UPPER TUOLUMNE RIVER ECOSYSTEM PROJECT

Preliminary Analysis of Available Data for Modeling Temperature in the Hetch Hetchy Reach (O'Shaughnessy Dam to Cherry Creek)

Technical Memorandum

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Prepared for:

The San Francisco Public Utilities Commission, Water Enterprise, Natural Resources and Lands Management Division and Hetch Hetchy Water and Power Division

September 4, 2008

About the Upper Tuolumne River Ecosystem Project

In June 2006, the San Francisco Public Utilities Commission (SFPUC) adopted the Water Enterprise Environmental Stewardship Policy and directed the Water Enterprise to integrate this policy into the planning and operation of the SFPUC water system infrastructure, including Hetch Hetchy Project dams and diversions. The policy establishes a management directive to protect and rehabilitate ecosystems affected by water system operations, within the context of meeting water supply, power generation, water quality, and existing minimum instream flow requirements. The policy further directs the nature of SFPUC instream flow releases such that they mimic, to the extent feasible, "…the variation of the seasonal hydrology (e.g., magnitude, timing, duration, and frequency) of their corresponding watersheds in order to sustain the aquatic and riparian ecosystems upon which native fish and wildlife species depend."

Subsequent to adoption of the Environmental Stewardship Policy, the SFPUC initiated the Upper Tuolumne River Ecosystem Project with the goal of conducting a set of long-term, collaborative, science-based investigations designed to (1) characterize historical and current river ecosystem conditions, (2) assess their relationship to Hetch Hetchy Project operations, and (3) provide recommendations for improving ecosystem conditions on a long-term, adaptively managed basis.

Primary partners include the SFPUC, Yosemite National Park, Stanislaus National Forest, and the U.S. Fish and Wildlife Service. The study area includes reaches of the Upper Tuolumne River mainstem and major tributaries regulated by the Hetch Hetchy Project, from O'Shaughnessy Dam to Don Pedro Reservoir, Cherry Creek downstream of Cherry Valley Dam, and Eleanor Creek downstream of Eleanor Dam.

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1 Purpose

The purpose of this preliminary study was to identify available information that would be sufficient to develop a dynamic, sub-daily model of flow and temperature in the Upper Tuolumne River between O'Shaughnessy Dam (Hetch Hetchy Reservoir) and the Cherry Creek confluence (known as the Hetch Hetchy Reach). For purposes of this review, a one-dimensional model representing longitudinal temperature variations is assumed, but a particular model has not been identified.

2 Introduction

Quantifying flow and temperature relationships in the Hetch Hetchy reach falls under several tasks outlined in the RMC and McBain & Trush (2007) report, including:

- Identifying and compiling existing information, identifying key information gaps;
- Summarizing and synthesizing available information; and
- Identifying short- and long-term future monitoring activities (RMC and McBain & Trush 2007).

Assessment of adequate water temperature requirements for aquatic systems has continuously evolved over the past decades. With advances in computing power and data collection methods and equipment, both computer models and knowledge of thermal regimes of rivers has increased markedly. Today, it is common to collect flow and temperature data and simulate flow and temperature conditions on a sub-daily basis (e.g., hourly) to effectively represent spatial and temporal variations in great detail. Such numerical tools show great promise not only in representing the physical conditions of system, but also to provide a basis for refining operations to more efficiently meet the multiple demands imposed upon available water resources. The value of a sub-daily flow and temperature tool on the Tuolumne River would include an ability to assess:

- Short duration temperature variability (spatial and temporal variations in daily maximum and minimum temperatures; rates of change of water temperature; duration, magnitude and frequency above identified thresholds, etc.);
- Travel time of flow changes for pulse flows and operational flow changes (including ramping rates), impacts of seasonal inputs from tributaries, as well as an ability to forecast the thermal impacts of such operations and conditions; and
- The role of meteorological conditions on the thermal regime of the river.

To assess the potential for implementing a sub-daily flow and temperature modeling framework, an inventory of necessary spatial and temporal information was completed.

3 Project area

The Upper Tuolumne River study reach (known as the Hetch Hetchy Reach) extends from O'Shaughnessy Dam to the Cherry Creek confluence below Early Intake – approximately 13 river miles (Figure 1). No major natural tributaries are in this reach.

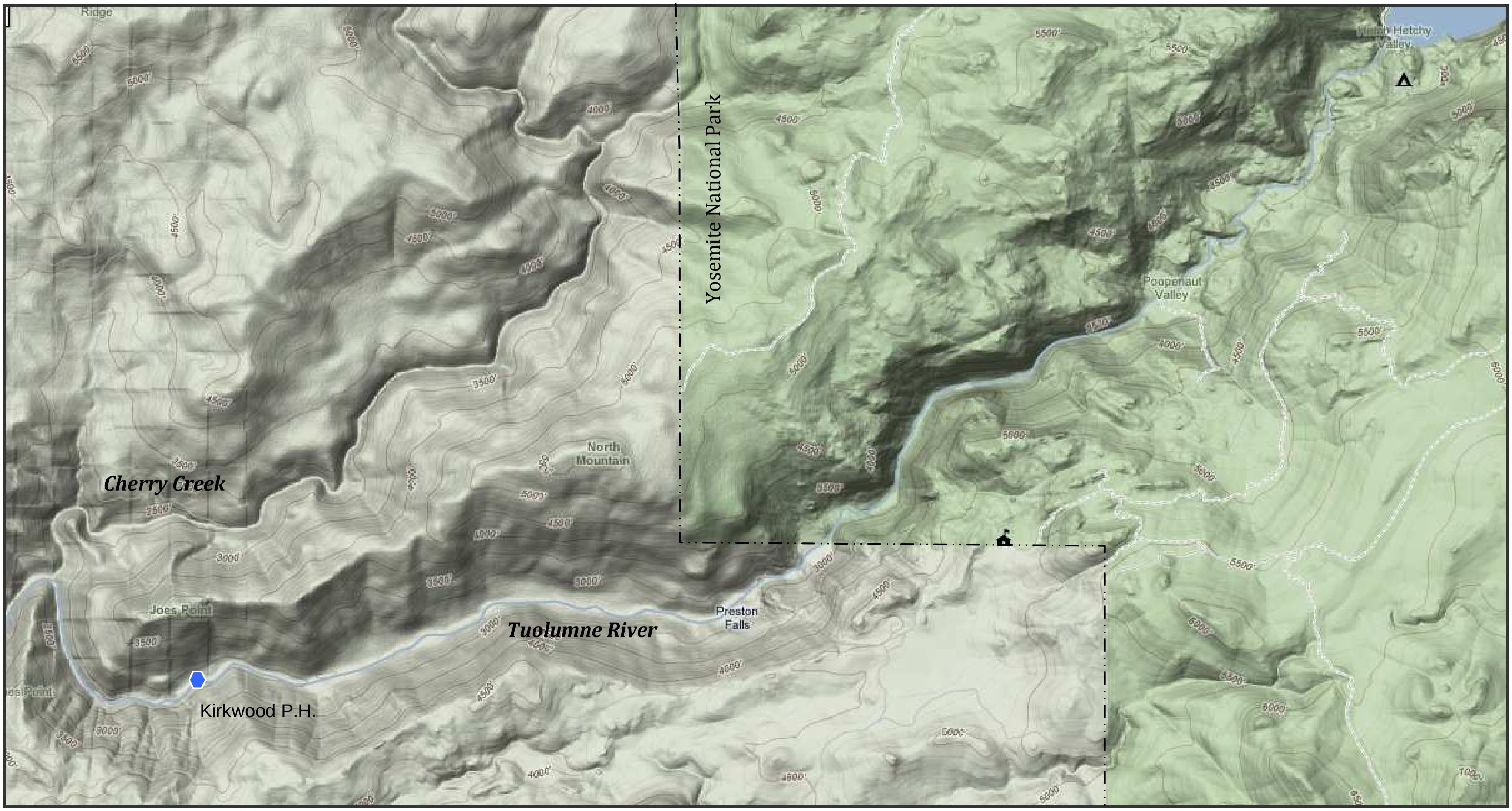

Figure 1. Project area. Source: http://maps.google.com

4 Spatial and temporal resolution

To support a flow and temperature model, geometric, meteorological, hydrologic, and water temperature data are required. Certain data sets, particularly the meteorological, hydrologic, and water temperature time series data, are generally limited in space and time. To provide the maximum flexibility to fully assess aquatic ecosystem attributes, the desire to simulate sub-daily water temperatures is assumed. Thus time series of water temperature and meteorological conditions will be investigated at the sub-daily level (e.g., hourly), and flow data will be assessed at the sub-daily and daily level. Geometric considerations will be assumed static (i.e., the location of the river and river form) for the time being. As additional information becomes available (e.g., associated with the May 2008 experimental flood released from O'Shaughnessy Dam), variations in channel geometry can be assessed. The availability and distribution of each data type presented above – geometry, meteorological, hydrologic, and water temperature – will be discussed in detail below.

5 Geometry

Geometry data necessary for modeling consist of several potential data types, including:

- River course: usually a plan view or longitudinal description of the river (e.g., UTM coordinates or latitude/longitude) to identify the location and aspect of the stream.
- River gradient: a longitudinal description of elevations along the river that is sufficient to characterize the gradient of the stream.
- Channel form: data typically consist of cross sectional (transverse to the principal axis of flow) surveys describing the shape of the river channel. In certain cases complete bathymetric maps of river reaches exist, but such data are typically local in nature and unavailable for longer reaches.
- Shade attributes: to represent the potential impacts of topographic and/or riparian features on incoming solar radiation.

5.1 River course and gradient

The coordinate (X,Y) description of the river location is referenced to the CA Stateplane NAD83 Zone 3 coordinate system in units of feet, and the associated elevation data is NAVD88, feet. These data were acquired from the channel centerline of the DTM provided to SFPUC by Towell, Inc. in 2007 (pers. comm. B Powell). River gradient data are available from a 10-meter digital elevation model (DEM) as presented in RMC and McBain & Trush (2007). The longitudinal profile (from which gradient can be derived) of the Tuolumne River between O'Shaughnessy Dam and Early Intake is shown in **Figure 2**.

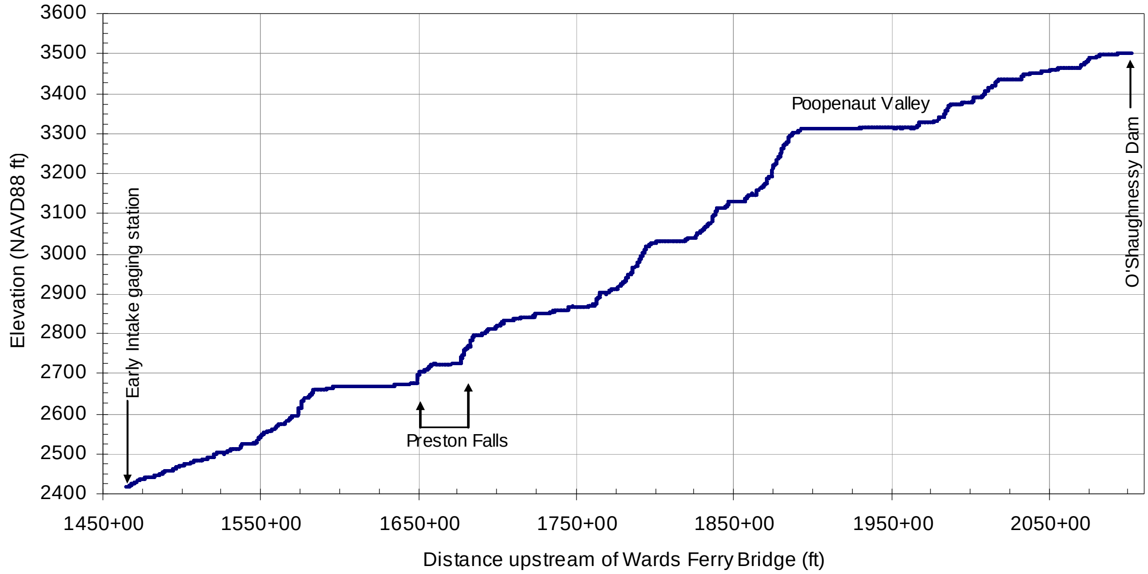

Figure 2. Upper Tuolumne River longitudinal profile of August water surface. Developed from 2007 photogrammetry-based DEM (Source: McBain and Trush).

5.2 Channel form

Channel form data are available for selected locations within the Upper Tuolumne River. Cross sectional data has been collected in the vicinity of Early Intake and just below the O'Shaughnessy Dam at the United States Geological Survey (USGS) gage. Seven cross sections are associated with Early Intake and two at the USGS gage (Table 1). The Early Intake cross sections were surveyed on 10/28/2007 and 10/30/2007, whereas the below Hetch Hetchy cross section were surveyed on 04/09/2007 and 10/30/2007. The cross sectional data also include high water marks (see Figure 3 as an example). The 5-foot photogrammetry from 2007 may also provide information concerning channel form.

Table 1. Upper Tuolumne River cross section data workbook names and data collection dates.

Workbook/File Name	Collection Date
Early Intake xs1472+35.xls	10/28/2007
Early Intake xs1474+90.xls	10/28/2007
Early Intake xs1477+10 .xls	10/28/2007
Early Intake xs1478+70.xls	10/28/2007
Early Intake xs1482+00.xls	10/28/2007
Early Intake xs1483+50.xls	10/30/2007
Early Intake xs1484+70.xls	10/28/2007
Hetchy Gage XS 2046+50 (cableway).xls	04/09/2007
Hetchy Gage XS 2049+75.xls	10/30/2007

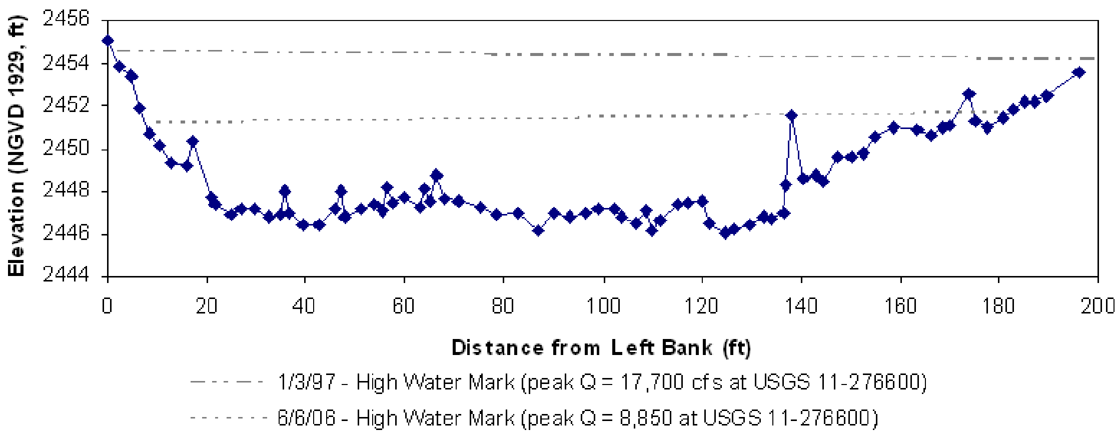

Figure 3. Example Upper Tuolumne River cross section with high water marks.

5.2.1 Other channel geometry information

Other channel geometry information that is useful includes flow relationships with stage, width, and depth; facilities descriptions; and bed forms.

- Flow Relationships: In addition to basic cross section shape, water levels and associated depths at various flow regimes are helpful during flow and temperature modeling to effectively represent velocity (and thus travel time), and depth-width conditions. Some of these data are available (see Figure 3), and additional information was collected during the May 2008 pulse flow event. USGS gage rating measurements (discussed below under "Flow") are also helpful.
- Facilities Descriptions: Because Early Intake and the associated impoundment are located within the study reach, design drawings are required to effectively represent this structure and facilities. SFPUC retains such materials in-house and will make them available when a temperature model is developed.
- Bed Form: Finally, descriptions of the bed are useful when considering channel roughness characteristics under varying spatial and temporal conditions. RMC and McBain & Trush (2007) provides initial insight to bed characteristics in their sub-reach descriptions that is sufficient for initial modeling exercises

5.3 Shade attributes

Specific shade data for the Tuolumne River in the study reach has not been developed. Shading in steep, bedrock-dominated streams is often dictated by topographic shading because large, dense, ubiquitous, near-shore vegetation is generally absent. Although not formally quantified, examination of aerial photos and site visits generally confirm these conditions in the Hetch Hetchy Reach. Thus, at the reach-scale riparian vegetation is expected to play a minimal role. This assumption does not address the potential effects of local shading on water temperatures. Side channels, alcoves, creek confluences, and other channel features where riparian vegetation is present may result in small-scale thermal refugia. A one-dimensional model representation will not provide thermal features associated with such lateral variability, and small scale studies would be needed to quantify these local attributes.

Topographic shading in the Upper Tuolumne River has the potential to affect water temperatures due to the general east-west orientation of the river, steep canyon walls, and confined river channel (Figure 1). Sufficient geospatial data, hydrography, and DEMs are available to provide a year-round estimate of shading throughout the study reach.

5.4 Geometry data recommendations

Recommendations for flow and temperature model geometry considerations in the study reach include:

- Assess quality of 10 meter DEM: ground truth channel gradient and specific elevation controls.
- Review information from the May 2008 pulse flow event to identify travel time, and flow:width and flow:depth relationships.
- As opportunities present themselves, collect additional cross section survey data within the study reach. Currently only a limited number of cross sections are present at selected locations. Useful additional information at notable changes in slope, changes in river width, or other hydrologic features that when distributed throughout the study reach would potentially provide a more comprehensive representation of the stream channel. Certain types of models may require considerably more cross section geometry than others.
- Shade attributes associated with riparian vegetation should be quantified to confirm or refute the assumption that riparian vegetation is a minor player in controlling reach-scale water temperature. Assess potential for seasonal, small-scale thermal refugia associated with riparian shading.

6 Flow

Flow data required for flow and temperature modeling include inflows to the system, outflows to the system, and if possible, flows at intermediate locations. Associated depths, velocities, and widths can also be helpful. Inflows and outflows are termed boundary conditions – locations at the "edge" of the modeling domain. Internal flow measurements and associated attributes (flow, velocity, width, and depth relationships) are useful during model implementation and calibration. Additionally, a stage-flow relationship may be required to represent a downstream boundary condition for a model application.

6.1 Available stream flow data

The USGS maintains three flow gages within the study reach (Table 2). The data are available from the California Data Exchange Center (CDEC) or the USGS website. In addition, the unimpaired flows downstream of O'Shaughnessy Dam have been computed on a daily basis by McBain and Trush (these flow data are not available via the USGS or CDEC websites).

Table 2. USGS gauging stations on the Upper Tuolumne River.

USGS Gage #	Description	Latitude	Longitude
11276500	Tuolumne River Near Hetch Hetchy	37.9375	119.7917
11276600	Tuolumne River Above Early Intake Near Mather	37.8794	119.9461
11276900	Tuolumne River Below Early Intake Near Mather	37.8817	119.9892
n/a	Unimpaired Tuolumne River Below Hetch Hetchy[1]	n/a	n/a

1. Unimpaired flows are generally calculated for a gaging station location, but are not actual gaged flows. The unimpaired flows were computed from the daily change in reservoir storage, canyon tunnel release, and USGS flows immediately below the dam. Evaporation losses were not included due to lack of continuous data (S. McBain pers. comm.)

Period of record for the three USGS stations in the study reach are shown in Table 3. Daily flow data are available throughout the period of record with no data gaps. Typically, data from the most recent six to nine months are termed provisional and are subject to change in the quality assurance process. Sub-daily data are available from USGS (typically fifteen-minute data) upon request for the stations listed in Table 2; however, older sub-daily data series may not be complete. Unimpaired flows were calculated based on daily flow records, and the record ends September 30, 2007 (end of water year 2007). Period of record data are shown graphically in Figure 4 through Figure 6.

Table 3. Start dates and data type for each flow data set.

Description	Start Date	End Date
Tuolumne River Near Hetch Hetchy, CA	10/01/1910	Present
Tuolumne River Above Early Intake Near Mather, CA	10/01/1970	Present
Tuolumne River Below Early Intake Near Mather, CA	10/01/1966	Present
Unimpaired Tuolumne River Below Hetch Hetchy	10/01/1923	09/30/2007

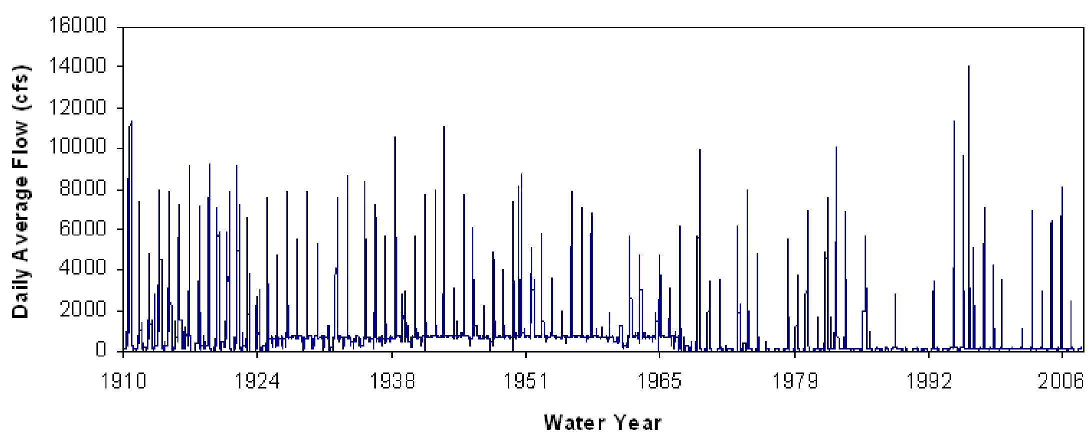

Figure 4. Daily average Tuolumne River flow near Hetch Hetchy (USGS 11276500).

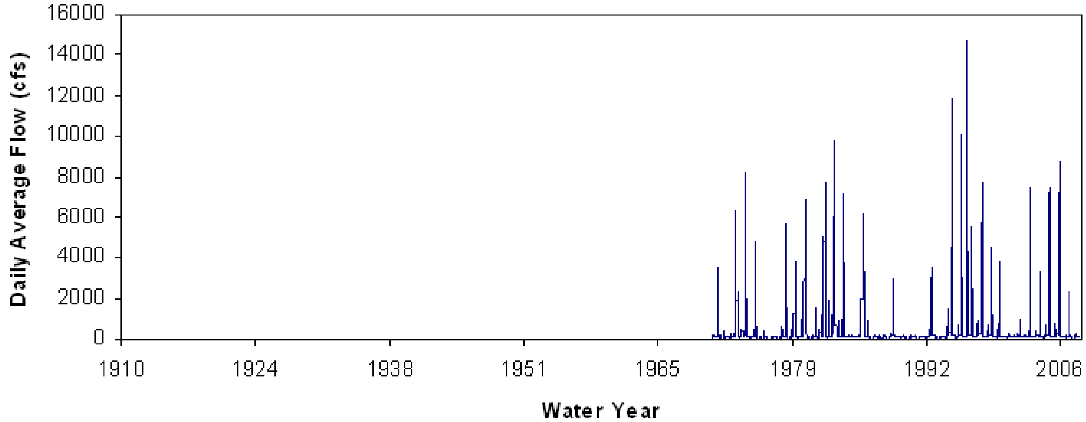

Figure 5. Daily average Tuolumne River flow above Early Intake (USGS 11276600).

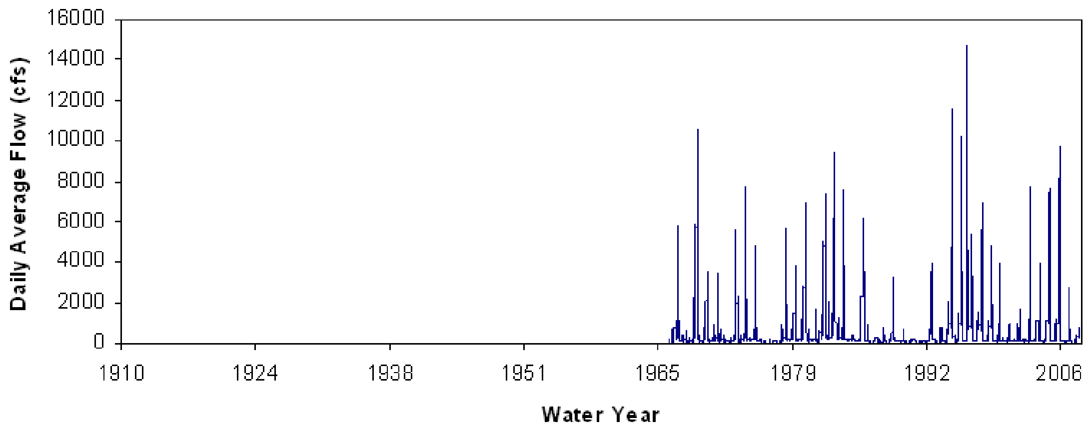

Figure 6. Daily average Tuolumne River flow below Early Intake (USGS 11276900).

McBain and Trush computed unimpaired daily flow data that are available for approximately 84 years (30,681 days) (Figure 7), but of those days 1,796 have negative unimpaired flows and an additional 19 days have no unimpaired flows (Figure 8).

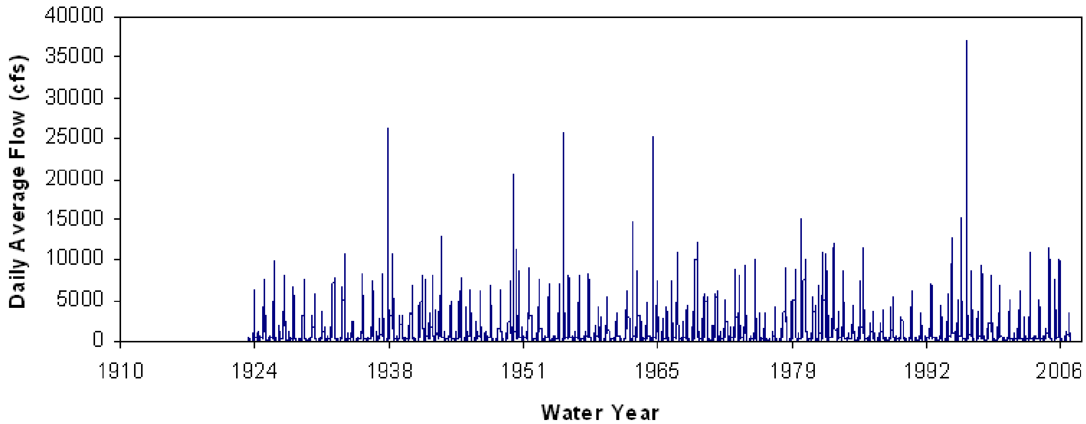

Figure 7. Daily average calculated unimpaired Tuolumne River flow below Hetch Hetchy by McBain and Trush.

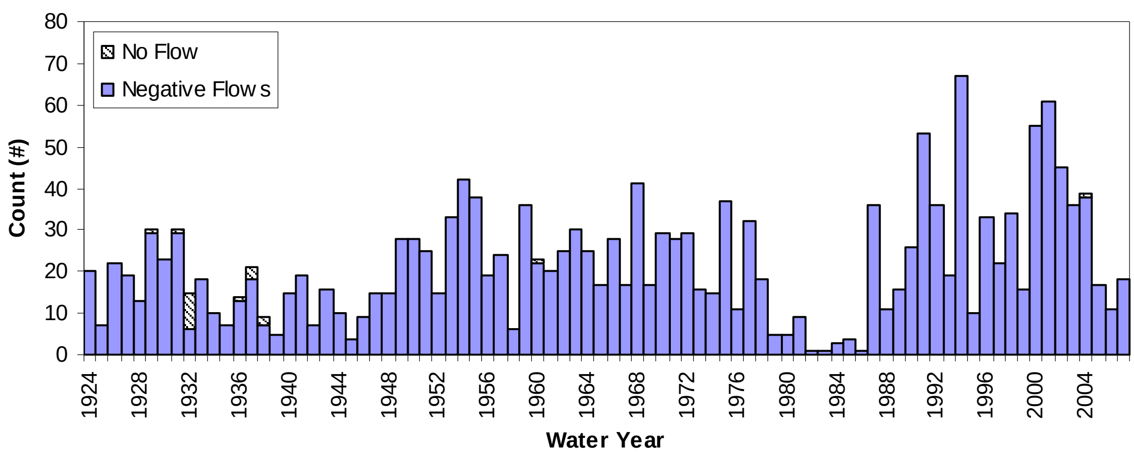

Figure 8. Count of negative calculated unimpaired flows occurring in each water year below Hetch Hetchy.

6.2 Powerhouse operations

The inflows from the Kirkwood Powerhouse would be a required input for any model. Peaking flows indicate that sub-daily (e.g., hourly) data would be most useful. The daily flow data begins on January 1, 1967. The daily flow ranges from zero (no flow) to 1,409 cfs (Figure 9). In general, the highest flows occur the spring and early summer (March through July) (Figure 10). To determine releases from the powerhouse to the Tuolumne River the difference between the USGS gage above Early Intake and the USGS Gage below Early Intake, while considering Canyon Tunnel Diversions can be employed. Further, delivery of Cherry Creek canal water to below Kirkwood PH or any potential Early Intake diversion used to supplement diversions should be considered to ensure correct representation of Kirkwood Powerhouse releases.

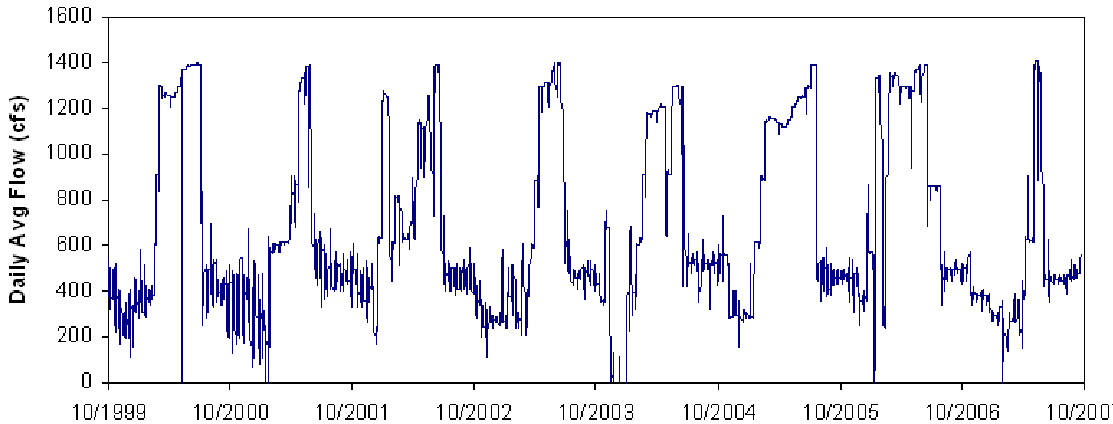

Figure 9. Daily average canyon power tunnel flows for WY2000 through WY2007.

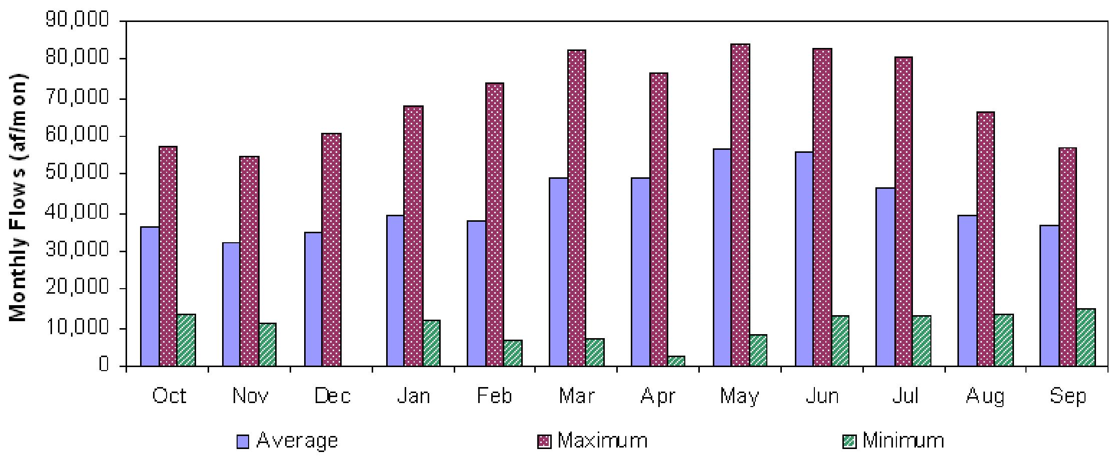

Figure 10. Monthly average, maximum, and minimum flows in the canyon power tunnel for 41-years (WY1967 to WY2007).

6.3 Other flow related data

Field measurements of river width, cross sectional area, mean velocity, and gage stage height are available at approximately monthly intervals for the entire period of record for each station in the study reach. Further, an HEC-RAS model has been developed for the Early Intake reach, Poopenaut Valley, and a short reach near the Hetch Hetchy gaging station. These data can be used for model input and to test model performance at each location, and the below Early Intake location data can be used to form a representative stage-flow relationship employed as a downstream boundary condition in the model.

6.4 Flow data recommendations

Recommendations for flow modeling in the study reach include:

- Consider collecting sub-daily or daily flow information at intermediate locations between the Hetch Hetchy gage and Early Intake, as well as sub-daily Kirkwood Powerhouse flows, to support flow modeling calibration.
- Explore the stage data collected by NPS in Poopenaut Valley and determine status of a rating curve associated with that data.

7 Water temperature

Water temperature data are available from the USGS and SFPUC at four locations (Table 4). The USGS monitors water temperature near Hetch Hetchy (USGS11276500), above Early Intake (USGS1127660), and below Early Intake (USGS11276900). The SFPUC's thermographs are available for two locations within the reach: at Preston Falls (PUC-TR1) and also below Early Intake (PUC-TR2).

The USGS temperature observations are coincident with the flow gaging stations. The longest record is for the station below O'Shaughnessy Dam. The location above Early Intake was changed from hourly data to 15 minute data in September of 2007 and below Early Intake was added in June of 2006. SFPUC data records are only recently available, starting in April of 2007. Currently, no Kirkwood Powerhouse outflow temperature data are available.

The SFPUC data sets are continuous throughout their period of record, while the USGS show various levels of completeness though the period of record. Generally they are complete, but notable data gaps occur as shown in Figure 11. Data gaps can filled in various manners including using temperature relationships developed between other station, estimated from release at Hetch Hetchy (and using existing temperature profiles in the reservoir), and modeled using heat exchange processes (if sufficient meteorological data is available). Overall, there is sufficient data to formulate long-term upstream temperature boundary conditions at O'Shaughnessy Dam and to test/calibrate a model using temperature from the above Early Intake location.

Table 4. Available water temperature data for the Tuolumne River.

ID	Description	Start Date	End Date	Type
USGS11276500	Near Hetch Hetchy, CA	10/01/1988	02/28/2008*	Hourly
NPS	Poopenaut Valley	4/27/07	Present	15-Minute
USGS11276600	Above Early Intake	10/01/1988	09/04/2007	Hourly
USGS11276600	Above Early Intake	09/05/2007	05/28/2008*	15-Minute
USGS11276900	Below Early Intake	06/01/2006	05/28/2008*	15-Minute
PUC-TR2	Below Early Intake	04/23/2007	05/07/2008*	30-Minute
PUC-TR1	At Preston Falls	04/23/2007	05/08/2008*	30-Minute

* These are active stations, but readily available data were only available up to the specified dates. USGS also has been collecting water temperature data above Hetch Hetchy Reservoir since 10/21/06.

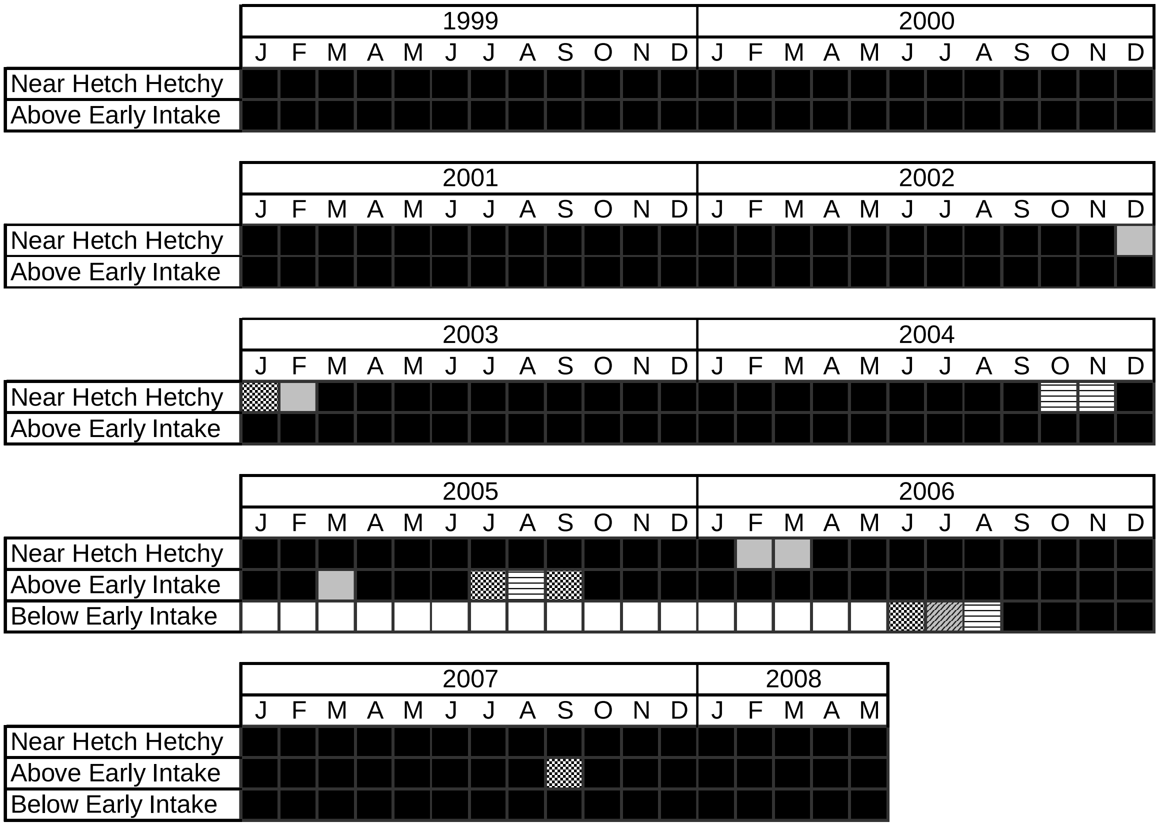

Figure 3. Water temperature data availability for USGS gages near Hetch Hetchy reservoir, above Early Intake, and below Early Intake.[1]

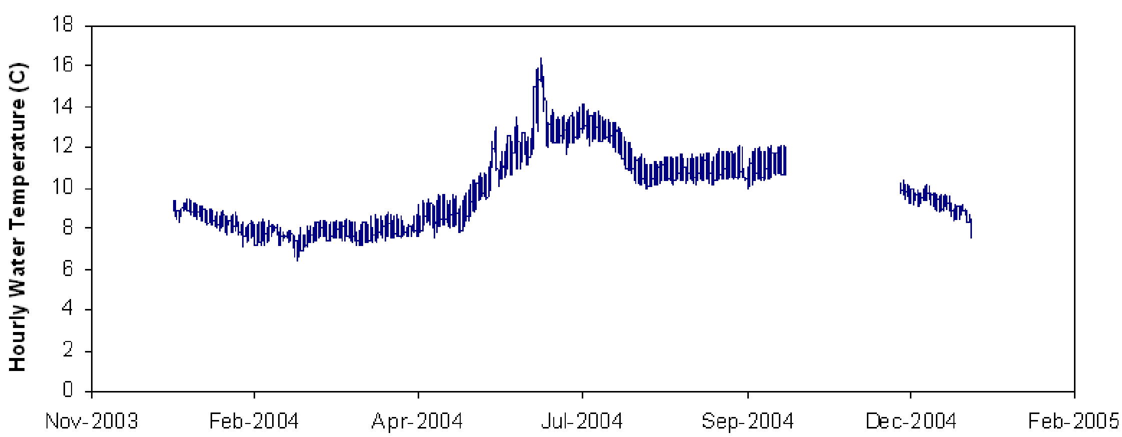

Figure 12. Example Tuolumne River water temperature near Hetch Hetchy (USGS11276500).

[1] Solid black boxes (■) indicate data available for all of the month (i.e., less than 5% of the month is missing); black and white speckled boxes (▩) indicated data is missing for less than 25% of the month; solid grey boxes (□) indicate data is missing for between 25% and 50% of the month; grey with black diagonal line boxes (▨) indicate data is missing for between 50% and 75% of the month; and solid white with black horizontal line boxes (▤) indicate that data is missing for more than 75% of the month. Note that solid white boxes (□) indicate data is not available (i.e., collection has not begun).

Since April 2007 there has been redundancy in temperature monitoring at the site Below Early Intake. A comparison SFPUC and USGS observations indicates that differences exist between the two sensors, with an average difference was 0.3°F and the maximum difference was 5.7°F (Figure 13). Such discrepancies may be the result of different instruments (accuracy, response time), deployment locations and methods, stream thermal variability, and other factors.

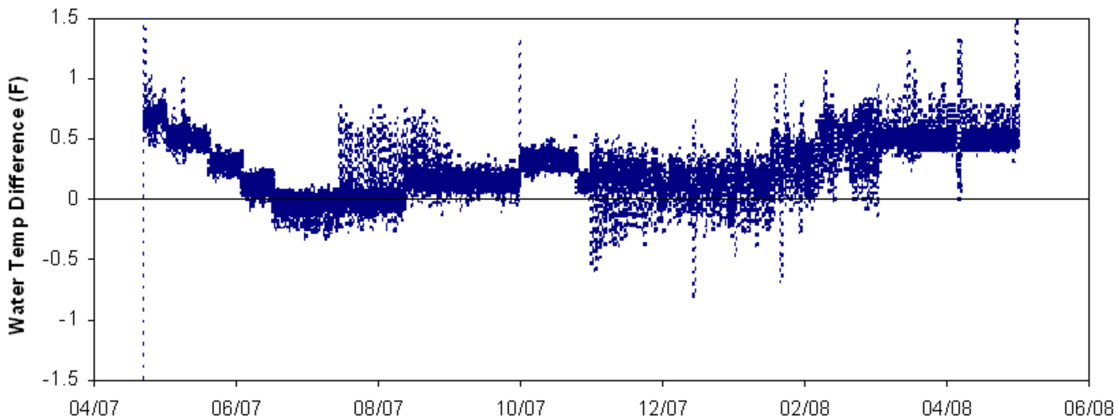

Figure 13. Comparison of SFPUC and USGS water temperature trace below Early Intake on the Tuolumne River.

7.1 Temperature data recommendations

Recommendations for temperature modeling in the study reach include:

- Monitor Kirkwood Powerhouse release temperatures.
- Complete a small scale study to assess temperature differences immediately below O'Shaughnessy Dam and the USGS Gage (approximately 1 mile downstream) to determine if there is appreciable heating or cooling between the dam and the USGS gage monitoring location.
- Recommend redundancy at the Hetch Hetchy gage location to minimize data gaps at this critical upstream boundary location.
- Coordinate with USGS and NPS on monitoring programs to assess spatial and temporal coverage and address issues of redundancy (which may be beneficial).

8 Meteorological conditions

Complete meteorological stations are located at five locations in the study region: the United States Forest Service (USFS) and USGS collect meteorological data at Buck Meadows and the Grand Canyon of the Tuolumne River, respectively. The National Park Service (NPS) collects meteorological data at Crane Flat Lookout and White Wolf, and the California Department of Water Resources (CDWR) collects meteorological data at Gin Flat and Dog House Meadow (Table 5).

- Buck Meadows is located about 19.3 miles south-west of Hetch Hetchy at an elevation of 3,200 ft msl (about 670' lower Hetch Hetchy Reservoir).
- Crane Flat Lookout is located about 13.9 miles south of Hetch Hetchy at an elevation of 5,957 ft msl (about 2,000' higher).
- White Wolf is located about 9.5 miles south east of Hetch Hetchy at an elevation of 7,900 ft msl (about 4,100' higher).
- Gin Flat is located about 12.7 miles south of Hetch Hetchy at an elevation of 7,050 ft msl (about 3,100' higher).
- Dog House Meadow is located about 12.9 miles south of Hetch Hetchy at an elevation of and 6,100 ft msl (about 2,200' higher)
- The Grand Canyon of the Tuolumne River gage is located about 7.2 miles south east of Hetch Hetchy at an elevation of 3,830 ft msl.

In addition, SFPUC collects air temperature at Hetch Hetchy (HHWP) and barometer and humidity near Poopenaut Valley (YNSP). These data are not available via CDEC or USGS and were not evaluated. In addition, SFPUC collects daily precipitation from Hetch Hetchy (CDEC station HTH).

Meteorological data required for temperature modeling includes air temperature, dew point temperature (or relative humidity), wind speed and direction, precipitation, solar radiation, and barometric pressure. At present, none of the stations evaluated collect all of the parameters. However, Buck Meadow, Gin Flat, and Dog House Meadow collect all but barometric pressure, and barometric pressure can be calculated based on elevation.

Table 5. Meteorological Stations near Hetch Hetchy Reservoir.

Description	Latitude	Longitude	Elevation	Distance (mi)[1]	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

1. Distance from Hetch Hetchy Reservoir to each site is measured by a straight line between the points.

Some combinations of these observations (as well as other meteorological parameters) are available from the five meteorological stations (Table 6) with the exception of atmospheric pressure and cloud cover. Atmospheric pressure can be calculated based on elevation, and cloud cover can be estimated by comparing theoretical maximum solar radiation (clear sky) with observations. Solar radiation is measured at Buck Meadows, Gin Flat, and Dog House Meadows and because solar radiation does not vary considerably over small distances this data will be useful.

Table 6. Start dates and data type for each meteorological data set.

Parameter	Buck Meadows	Crane Flat Lookout [1]	Gin Flat	Dog House Meadow	Tuolumne Grand Canyon	White Wolf
Air Temperature	07/19/1999	11/01/1992	10/01/1985	03/14/2005	11/28/2007	10/24/2007
Relative Humidity	07/19/1999	01/01/1995	10/15/2003	03/14/2005	11/28/2007	10/24/2007
Wind Speed	07/19/1999	01/01/1995	10/15/2003	03/14/2005	n/a	10/24/2007
Wind Direction	07/19/1999	01/01/1995	10/15/2003	03/14/2005	n/a	10/24/2007
Wind Peak Gust	07/19/1999	01/01/1995	10/15/2003	03/14/2005	n/a	10/24/2007
Wind Peak Gust Direction	07/19/1999	01/01/1995	10/15/2003	03/14/2005	n/a	10/24/2007
Precipitation	07/19/1999	11/01/1992	10/01/1985	03/14/2005	11/28/2007	10/24/2007
Solar Radiation	07/19/1999	n/a	08/21/2000[2]	03/14/2005	n/a	10/24/2007

1 Crane Flat Lookout data set appears to end on 11/29/2006.

2 Solar radiation readings at Gin Flat ceased on 12/01/2001 and were replaced by hourly average, minimum, and maximum readings beginning on 11/07/2001.

Buck Meadows, Gin Flat, Dog House Meadow, the Grand Canyon of the Tuolumne River, and White Wolf meteorological stations are still active and their most recent data are available via the Internet (see CDEC). The Crane Flat Lookout station is listed as active, but it appears to have been discontinued on 11/29/2006. Hourly solar radiation readings at Gin Flat ceased on 12/01/2001, but the hourly average, minimum, and maximum solar radiation readings are still reported. The data availability analysis below does not take into consideration the quality of the data (e.g., data gaps lasting days to weeks are present).

Most of the data sets appear to begin in the early late 1990's and early 2000's. None of the data sets (e.g., air temperature, relative humidity, wind speed and direction, precipitation, and solar radiation) are complete for all months in all years; all have data gaps of varying size (i.e., duration). Air temperature records begin in 1985 (Gin Flat), but are sporadic until July of 1999 (when Buck Meadows came on line) (Figure 14). Starting then fairly complete temperature records are available for one or more of the sites. Relative humidity records begin in 1995 (Crane Flat Lookout), but are sporadic until 1999 (Figure 15). Except for a period in late 2003 through mid-2004, fairly complete relative humidity records are available for at least one or more sites. Wind speed and direction are fairly similar; both records begin in 1995, but are sporadic (Figure 16 and Figure 17). Buck Meadows is the most complete record starting in 1999 (with a large gap in late 2003 through mid-2004). Once started, Dog House Meadows also has a fairly complete wind speed and direction record. Precipitation records begin in 1985 (Crane Flat Lookout), but are sporadic until 1995. After 1995 precipitation records are available from Crane Flat Lookout and Gin Flat, both of which are fairly complete (Figure 18). Buck Meadows also has fairly complete precipitation records (starting in 2000). Finally, fairly complete solar radiation readings are available from 2000 for Buck Meadows and Gin Flat (Figure 19). More recently, solar radiation readings from the Grand Canyon of the Tuolumne River and White Wolf are also available.

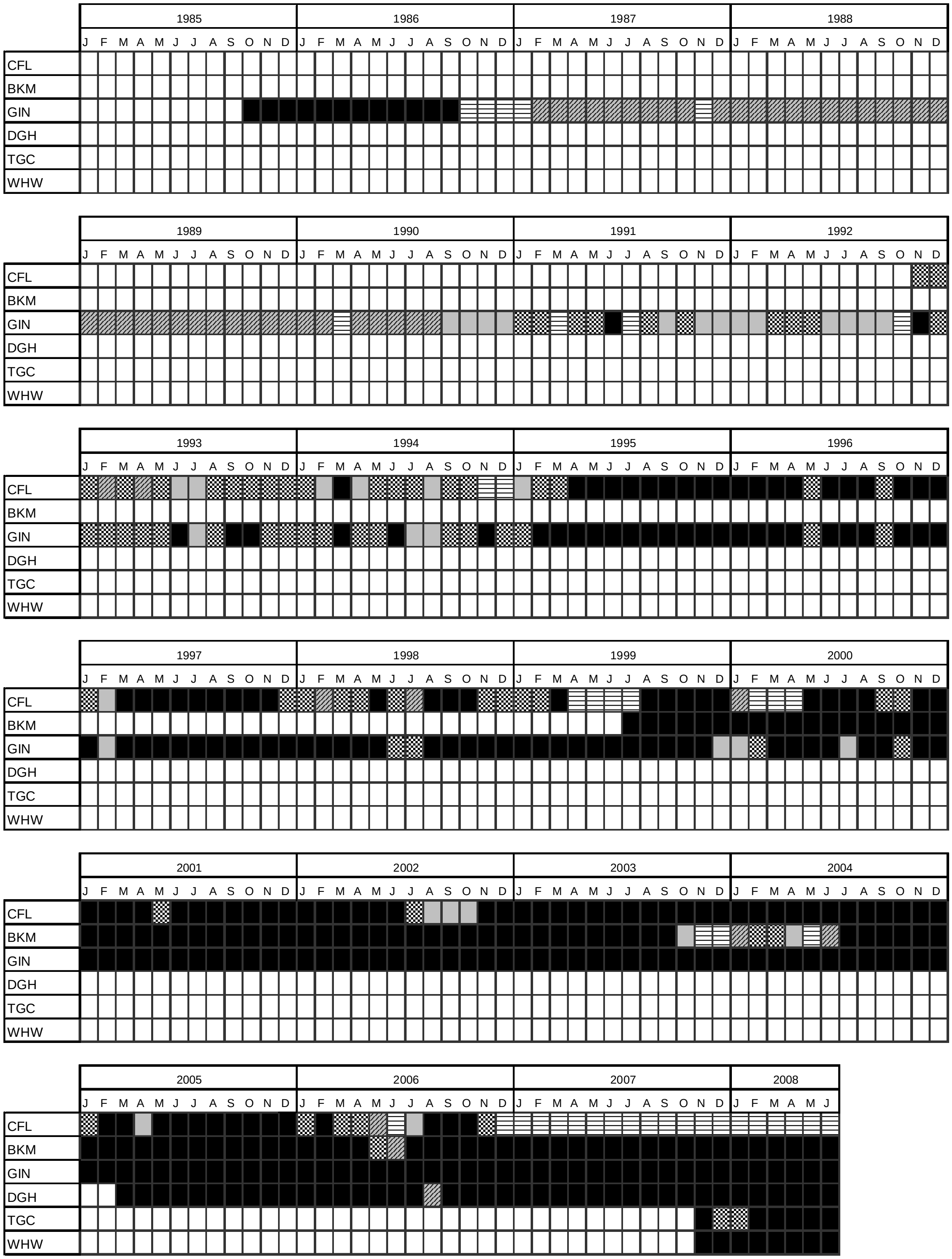

Figure 4. Air temperature data availability for Buck Meadows (BKM), Crane Flat Lookout (CFL), Gin Flat (GIN), Dog House Meadows (DGH), Tuolumne Grand Canyon (TGC), and White Wolf (WHW). (See footnote 1, on page 10 for the color key.)

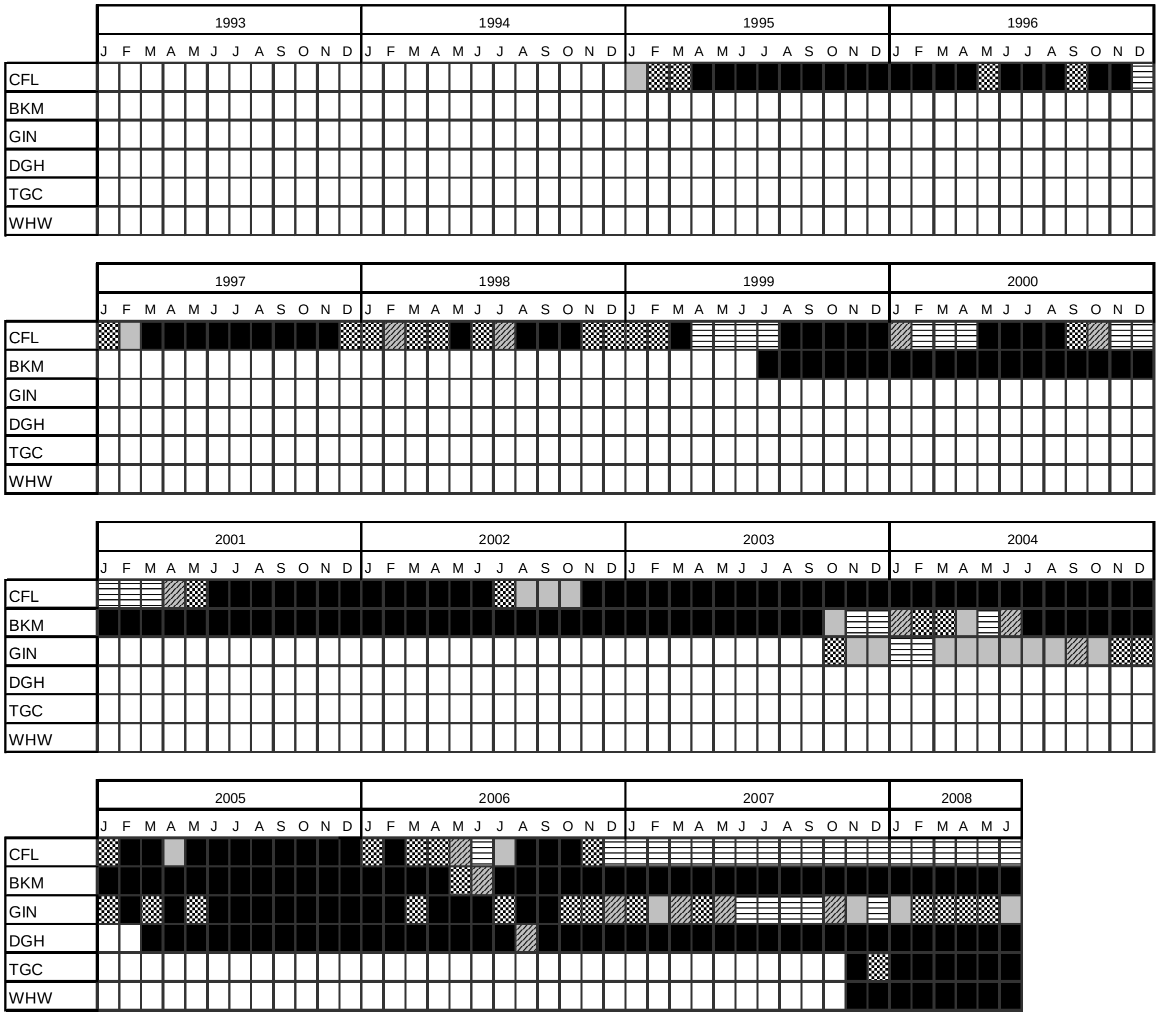

Figure 5. Relative humidity data availability for Buck Meadows (BKM), Crane Flat Lookout (CFL), Gin Flat (GIN), Dog House Meadows (DGH), Tuolumne Grand Canyon (TGC), and White Wolf (WHW). (See footnote 1, on page 10 for the color key.)

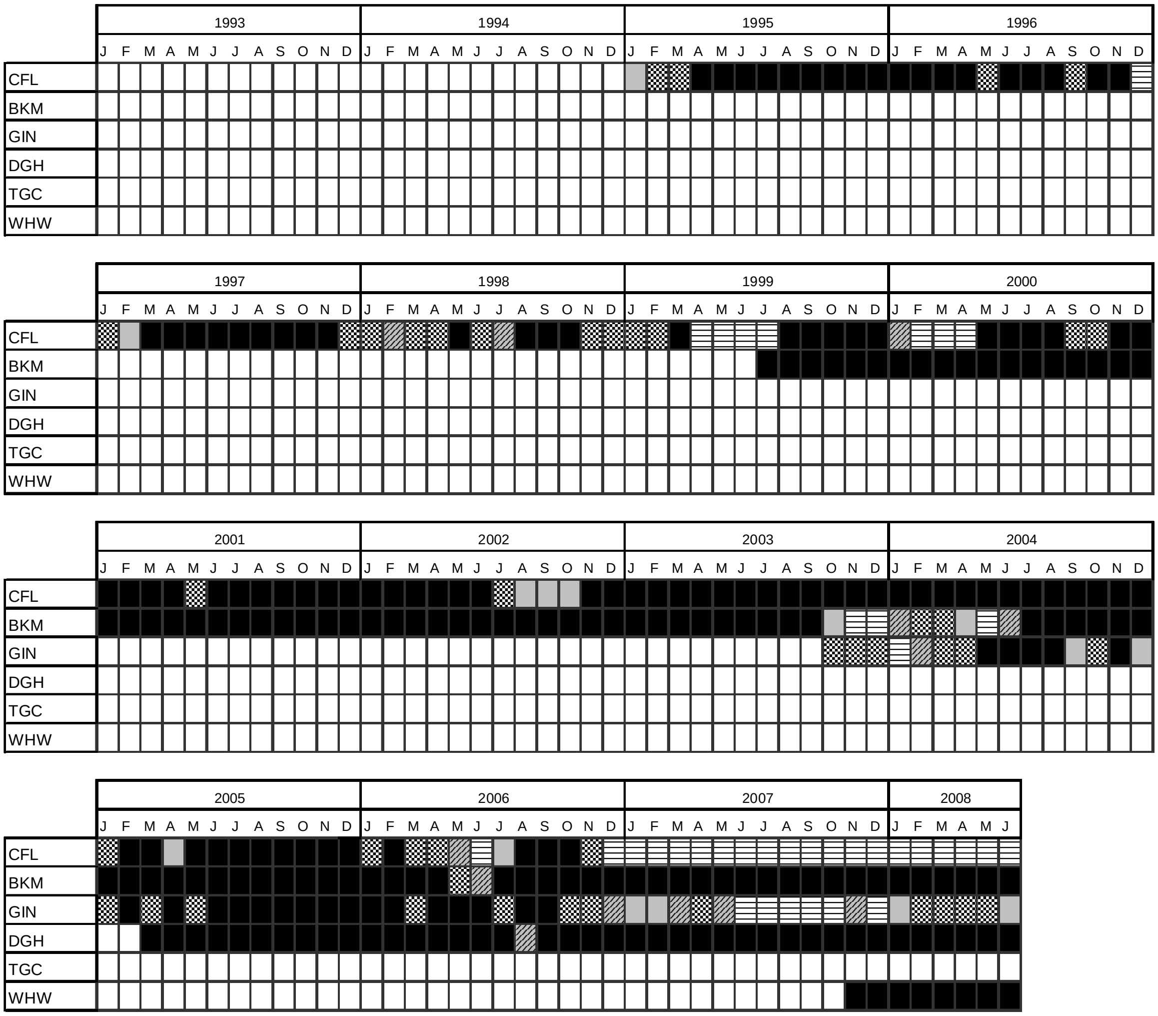

Figure 6. Wind speed data availability for Buck Meadows (BKM), Crane Flat Lookout (CFL), Gin Flat (GIN), Dog House Meadows (DGH), Tuolumne Grand Canyon (TGC), and White Wolf (WHW). (See footnote 1, on page 10 for the color key.)

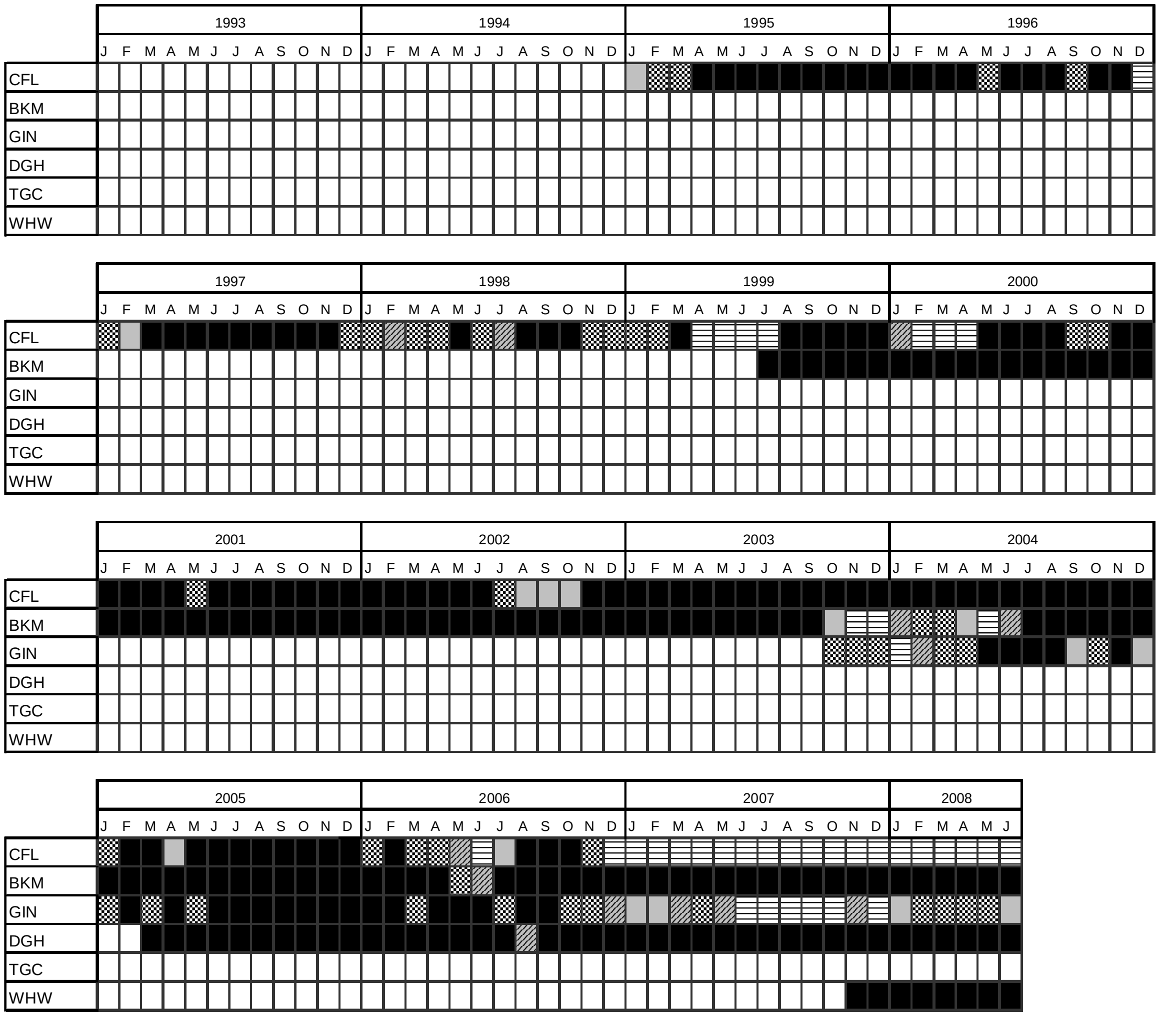

Figure 7. Wind direction data availability for Buck Meadows (BKM), Crane Flat Lookout (CFL), Gin Flat (GIN), Dog House Meadows (DGH), Tuolumne Grand Canyon (TGC), and White Wolf (WHW). (See footnote 1, on page 10 for the color key.)

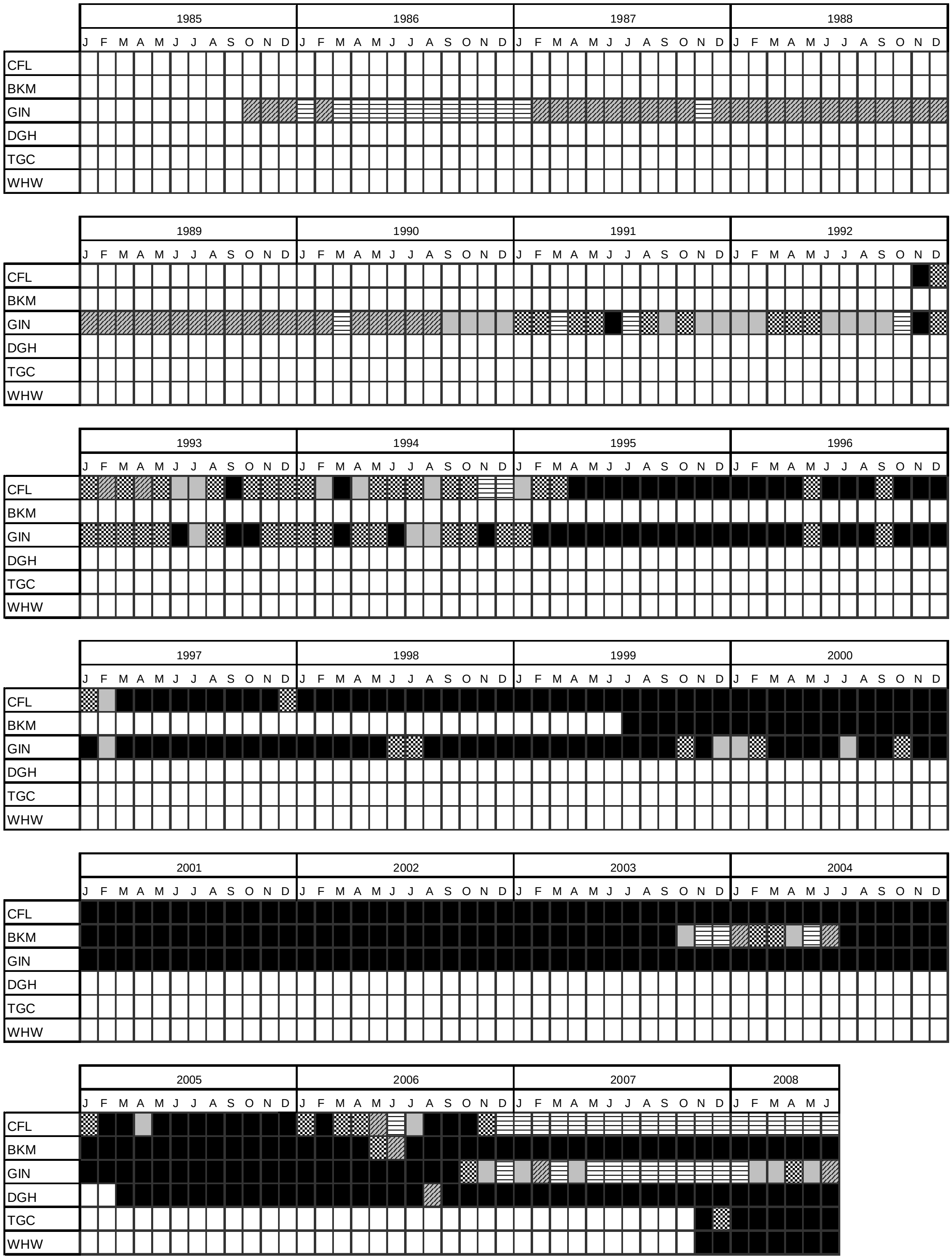

Figure 8. Precipitation data availability for Buck Meadows (BKM), Crane Flat Lookout (CFL), Gin Flat (GIN), Dog House Meadows (DGH), Tuolumne Grand Canyon (TGC), and White Wolf (WHW). (See footnote 1, on page 10 for the color key.)

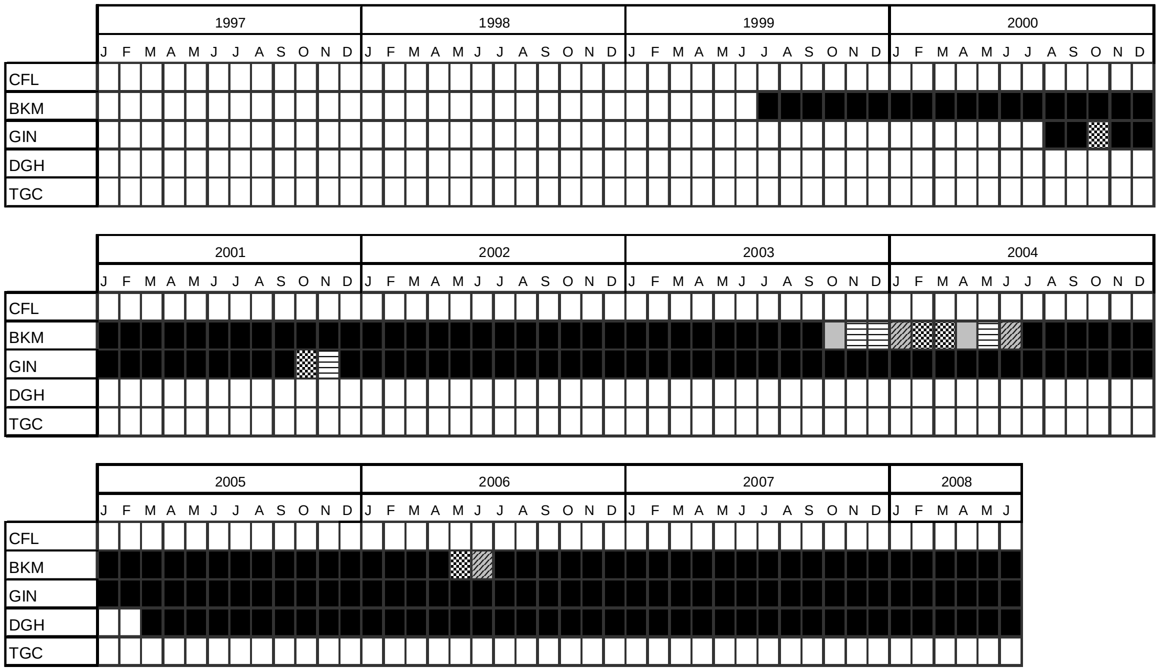

Figure 9. Solar radiation data availability for Buck Meadows (BKM), Crane Flat Lookout (CFL), Gin Flat (GIN), Dog House Meadows (DGH), and Tuolumne Grand Canyon (TGC). (See footnote 1, on page 10 for the color key.)

A brief comparison of conditions at the Buck Meadows and Crane Flat Lookout stations indicates that, despite an almost 3000' elevation difference, air temperature patterns at Crane Flat Lookout and Buck Meadows are fairly similar. The absolute temperatures tend to be within 15°F of each other, with Buck Meadows tending to be warmer (Figure 20), as would be expected considering theoretical lapse rates associated with increase in elevation.

Data quality questions exist as well, e.g., anomalous changes in air temperatures dropping from 59°F to 7°F in two hours (on October 16, 2000) and rising from 1°F to 58°F in one hour (on April 23, 2001). These data sets will require careful assessment prior to use in modeling exercises. All of the data sets appear to have similar issues (though Dog House Meadow and the Grand Canyon of the Tuolumne appear to have the least unexpected temperature changes).

Recommendations associated with meteorological data to support temperature modeling in the study reach include:

- In the short term there is sufficient meteorological information to model water temperatures in the study reach. However, if long-term assessment is of interest, installation of a meteorological station at Hetch Hetchy would be beneficial to avoid reliance on third party stations for support of water management decisions. Recommended monitoring parameters include air temperature (dry bulb), relative humidity (or dew point temperature), wind speed and direction, solar radiation, atmospheric pressure, and precipitation. Other parameters may be included to support other activities in the region. Options include SFPUC installation and maintenance or supporting USGS or the NPS to undertake this endeavor.

- Coordinate with the USGS, NPS and the U.S. Forest Service (USFS) and other agencies to (a) inform these other agencies of SFPUC data monitoring activities to provide sufficient coverage, issues of redundancy (which may be beneficial), and identify ongoing status and maintenance of the local meteorological stations

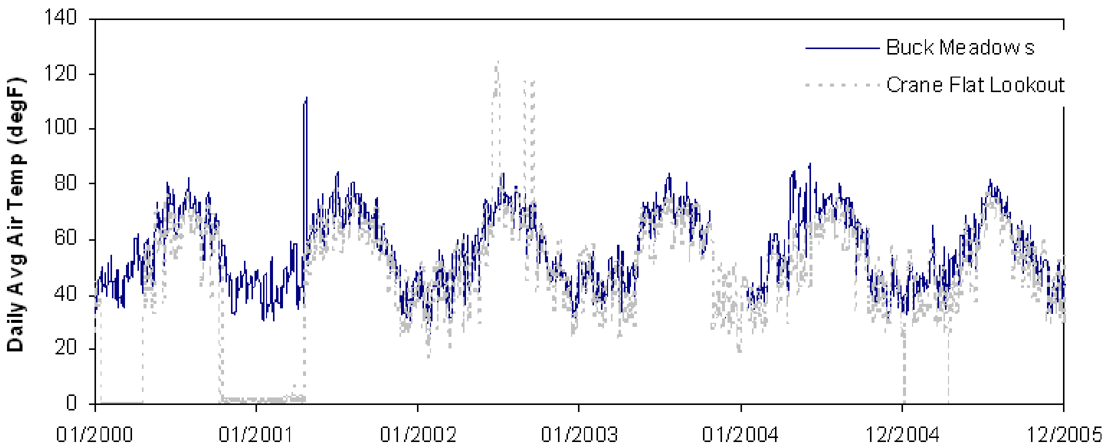

Figure 20. Comparison of daily average air temperature at Buck Meadows and Crane Flat Lookout (01/01/2000 through 01/01/2006).

9 Reservoir conditions

Two reservoirs in the study reach likely affect water temperature. Hetch Hetchy Reservoir forms the upper boundary of the study area and is the source of water releases in the study reach. Early Intake Reservoir is located approximately 12 miles downstream of Hetch Hetchy Reservoir, and likely affects the lower most mile of the study reach between Early Intake Diversion Dam and the Cherry Creek confluence. If future management activities include forecasting water temperatures associated with various storage conditions and/or flow release schedules, historical release temperatures may not provide representative conditions. In such cases, thermal conditions in the reservoirs, particularly Hetch Hetchy Reservoir, coupled with reservoir modeling, could readily be used to formulate an upper boundary inflow temperature to the Hetch Hetchy Reach. Outlined briefly herein are the geometric, flow, temperature, and meteorological considerations.

9.1 Geometry

Geometry considerations for a reservoir thermal assessment include:

- Bathymetric data describing the reservoir morphology;
- A stage-volume-area table or relationship; and
- Description of the dam including width-depth description; type, location, size, and capacity of outlets; and spillway design and capacity.

A detailed bathymetry of the reservoir is available (Figure 21), and an associated stage-volume-area curve has been developed. SFPUC retains designs and diagrams of outlet structures with appropriate elevation and location information; these data will be made available as necessary.

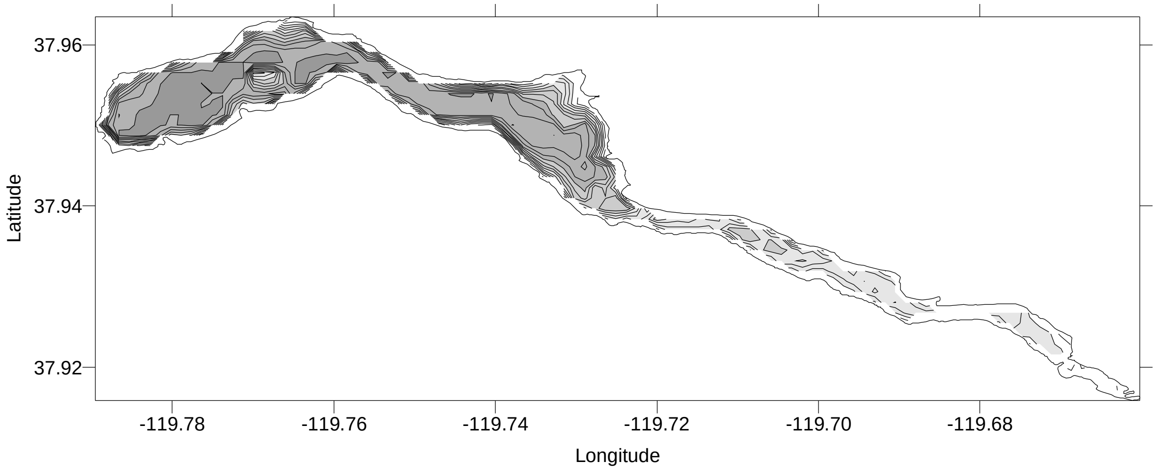

Figure 21. Hetch Hetchy Reservoir bathymetry (contour interval 20 feet, lowest contour 3500 feet).

9.2 Flow and hydrology

SFPUC maintains elevation (stage), storage and change in storage, inflow, outflow, and precipitation records for the Hetch Hetchy Reservoir. Most of the data available via CDEC starts in the early 1990's and continues to the present (Table 7).

Table 7. Start dates and data type for each reservoir conditions data set.

Description	Start Date	End Date	Type	Complete
Reservoir Elevation	01/08/1985	Present	Daily	No
Reservoir Storage	01/08/1985	Present	Daily	No
	10/01/1951	Present	Monthly	Yes
Reservoir Change in Storage	10/04/1993	Present	Daily	No
Reservoir Inflow	01/17/1994	Present	Daily	No
Reservoir Outflow	10/03/1993	Present	Daily	No
Precipitation	01/08/1985	Present	Daily	No

All of the daily data records have data gaps, ranging from single day to multiple months. The monthly and 15-minute data are continuous. However, a brief review of the data indicates that the available data would be sufficient to support temperature assessment/modeling of the reservoir. Further, operational information in the form of release locations (which outlets) is required to estimate release temperatures from the lake. These data are documented by SFPUC and will be made available as necessary.

9.3 Temperature

The SFPUC collects temperature profiles at approximately monthly intervals in Hetch Hetchy Reservoir. Water clarity is measured with a Secchi disc, and local meteorological conditions (air temperature, wind speed and direction, and sky conditions) are also recorded. Field observations are available from the SFPUC from 1997 to present.

9.4 Meteorological data

Meteorological data have been addressed previously and sufficient information is available to support temperature analysis of reservoir thermal conditions.

9.5 Reservoir data recommendations

Because reservoir outflow temperatures under a presumed future condition are not required at this time, no recommendations for future work in this area are provided.

10 Recommendations and conclusions

Review of available data suggests that sufficient geometric, flow, temperature, and meteorology information is available to implement and calibrate a one-dimensional temperature model (lateral and vertically averaged) in the study reach. Overall, time series of flow, temperature, and meteorological conditions vary in duration (Table 8). Of the various data types, meteorological data is the constraining parameter set. Considering the length of the meteorological record, data gaps present in water temperature and meteorological data, and the number of temperature monitoring sites available in the most recent years, flow and temperature modeling is recommended to focus on the 2000 to present period. Calibration efforts should focus on the most recent years where additional temperature data is present. If there is a desire to extend the thermal record back before 2000, data from the various meteorological stations may possibly be used to simulate temperatures back into the early to mid-1990's.

Table 8. Period of record comparison for available time series data.

Parameter	Period of Record		Notes
	Start	End	
Flow	1964	present	Complete
Water Temperature	1988	present	Data gaps present, only recent data available
Meteorology	July 1999	present	Crane Flat available prior to 1999, but station not currently in operation.

10.1 Data gaps

The length of gaps in the data sets reviewed in this report is variable. Some gaps extend for only a few time steps, while other gaps span days to weeks. The length and timing (when in the year) of the data gaps will influence which method(s) are used to fill-in the missing data. The proposed method for filling each data gap is described below.

10.1.1 Flow data gaps

The flow records for near Hetch Hetchy, above Early Intake, and below Early Intake are complete and do not have data gaps during the 2000 to present.

10.1.2 Water temperature data gaps

Water temperature gaps range from a single time step to weeks. For short data gaps (approximately less than 6 hours in length), linear interpolation will be used to fill in the missing data. Longer data gaps, during certain periods of the year (e.g., winter), can be filled in a similar fashion (i.e., linear interpolation) because there is little variability. Further, certain locations may show less variability and allow linear interpolation over extended periods. For example, water temperature downstream of O'Shaughnessy Dam is fairly stable due to the deep water source from Hetch Hetchy Reservoir.

For locations and periods of the year that illustrate considerable short-term variation (i.e., notable diurnal signal), more than one approach will be used. For shorter gaps, temperatures from adjacent periods (days, up to a week) can be used as surrogates for the missing period. For longer data gaps, an equilibrium temperature approach will be implemented wherein sub-daily temperatures are calculated based on meteorological and flow conditions in the system. Water temperatures from nearby stations may also be used as a surrogate for the missing data.

10.1.3 Meteorological data gaps

Meteorological data gaps range from a singe time step to weeks. For short data gaps (approximately less than 6 hours), use linear interpolation to fill-in the missing data. Longer data gaps, during certain periods of the year (e.g., winter), can be filled in a similar fashion (i.e., linear interpolation) because there is little variability. For locations and periods of the year that illustrate considerable short-term variation (i.e., notable diurnal signal), data from adjacent periods (days, up to a week) can be used as surrogates for the missing period. If longer periods are absent, data from nearby stations can be employed, taking into account differences such as elevation, lapse rate, wind sheltering, etc.

10.2 Modeling plan

The modeling plan identifies general development tasks and a schedule and budget. These steps are consistent with a one-dimensional, longitudinal flow and temperature.

10.2.1 Model development tasks

Model development included data management, model implementation, model calibration, analysis, and documentation. Project tasks are broken down into six phases; some of the phases occur in a concurrent fashion while others must be done sequentially.

1. Data manipulation and time series completion (filling data gaps): this phase includes manipulating the time series data for flow, temperature and meteorology identified herein into a format compatible for input into the model (e.g., fill data gaps, provide final quality assurance, construct input files). Geometry data is likewise formatted appropriately for model use.
2. Model implementation: implementation includes assembling all input data, selecting default model parameters, and producing a functional, but uncalibrated model. Activities that may occur during this stage include identifying appropriate spatial

and temporal simulation scales, refining system geometry, testing the model to ensure proper representation, and similar activities.

3. Model calibration: following implementation, the model is calibrated. Calibration data for flow and temperature are required within the model domain. For the Tuolumne River this would include, for example, any available flow and temperature observations in the reach between the dam and Early intake. Flow is calibrated initially, comparing total flow rate (and possibly stage and velocity). Parameters used in calibration typically include channel roughness, viscosity and other hydrodynamic parameters. Subsequently, temperature is calibrated through a similar process of comparing field observations with model results. Calibration parameters typically include the evaporative heat flux coefficients. Calibration statistics are developed for both flow and temperature to identify the range of performance expected in model application.
4. Model application and analysis: Once the model is calibrated, application and analysis can be completed. Boundary flows and temperatures can be modified, as can meteorological conditions, to determine the potential implications of various management actions or external conditions.
5. Model documentation: the principal tasks of data collection and gathering, model implementation, and calibration are documented to provide a record of methods and assumptions.
6. Project management.

10.2.2 Model development schedule and budget

A project of the magnitude identified herein on the Tuolumne River will take approximately five months (Table 9). Documentation should be done concurrently with each task (e.g., documentation of the calibration should be done while the model is being calibrated). Project management will be necessary to coordinate tasks and maintain the development schedule.

Table 9. Approximate model development schedule.

Phase	Month				
	1	2	3	4	5
Data manipulation, time series completion	■				
Model implementation;	■	■			
Model calibration;		■	■		
Model application and analysis;			■	■	
Model documentation	■	■	■	■	■
Project management.	■	■	■	■	■

The budget associated with this level of model development is approximately $94,592, as outlined in Table 9.

Table 10. Approximate model budget.

Phase	Amount
Data manipulation and time series completion	$ 8,328
Model implementation;	$ 19,664
Model calibration;	$ 11,800
Model application and analysis;	$ 21,512
Model documentation	$ 20,128
Project management.	$ 13,160
Total:	$ 94,592

11 References

McBain and Trush, Inc., and RMC Water and Environment. 2007. Upper Tuolumne River: Description of River Ecosystems and Recommended Monitoring Actions. Final Report, April 2007.