San Francisquito Creek Habitat Monitoring Project, Final Report
Stream Temperature Characterization

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Abstract
Stream water temperature regimes are determined by the complex interplay of various environmental factors, including prevailing meteorology, surface and subsurface flow patterns, and local riparian canopy structure as it affects solar exposure. We examined temperature regimes with respect to conservation of aquatic organisms for San Francisquito Creek (SFC) watershed (San Francisco Peninsula, CA) using a stream temperature characterization protocol that predicts water temperature regimes for any time period and location The protocol predicts stream temperature dynamics based on energy balance, with a focus on shortwave input from incoming solar radiation (insolation). Analyses synthesize measurements of meteorology from nearby weather stations, stream flow and water temperature from gaging stations, water temperature from a distributed sensor network, riparian canopy structure and solar exposure from hemispherical photography, and stream morphology from field characterization and geographic information system (GIS) analysis. For SFC, water temperature generally tracked air temperature, with significant lags (~ 4+ hr) and local effects. Subsurface flow through gravel beds decreased temperature (2-3° C decrease) and greatly lowered temperature variability. Stream reaches with open riparian canopy had high insolation and displayed relatively high temperature variability (up to 5° C differential from baseline), whereas reaches with closed canopy had low insolation and displayed modest temperature variability (0.5-1.0° C differential). Simulated tree removal demonstrates the power of the tool to evaluate human and natural impacts of riparian canopy modification. Analysis of the July 2006 heat wave demonstrates the value of the protocol for assessing impacts of extreme weather events. Management of SFC stream habitat to include a diversity of suitable temperature regimes is essential for conservation of species such as steelhead trout (*Oncorhynchus mykiss*), which requires relatively cool conditions, and California red-legged frog (*Rana aurora draytonii*) and western pond turtle (*Clemmys marmorata*), which require warmer conditions. Our stream temperature characterization protocol not only is valuable for the SFC watershed, but also can be applied to a broad spectrum of streams for habitat assessment, for conservation and restoration, and for examination of potential impacts of climate change on stream ecosystems.

1. Introduction

1.1 Motivation: Water temperature is a key determinant of habitat suitability for aquatic organisms (Matthews and Berg 1977, Ebersole *et al.* 2003, Huff *et al.* 2005). For example, among species of conservation concern in California, steelhead trout (*Oncorhynchus mykiss*) require relatively cool temperatures (Ringler 1975, Crisp 1990, Hostetler 1991, Nielson *et al.* 1994), whereas California red-legged frog (*Rana aurora draytonii*) and western pond turtle (*Clemmys marmorata*) require warmer temperatures (Figure 1) (Fellers *et al.* 2001). Conservation of native stream biota depends upon maintenance of suitable temperature regimes, with sufficient habitat heterogeneity required to maintain biodiversity of organisms with diverse temperature requirements (Poole and Berman 2001, Mohseni *et al.* 2003, Davies *et al.* 2004). Characterization of water temperature in streams is challenging because of the complexity involved. A comprehensive understanding of the factors influencing stream temperature, together with recent advances in energy balance models, sensor networks, hemispherical photography, and geographic information systems (GIS) provide the needed elements to address this challenge.

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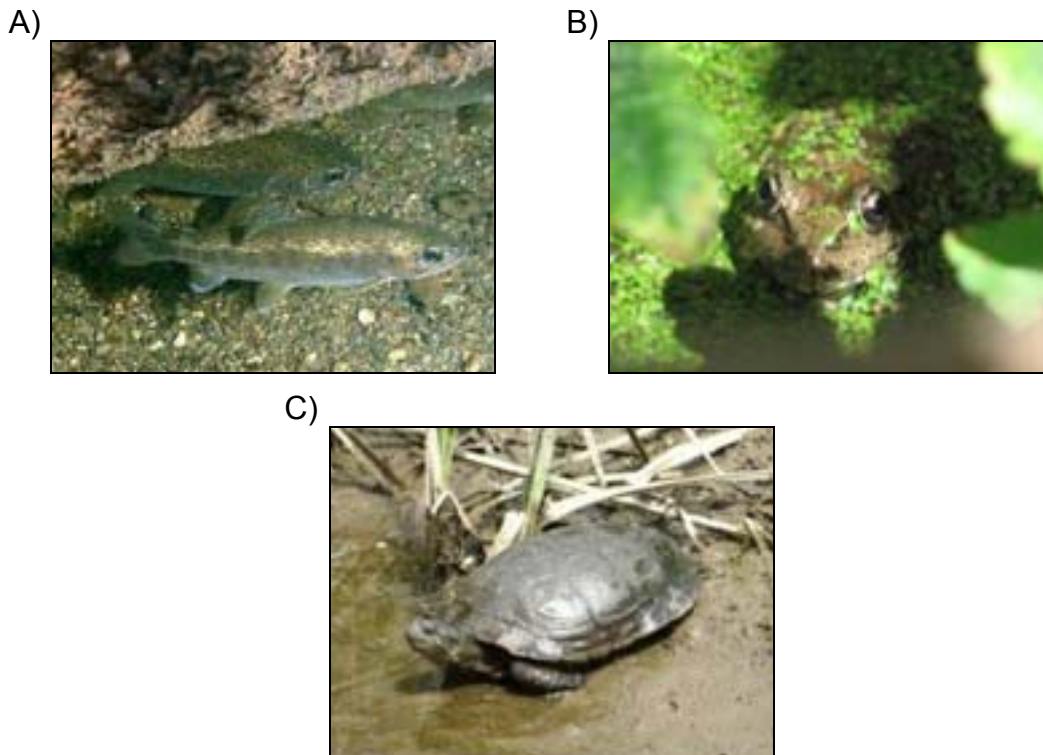
Figure 1. A primary goal of stream conservation is to ensure availability of habitat with appropriate temperature regimes for maintaining healthy population of species of conservation concern. For San Francisquito Creek, our focus is on three federally listed species: A) Steelhead trout (*Oncorhynchus mykiss*), which prefers cooler temperatures, B) California red-legged frogs (*Rana aurora draytonii*) and C) western pond turtles (*Clemmys marmorata*), which prefer warmer temperatures.

1.2 Factors Determining Water Temperature: Multiple environmental factors, including meteorology, surface and subsurface flow patterns, and solar exposure act together to determine stream water temperature regimes (Crisp and Howson 1982, Hewlett and Fortson 1982, LeBlanc

et al. 1997, Malcolm 2004, Danehy 2005, Webb and Crisp 2006, Flint and Flint 2008). Locally there is considerable variation in micrometeorology, stream flow and mixing, and riparian canopy structure. As a result stream temperature is variable in time and space. Herein we examine major factors that can be used to understand and predict stream water temperature, in particular air temperature, stream depth and subsurface flow as they moderate temperature changes, and riparian canopy structure as it affects solar exposure (Table 1).

Table 1. Major environmental factors that influence stream water temperature.

Category	Environmental Factor	Description	Dominant Energy Flux
Meteorology	Air Temperature	Source or sink for heat, depending on temperature differential between air and water; time lags due to rate of heat exchange, greater heat capacity of water associated with smaller temperature variation for water than air	Sensible and convective heat gain and loss
	Wind Speed and Relative Humidity	Greater evaporative heat loss with higher wind speed and lower relative humidity	Latent energy loss
	Cloudiness	Lower global insolation, higher diffuse radiation, and lower radiative heat loss with greater cloudiness	Shortwave energy gain, longwave energy loss
Flow and Mixing Properties	Volume	Greater heat stability with more volume	Mass flow, heat storage
	Depth	Heat exchange slower and temperature variability lower with depth (smaller temperature range, higher minimum, and lower maximum compared with surface)	Radiative and convective gain and loss, heat storage
	Subsurface Flow	Temperature variability lower where subsurface water flows to surface (smaller range, higher minimum, and lower maximum temperatures compared with surface-dominated flow)	Mass flow, heat storage
Riparian Canopy Cover	Solar Exposure	Heat loading higher for riparian canopy geometry with more solar radiation input (higher maximum temperatures)	Shortwave energy gain
	Sky Exposure	Radiative heat loss higher for riparian canopy with lower cover (lower minimum temperatures)	Longwave energy loss

Shallow surface water is subject to the strongest temperature fluctuations due to energy exchange across the water-atmosphere interface, typically with large heat gains from incoming solar radiation (insolation), moderate losses by longwave radiative transfer, moderate gains and losses by sensible heat flow, and moderate losses by latent energy flow (evaporation). Deep water and subsurface water are more stable in temperature due to slow rates of heat transfer and relatively small temperature differentials at water-water and water-land interfaces. Surface water flow patterns greatly influence water temperature as water is transported downstream and mixes with warmer or colder water masses. Significant buffering of shallow surface water temperature fluctuation results from mixing with water protected from insolation, and to an even greater degree from mixing with subsurface water, with such mixing causing cooling during the day and warming during the night. Air temperature influences water temperature proportional to the differential between air and water temperature, with radiative and convective heat transfer

showing marked lags because of relatively slow transfer rates (Cluis 1972, Stefan 1993, Webb *et al.* 2003). To a lesser degree relative humidity and wind speed influence water temperature by changing latent heat loss due to evaporation and rates of longwave radiative transfer between air and water (Webb and Zhang 2004). Riparian canopy cover, together with topographic shading from the stream channel and nearby topographic features, directly influences insolation, which in turn is the primary source of heat loading during the day (Amaranthus *et al.* 1989, Rutherford *et al.* 1997, Sugimoto *et al.* 1997, Davies *et al.* 2004, Johnson 2004, Moore *et al.* 2005). At night riparian canopy cover influences the rate of radiative heat loss, with greater canopy cover leading to lower rates of heat loss. Stream channel morphology influences air and water flow patterns, as well as insolation, all of which affect the rates of mixing and heat flow.

1.3 Our Approach: Our primary goal is to conserve native stream biota using the best available science. To achieve this goal, we developed a practical methodology for characterizing stream temperature regimes as they vary in time and space, based on a scientifically rigorous mechanistic understanding of energy balance. We employ an energy balance model that incorporates long-term monitoring records from stream gages and weather stations, detailed water temperature measurements from sensor networks, detailed insolation measurements from hemispherical photography, and GIS (Figure 2). This protocol has broad application for stream conservation, including managing and restoring habitat, mitigating impacts of human development, and planning for climate change.
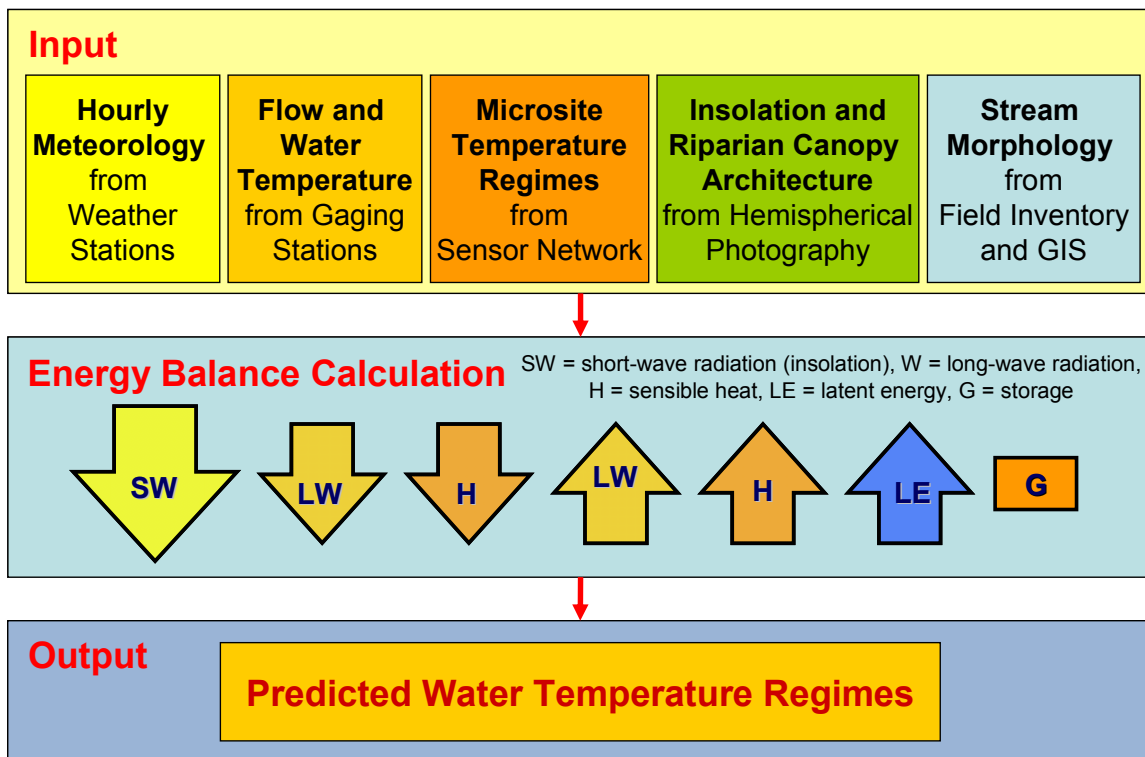
Figure 2. An energy balance modeling approach enables calculation of water temperature regimes based on first principles.

1.4 Energy Balance: Energy balance models calculate temperature regimes by considering all paths for energy flow (Figure 2). The largest energy input to the water is typically in the form of shortwave radiation (SW) from the sun, followed by longwave radiation (LW) from the atmosphere and nearby surfaces such as riparian vegetation and streambanks, and sensible heat (H) from the air. Heat losses from the water typically result from longwave radiation (LW) to the atmosphere and nearby surfaces, sensible heat (H) to the air, and latent energy (LE) loss via evaporation. Storage of energy (G), the net difference between energy gains and losses, is measurable as a change in temperature. Energy balance calculations are complicated by heterogeneity along the stream course, including stream channel morphology and adjacent topography, riparian canopy structure, stream depth, substrate, water flow patterns, and mixing between surface and subsurface water.

1.5 Sensor Networks: Distributed sensor networks (DSNs) promise to revolutionize the way we sense natural and human environment, by expanding our ability to collect information over an unprecedented range of spatial and temporal scales and with an unequaled degree of localized accuracy (Akyildiz *et al.* 2002, Yang *et al.* 2002, NSF 2003, Polastre 2003). DSNs are capable of realizing solutions to long-standing problems in ecology and conservation biology by providing a practical, flexible, and low-cost means for comprehensive sampling of key environmental factors such as temperature. DSNs have been used in a variety of military, business, and medical applications, and have been successfully deployed for such ecological applications as measuring snowmelt in high-elevation ecosystems (Lundquist *et al.* 2003), noninvasive tracking of water bird nesting activity (Mainwaring *et al.* 2002), characterizing topoclimatic and microclimatic conditions for Monarch butterfly winter habitat (Weiss 2005), and monitoring water temperature and pressure in coral reef ecosystems (Vasilescu *et al.* 2005).

1.6 Hemispherical Photography: Hemispherical photography, also known as fisheye or canopy photography, is a technique to estimate insolation and characterize plant canopy geometry using photographs taken looking upward through an extreme wide-angle lens (Rich 1990, Rich and Weiss 2007). Typically, the viewing angle approaches or equals 180-degrees, such that all sky directions are simultaneously visible. The resulting photographs record the geometry of visible sky, and conversely the geometry of sky obstruction by plant canopies or other near-ground features. This geometry can be measured precisely and used to calculate solar radiation transmitted through (or intercepted by) plant canopies, as well as to estimate aspects of canopy structure such as leaf area index (LAI). Detailed treatments of field and analytical methodology have been provided by Rich (1989, 1990). Hemispherical photography has been found to be useful for characterizing canopy structure and resulting spatial and temporal variability of light environment for diverse forest types (Clark et al. 1996, Breshears *et al.* 1997, Chen *et al.* 1997, Weiss 2000, Weiss *et al.* 1991). In recent years an increasing number of researchers and resource mangers have used hemispherical photography to characterize insolation in stream ecosystems (FSP 2000, OPSWMT 2000, Allen and Dent 2001, Ringold *et al.* 2003, Teti and Pike 2005, Lhotka and Loewenstein 2006). For example, hemispherical photography has been applied to predict characteristics of riparian canopies (Nagler *et al.* 2004), to examine insolation influences on periphyton production (DeNicola *et al.* 1992, Stoval *et al.* 2007), to understand distribution of the malaria vector *Anopheles flavirostris* (DeNicola *et al.* 1992), to analyze amphibian distribution and performance (Halverson *et al.* 2003), and to study tree seedling establishment and succession in Amazonia (King 2003).

1.7 Geographic Information Systems (GIS): GIS provides the means to organize, analyze, and display spatial information, data that are associated with specific geographic locations (Goodchild, *et al.* 1993, Maguire *et al.* 1997, Clarke *et al.* 2002, Clarke 2003). GIS technology integrates database operations such as query and statistical analysis with spatial analysis, modeling, and display capabilities. GIS analyses range from simple queries of what is where, to sophisticated models used for basic research, management, and planning. Results can be displayed as maps or images with overlay of diverse information.

2.0 Methods

2.1 Study Area: This study focused on quantifying water temperature dynamics for the San Francisquito Watershed (San Francisco Bay area, CA, ~37.45º N, -122.10º W) (Figure 3). San Francisquito Creek (SFC) and its tributaries, with headwaters in the Santa Cruz Mountains above Menlo Park and Palo Alto, drain a funnel-shaped area encompassing approximately 125 km^2 (48.9 mi^2) on the eastern San Francisco Peninsula, with about 670 m (2000 ft) vertical drop from the highest peaks to the mouth at the San Francisco Bay. The watershed consists of 24 tributaries, including three main tributaries: Los Trancos, Corte Madera, and Bear Creek. The latter two streams merge below Searsville Lake in Jasper Ridge Biological Preserve (JRBP), Stanford University, and the combined flow is known as SFC.

SFC still supports a diverse community of native aquatic organisms, including the federally listed steelhead trout and California red-legged frog, and the western pond turtle (a federal and state Species of Special Concern), as well as a nearly complete native fish fauna.

In the foothills, the stream is incised in a bedrock channel of varying width, with riffles, gravel beds, deep pools, shallow pools, logjams, and rock ledges. Continuous surface flow begins during the winter rainy season, and extends into or through the summer dry season. In many dry seasons, reaches of SFC become a series of pools connected by subsurface flow. At the mouth of the alluvial fan where SFC leaves the foothills, the lower reaches of SFC form the boundary between the city of Palo Alto and the cities of East Palo Alto and Menlo Park, and between San Mateo and Santa Clara counties. The lower reaches of the creek have little or no flow in the summer, but can flood in the winter. Flooding during the 1998 El Niño year caused an estimated $28 million in property damage in the surrounding cities of Palo Alto, East Palo Alto, and Menlo Park. Threats to the watershed include loss of riparian vegetation due to human development, channel modifications that lead to bare deep-cut banks, changes in stream flow due to surface water diversion and groundwater extraction, and water quality degradation.

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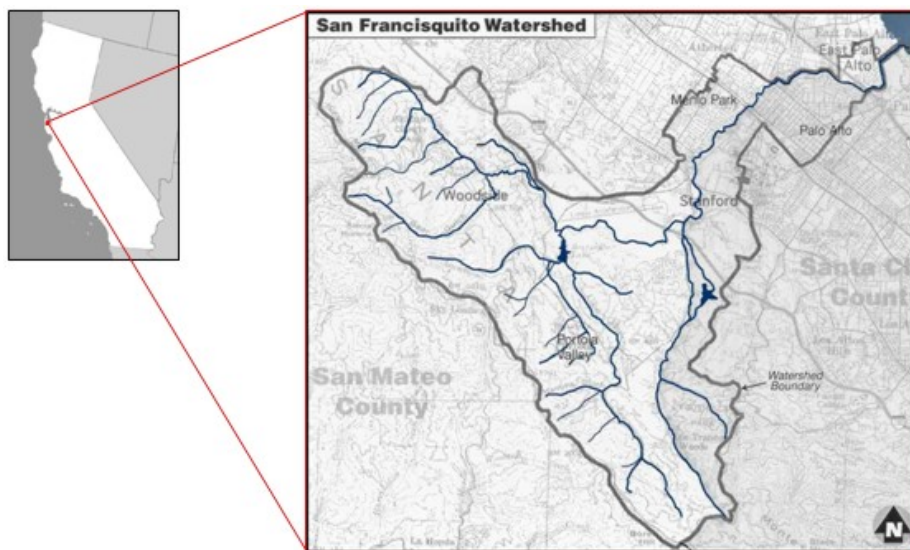
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Figure 3. Study area. A) Map depicting the San Francisquito Creek watershed location in south San Francisco Bay area, California. A mix of B) closed canopy and C) open canopy reaches provide the heterogeneous stream habitat required to support healthy populations of diverse aquatic organisms. D) Urban development up to the riparian zone is altering canopy structure, which in turn impacts temperature regimes by changing solar exposure.

2.2 Baseline flow and meteorologic records: Stream flow measurements from a gaging station at Bear Creek (located at Sand Hill Road) for the period July 2006 were provided by Balance Hydrologics. A full set of weather records for the years 1997-2007 was obtained from the weather station at JRBP (*http://jrbp.stanford.edu*). Records include daily measurements of maximum and minimum temperature, relative humidity, vapor pressure, wind velocity, and solar radiation.

2.3 Temperature sensor network: Detailed temperature measurements were acquired using iButton Thermochrons (Maxim Integrated Products, Model# DS1922L). Each dime-sized sensor contains a computer chip embedded within a stainless-steel hull that can record up to one reading per second and store 8KB of data, providing a continuous record of time and temperature that is stored until data are uploaded. The sensors were coated with nail polish to improve water resistance, strapped to bricks, and submerged at sample locations in the center of the stream channel (Figure 4).

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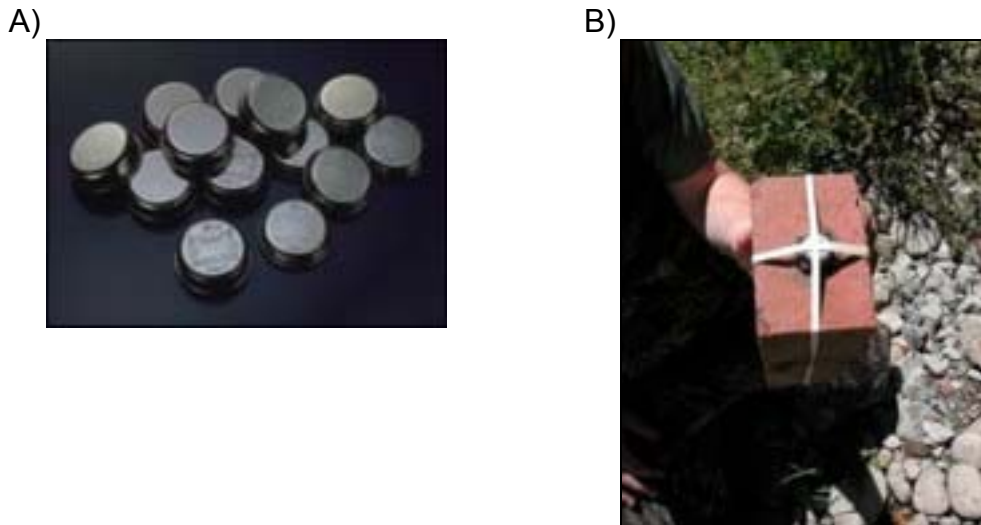
Figure 4. A DSN enables measurement of water temperature regimes at many stream locations. A) iButton thermochrons are inexpensive temperature sensors that log temperature over time. B) The thermochrons are fastened to bricks and deployed at strategic locations.

A set of 25 iButton Thermochrons was deployed to record water and air temperatures for sites along selected creek reaches ("Dennis Martin", "Lunar Rocks", "Los Trancos", "Bear Creek", and lower SFC) during the low flow period of September 2006. An additional 18 sensors were deployed during June-July, and 39 sensors during August 2007 for "Dennis Martin", "Lunar Rocks", "San Francisquito" "Los Trancos", "Bear Creek", and "Pumphouse" stream reaches. Data were processed to include only locations where complete accurate records were available, excluding locations where sensors malfunctioned or water levels dropped below sensor level (Table 2).

Table 2. Sensor deployment locations for September 2006, June-July 2007, and August 2007. See Figure 10 and Appendix 8 for maps of locations.

Phase 1 (September 2006)	Phase 2 (June-July 2007)	Phase 2 (August 2007)
"Trout Pool"	"Dennis Martin Mid Surf"	"Dennis Martin Pool 1"
"Dam Outlet"	"Dennis Martin Upstream"	"Dennis Martin Pool 2"
"CM Mouth"	"RLF Mid 15 cm"	"Dennis Martin Pool 3"
"Bear Upstream"	"RLF Mid 75 cm"	"Dennis Martin Pool 4"
"Bear Mouth"	"RLF Upper Pool"	"Dennis Martin Pool 6"
"Below Confluence"	"Dennis Martin Pool Downstream"	"Dennis Martin Downstream 1"
"Cement"	"Dennis Martin Downstream 2"	"Dennis Martin Downstream 2"
"Lunar Rocks 1"	"Channel 15 cm"	"Dennis Martin Downstream 3"
"Lunar Rocks 2"	"Channel Bottom"	"Dennis Martin Downstream 4"
"Lunar Rocks 3"	"Lunar Rocks"	"Dennis Martin Downstream 5"
"Dennis Martin Upstream"	"Sand Hill"	"Los Trancos AFL 1"
"Dennis Martin 1"		"Los Trancos AFL 2"
"Dennis Martin 2"		"Los Trancos Downstream 1"
"Dennis Martin Pool"		"Los Trancos Downstream 2"
"Dennis Martin Downstream 1"		"Pumphouse 5"
"Dennis Martin Downstream 2"		"Pumphouse 7"
"Dennis Martin Downstream 3"		"Pumphouse 8"
"San Francisquito Webb Bridge"		"San Francisquito Webb Bridge 1"
"San Francisquito Piers Bridge"		"San Francisquito Webb Bridge 2"
"Los Trancos Diversion"		"San Francisquito Webb Bridge 3"
"Los Trancos Ladera Bridge"		"San Francisquito Webb Bridge 5"
"Los Trancos Downstream Ladera"		"San Francisquito Webb Bridge 7"
"Los Trancos Mouth"		"San Francisquito Overpass 1"
"Los Trancos Ladera Br"		"San Francisquito Overpass 2"
"Downstream Los Trancos"		"San Francisquito Overpass 3"
"San Francisquito Sand Hill"		"San Francisquito Overpass 6"
		"San Francisquito Overpass 7"
25 functional; 0 malfunctioning, 0 dry	11 functional; 0 malfunctioning, 7 dry	27 functional; 7 malfunctioning, 5 dry

For each sensor we examined hourly temperature over the sample period, diurnal patterns based on hourly averages, and comparisons with corresponding air temperature. In an initial analysis of spatial patterns, we examined mean, maximum, and minimum temperatures in a longitudinal transect from upstream to downstream.

2.4 Hemispherical photography: Hemispherical photographs were acquired using 35 mm digital camera (Kodak DCS Pro SLR/n) digital camera with a hemispherical lens (Nikkor 8mm) fitted in a self-leveling mount on small floating platform (Figure 5) (see Appendix 1 for Hemiphoto Acquisition Protocol). The resulting hemiphotos were analyzed using Hemiview version 2.1 software (Rich *et al.* 1999). An initial set of 94 hemispherical photographs were acquired to determine riparian canopy effects on insolation for an initial set of transects for "Dennis Martin" and "Lunar Rocks" reaches. Hemiphotos were acquired at 2.5 m intervals to quantify spatio-temporal autocorrelations using geostatistics. Based on this preliminary sampling, an appropriate sampling interval was determined for assessment of closed-canopy creek reaches. During August and September 2007 the photomapping protocol was used to collect an additional set of 116 hemispherical photographs to characterize insolation for "Dennis Martin", "Lunar Rocks", "Los Trancos", "Bear Creek", and "Pumphouse" stream reaches, the same stream reaches where temperature sensor measurements were acquired, allowing analysis of insolation influences on water temperature.

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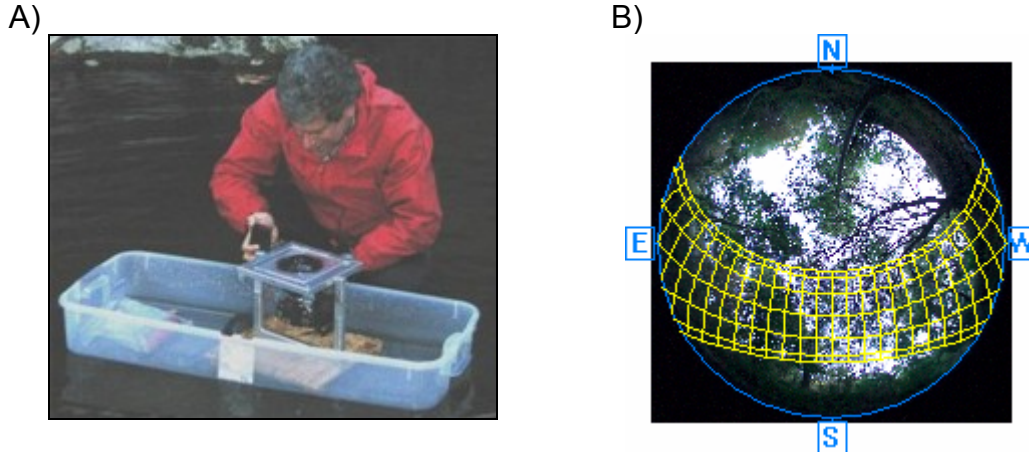
Figure 5. Upward-looking hemispherical canopy photography enables characterization of incoming solar radiation (insolation) and riparian canopy structure. A) A digital camera fitted with a hemispherical lens is mounted in a self-leveling mount fixed in a small floating "barge" to acquire hemispherical photographs near the water surface. B) The resulting circular hemispherical photograph provides a view of all upward directions simultaneously, with the zenith at the center and the horizons at the edges.

To demonstrate a technique for assessing effects of riparian canopy modification, image analysis ("chain saw tool" editing with Corel Photopaint) was used to simulate removal of a single mature California bay laurel tree (*Umbellularia californica*) along a 40 meter transect centered on the tree (Lunar Rocks reach position 80m). The resulting modified hemiphotos were used to calculate the influence of the tree on insolation along the stream reach.

2.5 GIS Analysis: Temperature sensor and hemispherical photography measurements were georeferenced using a Magellan MobileMapper CE global positioning system (GPS) (Figure 6, Figure 10, Appendix 8). GIS data layers for the watershed (hypsography, digital elevation model, orthophotography, streams, political boundaries, etc.) were compiled from JRBP in a geodatabase using ArcInfo 9.2 GIS software (ESRI, Inc.).

Figure 6. The major reaches of the San Francisquito Watershed. See Figure 10 and Appendix 8 for detailed maps of sample locations.

2.6 Water Temperature Model: An Excel-based stream-temperature model (State of Washington Department of Ecology rTemp model, *www.ecy.wa.gov/programs/eap/models.html*) was adapted for use in simulating stream temperatures in SFC as they are influenced by riparian vegetation. We assessed the influence of riparian canopy cover on daily temperature regimes by varying the solar exposure from 0% to 100% using September 2006 and June-July 2007 data.

2.7 Analysis of Extreme Weather Events: We examined patterns of air and water temperature for SFC during the July 2006 heat wave, with comparison of air temperatures at JRBP and water temperature at SFC, Los Trancos Creek/Arastradero Lane, Los Trancos Creek/Piers Lane, and Bear Creek gaging stations.

2.8 Red-Legged Frog Habitat Analysis: We examined temperature regimes within currently known red-legged frog habitat and related them to recent changes in this habitat.

3.0 Results

3.1 Air temperature regimes: Air temperature at JRBP during September 2006, June-July 2007, and August 2007 displayed a strong sinusoidal diurnal pattern, with significant day-to-day variation, and 10-30º C difference between minimum and maximum temperature (Figure 7).
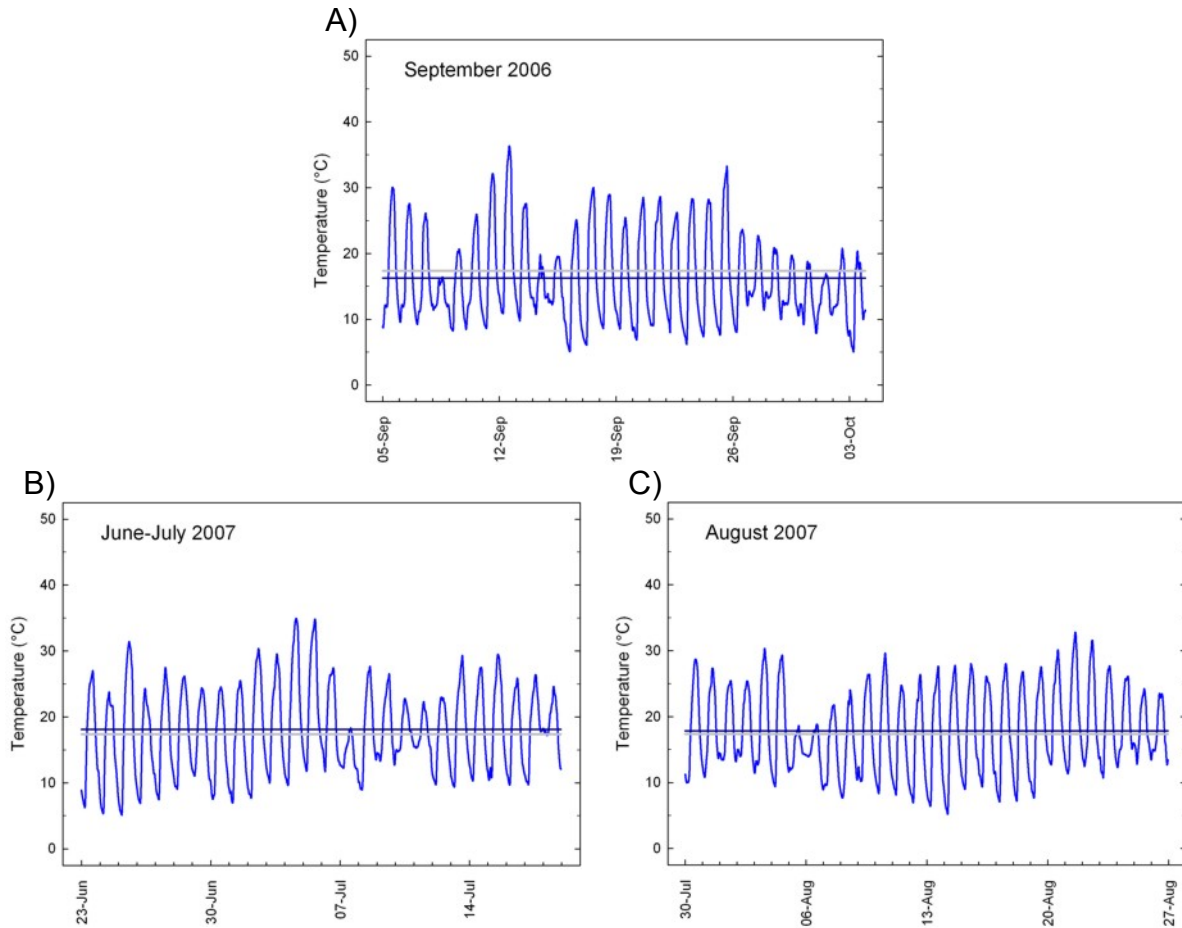
Figure 7. Air temperature at JRBP during A) September 2006, B) June-July 2007, and C) August 2007. The dark reference line shows average air temperature for the sample period, and the gray reference line shows average air temperature for all sample periods.

3.2 Water temperature regimes: Water temperature at Lunar Rocks reach during September 2006, June-July 2007, and August 2007 generally tracked air temperature, but with only a 1-4º C difference between minimum and maximum temperature (Figure 8). See Appendices 2-8 for water temperature regimes from all 64 locations sampled.
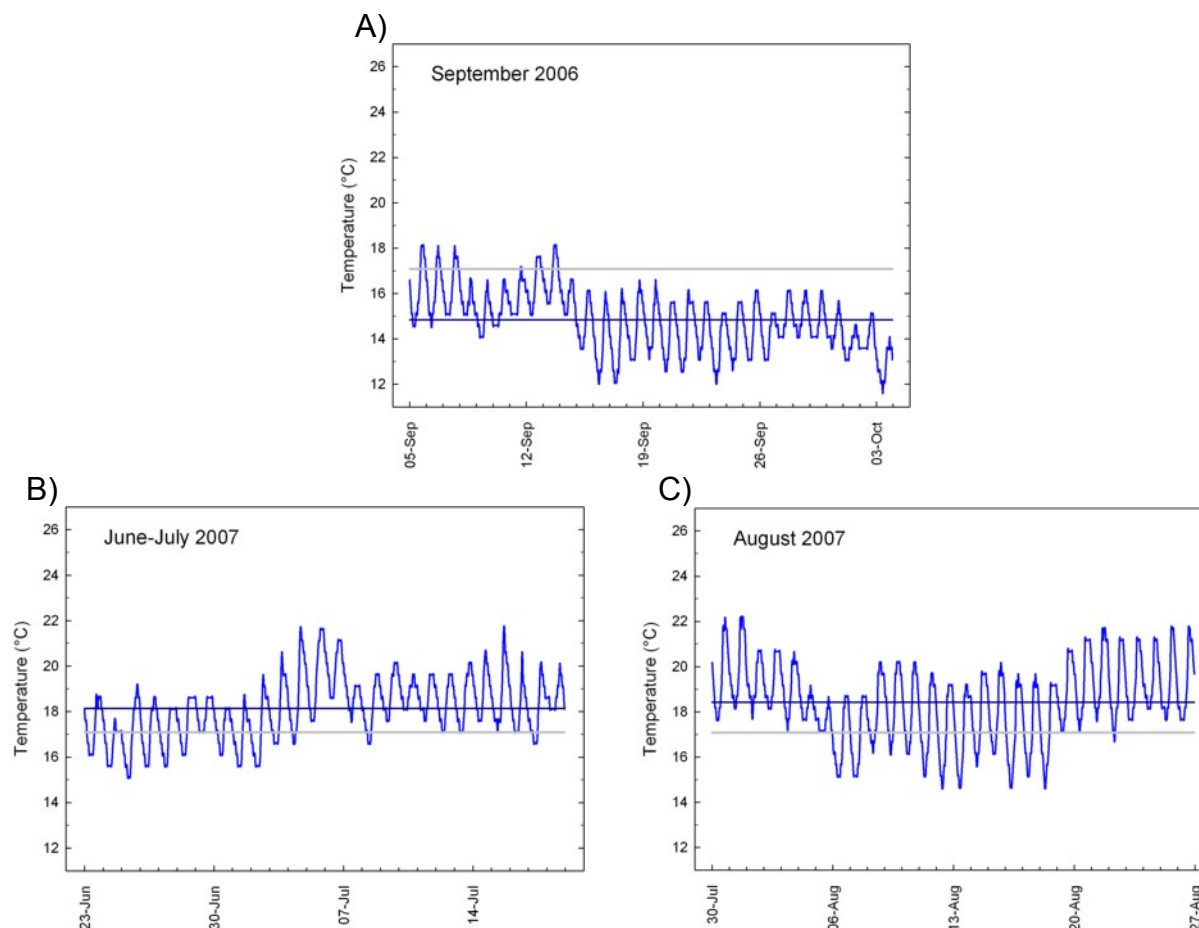
Figure 8. Water temperature at Lunar Rocks reach during A) September 2006, B) June-July 2007, and C) August 2007. The gray reference line shows the average water temperature for all sample periods.

3.3 Diurnal temperature patterns: Air temperature is lowest in the early morning before sunrise and peaks near midday (Figure 9A). Water temperature tracks air temperature, with ~ 4-8+ hour lags (Figure 9B). Air temperature was significantly warmer during the summer months in 2007, as compared with September 2006, especially at night. Similarly, water temperature was warmer during the summer months in 2007, as compared with September, with the highest values in August 2007 (about 2° C difference). On a daily basis, minimum temperature occurs between 04:00 and 12:00, and temperature peaks between 14:00 and 22:00.

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B)
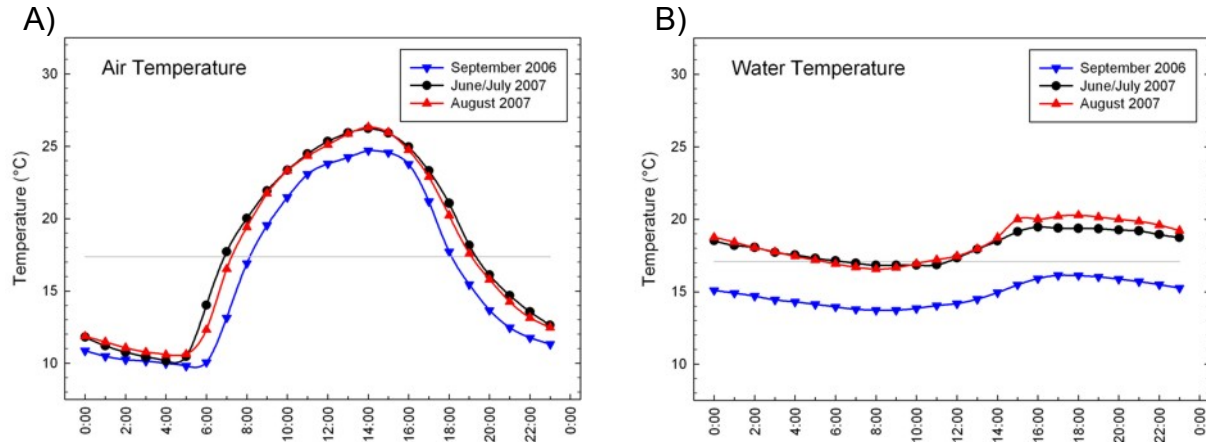
Figure 9. Diurnal temperature regimes. A) Mean daily air temperature regime and B) mean daily water temperature regime at Lunar Rocks reach. The gray reference line shows the average water temperature for all sample periods.

3.4 Spatial variation in temperature: Several major spatial patterns of temperature are apparent in a transect along the full extent of SFC in September 2006 (Figure 10). A brief tour of the map identifies the various study reaches. Near Searsville dam, sensors were placed in a small seep (Trout Pool), the surface outflow from the pool at the base of the dam. Downstream, the mouths of Corte Madera and Bear Creeks, Bear Creek at Sand Hill Road (Bear US, 400 m upstream of the confluence), and the combined flow below and 125 meters further were sampled. The Lunar Rocks reach starts at a sandstone ledge where the entire flow of the creek is in a natural flume, and is surrounded by a tall riparian forest including redwoods. Downstream, the Dennis Martin reach has large openings in the riparian canopy. Stations at Webb Bridge, Piers Lane, and Sand Hill capture temperature at key points before SFC enters the flatlands. On Los Trancos Creek, four stations from the Arastradero/Felt Lake Diversion down to the mouth of the creek capture temperature.

First, upstream to downstream trends in water temperature are subtle. Over the 8 km from Below Confluence (the beginning of SFC where Bear Creek enters) to SF Sand Hill (beginning of alluvial flats) average water temperature increases from 15º to 16.5º C. In contrast, temperature decreases by 1º C downstream along 4 km of Los Trancos Creek.

Second, reaches with the most open canopy (DM1 and DM2 through DM DS3) have greater diurnal variation than reaches with closed canopy (Lunar Rocks 1-3).

Third, in some reaches (e.g., from Dam Outlet to CM Mouth, and from DM2 to DM Pool) temperature and diurnal variation decrease downstream, as a result of subsurface flow through gravel beds.

Fourth, diurnal variability increases over scales of 100-500 m in the absence of deep pools and substantial subsurface flow. Over 400 m of Bear Creek from Bear US to Bear Mouth, diurnal range increases from 1.75ºC to 3.5ºC, and over 300 m from Lunar 1 to Lunar 3, diurnal range increases from 1.5º to 3.5ºC
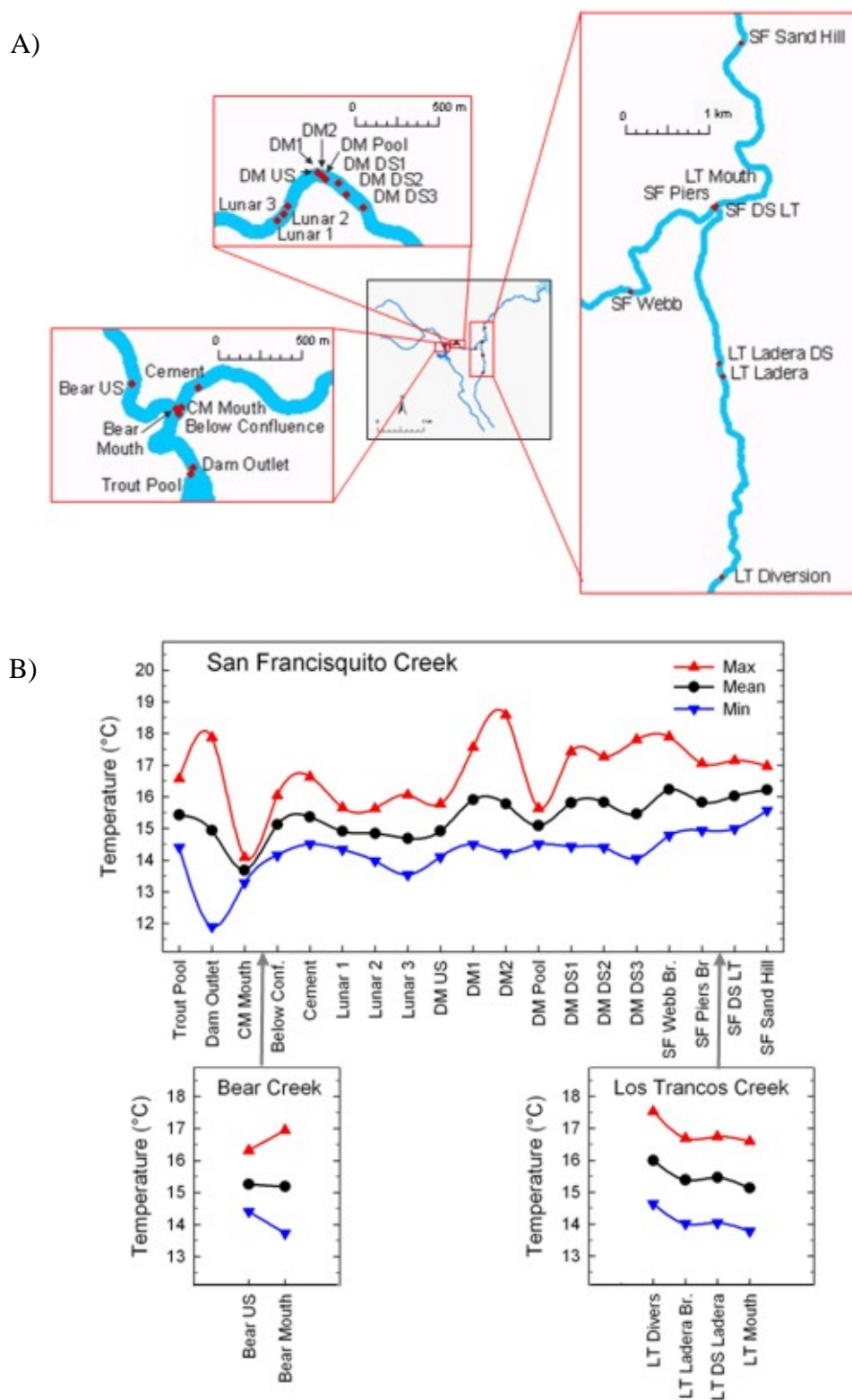
Figure 10. Longitudinal transect of temperature sensors during September 2006. A) Map of sensor locations. B) Mean, minimum, and maximum water temperature along transect from upstream to downstream. Note that this graph represents order, not actual distance along the stream.

*3.5 Depth effects:* Water temperature is much more stable with depth (Figure 11). Shallow water at 15.2 cm shows greater diurnal variation and reaches a higher daily temperature peak than deeper water at 45.7 cm (SFC Channel 15cm versus Channel Bottom sensors).

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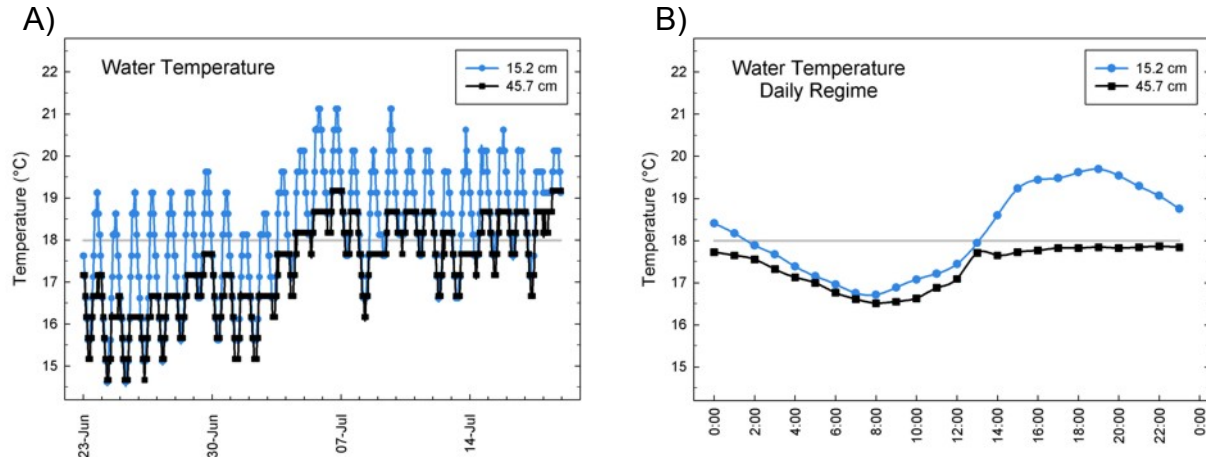
Figure 11. Depth effects on water temperature. A) Continuous and B) average hourly water temperature at different water depths during June-July 2007 in San Francisquito Creek. The reference line shows the average water temperature for all sample periods.

3.6 Subsurface flow effects: Subsurface flow moderates temperature variation, effectively damping most diurnal fluctuation where subsurface flow dominates (Figure 12). The Dam Outlet is the surface flow in the riffle below the large pool below Searsville Dam. The flow was subsurface for long stretches (with several surface pools) before the CM mouth site 500 meters downstream   At the Dam Outlet, diurnal range of 7-8ºC are damped to 0.5-1º C at the CM mouth. Also, the average temperature dropped by 1.5-2º C, indicating a substantial loss of heat to the gravel substrate.

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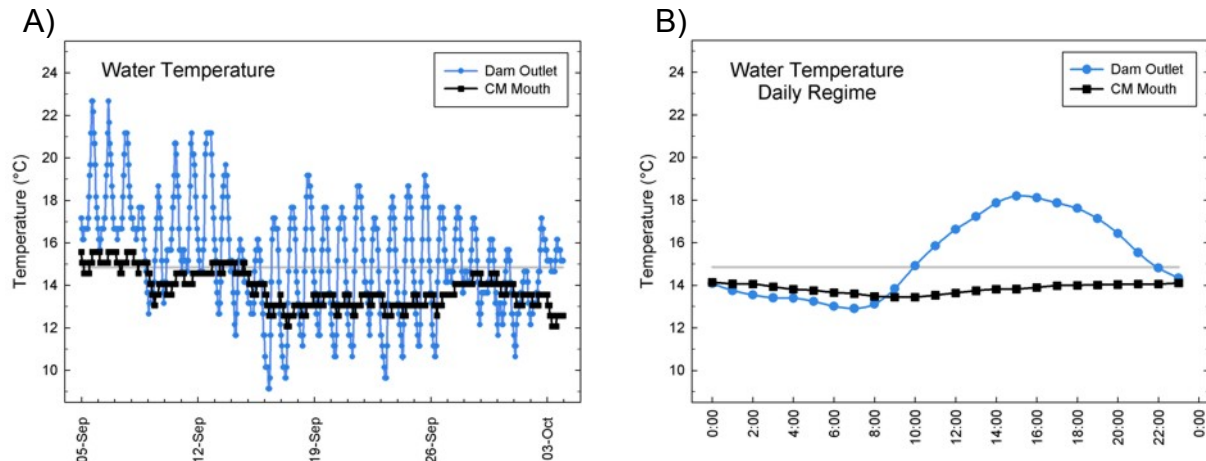
Figure 12. Subsurface flow effects on temperature. A) Water temperature through time and B) diurnal water temperature regime illustrate that subsurface flow in the "CM Mouth" stream reach greatly decreases diurnal water temperature variation as compared with the "Dam Outlet" stream reach. The reference line shows the average water temperature for all sensors during this period.

3.7 Canopy influences on temperature: Riparian canopy cover had a strong influence on water temperature (Figure 13). Closed-canopy (Fig. 13a) and open-canopy (Fig. 13b) along "Lunar Rocks" versus "Dennis Martin" stream reaches display markedly different temperature regimes, with much less day-to-day temperature variation for closed- versus open-canopy reaches (Figure 13c). On sunny days, greater insolation in the open-canopy reaches increases maximum temperature by more than 6º C compared with closed-canopy reaches. Thus solar exposure contributes to greater diurnal magnitude, with much higher peak values (Figure 13d). Between midnight and 07:00 open-and closed-canopy reaches display nearly identical water temperatures. Water temperature in open-canopy reaches rises rapidly from 08:00 to 12:00 when riparian canopy openings align with the solar track. There is a considerable lag in the closed-canopy reach such that maximum temperature is not reached until after 20:00.

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D)
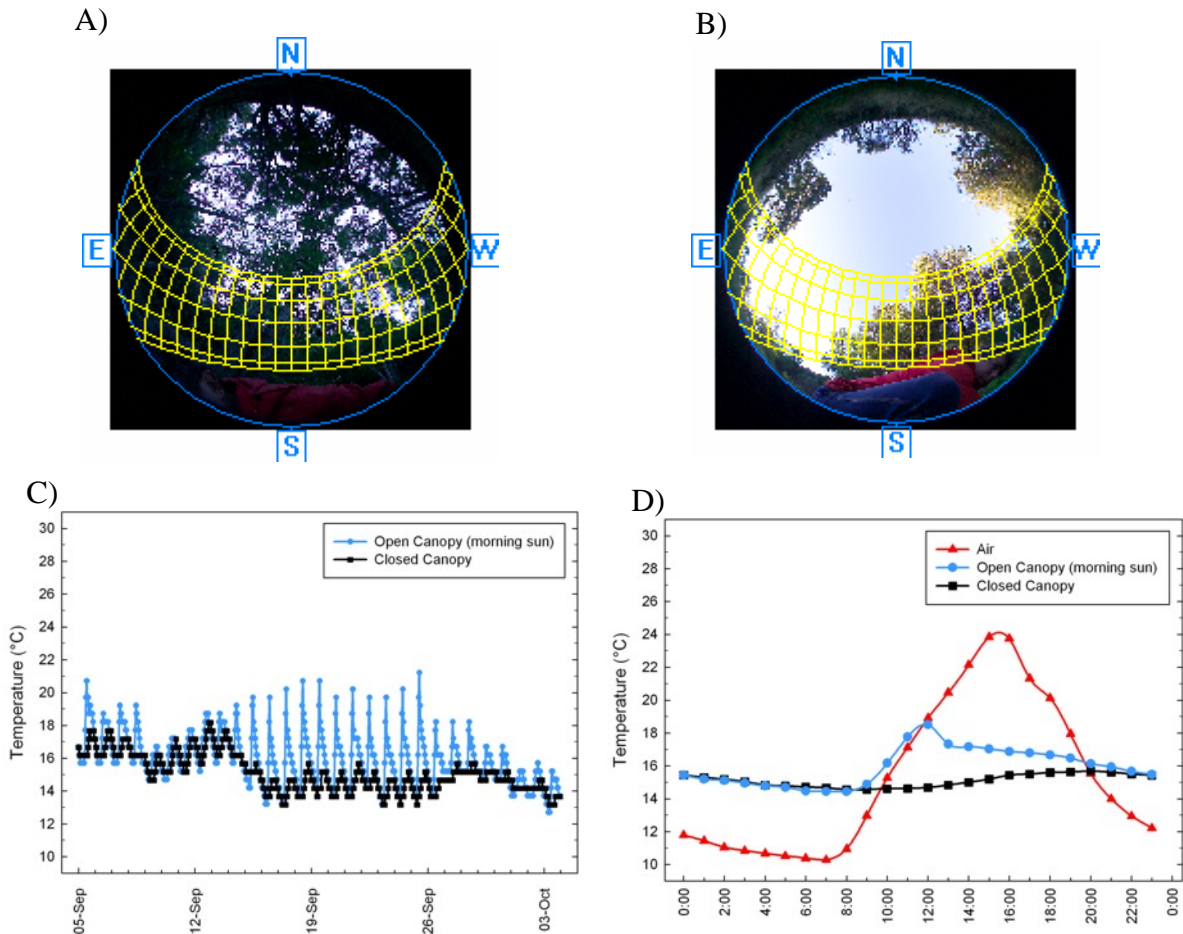
Figure 13. A) Closed-canopy versus B) open-canopy stream reaches, have C) markedly different temperature regimes over time and D) markedly different diurnal patterns of temperature. The depicted hemiphotos are A) Lunar Rocks 1 hemiphoto 56 and B) Dennis Martin 1 hemiphoto 16. Air temperature is from the "Lunar Rocks" gaging station, and the water temperatures are from Lunar 1 (closed canopy) and DM2 (open canopy) sensors.

3.8 Solar radiation regimes: Analysis of insolation based on hemispherical photographs acquired at 2.5 m intervals along 100-m transects demonstrate that the "Dennis Martin" reach has higher insolation than the "Lunar Rocks" reach (Figure 14). Closed-canopy insolation is typically less than 5 MJ/m^2/day, even during the summer months, whereas open-canopy insolation can be as high as 25 MJ/m^2/day during June/July. The open part of the "Dennis Martin" reach receives considerably higher insolation than the "Lunar Rocks" reach, In terms of seasonal variation, closed-canopy insolation values typically increase up to twofold (from about 2.5 to 5 MJ/m^2/day) between October and June/July, whereas open-canopy insolation increases more than fivefold (from about 5 to over 20 MJ/m^2/day).

Spatial autocorrelation for the "Lunar Rocks" reach displays semivariance peaks at 10-15 m, and determines that hemispherical photographs are best sampled at intervals of 10-20 m (Figure 14C).
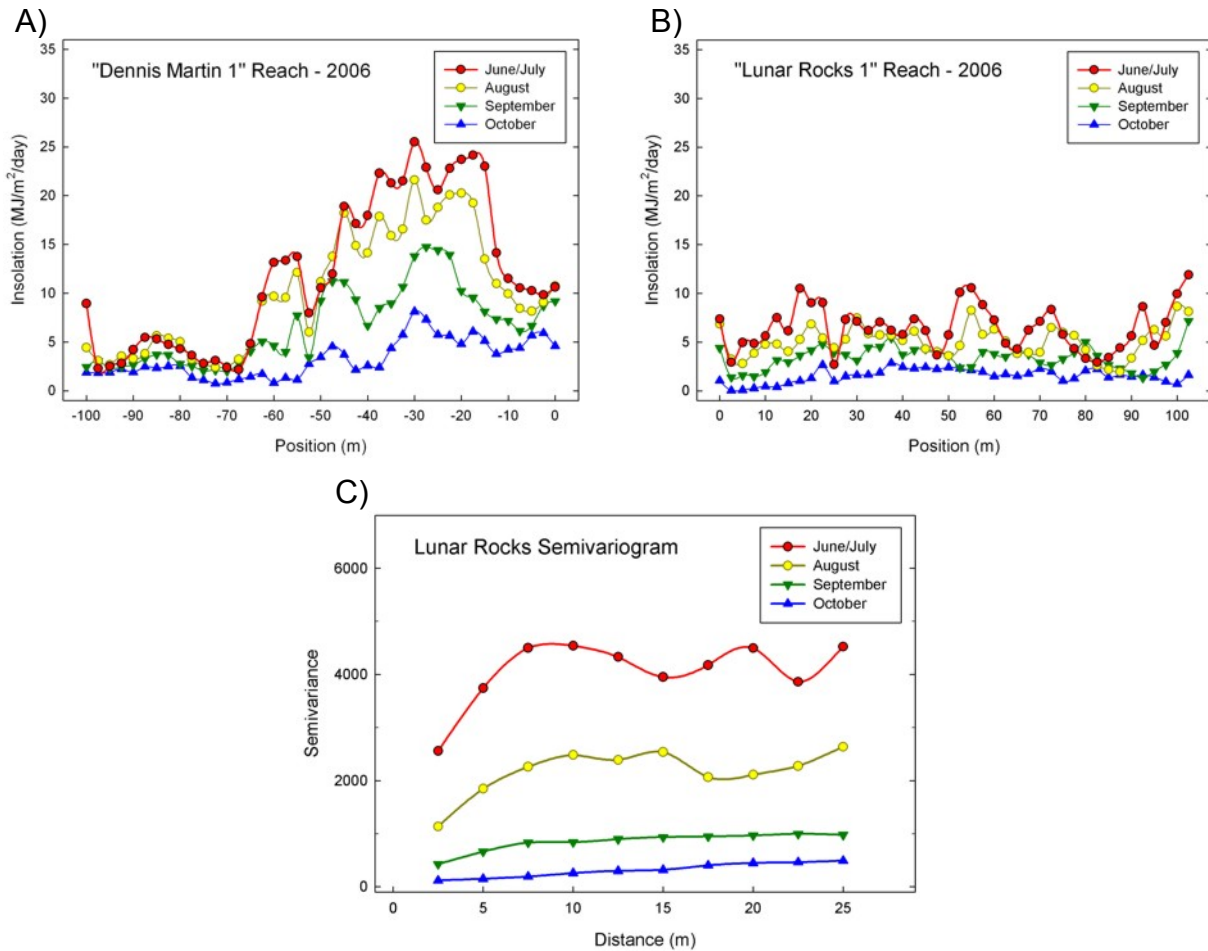
Figure 14. Solar radiation regimes along 100-m transects for A) the "Dennis Martin" reach and B) "Lunar Rocks" reach. C) Semivariogram for the "Lunar Rocks" reach.

3.8 Tree removal simulation: Simulated tree removal (Lunar Rocks reach position 80m) led to about a five-fold increase in solar exposure at the location, and the geometry of the riparian canopy opening caused significant increased insolation for more than five meters upstream and fifteen meters downstream (Figure 15).

A)

B)

C)
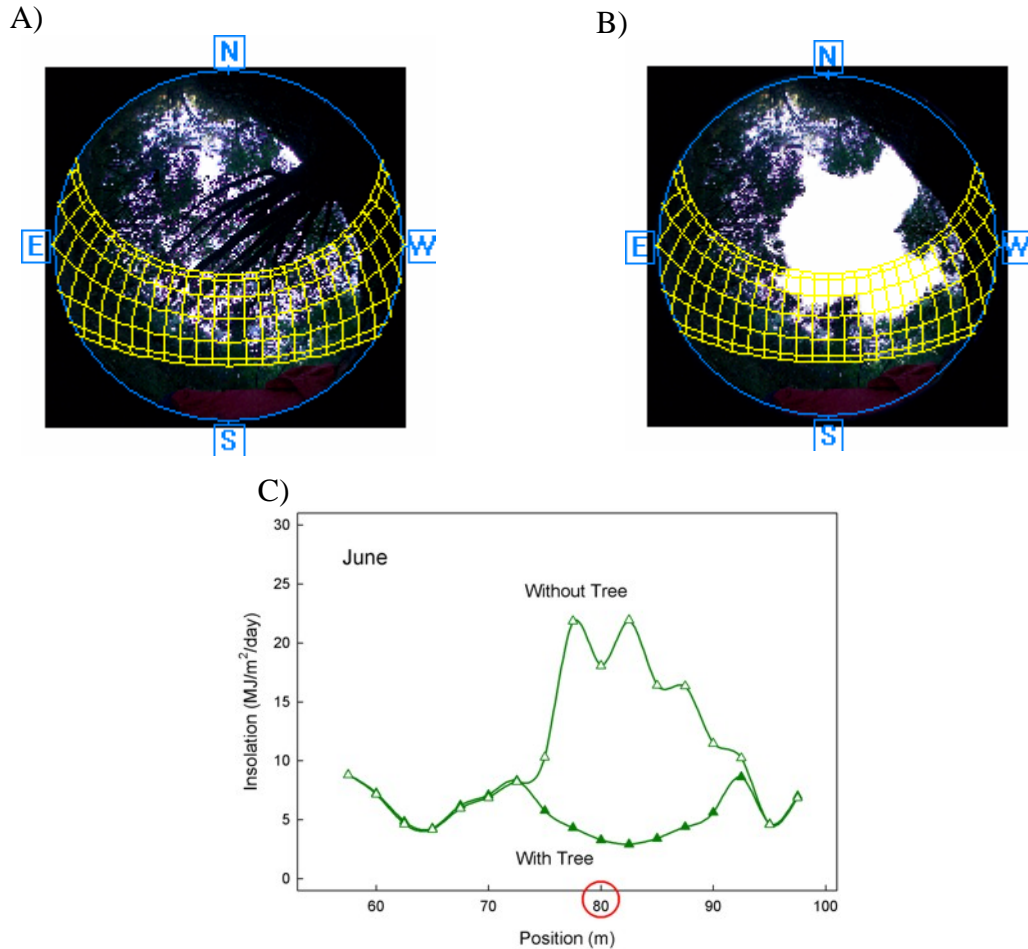
Figure 15. Simulation of tree removal. Transforming A) closed-canopy to B) open-canopy enables C) calculation of changes in June insolation as a function of stream position.

3.9 Solar exposure simulation: Based on September 2006 data, increasing solar exposure in rTemp from 0 to 100% led to an increase of about 6º C, with heat loading increasingly important from 10:00 to 18:00 hours and then declining gradually from 18:00 hours into the early morning (Figure 16, Table 3). For June/July 2007 solar exposure has an even greater effect on heat loading, with more than 8º C difference between 0 and 100% insolation scenarios, because potential insolation in July is greater than in September.

A)

B)
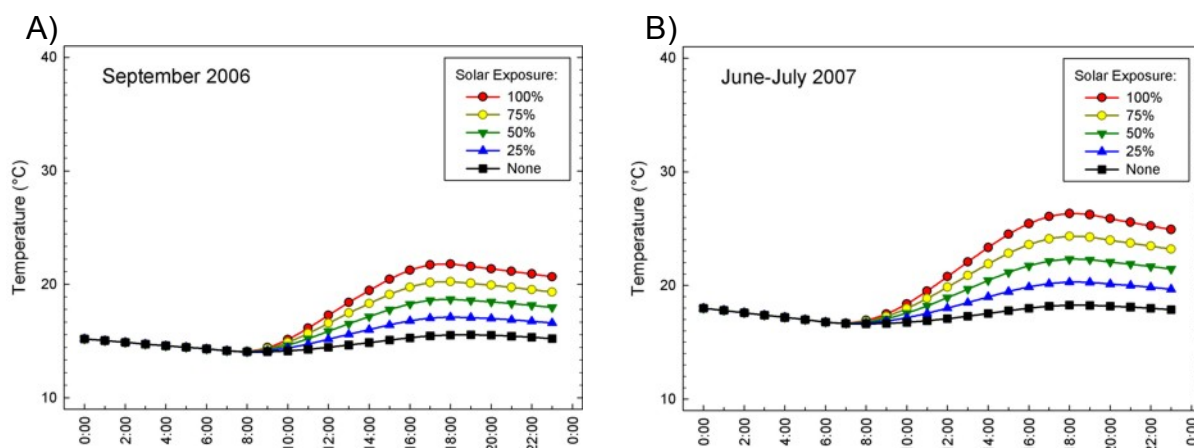
Figure 16. Predicted daily temperature regimes under different levels of solar exposure (0% to 100% solar exposure) during A) September 2006, and B) June-July 2007.

Table 3. Energy balance model parameters used for solar exposure simulations.

Parameter	Value
Latitude	37.45
Longitude	-122.10
Elevation	0
Initial response temperature	Sep 06: 15.2 ° C Jun/Jul 07: 18.0 ° C
Water depth	0.6 m
Effective shade	0.8

3.10 Analysis of 2006 heat wave: The extended period of high air temperature during July 2006 led to unusually high water temperature (Table 4, Figure 17).

Table 4. Air and water temperature records for the heat wave of July 2006.

Location	Average Temp (ºC)	Max Temp (ºC)	Min Temp (ºC)	Extreme Days	Extreme Hours (≥ 20º C)	Degree-Hours (≥ 20º C)
JRBP Weather Station	21.0	42.4	6.3	15 ≥ 30º C	373	2761
Los Trancos Creek/ Arastradero Lane Gaging Station	18.4	24.0	13.0	16 ≥ 20º C	184	240
Los Trancos Creek/Piers Lane Gaging Station	18.9	24.0	14.5	15 ≥ 20º C	216	275
Bear Creek Gaging Station	19.1	24.9	15.0	15 ≥ 20º C	242	464
San Francisquito Creek Gaging Station	20.6	26.7	16.5	27 ≥ 20º C	419	801
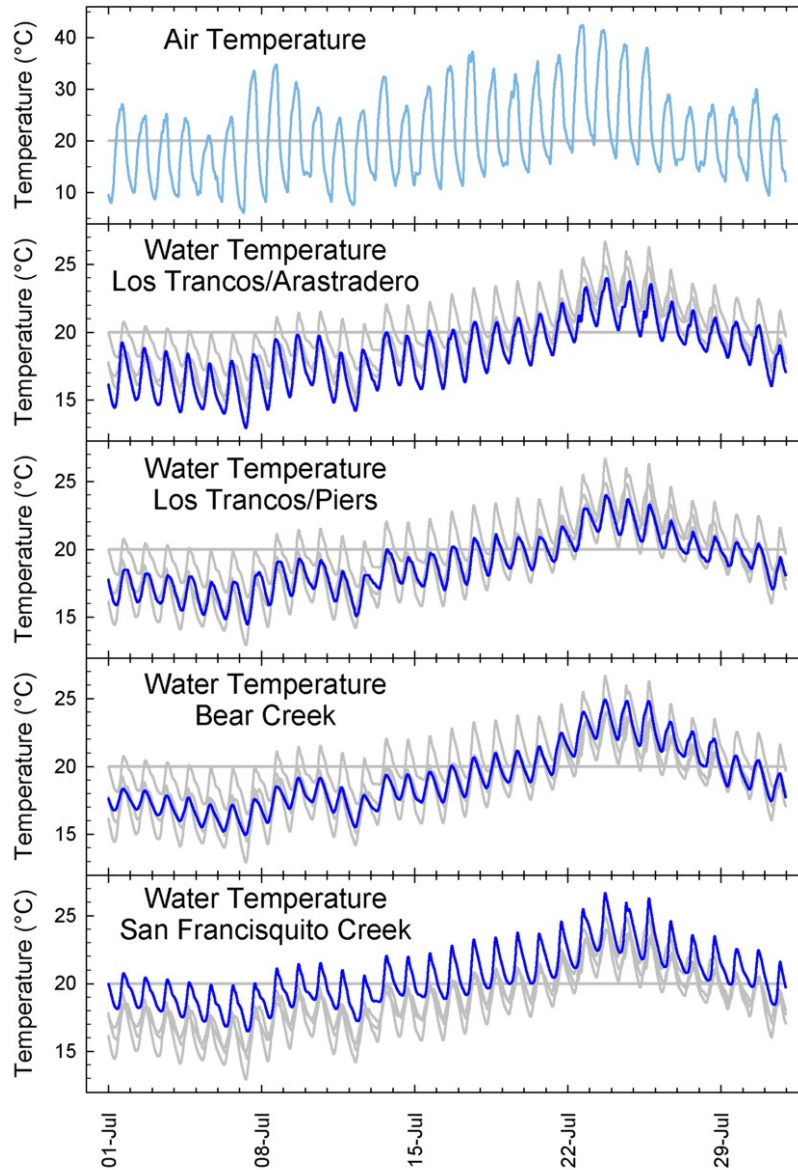
Figure 17. Air temperature at JRBP and water temperature at the four gaging stations during the July 2006 heat wave. The gray reference line depicts 20ºC and the gray curves depict water temperature at the other three gaging stations.

3.11 Analysis of Red-legged Frog Habitat: Analysis of temperature regimes in red-legged frog habitat reveals that this habitat has relatively low temperatures and relatively small temperature variability (Figure 18). We observed distinct thermal stratification, with deeper waters having lower temperatures and considerably less diurnal variation. The upper pool in particular displays low temperatures and markedly dampened diurnal variation.
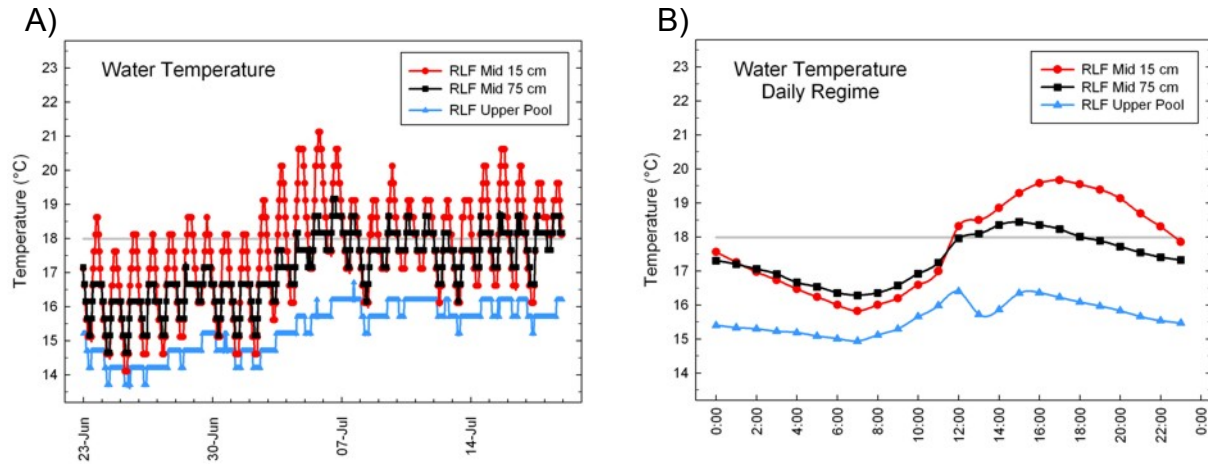
Figure 18. A) Continuous and B) average hourly water temperature in red-legged frog habitat during June-July 2007. The gray line is provided for reference and shows the average of all recorded water temperatures during these months.

4.0 Discussion

Water temperature is a fundamental determinant of habitat suitability. Most aquatic organisms have specific temperature regime requirements that limit their distribution and abundance. The temporal and spatial variability of water temperature is determined by the complex interplay between meteorology, flow and mixing properties, and riparian canopy cover. Our detailed study of temperature patterns for SFC required development of a stream temperature characterization protocol. This protocol is valuable as a tool for basic scientific analysis as well as conservation management. The site-specific characterization of temperature regimes for SFC is important for understanding this stream that still functions as a relatively intact set of aquatic ecosystems within a watershed that has significant human development.

4.1 Temperature Patterns for San Francisquito Creek: The temperature data set for SFC (Figures 7-18, Appendices 2-8) is extremely rich, and while full analysis is beyond the scope of this report, our initial analyses illustrate the effects of major environmental factors that influence temperature, with quantification of these effects herein referred to as "leverage" (Table 5).

Table 5. Observed effects of major environmental factors on stream water temperature for SFC.

Category	Environmental Factor	Observed Effect/Leverage
Meteorology	Air Temperature	Water temperature generally tracked air temperature, with 4+ hour lag; during September 2006 14.8° C mean daily air temperature range associated with 2.4° C mean water temperature range; during June-July 2007 16.1° C mean daily air temperature range associated with 2.6° C mean water temperature range; during August 2007 15.7° C mean daily air temperature range associated with 3.5° C mean water temperature range
	Wind Speed and Relative Humidity	Not examined in this study
	Cloudiness	Not examined in this study
Flow and Mixing Properties	Volume	Not examined in this study
	Depth	Water temperatures less variable with depth; 30 cm increase in depth associated with 2° C decrease in maximum water temperature, 0.2° C decrease in minimum water temperature, and decrease in temperature range from 3° C to 1.4° C during June-July 2007 (SFC Channel 15cm vs. Channel Bottom sensors)
	Subsurface Flow	Water temperatures less variable when mixed with subsurface waters; during September 2006 diurnal ranges of 7-8° C damped to 0.5-1° C by subsurface flow; average water temperature dropped by 1.5-2° C (Dam Outlet vs. CM Mouth).
Riparian Canopy Cover	Solar Exposure	Water temperature more variable in open-canopy reaches than closed-canopy reaches (e.g. "Dennis Martin" vs. "Lunar Rocks" reaches); solar exposure simulations show that increasing solar exposure from 0% to 100% causes a 6 ºC increase in peak water temperature in September 2006, and an 8° C increase in June-July and August 2007 (Lunar Rocks data)
	Sky Exposure	Minimum water temperature lower in open-canopy reaches than closed-canopy reaches; 1° C lower minimum temperature during September 2006 for open- vs. closed-canopy reaches (Bear Creek Upstream vs. Mouth sensors)

For SFC water temperature generally tracks air temperature, so that seasonal shifts in air temperature are reflected in water temperature. Seasonal patterns of warmer water temperatures are associated with both warmer air temperature and lower flow volumes. The greatest extremes in maximum temperature occur during these low-flow summer months and represent the times of greatest vulnerability of aquatic organisms that require cooler conditions. There is about one order of magnitude less diurnal variation in water temperature (~1-4º C) than in air temperature (~10-30º C) and significant lags (~4-8+ hours later peaks and troughs for water vs. air temperature).

For SFC, increasing depth and mixing with subsurface waters is associated with greater temperature stability. Subsurface flow through gravel beds (hyporheic flow) dampens diurnal range and truncates temperature peaks. Locations of major contribution of subsurface water are recognizable based on much lower diurnal temperature variations compared with surface flows. Deep pools and locations dominated by subsurface flow are most protected from extreme temperatures, with about an order of magnitude decrease in daily range (e.g. CM Mouth and DM

Pool). This buffering is key to maintaining cool water refugia, and avoiding cumulative overheating.

For SFC, canopy cover and insolation effects are large, with potential forcing on the order of 5-6º C in the absence of canopy cover. Stream reaches with more open riparian canopy have greater diurnal variation (3º C) than closed-canopy reaches (1.5-2º C), resulting from higher insolation during the day and higher radiative loss at night. Massive loss of canopy cover will greatly increase maximum water temperature. Cumulative effects of a 25% loss of canopy cover may be ~ 2º C.

For SFC, riparian canopy plays a major role in determining local water temperature regimes. For example, the more open canopy reaches such as Dennis Martin have the greatest temperature variability, the warmest habitat, and the greatest susceptibility to temperature extremes. Hemispherical photography, acquired during full canopy leafout, proved to be a reliable methodology for measuring canopy structure and insolation variability during the low-flow summer and early fall. We only focused on the low-flow periods when higher water temperature driven by solar exposure becomes important for organisms of conservation concern. For SFC, the riparian canopy structure changes dramatically during the winter when leaves drop such that an additional set of photographs would be required to characterize the higher insolation during that seasonal period. However, during leafoff water temperatures are driven primarily by high flow volume and mixing rather than by insolation. Spatial autocorrelation analysis of hemispherical photographs acquired at 2.5 m intervals determined that a 10 m sampling interval was sufficient for characterizing closed-canopy reaches of SFC, and was straightforward to implement. While it would generally be best to conduct such preliminary transect sampling when characterizing other streams, the 10 m interval is probably adequate for most streams.

The simulated tree removal (Figure 15) demonstrates the value of hemispherical photography for assessing either actual or potential impacts of riparian canopy changes, in terms of changes in insolation and associated changes in heat loading. Removal of a single large tree was observed to increase insolation by about five-fold, with effects apparent upstream and downstream for about 5-15 m distance, depending upon the local geometry. We recommend assessing such effects whenever major tree removal is planned for the SFC system.

Simulations of solar exposure scenarios for SFC using the rTemp model (Figure 16) provide a first-order estimate of solar forcing on diurnal temperature variation. These simple examples can form the basis of a cumulative impacts analysis, where multiple small changes in canopy over a long reach may result in higher risks of warmer temperatures. They also demonstrate the tremendous potential of further developing such an energy balance modeling capabilities for SFC.

Analysis of air and water temperature during the July 2006 heat wave, with temperatures in excess of 25º C (Table 4, Figure 17) demonstrates the importance of being able to predict impacts of extreme weather events, which are expected to become more common as global warming proceeds. As would be expected, the greatest water temperature increases occurred at downstream locations. While beyond the scope of this report, a full spatio-temporal analysis for SFC is readily feasible using our temperature characterization protocol.
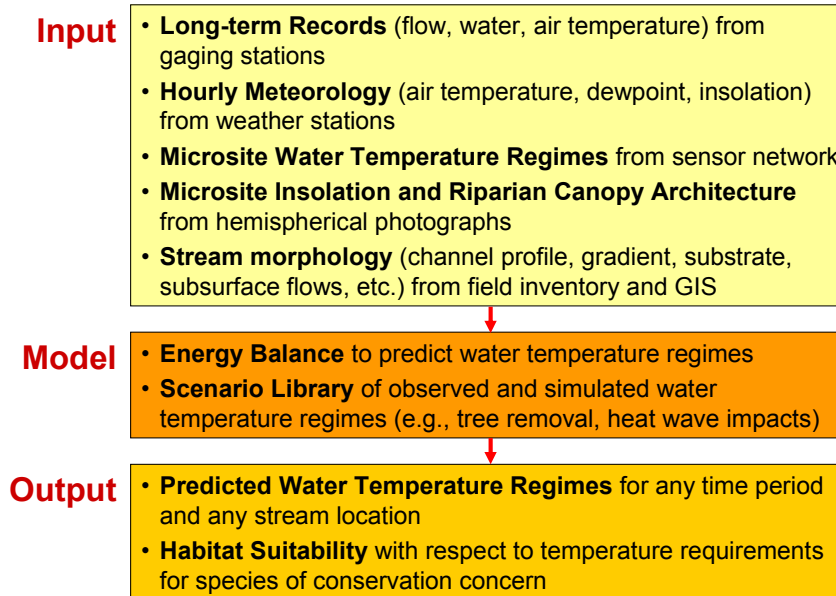
The current known red-legged frog habitat does not have a suitable temperature regime for breeding (Figure 18). Formerly red-legged frogs were known to breed in a nearby open pool that received higher solar exposure, but that is now filled with gravel and no longer provides suitable habitat. Subsequent to the degradation of the breeding habitat red-legged frogs have only been observed in the more marginal habitat and breeding has not been observed. This is consistent with observations for other sites, specifically that low temperatures restrict red-legged frog breeding (Fellers *et al.* 2001). Our temperature analyses demonstrate the value of the approach for use to assess habitat suitability, as well as to make recommendations for habitat enhancement. Temperature analyses will be valuable for future habitat management and restoration, such as construction of breeding ponds (Launer, personal communication).

The ability to characterize spatio-temporal patterns of stream temperature for SFC can be used to address basic scientific questions, such as what is the relative importance of insolation versus mixing with subsurface waters in determining water temperature, how do water temperature regimes change with changes in climate, how does variation in riparian canopy structure affect temperature regimes, and how does the availability of diverse local temperature conditions affect aquatic organism populations and biodiversity? Baseline characterization and monitoring of temperature regimes is important for conservation management, especially with respect to aquatic species that are vulnerable to loss of habitat with suitable temperature regimes. Baseline temperature characterization is needed as the basis for measuring changes that result from urbanization and climate change.

For SFC, the initial temperature characterization as well as the tools are available for use by stakeholders of the watershed. For scientists, for example those who focus research at JRBP, these results can be used as the basis for study of specific aquatic organisms or for stream ecosystem studies. For resource managers and planners the protocol can be used to mitigate impacts of development and to restore stream health for reaches that have been adversely impacted. Of immediate conservation concern is that sufficient cool-temperature stream habitat be available to support viable populations of steelhead trout. Similarly, sufficient warm-temperature habitat is needed to protect red-legged frog and western pond turtle populations. Cases where the riparian canopy is being modified present an opportunity to validate the predictive capabilities of the protocol for SFC, while assessing actual impacts.

4.2 Stream temperature protocol: Herein, we have provided a stream temperature characterization protocol that predicts water temperature regimes for any time period and any stream location (Figure 19).

• **Long-term Records** (flow, water, air temperature) from gaging stations
• **Hourly Meteorology** (air temperature, dewpoint, insolation) from weather stations
• **Microsite Water Temperature Regimes** from sensor network
• **Microsite Insolation and Riparian Canopy Architecture** from hemispherical photographs
• **Stream morphology** (channel profile, gradient, substrate, subsurface flows, etc.) from field inventory and GIS

Model • **Energy Balance** to predict water temperature regimes
• **Scenario Library** of observed and simulated water temperature regimes (e.g., tree removal, heat wave impacts)

Output • **Predicted Water Temperature Regimes** for any time period and any stream location
• **Habitat Suitability** with respect to temperature requirements for species of conservation concern

Figure 19. Conceptual design of stream temperature modeling protocol.

Water temperature regimes are calculated based on input values from gaging stations, weather stations, and focused field sampling with temperature sensors and hemispherical photography. At the heart of the protocol is a scientifically rigorous energy balance model that accounts for major fluxes of energy that affect water temperature. Two advanced technologies are key for the protocol: a sensor network to measure temperatures, and hemispherical photography to measure riparian canopy structure and model insolation.

As we demonstrated in the case of impacts of tree removal on insolation, it is practical to assess potential or actual impacts of riparian canopy modification, shading by the stream bank, or shading by human structures, both at a local scale, and in the bigger picture of how such modification affects temperature regimes downstream. The protocol also makes it possible to assess potential or actual changes in climate, in particular impacts of warmer temperatures and increased frequency of extreme events expected with global warming. The tool even provides for the possibility of mitigating some climate change impacts, for example by prescribing riparian restoration required to buffer stream temperature increases. Further, as a conservation tool, the protocol can be applied to plan and engineer optimal mix of temperature regimes.

Long-term records of flow at gaging stations, along with water and air temperature, provide both the historical baseline against which to compare measurements and basic parameterization for the energy balance model. Hourly meteorology from nearby weather stations, in particular air temperature, relative humidity, and insolation, provide the basic input to drive the energy balance model. In essence, the approach translates the meteorological measurements of prevailing air temperature into spatially and temporally resolved water temperature based on microsite conditions and the resulting local energy fluxes. The sensor network allows comprehensive characterization of spatial and temporal temperature variation by strategic deployment of sensors in key locations, including stream reaches with different canopy structure, flows, convergences, depth, and surface versus subsurface flow. The iButton Thermochron sensors have the

advantages of being inexpensive, self contained, relatively reliable, readily moved and deployed in different locations, and capable of recording underwater measurements for a period of one month. They have the disadvantages that they cannot be permanently deployed and cannot be remotely read without costly data loggers. For the purposes of basic stream characterization permanent deployment is not necessary, and the temporary sensor network performance is highly satisfactory.

Hemispherical photography enables measurement and modeling of local riparian canopy structure and the resulting insolation regime with high temporal and spatial resolution. The technique has the advantage that it directly measures the geometry of the overlying riparian canopy, and enables calculation of direct and diffuse components of insolation for any time period, assuming the geometry does not change. It has the disadvantages that it requires specialized equipment and experienced field personnel working in even light conditions (early morning, late afternoon, or during overcast periods) to acquire quality data sets. By acquiring hemispherical photographs at the water's surface from a small floating platform it is feasible to estimate insolation for key locations and along transects to characterize entire stream reaches. Preliminary sampling along transects is generally necessary to determine optimum sampling distances. Repeated acquisition of hemispherical photographs at the same location is not required unless the riparian canopy structure changes. Hemispherical photography is much better suited to stream environments than networks of solar radiation sensors, which require a much greater investment of time and effort to acquire data sets for even relatively short time periods. Calibration and validation with solar radiation sensor measurements from nearby weather stations, where available, can be used to refine estimates from hemispherical photography, but is not essential, such that hemispherical photographs can be used effectively even in remote locations.

The stream temperature characterization protocol can be viewed as a rigorous science and management tool that integrates long-term records, hourly meteorology, water temperature from a sensor network, and insolation from hemispherical photographs to predict water temperature regimes. Additional measurements of stream morphology, including channel profiles, flow gradients, substrate, water depth, and subsurface flow patterns, can further refine results from the protocol. Use of the stream temperature protocol to generate scenario libraries, which archive water temperature regimes resulting both under typical conditions and under special conditions (such as before and after tree removal, or during extreme weather events) can provide the basis for responsible stream management and conservation.

4.3 Future Work:

While the stream temperature characterization protocol is sufficiently mature to be readily applied to any stream, and while the specific characterization of SFC is relatively comprehensive, more work is needed (Table 6).

Table 6. Future work on stream temperature protocol and characterization of San Francisquito Creek.

Activity	Description
Monitoring Data	Compile gaging station (flow, air and water temperature) and meteorology data (air temperature, dewpoint, and insolation), including capability for web-based access.
Geographic Information System (GIS)	Provide access to baseline map layers (watershed boundaries, DEM, hypsography, orthophotos, streams, etc.), associated monitoring data, sampling locations, and library of model results.
Water Temperature Sensor Networks	Deploy temperature sensor networks use thermochrons and new fiber optic technology.
Insolation and Riparian Canopy Architecture	Acquisition of hemispherical photography; repeat every 2-3 years to assess changes.
Stream Morphology	Map stream morphology (channel profile, gradient, substrate, subsurface flows, etc.).
Data Analysis	Analyze spatial and temporal patterns of temperature variation and relate to habitat suitability for species of conservation concern.
Model Development and Validation	Continue to develop and validate energy balance models, leading to better match between observed and predicted values, sensitivity analysis of key parameters.
Scenario Library	Produce online scenario library of key temperature regime patterns and cases of interest (e.g., tree removal, heat wave)
LIDAR Studies	Collaborate on LIDAR studies 1) to map stream channel characteristics at very high resolution, and 2) to examine riparian canopy architecture as it relates to solar heat loading.
Collaboration	Expand collaboration with agencies, resource managers, Stanford researchers and facilities personnel, JRBP scientists, etc.
Education and Outreach	Inform resource managers, decision makers, and public; make results and tools available.

For SFC we propose to compile and provide access to historic and recent monitoring data including gaging station and meteorology records, and GIS map layers, ideally with web-based access and consistent quality control. We also propose to acquire additional temperature sensor network data needed to complete a set of measurements of SFC at key spatial locations, across a full spectrum of seasons, and ideally repeated on an annual basis as a resource to watershed stakeholders. Similarly, it would be desirable to acquire sets of hemispherical photographs for many key stream reaches, for different stages of canopy leaf-on and leaf-off, and repeated every 2-3 years (or after any riparian modification) to assess changes over time.

Placement of a more permanent embedded distributed sensor network to monitor SFC would be desirable because the watershed is heavily developed, because it provides habitat for several temperature-sensitive aquatic species of conservation concern, and because the SFC stream system can serve as a testbed for further stream temperature work. For example, new fiber optic technology (Day-Lewis and Lane 2006, Lane 2007) involves sending laser light along a submerged fiber-optic cable and analysis of Raman and Brillouin backscatter to determine temperature, with spatial resolution of about one meter, thermal resolution of about 0.01° C, and a cable length of up to 30 km (*http://water.usgs.gov/ogw/bgtas/fiber-optics*).

For SFC, detailed maps of stream morphology would be of value for further refinement of the stream temperature protocol. Stream morphology characteristics would include channel profiles,

viewsheds (depicting sky visibility geometry based on topography), flow gradients, streambed substrate, and subsurface flow patterns. Such characterization of streambed morphology would be based on a combination of ground measurements by experts and analyses using GIS, in particular using high resolution digital elevation models (DEMs) and orthophotography. Again, it would be desirable to make these datasets available to watershed stakeholders via the web, subject to any restrictions placed by data providers/owners.

The temperature regime datasets acquired to date are extensive, and require further analysis to understand more fully the spatial and temporal patterns of temperature variation, and to relate these patterns to habitat suitability. Similarly, further work is needed to develop and validate the energy balance model, in particular improving the match between predicted and observed water temperatures, performing sensitivity analysis of key parameters, and providing a turnkey version of the model for use by watershed stakeholders. A complete scenario library of model runs would also be of value to stakeholders.

Light detection and Ranging (LIDAR) is a valuable technique for production of high-resolution DEMs, as well as to study canopy structure (Drake *et al.* 2002, Reutebuch *et al.* 2005). We propose two collaborative LIDAR studies for SFC. First, we propose to examine the utility of existing high-resolution LIDAR-based DEMs to characterize stream morphology characteristics such as stream channel profiles, substrate, and flow gradients. Second, we propose to examine relations between airborne LIDAR-based characterization of riparian canopy architecture and ground-based characterization using tree mapping and hemispherical photography. This would involve collaboration with researchers at Stanford and the Carnegie Institute who have recently acquired an airborne LIDAR system and are applying it to studies at JRBP. Among the primary questions is whether airborne LIDAR could yield reasonable estimates of insolation remotely, reducing the need for extensive field sampling.

Finally, in conjunction with providing access to key data for SFC watershed stakeholders, we propose an expanded education and outreach effort to inform stakeholders about the importance of riparian canopy and stream temperature in conservation and stream management, and to make results and tools available.

5.0 Conclusion

Detailed analysis of temperature regimes for SFC is of value for scientific understanding and for responsible conservation management. For conservation management, the goal is to protect natural resiliency of the SFC stream ecosystems by maintaining sufficient spatial variability of riparian canopy structure, along with surface and subsurface flow conditions, to provide a desirable spectrum of temperature regimes. Sufficient temperature variability and redundancy buffers against cumulative impacts of urbanization, extreme climate events, and climate change, thereby protecting habitat for aquatic organisms. Our stream temperature protocol provides a scientifically rigorous tool to gather detailed site-specific information about the temporal and spatial variability of water temperature regimes. Its use of readily available gaging and meteorology data, easily deployed temperature sensor networks, along with hemispherical photography to quantify riparian canopy effects on insolation, enables calculation of temperature

regimes based on energy balance. In the case of calculation of insolation from hemispherical photographs, as well as the case of stream position effects, space and structure enable us to use geometry to account for temporal dynamics. The result is a powerful tool that can be used to analyze water temperature regimes for any location and time period for any stream where basic flow and meteorology records are available along with modest field sampling with temperature sensors and hemispherical photography. As a pragmatic tool for riparian canopy protection, the protocol can be tailored to any stream system, and used to understand actual and potential impacts of modifications of riparian canopy. While more work is needed to understand SFC's temperature patterns, our knowledge has reached a sufficient level of maturity to be of immediate use to identify vulnerabilities to the health of SFC's stream ecosystems. The ability to understand stream water temperature regimes is needed for diverse applications, ranging from basic scientific study of ecosystems to pragmatic conservation planning and management to mitigate impacts of urbanization and climate change.

6.0 Acknowledgments

7.0 References

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