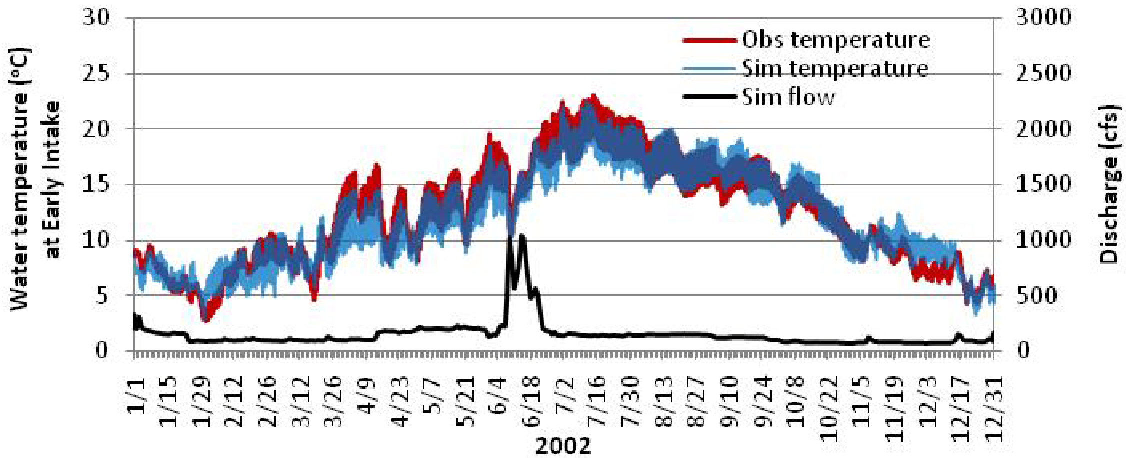

Figure 22. Comparison of simulated and observed water temperatures at the Tuolumne River above Early Intake gauge during 2002 using water temperatures observed in the SE Tributary and in the Tuolumne River above Hetch Hetchy Reservoir to define accretion water temperatures.

Table 9. Performance statistics of the Hetch Hetchy reach model for the 2002 simulation that define accretion water temperatures using water temperature data observed in the SE tributary and in the Tuolumne River above Hetch Hetchy Reservoir.

Case 3, 2002 Statistics	Hourly	Daily Max	Daily Min	Daily Avg
Mean Bias (°C)	0.26	-0.04	0.62	0.26
Mean Absolute Error (°C)	1.00	0.04	1.07	0.95
Root Mean Squared Error (°C)	1.24	1.26	1.31	1.17
Number of Data Points	8,760	365	365	365

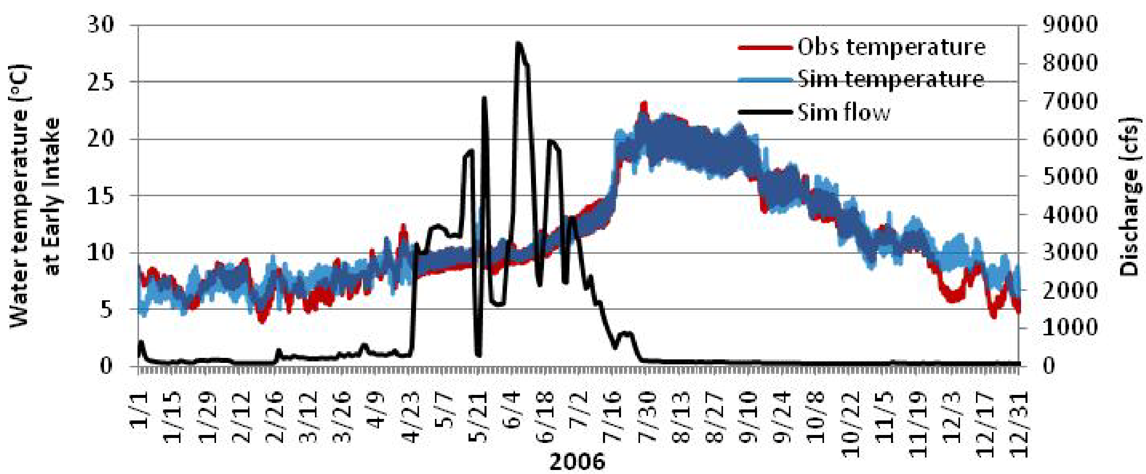

Figure 23. A comparison of simulated and observed water temperatures at the Tuolumne River above Early Intake gauge during 2006 using water temperatures observed in the SE tributary and in the Tuolumne River above Hetch Hetchy Reservoir to define accretion water temperatures.

Table 10. Performance statistics of the Hetch Hetchy reach model for the 2006 simulation that define accretion water temperatures using water temperature data observed in the SE tributary and in the Tuolumne River above Hetch Hetchy Reservoir.

Case 3, 2006 Statistics	Hourly	Daily Max	Daily Min	Daily Avg
Mean Bias (^{o}C)	-0.31	-0.46	-0.14	-0.31
Mean Absolute Error (^{o}C)	0.79	0.46	0.73	0.66
Root Mean Squared Error (^{o}C)	1.09	1.17	1.00	0.98
Number of Data Points	8,760	365	365	365

Daily minimum results the 2002 simulation had a mean absolute error (MAE) of 1.07^{o}C and root mean squared error (RMSE) of 1.31^{o}C. Daily maximum results during the 2006 simulation had a MAE of 0.46^{o}C and RMSE of 1.17^{o}C. Daily average results performed for both simulations had a MAE of 0.95^{o}C and RMSE of 1.17^{o}C during the 2002 simulation and a MAE of 0.66^{o}C and RMSE of 0.98^{o}C during the 2006 simulation. Overall, simulations using the SE tributary as the accretion boundary condition improved winter temperature model performance.

7.3. Sensitivity analysis

Once the Hetch Hetchy reach model was calibrated, its sensitivity to input parameters and boundary conditions was examined. Sensitivity indicates how responsive the model is to changes in a parameter value. Input parameters included dead pool area, bed temperature, terrestrial long wave radiation, and evaporation coefficients. A range of values were tested, and final values were selected based on the best fit of results to the observed data. A quantitative sensitivity analysis of those input parameters was not conducted; rather a qualitative assessment was completed. Boundary conditions were also defined and analyzed for their sensitivity. Though most data was available to implement the Hetch Hetchy reach model, meteorological and accretion/depletion water temperature data sets were incomplete. To test the model's sensitivity to meteorological data, a sensitivity analysis was performed on both 2002 and 2006 simulations using Modesto meteorological station data; the 2002 simulation was also tested using Crane Flat Lookout meteorological station data. The 2006 simulation was also tested using Dog Meadows meteorological station data. Crane Flat Lookout data were not available for 2006; Dog Meadows data were not available for 2002. To test the model's sensitivity to water temperature data, three sets of water temperature data were used to define accretions: the Tuolumne River above and below Hetch Hetchy, and the SE tributary.

7.3.1. Sensitivity to input parameters

A range of values were tested before final values were defined for the input parameters. During this testing, the model's sensitivity to changes in parameter values was observed. but not quantitatively evaluated. A summary of the input parameters and their relative sensitivity is presented in Table 11.The model was generally insensitive to changes in topographic shade, dead pool area, terrestrial long wave radiation, and emissivity. The model showed more sensitivity to evaporation coefficients, bed temperature, and the bed heat exchange coefficient. The model was most sensitive to Manning's *n* and slope factor values. This increased sensitivity may be due to the parameters' effect on travel times, as changes in travel time affects exposure to meteorological conditions in the study reach.

Table 11. A summary of the relative sensitivity of the Hetch Hetchy reach model's input parameters.

	Calibration parameter	Sensitivity (Low / Med / High)	Notes
Hydraulic	Manning *n*	High	Affects travel time, can affect phase of diurnal cycle/variation of water temperature
	Slope factor	High	Affects travel time, can affect phase of diurnal cycle/variation of water temperature
Water temperature	*a* & *b* evaporation coefficients	Medium	Affects evaporative cooling. In this application, these coefficients had a modest impact on temperature
	Topographic shade	Low	Reduces solar radiation, a principal component of the heat budget. The topographic relief was not globally sufficient for this parameter to have a large effect.
	Dead pool area (m^2)	Low	Affects diurnal variation of water temperature
	Terrestrial long wave (%)	Low	Contributes slightly to heat budget
	Emissivity	Low	Contributes slightly to heat budget
	Bed temperature (°C)	Medium	A moderately sensitive parameter that affects both mean temperature and diurnal range. Seasonal values used.
	Bed heat exchange coefficient ($W/m^2/^oC$)	Medium	A moderately sensitive parameter that affects both mean temperature and diurnal range. Seasonal values used.

7.3.2. Sensitivity to meteorological data – 2002

Hetch Hetchy reach model was calibrated using Buck Meadows meteorological data. For sensitivity analysis meteorological data from Modesto (2002 and 2006), Crane Flat Lookout (2002) and Dog Meadows (2006) were used. Each case the simulated water temperature at Early Intake was compared with calibrated results using Buck Meadows.

Hetch Hetchy reach model results were examined for mean bias, mean absolute error (MAE), and root mean square error (RMSE). They were also compared to simulations that used Buck Meadows data.

The Hetch Hetchy reach model was moderately sensitive to changes in meteorological data. Simulations using Crane Flat Lookout data generally predicted water temperatures that were lower than calibrated results, with mean bias between 0.0°C and 0.57°C (Figure 24 and Table 12). Daily maximum results had a MAE of 0.57°C and RMSE of 1.02°C. Daily minimum water temperature results had a MAE of 0.38°C and RMSE of 0.51°C.

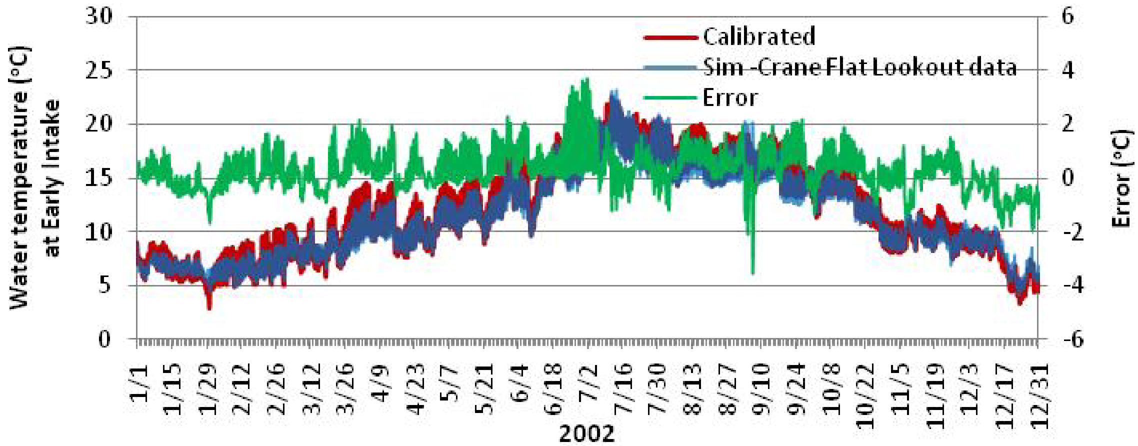

Figure 24. Sensitivity results using Crane Flat Lookout meteorological station data for the 2002 simulation.

Table 12. Performance statistics of the Hetch Hetchy reach model for the 2002 simulation using Crane Flat Lookout meteorological station data compared to calibration.

Simulated with CFL met data, 2002 Statistics	Hourly	Daily Max	Daily Min	Daily Avg
Mean Bias (^{o}C)	0.31	0.57	0.00	0.31
Mean Absolute Error (^{o}C)	0.60	0.57	0.38	0.55
Root Mean Squared Error (^{o}C)	0.79	1.02	0.51	0.68
Number of Data Points	8760	365	365	365

Simulations using Modesto data generally underestimated hourly, daily minimum, daily maximum and daily average water temperatures, (Figure 25 and Table 13). Similarly to simulations using Crane Flat Lookout data, daily maximum water temperature results had a MAE of 1.12°C and RMSE of 1.75°C. Daily minimum water temperature results had lower MAE and RMSE, 1.03°C and 1.28°C, respectively.

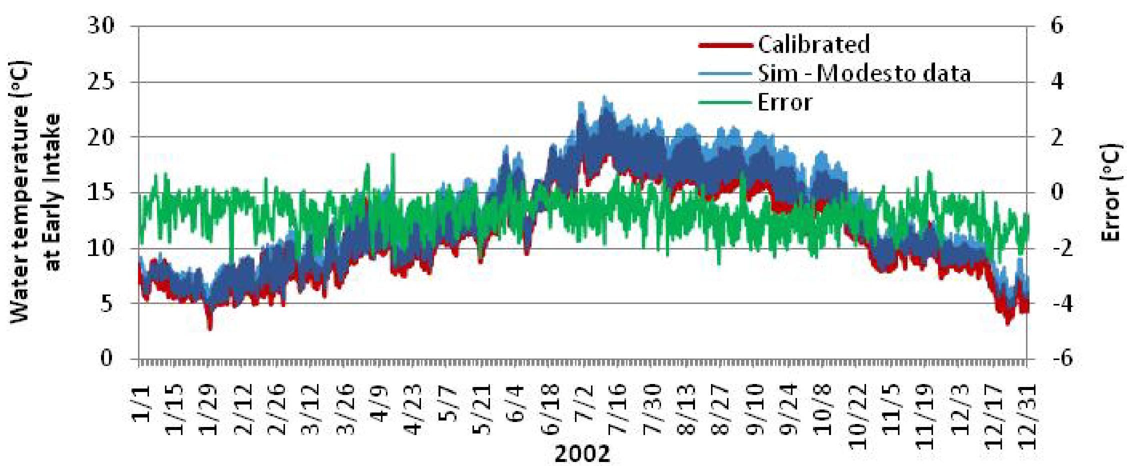

Figure 25. Sensitivity results using Modesto meteorological station data for the 2002 simulation.

Table 13. Performance statistics of the Hetch Hetchy reach model for the 2002 simulation using Modesto meteorological station data compared to calibration.

Simulated with Modesto met data, 2002 Statistics	Hourly	Daily Max	Daily Min	Daily Avg
Mean Bias (°C)	-0.77	-1.07	-0.55	-0.77
Mean Absolute Error (°C)	0.80	1.07	0.58	0.78
Root Mean Squared Error (°C)	0.95	1.23	0.73	0.88
Number of Data Points	8760	365	365	365

Comparing water temperature results and statistical performances from the 2002 simulation illustrates that the Hetch Hetchy reach model is slightly sensitive to meteorological data. The water temperature results indicate that the model shifted from overestimating water temperatures to generally underestimating water temperatures when simulations were made using Crane Flat Lookout meteorological data to Modesto meteorological data. Except for daily maximum water temperature results, RMSE decreased in the Modesto meteorological data simulation results; daily maximum water temperatures showed a RMSE increase of 0.03°C, which is within the noise of the results.

7.3.3. Sensitivity to meteorological data – 2006

As the Crane Flat Lookout meteorological station only provided data for 2002, a second sensitivity analysis was performed on the 2006 simulation using data collected at the Dog Meadows- meteorological station. Details describing the station location are provided in section 5.4. Results were examined for mean bias, mean absolute error (MAE), and root mean square error (RMSE). They were also compared to simulations that used Buck Meadows data.

Simulations using the Dog Meadows- meteorological data record generally overestimated water temperatures when compared to the calibrated simulation, with a mean bias between 0.40°C and 0.77°C (Figure 26 and Table 14). Hourly and daily maximum water temperature simulation results had a MAE of 0.71°C and 0.77°C, respectively, as well as a RMSE of 0.90°C and 0.99°C. Daily average water temperature results had a lower MAE and RMSE, 0.54°C and 0.68°C, respectively.

Simulations using Modesto meteorological station data underestimated water temperatures for the 2006 simulation when compared to the calibrated simulation, with mean bias ranging between -0.28°C to -0.71°C (Figure 27 and Table 15). Daily maximum water temperature results had a MAE of 0.84°C and a RMSE of 1.13°C. Daily minimum water temperature results had a MAE of 1.16°C and a RMSE of 1.67°C.

Comparing water temperature results and statistical performances from the 2006 simulation again illustrates that the Hetch Hetchy reach model is slightly sensitive to meteorological data. The water temperature results show that the model shifted from overestimating water temperatures to generally underestimating water temperatures when simulations were made using Dog Meadows meteorological data to Modesto meteorological data. For hourly, daily maximum, daily minimum, and daily average temperature results, RMSE increased in the Modesto meteorological data simulation results; daily maximum water temperatures showed the greatest RMSE increase of 0.51°C.

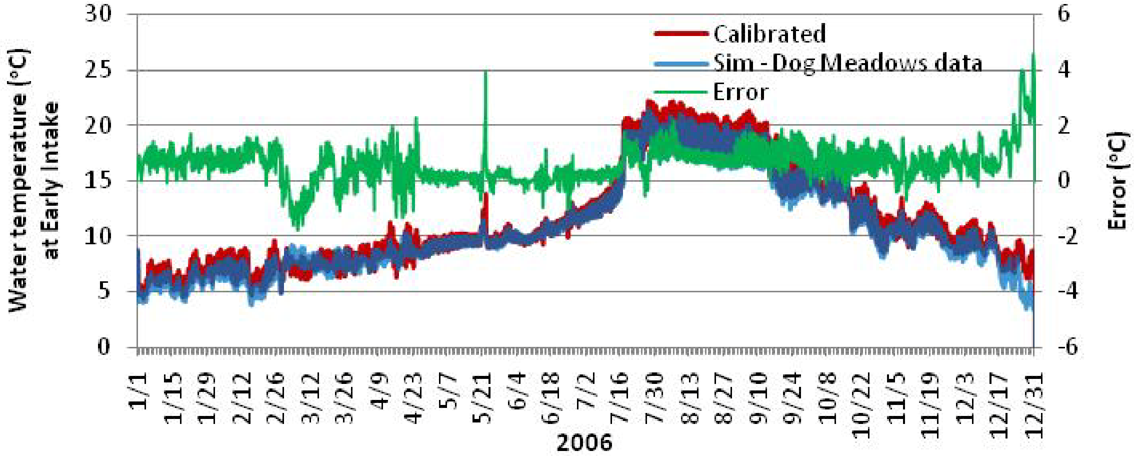

Figure 26. Sensitivity results for the 2006 simulation using Dog Meadows meteorological station data.

Table 14. Performance statistics of the Hetch Hetchy reach model for the 2006 simulation using Dog Meadows meteorological station data - compared to calibration.

Simulated with Dog Meadows met data, 2006 Statistics	Hourly	Daily Max	Daily Min	Daily Avg
Mean Bias (°C)	0.62	0.77	0.40	0.62
Mean Absolute Error (°C)	0.71	0.77	0.54	0.68
Root Mean Squared Error (°C)	0.90	0.99	0.72	0.84
Number of Data Points	8760	365	365	365

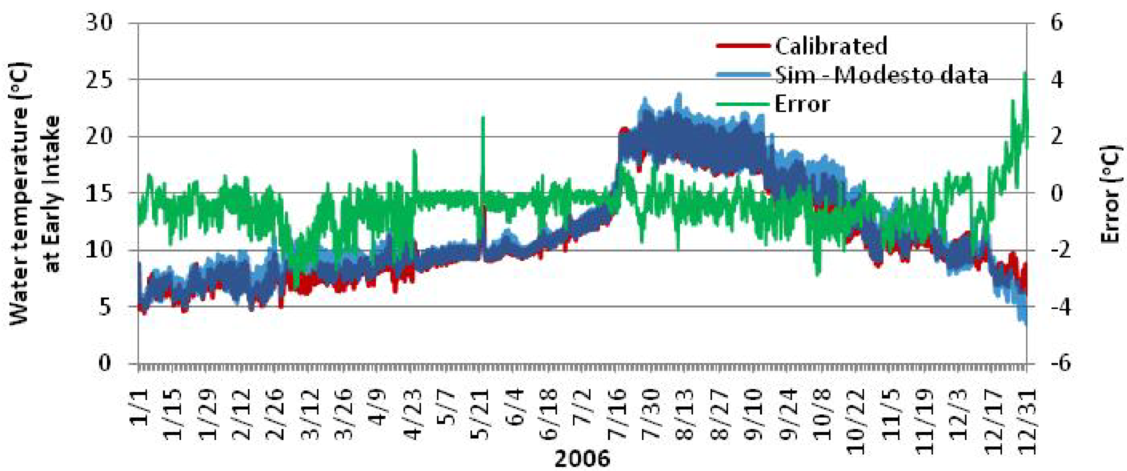

Figure 27. Sensitivity results for the 2006 simulation using Modesto meteorological station data.

Table 15. Performance statistics of the Hetch Hetchy reach model for the 2006 simulation using Modesto meteorological station data.

Simulated with Modesto met data, 2006 Statistics	Hourly	Daily Max	Daily Min	Daily Avg
Mean Bias (°C)	-0.44	-0.71	-0.28	-0.44
Mean Absolute Error (°C)	0.63	0.71	0.49	0.59
Root Mean Squared Error (°C)	0.86	1.09	0.72	0.78
Number of Data Points	8760	365	365	365

7.3.4. Sensitivity to water temperature data – 2002

To test the Hetch Hetchy reach model's sensitivity to accretion water temperatures, water temperature data gathered above and below Hetch Hetchy were used to run the 2002 simulation. The results were compared to the calibrated model, which used a combination of tributary and mainstem water temperature data to define accretion water temperatures. Details describing the station location are provided in section 5.3.1. Results were examined for mean bias, mean absolute error (MAE), and root mean square error (RMSE).

The Hetch Hetchy reach model was slightly sensitive to different accretion water temperatures. Simulations using the Tuolumne River above Hetch Hetchy water temperature data generally overestimated water temperatures when compared to the calibrated simulation, with a mean bias between 0.04°C and 0.08°C (Figure 28 and Table 16). The results indicate that the trend was not consistent during the entire simulation year. Water temperatures were generally underestimated in the winter and overestimated in the summer. Daily minimum temperatures had a MAE of 0.24°C and RMSE of 0.34°C. Daily maximum temperatures had a MAE of 0.08°C and RMSE of 0.29°C.

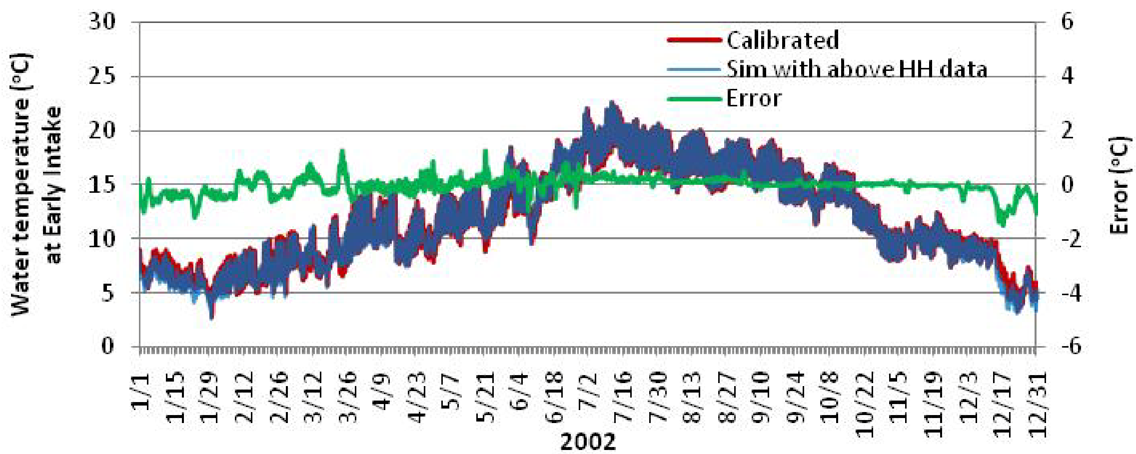

Figure 28. Sensitivity results using the Tuolumne River above Hetch Hetchy water temperature data to define accretion water temperatures for the 2002 simulation.

Table 16. Performance statistics of the Hetch Hetchy reach model for the 2002 simulation using Tuolumne River above Hetch Hetchy water temperature data to define accretion water temperatures.

Above Hetch Hetchy Tw, 2002 Statistics	Hourly	Daily Max	Daily Min	Daily Avg
Mean Bias (°C)	0.06	0.08	0.04	0.06
Mean Absolute Error (°C)	0.22	0.08	0.24	0.21
Root Mean Squared Error (°C)	0.32	0.29	0.34	0.30
Number of Data Points	8760	365	365	365

Simulations using the Tuolumne River near Hetch Hetchy water temperature data generally underestimated water temperatures, with a mean bias between -0.22°C and -0.20°C, though that trend was not consistent throughout the simulation period (Figure 29 and Table 17). Daily minimum temperatures had a MAE of 0.23°C and RMSE of 0.44°C. Daily maximum temperatures performed had a slightly lower MAE of 0.20°C and RMSE of 0.41°C.

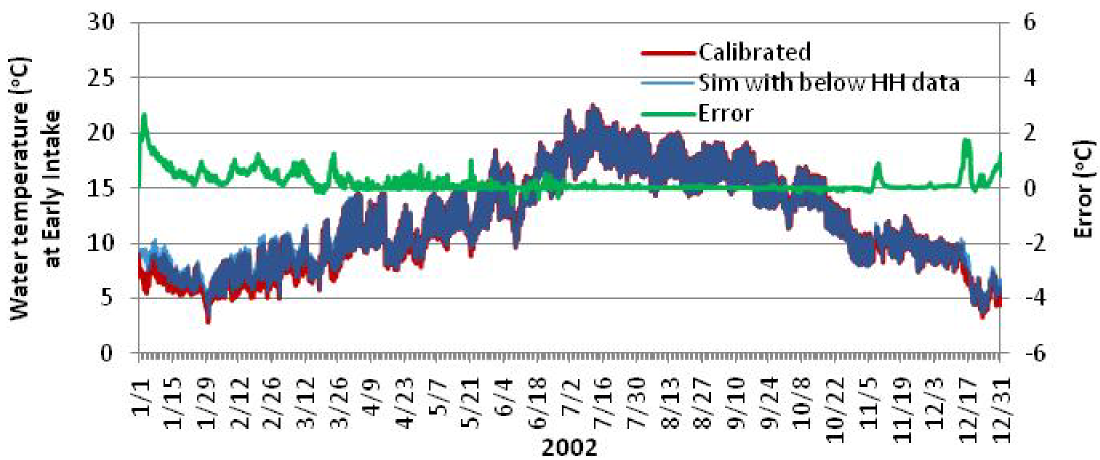

Figure 29. Sensitivity results using the Tuolumne River near Hetch Hetchy water temperature data to define accretion water temperatures for the 2002 simulation.

Table 17. Performance statistics of the Hetch Hetchy reach model for the 2002 simulation using Tuolumne River near Hetch Hetchy water temperature data to define accretion water temperatures.

Below Hetch Hetchy Tw, 2002 statistics	Hourly	Daily Max	Daily Min	Daily Avg
Mean Bias (°C)	-0.20	-0.20	-0.22	-0.20
Mean Absolute Error (°C)	0.22	0.20	0.23	0.21
Root Mean Squared Error (°C)	0.42	0.41	0.44	0.41
Number of Data Points	8760	365	365	365

7.3.5. Sensitivity to water temperature data – 2006

Like the 2002 simulation, a sensitivity analysis was performed on the 2006 simulation using water temperature data from the Tuolumne River above and below Hetch Hetchy. The results were compared to the calibrated model, which used a combination of tributary and mainstream water temperature data to define accretion water temperatures. Details describing the station location are provided in section 5.3.1. Results were examined for mean bias, mean absolute error (MAE), and root mean square error (RMSE).

Simulations using the Tuolumne River above Hetch Hetchy water temperature data generally overestimated water temperatures, with mean bias ranging from 0.20°C to 0.26°C, though that trend was not consistent throughout the simulation period (Figure 30 and Table 18). Water temperatures were generally overestimated in the winter and underestimated in the summer. Hourly temperatures had a MAE of 0.47°C and RMSE of 0.62°C, and daily maximum temperatures had a MAE of 0.26°C and RMSE of 0.58°C.

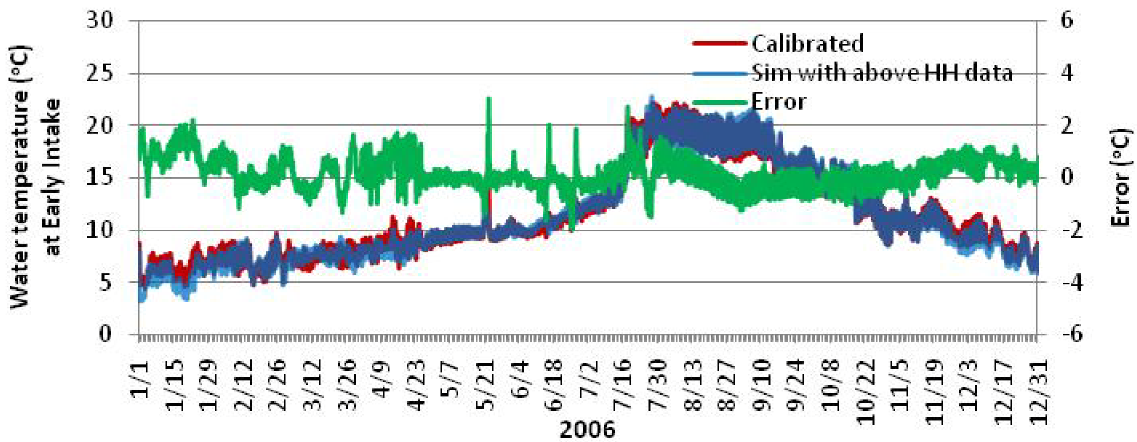

Figure 30. Sensitivity results using the Tuolumne River above Hetch Hetchy water temperature data to define accretion water temperatures for the 2006 simulation.

Table 18. Performance statistics of the Hetch Hetchy reach model for the 2006 simulation using Tuolumne River above Hetch Hetchy water temperature data to define accretion water temperatures.

Above Hetch Hetchy Tw, 2006 Statistics	Hourly	Daily Max	Daily Min	Daily Avg
Mean Bias (°C)	0.22	0.26	0.20	0.22
Mean Absolute Error (°C)	0.47	0.26	0.43	0.41
Root Mean Squared Error (°C)	0.62	0.58	0.57	0.55
Number of Data Points	8760	365	365	365

Simulations using the Tuolumne River near Hetch Hetchy water temperature data generally underestimated water temperatures, with mean bias ranging from -0.46°C to -0.35°C (Figure 31 and Table 19). Water temperatures were generally underestimated in the winter and overestimated in the summer. Hourly temperatures had a MAE of 0.56°C and RMSE of 0.84°C, while daily maximum temperatures had a MAE of 0.35°C and RMSE of 0.78°C.

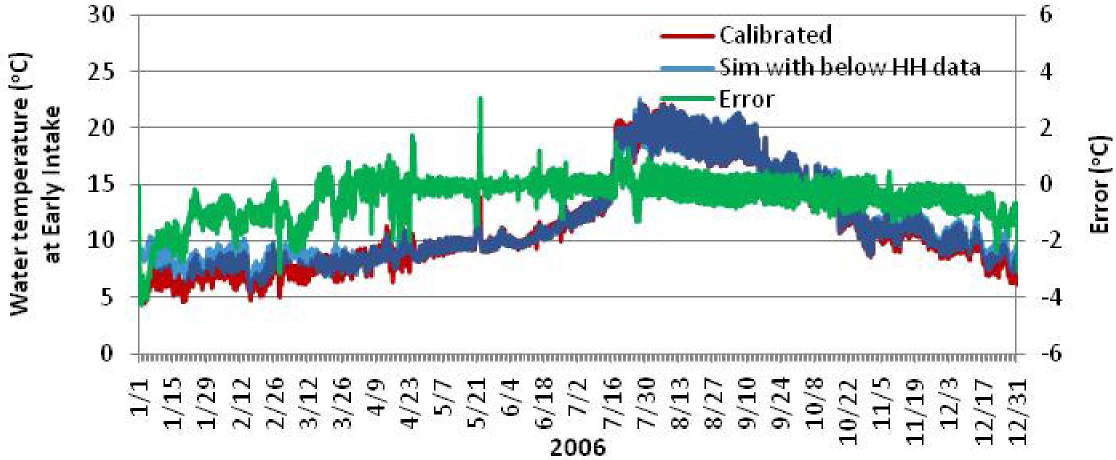

Figure 31. Sensitivity results using the Tuolumne River near Hetch Hetchy water temperature data to define accretion water temperatures for the 2006 simulation.

Table 19. Performance statistics of the Hetch Hetchy reach model for the 2006 simulation using Tuolumne River above Hetch Hetchy water temperature data to define accretion water temperatures.

Below Hetch Hetchy Tw, 2006 Statistics	Hourly	Daily Max	Daily Min	Daily Avg
Mean Bias (°C)	-0.40	-0.35	-0.46	-0.40
Mean Absolute Error (°C)	0.56	0.35	0.52	0.48
Root Mean Squared Error (°C)	0.84	0.78	0.84	0.79
Number of Data Points	8760	365	365	365

7.4. Summary

The Hetch Hetchy reach model was tested for its sensitivity to changes in input parameter values and boundary condition data. A range of values were defined for dead pool area, bed temperature, terrestrial long-wave radiation and evaporation coefficients during calibration. The model was more sensitive to bed temperature, evaporation coefficients, and bed heat exchange coefficients, and less sensitive to topographic shade, dead pool area, terrestrial long-wave radiation, and emissivity. The model was also tested for its sensitivity to boundary condition data. Alternative boundary conditions were defined for meteorological data and accretion water temperature data.

The model was more sensitive to meteorological data than to accretion water temperatures. The model was particularly sensitive to changes in meteorological boundary conditions during the spring and winter simulation. This may be because the other meteorological stations were located at lower elevations, with warmer air temperatures and higher solar radiation, which contribute to increased heating in the summer and less cooling in the winter. Generally, hourly simulation results were within ±2.0°C of observed values. The model was less sensitive to accretion water temperatures during dry year simulations that wet year simulations. During the 2002 dry year simulation, simulation results were within ±2.0°C of observed values during winter and less than ±1.0°C of observed values during summer. During the 2006 wet year simulation, the model was more sensitive to accretion water temperatures. Except during periods of very high discharge, hourly simulation results were within ±2.0°C of observed values.

8. Model Application

The calibrated model was applied to years 2000, 2001, 2003, 2004, 2005, 2007, and 2008 for validation. By testing the model against two independent data sets, its overall performance could be validated and the model could be applied more extensively. Following the validation exercise, the period (2000-09) was used as an ecological evaluation time series, where temperature model results were used in a gaming tool for the SFPUC to evaluate different flow scenarios. This gaming tool was developed separately from the Tuolumne River flow and temperature model and a brief description is presented in the appendix.

8.1. Validation

The Hetch Hetchy reach flow and water temperature model was validated by simulating water temperatures for the 2000-2008 period, excluding 2002 and 2006, which were used for calibration (due to insufficient data, 2009 was not included in the validation). Due to incomplete water temperature records, accretion water temperatures were represented using the SE tributary water temperature data for 1 January through 31 March and 1 November through 31 December for all application years. Similarly, water temperature data collected in the Tuolumne River above Hetch Hetchy was used for 1 April through 31 October. Due to incomplete meteorological records at any single station, meteorological data was compiled from local and regional meteorological stations. Therefore missing data were filled one of Crane Flat Lookout, Modesto and Dog Meadows data depending on availability and quality.

Results for each validation simulation are presented in Table 20. The validation simulations showed consistent performance of the calibrated Hetch Hetchy reach flow and temperature model. Namely, mean bias is very low (ranging from -0.04°C to 0.15°C with the exception of 2000); MAE ranging from 1.08°C to 1.63°C for hourly and 0.90°C to 1.49°C for daily average results; and RMSE less than ±2.0°C.

Table 20. Model performance statistics.

	Hourly	Daily Max	Daily Min	Daily Avg
2000				
Mean Bias (^oC)	-1.08	-1.74	-0.55	-1.08
Mean Absolute Error (^oC)	1.55	1.74	1.20	1.38
Root Mean Squared Error (^oC)	1.98	2.34	1.54	1.76
Number of Data Points	8760	365	365	365
2001				
Mean Bias (^oC)	-0.04	-0.41	0.28	-0.04
Mean Absolute Error (^oC)	1.36	0.41	1.25	1.19
Root Mean Squared Error (^oC)	1.69	1.74	1.59	1.52
Number of Data Points	8760	365	365	365
2003				
Mean Bias (^oC)	-0.06	-0.44	0.22	-0.06
Mean Absolute Error (^oC)	1.08	0.44	0.89	0.90
Root Mean Squared Error (^oC)	1.33	1.45	1.14	1.13
Number of Data Points	8760	365	365	365
2004				
Mean Bias (^oC)	0.14	-0.24	0.42	0.14
Mean Absolute Error (^oC)	1.42	0.24	1.33	1.27
Root Mean Squared Error (^oC)	1.83	1.85	1.72	1.65
Number of Data Points	8760	365	365	365
2005				
Mean Bias (^oC)	0.15	-0.16	0.41	0.15
Mean Absolute Error (^oC)	1.11	0.16	1.06	0.98
Root Mean Squared Error (^oC)	1.41	1.47	1.41	1.27
Number of Data Points	7504	311	311	311
2007				
Mean Bias	0.08	-0.32	0.38	0.08
Mean Absolute Error	1.63	0.32	1.55	1.49
Root Mean Squared Error	2.00	2.13	1.85	1.84
Number of Data Points	8,760	365	365	365
2008				
Mean Bias (^oC)	0.08	-0.29	0.43	0.08
Mean Absolute Error (^oC)	1.23	-0.29	1.11	1.07
Root Mean Squared Error (^oC)	1.55	1.62	1.38	1.36
Number of Data Points (^oC)	8304	346	346	346

8.2. Gaming tool scenarios

The second application of the Hetch Hetchy reach model was to develop a suite of runs that simulate water temperatures based on a range of flows released from O'Shaughnessy Dam. Ten year (2000 – 2009) Alternative flow and water temperature boundary conditions were defined for a ten-year period (2000-2009), for which a range of downstream water temperatures were simulated. The alternative flow simulations assumed no depletion in the system; calculated accretions were included. Daily minimum, maximum and average water temperature results and daily average flow results at four locations were input to the gaming tool. Results from the gaming tool are not presented herein. The four locations for assessing model output were:

1. O'Shaughnessy Dam,
2. Poopenaut Valley, 3.27 miles downstream from O'Shaughnessy Dam
3. Albino Rock, 11.22 miles downstream from O'Shaughnessy Dam
4. Early Intake, 12.10 miles downstream from O'Shaughnessy Dam

A scale of species-specific ecological benefit was applied to ranges of flows and water temperatures at each location. Details describing the relationship between flow, temperature, and ecological benefits defined by the gaming tool are included in the appendix.

8.2.1. Alternative flow scenarios

To plan for future flow conditions in the Tuolumne River, alternative flow release schedules for 10 years (2000-2009) were developed for Hetch Hetchy Reservoir by McBain & Trush. Flow rates from O'Shaughnessy Dam were defined as bi-weekly step functions (Figure 32 and Figure 33). Flow rates calculated at Early Intake include accretion/depletion flows.

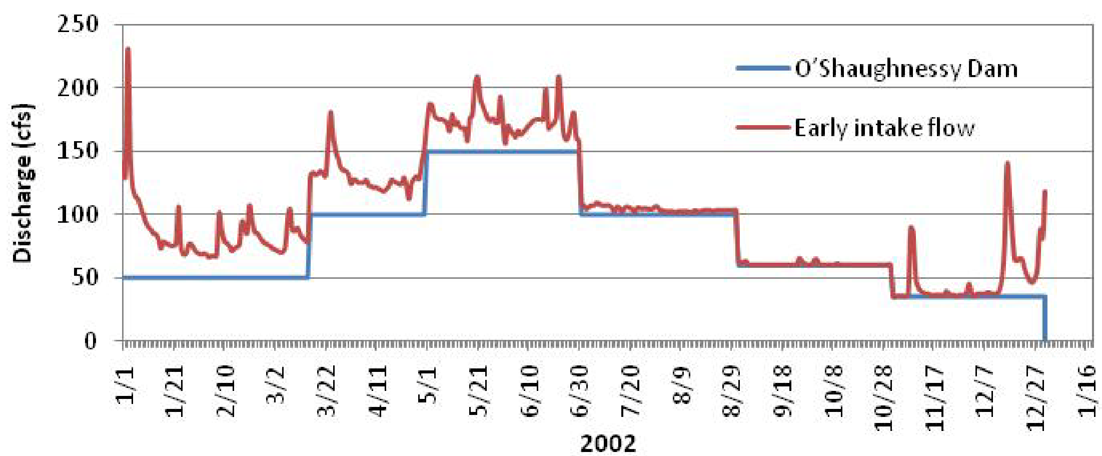

Figure 32. Alternative flow schedule developed for Hetch Hetchy reservoir releases into the Tuolumne River for 2002 meteorological and hydrologic conditions (a drier year).

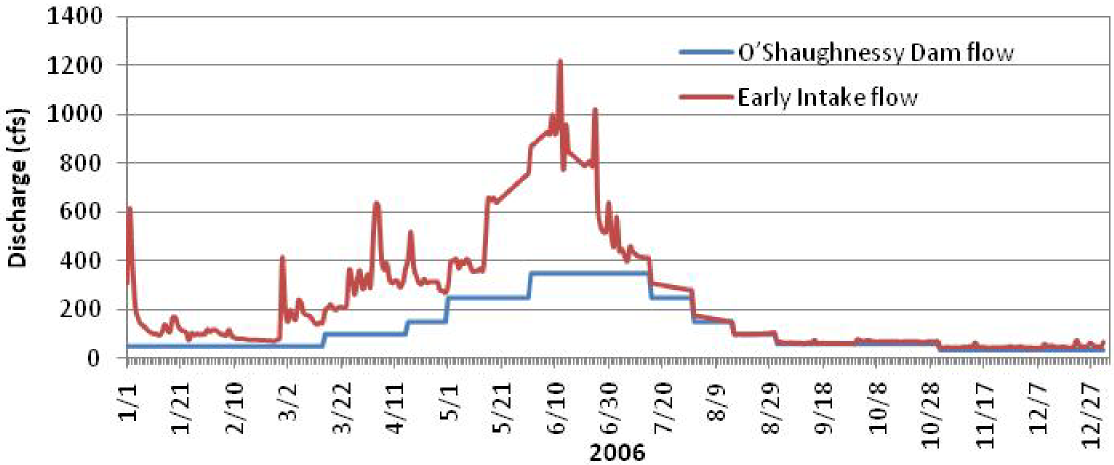

Figure 33. Alternative flow schedule developed for Hetch Hetchy reservoir releases into the Tuolumne River for 2006 meteorological and hydrologic conditions (a wetter year).

8.2.2. Alternative water temperature scenarios

Once alternative flow releases were developed for the Hetch Hetchy reach model, future O'Shaughnessy water temperature data were predicted by McBain & Trush. Average daily water temperatures were predicted based on SFPUC water temperature profiles in Hetch Hetchy Reservoir, time of year, reservoir elevation and reservoir outlet elevation (Figure 34 and Figure 35). The same accretion water temperatures used for the model validation were used for these simulations as well.

8.2.1. Results

Once alterative flow releases and water temperature boundary conditions were developed for the Hetch Hetchy reach model 2000 – 2009 time series, water temperature results were calculated based on study year meteorological conditions. A sample of water temperature results are presented in Figure 36 and Figure 37. Daily average water temperatures results are shown for four downstream study sites where ecological evaluations are being conducted; O'Shaughnessy Dam Site, Poopenaut Valley, Albino Rock, and Early Intake.

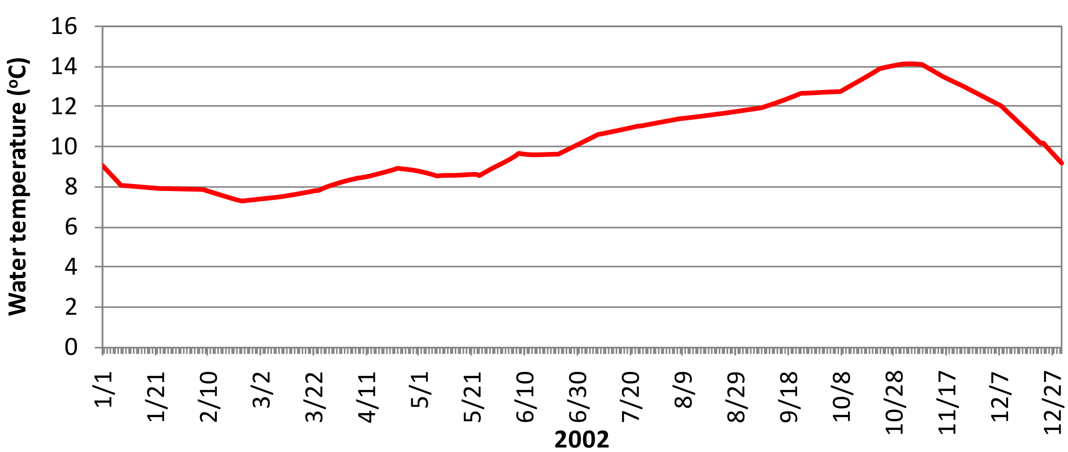

Figure 34. Predicted future water temperature data for releases from Hetch Hetchy reservoir in 2002, from McBain & Trush.

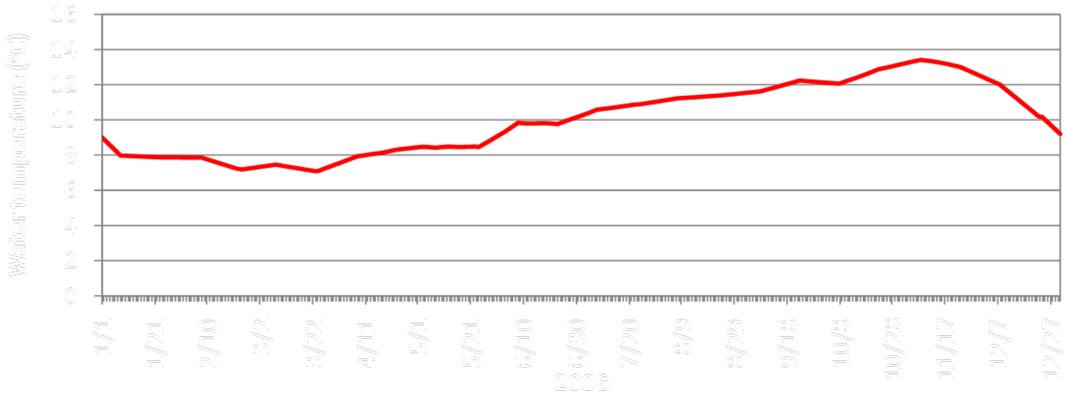

Figure 35. Predicted future water temperature data for releases from Hetch Hetchy reservoir in 2006, from McBain & Trush.

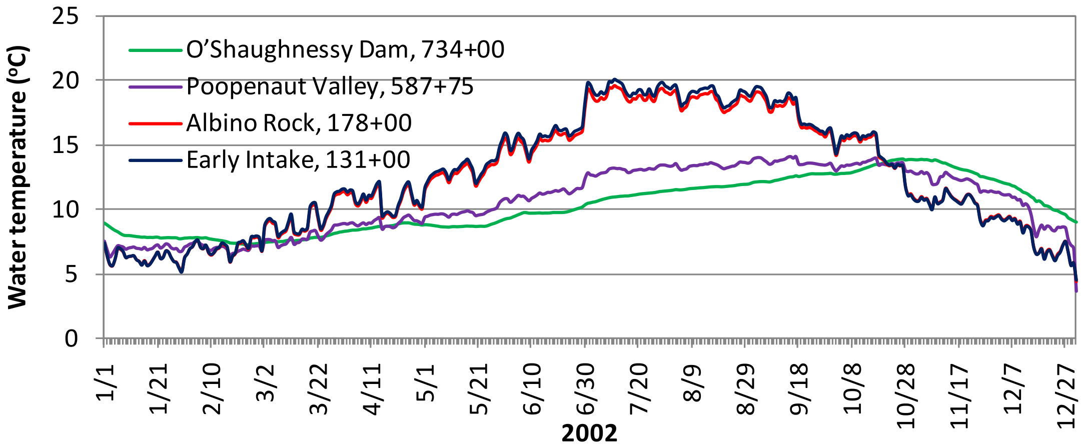

Figure 36. Daily average water temperature results for the 2002 alternative flow and water temperature simulation. Daily average water temperature results are presented for four ecological sites within the Hetch Hetchy reach.

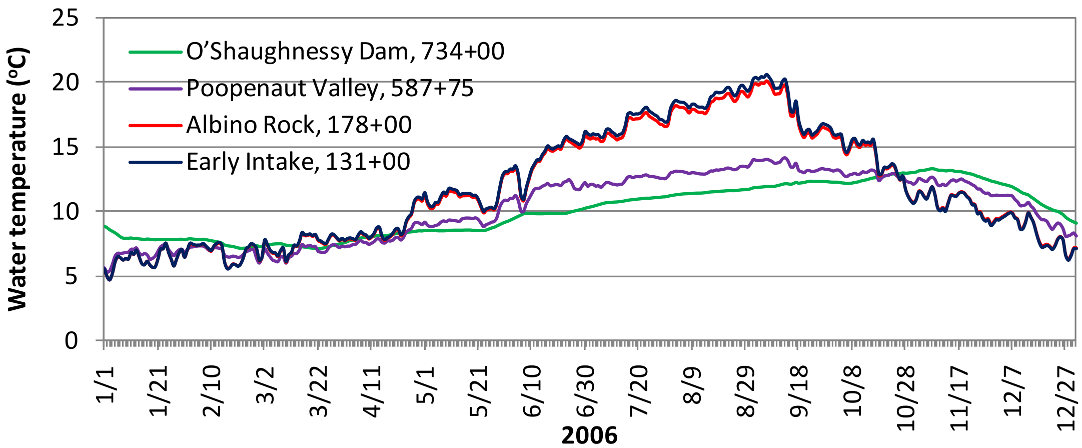

Figure 37. Daily average water temperature results for the 2006 alternative flow and water temperature simulation. Daily average water temperature results are presented for four ecological sites within the Hetch Hetchy reach.

8.3. Summary

Once the Hetch Hetchy reach flow and water temperature model was implemented, calibrated, and tested for sensitivity, the model was used to predict 2000 – 2009 water temperature for alternative flow scenarios. Alternative flow releases, ranging from 35 cfs to 300 cfs were developed for the 2000-2009 period. O'Shaughnessy Dam release water temperatures during these alternative flow schedules were predicted based on Hetch Hetchy Reservoir conditions and outlet elevations. Examples of the water temperatures results from the alternative flow simulations indicate that the model accurately predicts thermal response at several downstream locations over a range of flow releases and meteorological conditions. The water temperature model was run using alternative flow scenarios and results will serve as input data for the water management gaming tool.

9. Summary and Conclusion

The Hetch Hetchy reach flow and temperature model was developed to simulate water temperatures for the Hetch Hetchy study reach that begins below Hetch Hetchy Reservoir and ends 12.97 mi downstream at Early Intake. Flow and water temperature were simulated using RMA2 and RMA11 models.

Historical data was used to implement, calibrate, and validate the model. A drier (i.e. 2002) and wetter (2006) year were selected for implementation and calibration to simulate a range of flow conditions in the Hetch Hetchy reach. Flows ranged from 32 cfs to 6,200 cfs. Observed travel times for this range of flows were used to calibrate the RMA-2 hydrodynamics model. Observed water temperature data during 2002 and 2006 were used to calibrate the RMA-11 water temperature model. Model calibration for both 2002 and 2006 gave good results with less than 1.0^{o}C mean absolute error. The calibrated model was applied to years 2000, 2001, 2003, 2004, 2005, 2007, and 2008 for validation. The model bias was typically low (near zero with an average of -0.09^{o}C) and mean absolute error ranged from 0.79^{o}C to 1.69^{o}C with an average of 1.24^{o}C for hourly results and 0.66^{o}C to 1.49^{o}C with an average of 1.10^{o}C for daily mean results.

A sensitivity analysis was performed for the model's input parameter and boundary condition data. The model was most sensitive to meteorological data, with an range of ±2.0^{o}C. The model was also sensitive to accretion water temperatures, with both seasonal and year-type variability. The model was less sensitive to accretion water temperatures during dry year simulations than wet year simulations. During the 2002 dry year simulation, simulation results were within ±2.0^{o}C during winter and less than ±1.0^{o}C during summer. During the 2006 wet year simulation, the model was more sensitive to accretion water temperatures; except during periods of very high discharge, results were within ±2.0^{o}C. A potential water management alternative was then combined with historical meteorological data to predict downstream water temperature responses. The results from this alternative scenario simulates will be used in a gaming tool for the SFPUC to evaluate potential ecological tradeoff for different environmental flow strategies. Details of this tool are provided at the end of this document.

10. Recommended model refinements

The flow and temperature model for the Hetch Hetchy reach of the Tuolumne River performs well. In all of the calibration and application years, the model slightly under-predicts early summer water temperature and over-predicts the early winter temperature. This may be associated with limited tributary water temperature data, because tributary flow and temperature can be quite variable. The model can be further refined provided additional data are acquired. Recommendations include:

- Surveying additional cross-section data to describe the low flow channel geometry. Currently, detailed geometry is only available above the elevation of the 87 cfs water surface.

- Monitoring flow and water temperature in tributaries and mainstem locations to refine inflow water temperature distribution for accretions and depletions. Such data are particularly important during periods of the year when accretions are most notable, namely winter and spring (precipitation events and snowmelt runoff) to extend a short period record at Early Intake to a longer period of record (e.g., 2000 – 2009).

- Installation of a local meteorological station, in the vicinity of Early Intake, would allow local data to be compared with neighboring meteorological stations. There may be the potential to develop relationships between two stations for certain parameters (e.g., air temperature).

- Identify local shading elements that may reduce solar insulation at lower stream flows, such as riparian vegetation, large boulders, boulder gardens, stream banks and other features that may provide considerable shading, but are too small to be identified in the digital elevation models used to formulate topographic shading.

11. References

Brown, L.C. and T.O. Barnwell, Jr. 1987. *The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS: documentation and user's manual*. EPA/600/3-87/700. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens GA. May.

Deas, M.L. and G.T. Orlob. 1997. "Iterative calibration of hydrodynamic and water temperature models – application to the Sacramento River." In *Proceedings Water for a Changing Global Community.* 27th Congress of the International Association for Hydraulic Research and hosted by the American Society of Civil Engineers Water Resources Division, August 10-15, San Francisco, CA, 1997.

Jarrett, R. D. 1984. " Hydraulics of high gradient streams." *ASCE Jour Hydraulic Engin*. 110(11), pp 1519-1539

Jobson, H.E. 1977. "Bed conduction computation for thermal models." *ASCE Jour Hydr Div*. 103(10), pp 1213-1222.

King, I.P., 2008. RMA2 - A Two Dimensional Finite Element Model for Flow in Estuaries and Streams, Version 8.1b. Resource Modeling Associates, Sydney, Australia.

King, I. P., 2009. RMA-11 - A Three Dimensional Finite Element Model for Water Quality in Estuaries and Streams, Version 8.3 (MKL Version) Resource Modeling Associates, Sydney, Australia.

Merritt Smith Consulting (MSC). 2008. *Upper Tuolumne River Flow and Temperature Model – Conceptualization and Data Assessment*. Submitted to the San Francisco Public Utilities Commission. September 4, 36 pp.

RMC Water and Environment and McBain & Trush, Inc (RMC-M&T). 2007. *Upper Tuolumne River: Description of River Ecosystem and Recommended Monitoring Actions Final Report*. Report prepared for the San Francisco Public Utilities Commission

Appendices

Appendix A. The Tuolumne River Gaming Tool

The Tuolumne River Gaming Tool (Gaming Tool) assesses the number of good days (NGD) of temperature and habitat conditions for rainbow trout, foothill yellow-legged frogs, and benthic macro-invertebrate at the Early Intake/Albino Rock and O'Shaughnessy Dam sites on the Tuolumne River. The Gaming Tool was developed in Microsoft Excel 2007 and is composed of multiple worksheets that store data, contain user specified parameter values, calculate the NGD, or report the results.

The user must specify the daily average flow and daily minimum, maximum, and average water temperature for the Early Intake/Albino Rock and O'Shaughnessy Dam sites based on the results from Hetch Hetchy Reach Flow and Temperature Model. The user must also specify the threshold flows and temperatures, dates when these thresholds apply, and the cross sections (flow and water surface elevation) for the sites.

Based on the data provided, the model assesses the number of days within each criteria category (the criteria categories are based on the threshold temperatures and flows). The temperature criteria determine the number of "good," "upper fair," and "lower fair" growth dates for rainbow trout and the number of "good" days for benthic macro-invertebrates. The model also determines the number of days when conditions are "lethal" or lead to "torpor" for rainbow trout. The habitat criteria determine the number of "Abundant" and "Low" days based on known flows for each site and type (e.g., steep boulder riffles, depositional and step riffles, etc.). The criteria cannot overlap (i.e., a given flow cannot both be in the "abundant" and "low" category).

For example, consider Early Intake and Albino Rock site for rainbow trout in steep boulder riffles (Table 21). If the daily average water temperature was 15.0°C, then it would be considered a "good growth day", whereas if the daily average temperature was 26.0°C it would be considered a "lethal growth day." If the daily average flow was 250 cfs, it would be considered an "abundant habitat" day, whereas a flow of 50 cfs, would result in a "low habitat" day.

Table 21. Example criteria for rainbow trout at the Early Intake and Albino Rock site for steep boulder riffles.

	Criteria
Torpor	$T_w \leq 5.0$°C
Lower Fair Growth	7.0°C $\leq T_w <$ 9.3°C
Good Growth	9.3°C $\leq T_w <$ 20.3°C
Upper Fair Growth	20.3°C $\leq T_w <$ 22.8°C
Lethal (Daily Avg)	25.0°C $\leq T_w$
Lethal (Daily Max)	27.0°C $\leq T_w$
"Abundant"	130 cfs $\leq Q <$ 400 cfs
"Low"	0 cfs $< Q \leq$ 80 cfs

The number of days in each category is determined and summarized on the *Results* worksheet. The temperature criteria is only assessed for rainbow trout, whereas the habitat analysis is performed for rainbow trout, benthic macro-invertebrate, and foothill yellow legged frogs.

The Gaming Tool also includes a frog reproduction analysis. The known flow rates (and associated water surface elevation) and water temperature are used to determine the date when frog eggs are laid and if they survive to hatch (i.e., eggs do not desiccate due to flows dropping the water surface elevation below their level). Subsequently, the Gaming Tool determines the number of days until various developmental stages occurs, and reports the number of egg laying dates that correspond to a successful hatching. The Gaming Tool also reports the number of days for frog growth (days from when full metamorphosis is complete to when over-wintering begins).