RESPONSE TO RESTORATION: WATER TEMPERATURE CONDITIONS IN BIG SPRINGS CREEK AND SURROUNDING WATERWAYS, 2009-2011

A Report for The Nature Conservancy

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Executive Summary

The Nature Conservancy (TNC) and Watercourse Engineering, Inc. (Watercourse) conducted a three-year study of Big Springs Creek, located in Siskiyou County, California, to assess the creek's response to restoration actions from 2009 through September 2011. This work was supported by an award from the National Oceanic and Atmospheric Administration – American Recovery and Reinvestment Act grant in 2009. The objective of the restoration actions was to reduce peak water temperatures, which had been identified as the key limiting factor to coho salmon survival and recovery in Big Springs Creek. As well as designing, implementing, and analyzing the results of the water temperature monitoring program, Watercourse updated an existing water temperature model of Big Springs Creek, called the Big Springs Model (TBSM), and applied TBSM to evaluate potential restoration actions that could be implemented to further reduce peak water temperatures given the 2011 conditions. The main findings of this study are:

1. Big Springs Creek experienced a rapid and substantial response to restoration actions that were implemented in 2009, particularly cattle exclusion via riparian fencing. These restoration activities should be maintained in the future. Maximum seasonal water temperatures declined by approximately 4°C from pre-restoration conditions to current conditions. In 2011, maximum water temperatures generally peaked *below* 20°C but occasionally exceeded 20°C, whereas pre-restoration temperatures generally peaked *above* 20°C and occasionally exceeded 25^{o}C. Big Springs Creek currently provides a relatively large volume of cool water that supports a robust aquatic ecosystem and generally provides cool water to the Shasta River downstream of the Big Springs Creek confluence.

2. There are four principal factors that largely affect water temperature in Big Springs Creek: groundwater-fed springs, channel geometry, meteorological conditions, and aquatic vegetation. Groundwater-fed springs and channel geometry form the foundation of the thermal regime in Big Springs Creek, while meteorological conditions and aquatic vegetation growth influence seasonal and inter-annual variability in water temperatures. Seasonal growth of aquatic vegetation dramatically changes channel geometry conditions and has a profound impact on the summer water temperature regime.

3. A key factor controlling water temperatures in Big Springs Creek that can readily be modified via restoration activities is aquatic vegetation. Dense, emergent aquatic vegetation covered over 50% of the stream in 2011 (versus insignificant cover under pre-restoration conditions). Field measurements quantified the amount of shade provided by emergent aquatic vegetation to be approximately 88% to 93% (i.e., the amount of solar radiation that reached the water surface was reduced by 88% to 93% in areas where emergent aquatic vegetation was present). This amount of shade was comparable to that provided by woody riparian vegetation typically found in the basin. However, these effects were only seasonal, as aquatic vegetation had an annual growth and senescence cycle. Peak

water temperatures under the post-restoration period occurred between April and June, prior to seasonal aquatic vegetation growth emergence (i.e., provided no appreciable shade to the creek), yet during a period when potentially adverse meteorological conditions could occur. However, pre-emergent vegetation may already be present in the channel during these periods providing some thermal benefit by increasing roughness in channel margins and restricting flow to a narrower, deeper channel.

4. Future water temperature reductions due to on-going recovery or alternative, additional restoration actions were examined using TBSM based on 2011 conditions in Big Springs Creek. This analysis included simulations of the long-term response to already-implemented restoration actions (e.g., maintained riparian fencing and riparian planting), active channel restoration alternatives, and in-stream flow dedications of water rights associated with Shasta Big Springs Ranch. Analysis results of these potential restoration actions suggest that:

    a. The long-term effects of already-implemented restoration actions may result in further water temperatures reductions (<0.5°C). These reductions are projected to be greater in the spring and early summer – an important period because the effects of seasonal aquatic vegetation growth have not yet been realized.

    b. The effects of in-stream flow dedications ranged from modest benefits to ineffectual and, in some cases, increased water temperatures. The effects of in-stream dedications were sensitive to ambient climate conditions (e.g., warm and dry vs. cool and wet conditions) and the seasonal timing of the in-stream dedication.

5. The monitoring program, which was originally designed to inform a broad range of questions related to on-going restoration actions, was redesigned as a targeted program suitable for long-term baseline monitoring that can be easily accessed remotely and readily expanded to address future questions. Automated data collection is an on-going outcome of this project.

6. Future restoration actions will depend on current and future management objectives for Big Springs Creek. Among the issues that should be considered are whether local improvements (i.e., improvements that might be limited to Big Springs Creek) or system-scale improvements (i.e., improvements that may benefit both Big Springs Creek and downstream Shasta River reaches) are priorities. These priorities can be determined based on consideration of the overall management objective (i.e., improvement of anadromous fish populations and habitat) and relative effect of local versus system-scale actions.

Response to Restoration: Water Temperature Conditions in Big Springs Creek and Surrounding Waterways, 2009-2011

1. Introduction

Big Springs Creek is a 3.6 km (2.2 mi), cool-water tributary to the Shasta River in Siskiyou County, California, and has been the focus of long-term monitoring and management efforts related to the recovery of coho salmon populations in the Shasta Basin. With the award of federal grant funding, The Nature Conservancy (TNC) implemented restoration and adaptive management actions on Shasta Big Springs Ranch and on parts of Busk Ranch to restore Big Springs Creek beginning in 2009. One of the objectives of this effort was to reduce peak water temperatures during the spring and summer juvenile rearing lifestage of coho salmon (approximately April through September). To monitor and guide restoration efforts, Watercourse Engineering, Inc. (Watercourse) designed and implemented a two-phase approach. The first phase of this approach was to design and implement a water temperature monitoring program that examined the effects of restoration activities and helped TNC identify the highest-value restoration actions. The second phase of this approach was to update the existing two-dimensional Big Springs Creek hydrodynamic and water temperature model to evaluate potential benefits of alternative future restoration and management activities. The results of this approach are meant to illustrate Big Springs Creek's response to restoration actions, characterize the current status of water temperatures in the creek, and provide guidance to potential future restoration actions.

This report documents the design and results of the monitoring and modeling efforts in Big Springs Creek through the study period, which began in March 2009 and continued through October 2011. First, an overview of the project scope and design is provided. Second, background information is provided that describes the initial monitoring efforts in Big Springs Creek that resulted in the purchase of a portion of Busk Ranch by TNC and the establishment of a conservation easement on the remaining Busk Ranch. Third, the monitoring program is described, including its evolution from its initial conception to the current design and objective. Fourth, there is a detailed discussion of water temperature conditions in Big Springs Creek, including a description of the four primary controlling factors of Big Springs Creek water temperatures. Also, the temperature conditions of other waterways on Shasta Big Springs Ranch are discussed, though these other waterways were not the focus of this project. Finally, given 2011 conditions, future potential restoration and management actions are presented and analyzed for long-term effectiveness. Conclusions and recommendations summarize the key elements of a long-term management program that could maintain and manage the benefit provided by Big Springs Creek to the recovery of cool-water fisheries populations (particularly coho salmon) in the Shasta Basin.

2. Project Scope

The scope of this project included an assessment of restoration and adaptive management actions that were implemented on Shasta Big Springs Ranch over an 18-month period (however, data were collected for a 24-month period; actions over a period from 2008-2011 are also considered in the findings of this report). The principal restoration focus was on salmonid habitat, namely habitat suitable for coho salmon.

The project consisted of three primary tasks:

1. Refine, calibrate, and implement the existing flow and temperature model,
2. Coordinate and implement the baseline monitoring plan, and
3. Coordinate project management and reporting, which includes the production of quarterly technical memoranda that track the progress of implemented restoration actions and recommend adaptive management alternatives.

These tasks were designed to identify optimal, science-based decisions to inform and support restoration processes from inception through implementation and evaluation. Each task is outlined in more detail below.

2.1. Task 1: Modeling

The modeling project tasks included additional system characterization, model refinement and calibration, and application. Additional field data describing Big Springs Creek's current geometry, flow, water temperature and meteorological characteristics were gathered to update, refine, and calibrate the Big Springs Model's (TBSM's) existing configuration to accommodate assessment of riparian vegetation restoration and irrigation system improvement. Watercourse worked closely with the project team to develop restoration alternatives and determine optimal restoration approaches.

2.1.1. Additional System Characterization

TBSM data needs include: channel geometry, flow, water temperature, and meteorological data. Vegetation data is included with channel geometry. The preliminary version of TBSM was developed in 2008 and was the basis for all updates, which extended the model to reflect current (i.e. 2011) stream conditions. These changes yielded more accurate simulations of the creek in response to irrigation activities.

2.1.1. Model Refinement and Calibration

Once the additional system characterization was completed, the data was used to update, refine, and calibrate the model. Model updates included identifying the current vegetation growth configuration, refining the amount of shade provided by different stream elements, and including return flow inputs. The goal of model calibration was to replicate the longitudinal profile within 1^{o}C of observed water temperatures during a given week.

Model refinement and calibration used hydrodynamic modeling software: RMAGEN, RMA-2, and RMA-11. A suite of modeling software, RMA-2 for hydrodynamics (v8.1(a)) and RMA-11 (v8.1(b)) for water temperature, was selected to represent Big Springs Creek as a two dimensional, depth-averaged, finite element model. RMAGEN (v7.3(g)) was used to create a geometry file of Big Springs Creek that was used by both the hydrodynamic and water temperature models. RMA-2 is a two-dimensional, finite element, depth-averaged numerical model that calculates velocity, water surface elevation, and depth at defined nodes on the boundary of each grid element in the geometry file. RMA-11 is a finite element water quality model that uses the depth and velocity results from RMA-2 to solve advection diffusion constituent transport equations.

2.1.1. Model Application

One the existing flow and temperature model was updated, alternative restoration configurations were simulated to determine the optimal vegetation planting and irrigation management programs. Watercourse worked with TNC's stream restoration and ranch management teams to develop restoration alternatives, simulate the alternatives using the refined and calibrated flow and temperature model, and recommend optimal restoration options.

2.1.1. Deliverables

Findings of modeling task elements are documented herein. Model files are provided in electronic format with associated data sets, a listing of which is included in the appendices of this report.

2.1. Task 2: Monitoring

Using protocols consistent with the baseline assessment (Jeffres *et al*., 2009), Watercourse coordinated with TNC and University of California, Davis, Center for Watershed Sciences (U.C. Davis Center for Watershed Science) to implement a monitoring program to track restoration progress using the following parameters, at minimum: water flows, water temperature, channel geomorphology, fish assemblages and habitat usage, and aquatic and riparian vegetation. Field monitoring for several of these parameters was continued after the baseline assessment study was completed; therefore, the data record contains both the seasonal response of the creek to new management practices, as well as the baseline status of Big Springs Creek and the Shasta River before restoration activities began in 2009. Each element represents a critical component of the primary restoration goal: to improve salmonid habitat. Thus, restoration goals are based on high quality salmonid habitat criteria. The monitoring completed under by U.C. Davis Center for Watershed Science was funded separately by the National Fish and Wildlife Foundation. Although coordinated monitoring protocols were developed among the projects to ensure sampling methods complimented one another, the data collected under the National Fish and Wildlife Foundation project is reported separately (Willis *et al*., 2012).

2.1.1. Deliverables

Task 2 deliverables include a report summarizing baseline monitoring plan elements and methods, including a list of special studies that may occur in addition to baseline monitoring elements; a template of quarterly technical memoranda to be used by project team members to track activities and monitoring efforts; and quarterly technical memoranda that summarize the progress, findings, and adaptive management recommendations for each monitoring element.

Quarterly technical memoranda (actually, a total of 12 memoranda were submitted to address the six quarterly reporting intervals) that summarize the progress, findings, and adaptive management recommendations are compiled and included in the appendices. This compilation of studies and analyses focuses on the temperature monitoring element, but broadly supports the baseline monitoring plan, identifies additional information findings, track progress and adaptive management decisions, and generally documents a wide range of science activities on the SBSR. All data collected during the project are included in an Excel spreadsheet, submitted with this final report.

2.2. Task 3: Project Management and Reporting

Watercourse proposed to coordinate communications within and among the various entities providing on-the-ground restoration actions and supporting the science teams. Effective and efficient use of project funds depended on a well-maintained communication structure between the science, ranch management, policy groups, and others. Watercourse documented the progress of the science team through quarterly technical memos (described in Task 2) and coordinated with the ranch management and policy teams via phone and in-person conferences throughout the project. At the end of the project, Watercourse produced a First Year Restoration Assessment Report (herein referred to as the Response to Restoration report, including appendices) describing on-the-ground restoration activities, Big Springs Creek's response to each restoration activity, adaptive management decisions, and recommendations for future restoration actions on Shasta Big Springs Ranch. Watercourse was provided an Excel template to follow with regards to the quarterly resources used to track activities and monitoring efforts. These Excel spreadsheets identify employee, period of work, activities, and status, and were submitted each quarter to The Nature Conservancy.

2.2.1. Deliverables

Phone calls and meetings were completed in a timely fashion to coordinate with science team members and policy and irrigation team leads, and a final report and technical memoranda (described in Task 1 and 2) was completed (including electronic versions of all data).

3. Background

Prior to 2008, only a sparse amount of data was available to characterize the physical and biological characteristics of Big Springs Creek. Historical data was limited to qualitative surveys, such as the 1856 United States Bureau of Land Management Land Office survey (U.S. BLM, 1856) or limited spot measurements (DPW, 1925); however, no comprehensive physical and biological assessment of Big Springs Creek had been performed. In the early 1980s, a preliminary assessment of Big Springs Creek examined various physical and biological characteristics; however, this preliminary assessment was limited to observations made during two days in the fall of 1982 (Moyle, 1983). Notably, Moyle (1983) concluded that "the real challenge would be to improve [Big Springs Creek] for fish and wildlife in a way that is compatible with a working cattle ranch" (pg. 5). However, following this assessment, ownership of this area was transferred between private parties, and another opportunity to evaluate Big Springs Creek did not occur for decades.

3.1. 2008 Baseline Assessment

Focus returned to evaluating Big Springs Creek following the Year-In-The-Life study of Nelson Ranch (Jeffres *et al*., 2008), which examined the lifestage conditions for salmonids through a single year (2007) in the 7.6 km (4.7 mi) Shasta River reach on Nelson Ranch. This study concluded that elevated water temperatures, inherited from upstream sources, limited over-summering habitat for juvenile salmonids. In 2008, access was provided to Busk Ranch and its waterways, which include a 4.8 km (3.0 mi) reach of the Shasta River, portions of Hole in the Ground Creek and Parks Creek, and Big Springs Creek and Little Springs Creek in their entirety (Figure 1). Limited resources resulted in the focus of the 2008 study to be on Big Springs Creek. A comprehensive physical and biological assessment was made of Big Springs Creek (Jeffres *et al*., 2009); to support this work, as well as to evaluate the restoration potential of Big Springs Creek, a two-dimensional hydrodynamic and water temperature model was also developed. The analysis of data collected during the baseline assessment indicated that water temperatures in Big Springs Creek were the key limiting factor to the survival and recovery of cool-water fish populations, particularly during the spring (April to June) and summer (July to September); physical habitat was also limited. The report further concluded that given improved water temperature and habitat conditions, Big Springs Creek could support robust anadromous fish populations and would be a key factor in the recovery of those species.

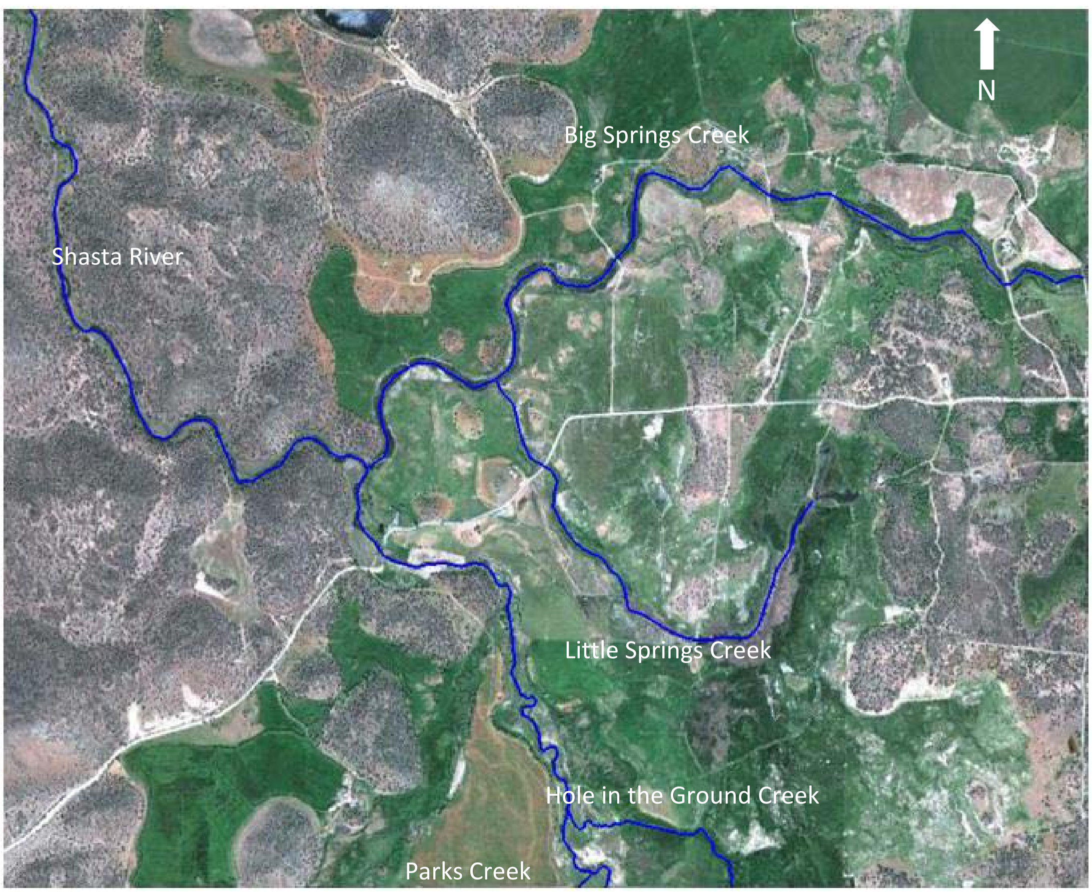

Figure 1. A map of the waterways on Shasta Big Springs Ranch and Busk Ranch.

3.2. Restoration Activities

Following the completion of the baseline assessment, TNC exercised its option to purchase a portion of the Busk Ranch (this portion was renamed Shasta Big Springs Ranch) and place a conservation easement on the portion of Big Springs Creek located on the remaining Busk Ranch lands. In March 2009, TNC acquired Shasta Big Springs Ranch and began restoration activities on Big Springs Creek and surrounding waterways. Following the purchase of Shasta Big Springs Ranch, TNC applied for and was awarded federal grant funds through the National Oceanic and Atmospheric Administration – American Reinvestment and Recovery Act (NOAA-ARRA). Among the restoration activities funded by the NOAA-ARRA grant was the fencing of the riparian zone surrounding Big Springs Creek, which resulted in cattle exclusion. Cattle exclusion began in March 2009 on the lower 2.7 km (1.7 mi) of Big Springs Creek; cattle exclusion on the upper 0.8 km (0.5 mi) began in July 2009. Other restoration activities included extensive riparian planting as well as on-going efforts to improve irrigation efficiency and manage tailwater on Shasta Big Springs Ranch.

To monitor the effectiveness of restoration actions funded by the NOAA-ARRA grant, the baseline monitoring program was extended through 2011 with the additional support of grants from National Fish and Wildlife Foundation and was redesigned as a "response to restoration," or recovery, monitoring program. Although many of the physical and biological elements that were part of the original baseline assessment were monitored during the implementation of restoration activities, only the water temperature monitoring was directly funded by the NOAA-ARRA grant. As such, this report focuses on the response of water temperatures to restoration activities and recommended future actions for water temperature management. Other physical and biological elements that were concurrently monitored included geomorphology, hydrology, hydraulics, primary productivity (i.e., aquatic vegetation), macroinvertebrates, and fish assemblage and distribution. The results of those monitoring efforts are presented in a series of reports, which are available on the University of California, Davis, Center for Watershed Sciences website (http://watershed.ucdavis.edu/research/shasta.html, accessed 27 Oct 2011).

4. Monitoring Program

Though grant funding supported monitoring of only a few of the physical and biological elements identified in the baseline assessment, a recovery monitoring program was developed that identified potential response targets, monitoring methods, and monitoring locations for all elements being monitoring during the study period, whether funded by or separately from the NOAA-ARRA grant (Willis *et al.*, 2010b). The purpose of combining separate monitoring efforts under a single monitoring plan was to emphasize the critical concept that individual creek components, such as water temperature or fish assemblage and distribution, were closely related to the condition of other components, such as geomorphology or aquatic vegetation. The response of any individual component depended on the collective response of all elements to restoration actions. As such, a comprehensive understanding of a single component depended on a similarly comprehensive understanding of other physical and biological components.

An overview of the water temperature component of the monitoring program is presented herein. Targets and methods are briefly discussed. For a full description of the monitoring plan, the reader is referred to the Shasta Big Springs Ranch Monitoring Plan (Willis *et al*., 2010b). The monitoring plan was designed as an adaptive management approach due to the need for immediate restoration action and uncertainty regarding the system when the plan was developed. Changes to the water temperature monitoring program are described for each field season. Finally, this project also included opportunities to perform special studies to reduce uncertainty surrounding specific questions and guide monitoring and restoration activities. These special studies were documented separately from this report. Where applicable, brief descriptions of the special studies and their relationships to water temperature conditions in Big Springs Creek are provided.

4.1. Targets

Restoration activities were designed to address the key impairment to anadromous fish habitat identified in the baseline assessment: elevated water temperatures, particularly in the spring (April to June) and summer (July to September). During this period, maximum water temperatures in Big Springs Creek frequently exceeded 20°C, and at times exceeded 25°C, before restoration activities began. Recognizing that reducing peak water temperatures would likely take multiple restoration activities implemented over the full study period, two targets were identified:

1. In the first 24 months of restoration, daily maximum temperatures at the mouth of Big Springs Creek should be less than or equal to 20^{o}C.

2. After five years of restoration activity, daily maximum temperatures should be less than or equal to 18^{o}C.

The first target was based on projected benefits following the implementation of priority restoration activities that would have an immediate and substantial effect. The second target was based on projected benefits of potential future restoration activities that would likely involve greater expense and resources than priority restoration actions and would likely produce smaller benefits. Finally, these targets were contingent on all other components of Big Springs Creek showing optimal improvement.

4.2. Methods

Multiple monitoring methods were used to measure water temperatures throughout Big Springs Creek and its surrounding waterways. These methods evolved based on improved understanding of the thermal characteristics of Big Springs Creek, the effect of Big Springs Creek on water temperatures in the Shasta River, and long-term management strategies. Initially, water temperatures were measured using the direct deployment of temperature loggers. HOBO U22 Water Temp Pro v2 data loggers from Onset Computer Corporation were used to collect data at 30-minute increments throughout the project area. These loggers have an accuracy of 0.2°C over the range 0°C to 50°C (Onset, 2009). Instruments were deployed consistent with protocols developed on the Nelson Ranch (Jeffres *et al*., 2008). Permanent monitoring stations that reported water temperature data in real-time were added to the monitoring array as high-value monitoring locations were identified. These remote stations were equipped with a Campbell Scientific 109-L water temperature data sensor (CS109-L). The CS109-L was programmed to collect data at 30-minute increments and has an accuracy of 0.25°C over the range -10°C to 70°C (Campbell Scientific, 2012). All remote sensor stations were backed up by a HOBO U22 Water Temp Pro v2 data logger to mitigate for potential equipment malfunction.

4.3. Locations

Throughout the monitoring season, monitoring locations were added or removed based on long-term location value, study objective, or season. Locations that monitored discrete stream flow sources to Big Springs Creek and locations that characterized a reach prior to its confluence with another substantial water source had high long-term management value. As such, these locations were generally monitored continually through the entire study period (March 2009 through October 2011). The monitoring network was expanded between April and September, when daily peak water temperatures were at their highest and opportunities existed to refine understanding of heating and cooling dynamics through special, short-term experiments and studies. These "special study" monitoring locations were specific to the study objective of the short-term experiment and, due to the long project period and limited monitoring resources, were generally not maintained after the experiment was completed. The monitoring network was reduced between October and March to maintain a complete dataset for the long-term monitoring array as well as provide insight to seasonal water temperature dynamics. However, as elevated water temperatures were not a concern during winter months, no special studies or short-term experiments were performed.

4.3.1. 2009 Monitoring

In 2009, the water temperature monitoring array was designed to maintain sites that were established during the 2008 baseline assessment as well as extend the monitoring array to include additional sites such as groundwater sources and surrounding waterways (Figure 2). Six groundwater spring sources were monitored in the upper 0.6 km (0.4 mi) of Big Springs Creek, as well as water released from Big Springs Lake. Nine downstream sites were monitored to provide information regarding key heating reaches as well as water temperatures at the mouth of Big Springs Creek. Other waterways that were monitored on Shasta Big Springs Ranch included the Shasta River, Parks Creek, Hole in the Ground Creek, and Little Springs Creek. These sites were monitored to provide information regarding water temperatures at the ranch's property boundaries as well as water temperatures above confluence locations.

Remote sensors were installed at Big Springs Dam to monitor water temperature and air temperature. These sensors were part of a pilot project to determine whether meteorological conditions (e.g., solar radiation, precipitation, wind speed and direction, etc.) should be monitored locally versus using a regionally located meteorological station (Weed Airport) as well as to determine the feasibility of using remotely accessible monitoring equipment. Finally, the remote sensor station provided easier and timely access to water temperature data at a monitoring location where access was limited due to property ownership conditions.

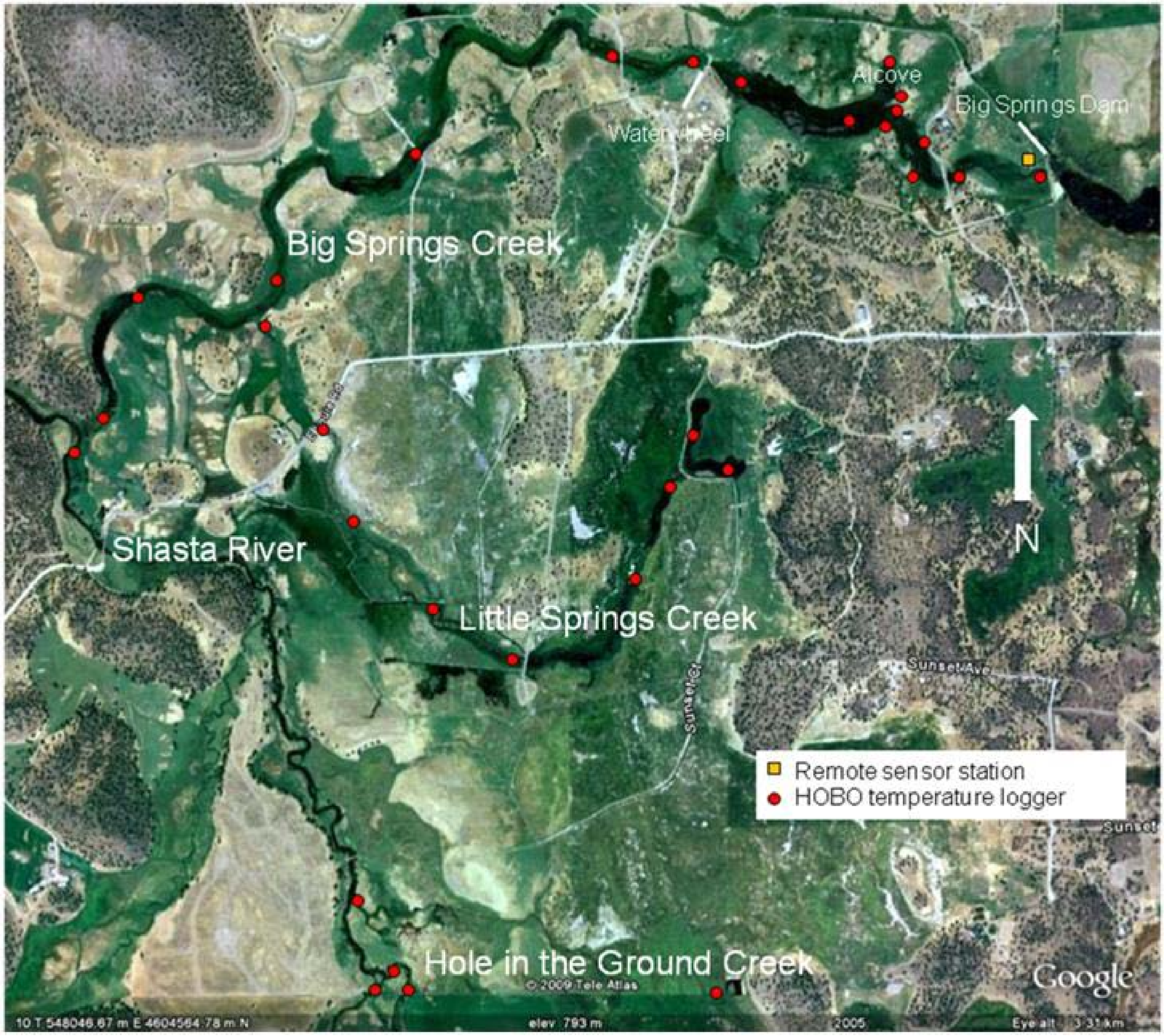

Figure 2. The water temperature monitoring array during the 2009 field season (April to October 2009).

4.3.2. 2010 Monitoring

Based on the results of the 2009 field season water temperature data, the water temperature monitoring array was adjusted in 2010 (Figure 3). One of the groundwater spring monitoring sites was moved closer to the spring source and other sites were eliminated due to redundancy (e.g., in the Shasta River) or because of limited resources (e.g., Little Springs Creek). Additional remote sensor stations were added to the network; two stations were installed in Big Springs Creek and two were installed above discharge points for irrigation return flow on Shasta Big Springs Ranch. These additional stations allowed for timelier access to water temperature data in Big Springs Creek and provided an opportunity to relate stream condition considerations to irrigation activities on Shasta Big Springs Ranch.

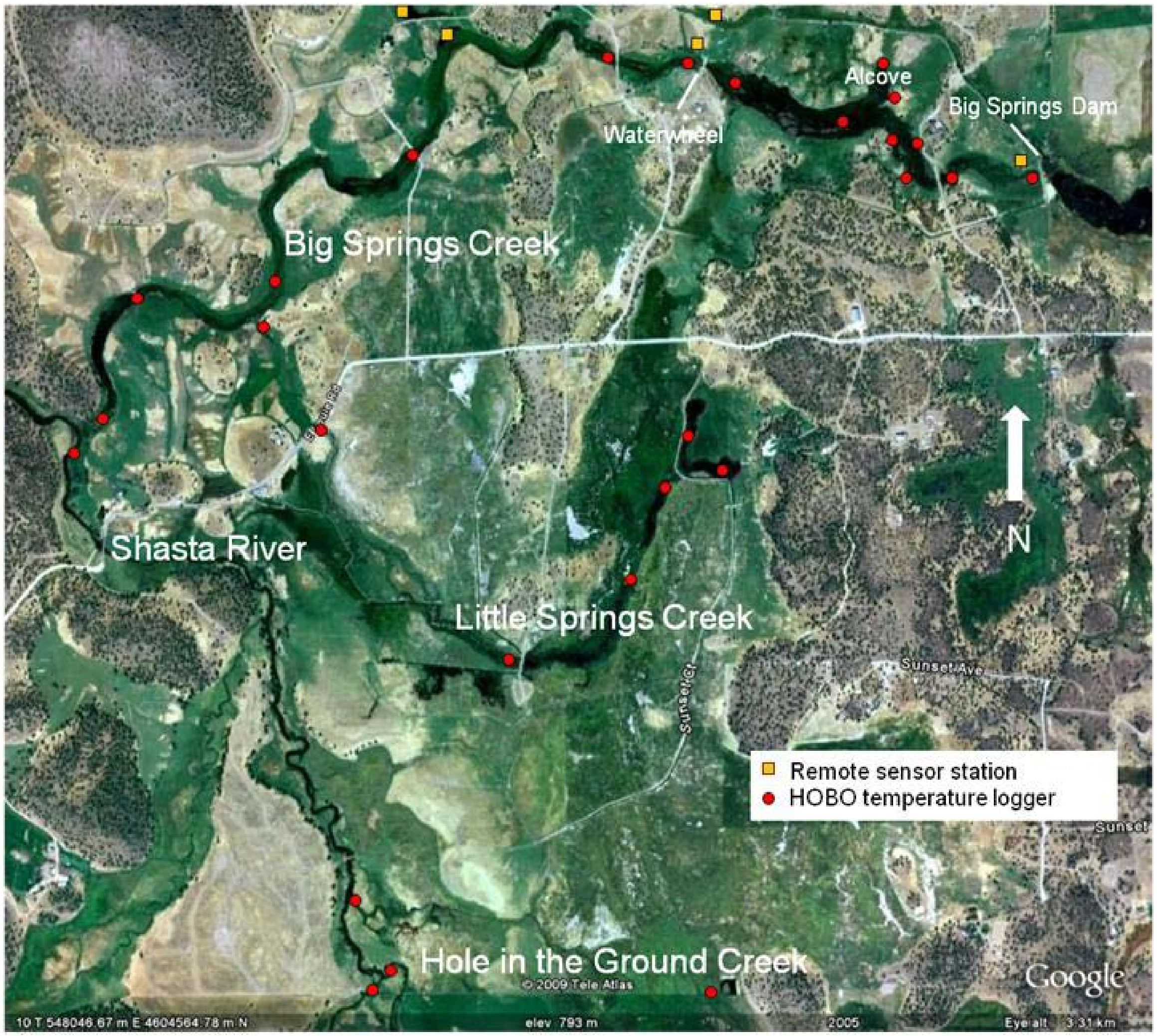

Figure 3. The water temperature monitoring array during the 2010 field season (April to October 2010).

4.3.3. 2011 Monitoring

The existing water temperature monitoring locations were maintained from 2010 to 2011, and additional locations were monitored during the 2011 field season (April-October 2011) (Figure 4). Three transects were added to the water temperature monitoring array in Big Springs Creek to examine a key heating reach where diurnal, two-dimensional water temperature trends had been previously identified.

The remote sensor network was expanded to include three additional water temperature monitoring stations and one meteorological monitoring station. One water temperature station and the meteorological station were installed on Big Springs Creek. Two water temperature monitoring stations were installed on the Shasta River. These locations were selected based on the value of long-term monitoring data at these points.

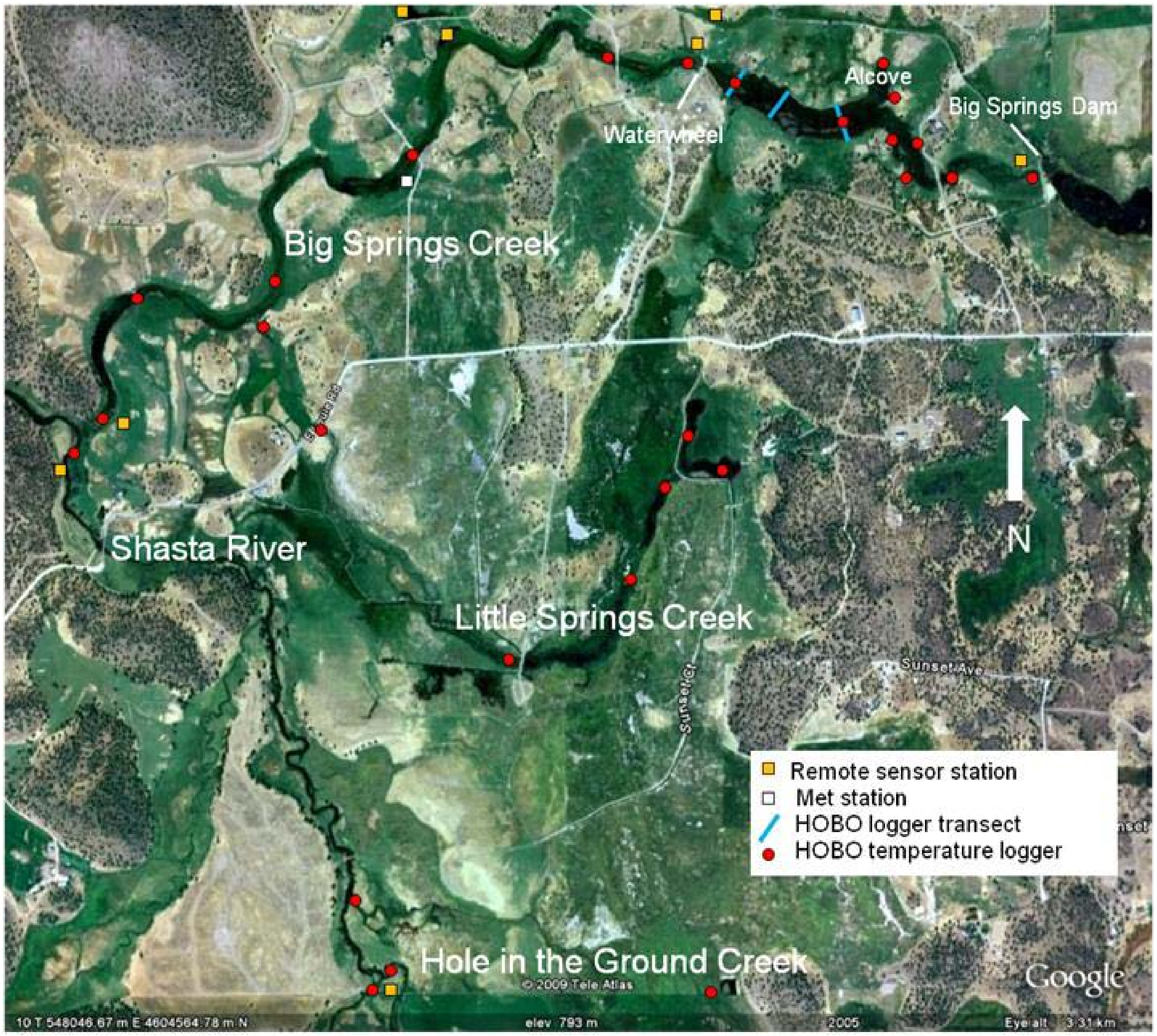

Figure 4. The water temperature monitoring array during the 2011 field season (April to October 2011).

5. Temperature Conditions

Water temperature data were examined to gain insight into which factors potentially affected water temperature conditions in Big Springs Creek as well as to characterize water temperature conditions in Big Springs Creek and the surrounding waterways. First, a brief description of each controlling factor and its role in Big Springs Creek's thermal regime is provided. After describing the foundation of water temperature dynamics in Big Springs Creek, a detailed discussion of water temperature conditions in Big Springs Creek, and how they have responded to restoration actions, is provided in Section 5.2. Finally, a general overview of water temperature conditions in other waterways on Shasta Big Springs Ranch is provided in Section 5.3.

5.1. Controlling Factors in Big Springs Creek

Four principal controlling factors of water temperature conditions were identified in Big Springs Creek:

1. Groundwater-fed springs,
2. Channel geometry,
3. Meteorological conditions, and
4. Aquatic vegetation.

Other factors that can play a role in stream water temperature include riparian vegetation, local geography (topographic shading and long-wave radiation from land surfaces or vegetation), and bed conduction. Generally, the identified principal factors had a substantial effect on water temperatures, though the relative importance of meteorological conditions and vegetation varied throughout the study period (March 2009 through October 2011). Groundwater-fed springs defined the foundation of Big Springs Creek's thermal regime. Channel geometry affected the fate of water temperatures in Big Springs Creek, particularly in reaches where channel geometry promoted accelerated heating. Meteorological conditions seasonally characterized water temperature conditions in Big Springs Creek. Aquatic vegetation also seasonally characterized water temperatures in Big Springs Creek, though these effects were more apparent beginning in 2010, after a year of recovery had occurred. A detailed description of each factor is presented below.

5.1.1. Groundwater-Fed Springs

Groundwater-fed springs were the primary source of cool (10 to 12°C) water in Big Springs Creek. Springs were generally located in the 0.6 km (0.4 mi) reach below Big Springs Dam and were located both in the channel and on the channel margins. To generally characterize the water temperature of the springs, data loggers were placed in five locations where discrete spring inflows were observed (Figure 5). These locations were named:

1. North alcove spring,
2. East alcove spring,
3. Below Busk house bridge, river right (RR),
4. Below Big Springs island, river left (RL), and
5. Below Busk house bridge, RL.

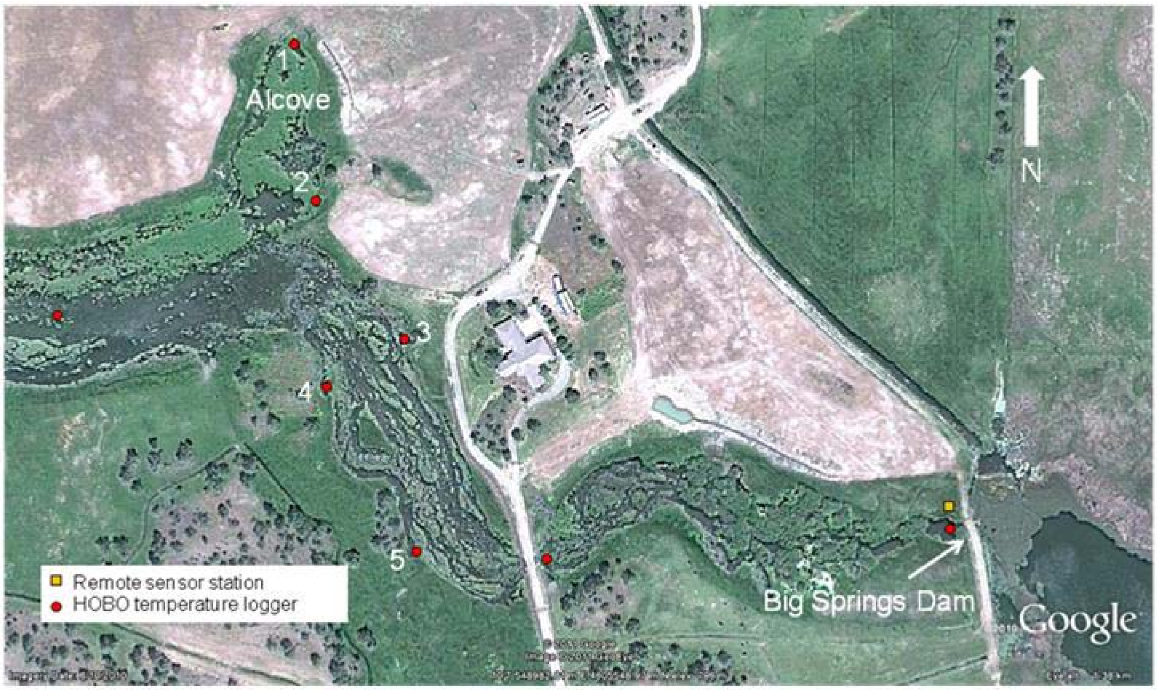

Figure 5. A map of the groundwater-fed spring monitoring sites, as well as other mainstem monitoring sites, in Big Springs Creek. Groundwater-fed spring monitoring sites are numbered 1 to 5.

Due to the diffuse nature of each spring, quantifying the discharge volume of individual springs was challenging. However, previous studies have identified that the springs contribute approximately 40 to 50 cubic feet per second (cfs) to the overall discharge in Big Springs Creek (Jeffres *et al*., 2009; Jeffres *et al*., 2010). Seasonal fluctuations may be due to a range of factors, including snowpack volumes on Mount Shasta, year type, and seasonal groundwater and surface water use, and have not been characterized.

Water temperatures at each of the spring monitoring sites were unique, though all ranged between approximately 10 to 12°C throughout the study period. Monitoring sites 2 through 5 were located near stream banks where water from the mainstem channel could mix with spring water, depending on the season and discharge volumes from Big Springs Dam. However, mixing appeared to have minimal effects on the overall temperature trends at these sites. For example, the spring located at site 2, East alcove spring, was seasonally inundated as stream stage (i.e., depth) increased with aquatic macrophyte growth. However, water temperatures measured at the spring source ranged between 10.5°C and 11.3°C throughout the study period (Figure 6). The spring located at site 3, Below Busk bridge, produced the coolest water, with temperatures ranging between 10.4°C and 10.9°C (Table 1).

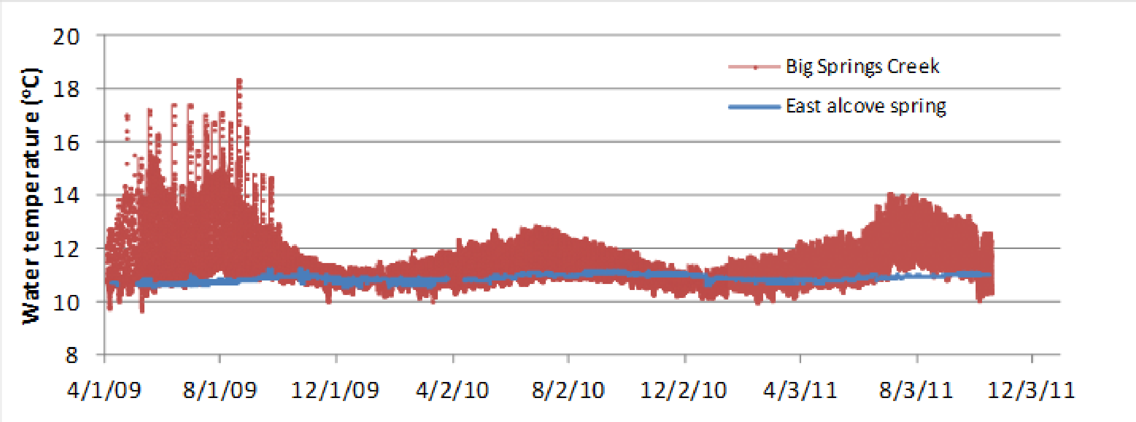

Figure 6. Water temperatures in the East alcove spring (site 2), compared to water temperatures in Big Springs Creek upstream of the spring.

Table 1. A summary of the water temperature characteristics of discrete springs that were monitored in Big Springs Creek.

Site #	Monitoring Site	High (°C)	Low (°C)	Average (°C)
1	North alcove spring	12.4	11.7	12.0
2	East alcove spring	11.3	10.5	10.9
3	Blw. Busk bridge, RR	10.9	10.4	10.6
4	Blw. Big Springs island, RL	13.2	11.1	11.5
5	Blw. Busk bridge, RL	12.2	11.2	11.7

The water emanating from the discrete spring sources had the greatest effect on water temperatures in Big Springs Creek. A box-plot analysis of water temperatures at monitoring locations from Big Springs Dam (river kilometer (RK) 3.6/river mile (RM) 2.2) to the mouth (RKM 0.0/RM 0.0) illustrates that the springs, and not inflows from Big Springs Dam, defined the creek's thermal regime (Figure 7). Although inflow water temperatures from Big Springs Dam generally contributed water warmer than 12°C, water temperatures in Big Springs Creek were generally cooler and showed substantially less variation at RKM 3.0 (RM 1.9), the monitoring site located downstream of the extensive discrete spring sources. The range of water temperatures measured at RKM 3.0 (RM 1.9) during the 2011 field season (April to September) were consistent with those measured in the discrete spring sources, indicating that the springs sources act to "reset" whatever thermal conditions that were inherited from upstream.

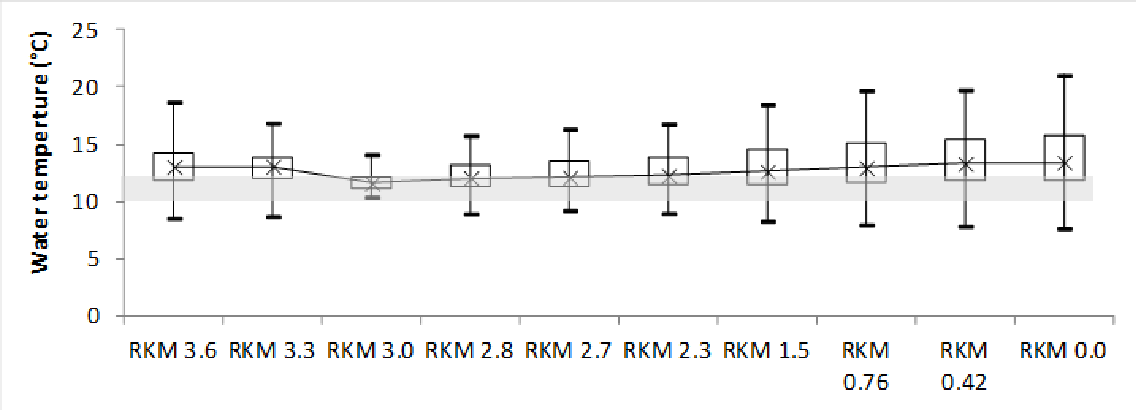

Figure 7. A box-and-whisker quartile plot of water temperatures from April 1-September 30, 2011 in Big Springs Creek from Big Springs Dam (RKM 3.6/RM 2.2) to the mouth (RKM 0.0/RM 0.0). The line plots the median water temperature at each monitoring location, while the box represents the upper and lower quartile range. The whiskers and dashes illustrate the absolute maximum and minimum water temperatures for each location. The grey band illustrates water temperatures between 10 to 12°C for reference purposes.

5.1.2. Channel Geometry

An understanding of channel geometry is critical to understanding water temperature trends in Big Springs Creek because the principal stream response of cattle exclusion was a dramatic evolution of channel form. Though channel geometry was not explicitly monitored as part of this project, detailed descriptions of channel geometry monitoring are provided in Jeffres *et al*. (2009; 2010), including monitoring methodologies, locations, schedules, and analyses. To provide a better understanding of the relationship between channel geometry and water temperature trends in Big Springs Creek, a subset of geometry data was provided by the U.C. Davis Center for Watershed Science and is discussed herein.

Channel geometry describes the aspect (i.e., general orientation), channel form (i.e., width and depth variations), and slope (i.e., gradient) of a waterway. Big Springs Creek generally flows from east to west (Figure 1), with a wide and shallow channel form, resulting in a large, exposed surface area (Figure 8). The channel form can be described by the width-to-depth ratio (hereafter referred to as width:depth):

- A large width:depth (e.g., greater than 100) indicates that the channel is relatively wide and shallow, and
- A small width:depth (e.g., less than 50) indicates that the channel is relatively narrow and deep.

An examination of the width:depth identified that Big Springs Creek is widest and shallowest in the stream reach between Big Springs Dam (RKM 3.6/RM 2.2) and the waterwheel (RKM 2.7/RM 1.7); width:depth in this reach were generally greater than 100 and peaked at 250. This reach is also the location of the discrete groundwater-fed spring sources that contribute the majority of flow to Big Springs Creek. Between the waterwheel (RKM 2.7/RM 1.7) and the mouth (RKM 0.0/RM 0.0), width:depth decreased and were generally less than 100, and at times less than 50, indicating that the stream channel was narrower and deeper in this reach.

There are also four distinct reaches where different slopes are observed. Reach 1 begins at Big Springs Dam (RKM 3.6/RM 2.2) and ends where the alcove meets Big Spring Creek (RKM 3.3/RM 2.0). The slope in this reach is moderate (*S*=0.003). Reach 2 begins at RKM 3.3 (RM 2.0) and ends at the waterwheel (RKM 2.7/RM 1.7). This is the least steep reach (*S*=0.0003). Reach 3 begins at RKM 2.7 (RM 1.7) and ends at RKM 1.9 (RM 1.2), upstream of the tail water return point from the pond on the north side of the creek. Reach 3; is the steepest in the creek (*S*=0.006). Finally, the slope returns to a moderate gradient in Reach 4 (*S*=0.003), which begins at RKM 1.9 (RM 1.2) and ends at the mouth of Big Springs Creek (RKM 0.0/RM 0.0).

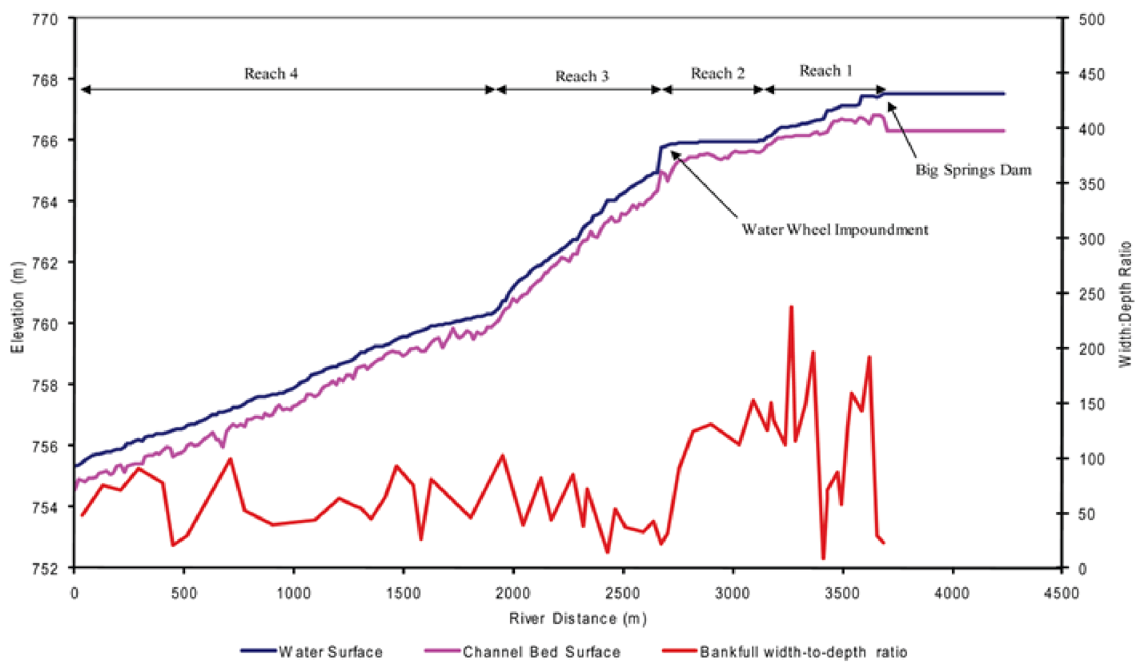

Figure 8. The elevation profile of the channel bed and water surface in Big Springs Creek, as well as width:depth. Figure provided by Andrew Nichols (U.C. Davis Center for Watershed Sciences).

Channel geometry had a substantial effect on the fate of water temperatures in Big Springs Creek, particularly regarding heating rates in some reaches (the heating rate describes the rate at which water temperatures increase over a specified reach). Daily average heating rates were calculated for each of the four reaches previously described (Figure 9). These calculated heating rates were based on water temperature data for the period April 1 to October 1, 2011.

Reaches with the highest width:depth and the smallest slopes generally illustrated higher heating rates. The relationship between channel geometry and heating rates seemed strongest in Reach 2, particularly between June and September. This reach was characterized by the widest and shallowest channel geometry, as well as the smallest slope; it also contained the highest observed heating rates. The peak daily average heating rate was approximately 4°C/km (6.5°C/mi). Lower heating rates were observed in Reaches 3 and 4, which were both characterized by a narrower, deeper channel and steeper slope. Reach 1 was the only reach in which channel geometry seemed to have a minimal effect on heating rates, as it was generally a cooling reach, where water temperature decreased. However, this cooling trend is due to the voluminous inflow from groundwater-fed springs rather than stream geometry (other reaches have little or no effect of from groundwater-fed spring inflows).

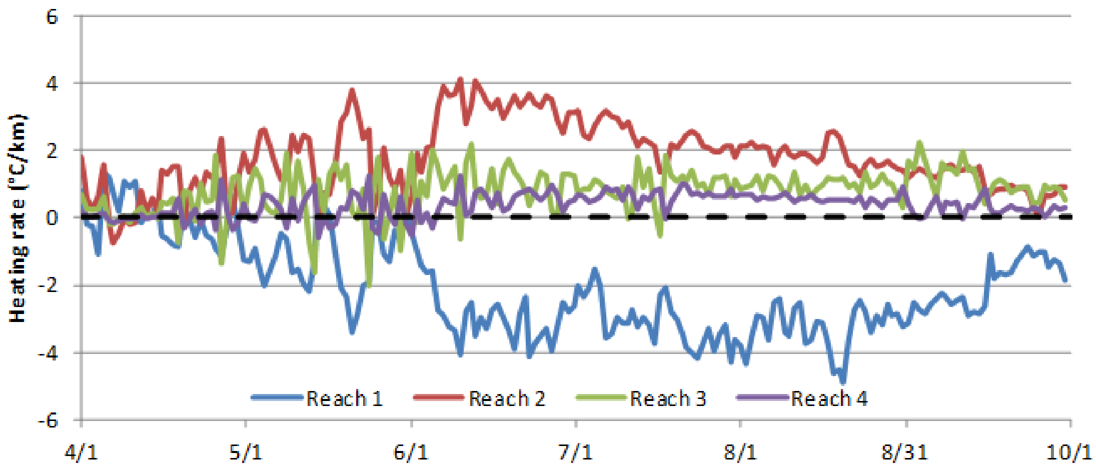

Figure 9. Daily average heating rates in the four reaches of Big Springs Creek in 2011.

5.1.3. Meteorological Conditions

While the groundwater-fed springs and channel geometry form the foundation of the water temperature regime in Big Springs Creek, the seasonal and inter-annual water temperature characteristics are defined by meteorological conditions. Meteorological conditions describe the ambient climate surrounding Big Springs Creek and refer to several meteorological elements, including solar radiation, air temperature, relative humidity (or related vapor pressure terms of dew point or wet bulb temperature), wind speed and direction, and barometric pressure. Although cloud cover was not measured in the field, a daily average value is estimated from theoretical total daily solar radiation and actual measured total daily solar radiation.

These elements all play a role in the overall heat budget (i.e., the net effect of various sources and sinks of heat on the thermal energy, as measured by water temperature, of Big Springs Creek), but do not affect water temperatures equally. The energy budget terms used in the Big Springs Creek model analysis and the measured meteorological parameters used in each term, as applicable, are presented in Table 2. Detailed descriptions of energy budget terms can be found in Deas and Lowney (2001).

Heat budget terms can be heat sources and/or sinks, and affect different heating and cooling processes (Figure 10). Meteorology plays a critical role in determining water temperature response in the short-term (sub-daily), medium-term (days to weeks), and long-term (months to seasons); however, channel geometry also plays an important role in heating rates, as noted above.

Table 2. Energy budget terms used in the Big Springs Creek model analysis and meteorological parameters used in calculating term.

Energy Budget Term	Meteorological Parameter				
	Solar Radiation	Air Temperature	Vapor Pressure*	Wind Speed/ Direction	Barometric Pressure
Short-wave Radiation (q_{sw})	X	-	-	-	-
Down-welling Long-wave Radiation (q_{atm}) (atmospheric)	-	X	-	-	-
Upwelling Long-wave Radiation (q_b) (water)**	-	-	-	-	-
Latent Heat Flux (Evaporation/ Condensation) (q_l)	-	-	X	X	X
Sensible Heat Flux (Conduction) (q_h)	-	X	X	X	X
Bed Conduction** (q_g)	-	-	-	-	-

* Vapor pressure terms include relative humidity, dew point temperature, and/or wet bulb temperature.
** Upwelling long-wave radiation is a function of water temperature only, but is included for completeness. Bed conduction is not typically a function of meteorological data (occasionally a short-wave extinction term for solar radiation that reaches the bed is included), but is included for completeness.

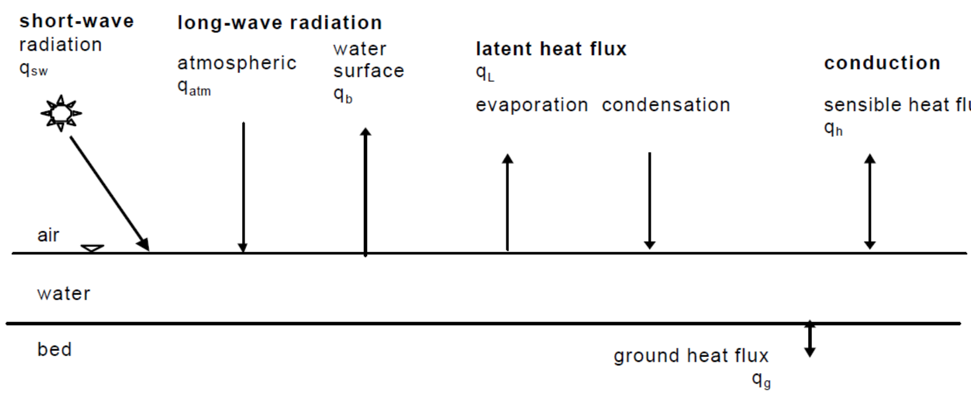

Figure 10. Sources and sinks of heat energy (from Deas and Lowney (2001)).

A meteorological monitoring station was installed near Big Springs Creek in April 2011 to provide data for each of the previously described meteorological parameters (Figure 4). This data was used to increase understanding of seasonal and daily water temperature trends in Big Springs Creek. Seasonal meteorological were examined to determine periods when peak temperatures were likely to occur. As the key impairment to anadromous fish habitat in Big Springs Creek was elevated water temperatures, examining periods where water temperatures were at their seasonal peak helped focus the scope of the study. Daily meteorological conditions were examined to determine the effect of meteorological conditions on daily maximum water temperatures; particularly on days when maximum water temperatures exceeded project targets.

5.1.4. Aquatic Vegetation

Aquatic vegetation also strongly influenced seasonal water temperatures in Big Springs Creek, particularly during the period when growth emerged above the stream's water surface (approximately July through September). Aquatic vegetation seasonally reduced the amount of solar radiation that reached the water surface (i.e., aquatic vegetation provided shade to Big Springs Creek), though the benefit varied depending on when the aquatic vegetation emerged above the water surface during the growing season and also on spatial distribution of plant growth. Aquatic vegetation also affected channel hydraulics, specifically water depths and velocities. The effect of aquatic vegetation on water temperatures in Big Springs Creek is discussed in detail in section 5.2 and in Willis *et al*. (2012); herein, only an overview of the relationship between aquatic vegetation and heating factors is presented.

5.1.4.1. Shade

Emergent aquatic macrophytes (i.e., aquatic macrophytes that emerged above the water surface) limited the amount of heating in Big Springs Creek by blocking a portion of the solar radiation that reached the water surface. A preliminary study, completed in July 2011, compared the shade provided by aquatic macrophytes to partial and dense willow cover (Willis and Deas, 2011b). The results of the preliminary study were tested during a follow-up study in August 2011. Both studies suggested aquatic macrophytes substantially reduced the amount of solar radiation that reached the water surface of Big Springs Creek. When compared to open areas (i.e., areas where no cover existed over the water surface), the amount of solar radiation measured under areas of aquatic vegetation was reduced by an average of 84% to 93% (Table 3). A survey of aquatic macrophyte distribution toward the end of the 2011 growing season indicated that aquatic macrophytes covered approximately 52% of the surface of Big Springs Creek. A detailed discussion of the relationship between aquatic vegetation and water temperatures in Big Springs Creek is presented in section 5.2.1.1.

Table 3. A summary of solar radiation (SR) measured at the water surface of Big Springs Creek under open (i.e., unimpaired) and aquatic macrophyte areas. Time of measurement is provided in parenthesis (when applicable).

Date	Cover Type	Maximum SR (W/m^2)	Minimum SR (W/m^2)	Percent Shade (max/min)	Average Shade
Jul 20, 2011	Open	1020 (1 pm)	700 (10 am)	NA	NA
Jul 20, 2011	Aquatic macrophyte	180 (3 pm)	35 (10 am)	95%/79%	84%
Aug 23, 2011	Open	919 (1 pm)	605 (10 am)	NA	NA
Aug 23, 2011	Aquatic macrophyte	114 (3 pm)	22 (2 pm)	97%/89%	93%

5.1.4.2. Hydraulics

Submerged and emergent aquatic vegetation reduced heating by channelizing stream flow into open (i.e., unvegetated) portions of the stream channel and increasing the velocities (i.e., reducing the travel time) through the creek. U.C. Davis Center for Watershed Science completed detailed flow-velocity transect surveys in Big Springs Creek to examine the relationship between aquatic vegetation, local velocities, and stream flow (Figure 11). Surveys were completed during two periods: early in the growing season (e.g., March), before aquatic vegetation emerged above the water surface, and later in the growing season (e.g., August), after aquatic vegetation emerged above the water surface and aquatic biomass was near its seasonal peak (see Willis *et al*. (2012) for details describing biomass trends).

Early season surveys showed that stream flow was concentrated into open portions of the stream channel. These areas were characterized by higher velocities (0.2 m/s to 1.0 m/s) than areas where vegetation was present (less than 0.1 m/s). Mean velocities generally decreased as aquatic vegetation density and distribution increased. Later season surveys showed that stream flow velocities had generally decreased throughout the channel and submergent and emergent vegetation was also present throughout.

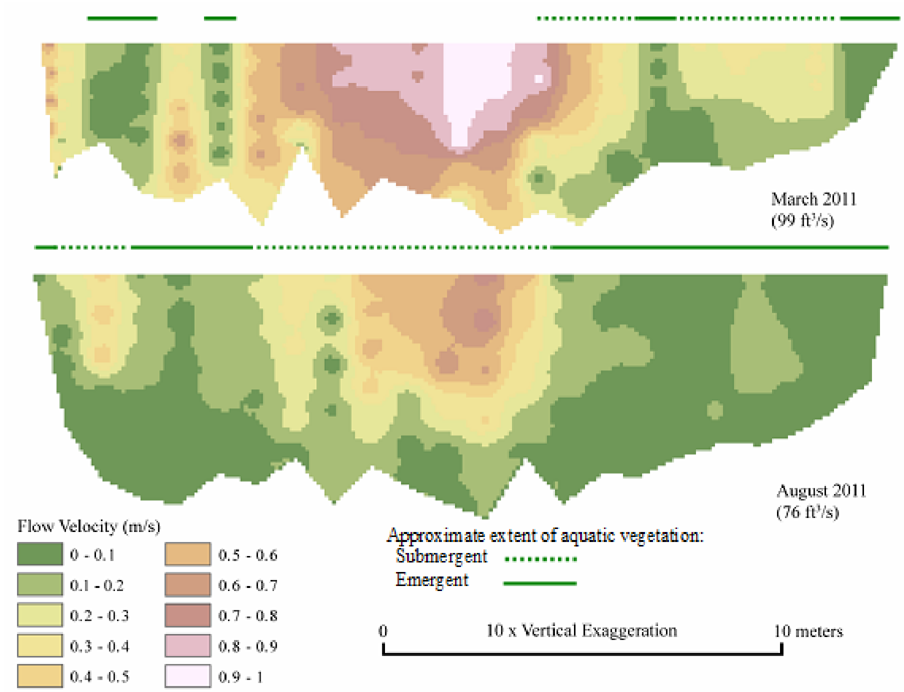

Figure 11. Flow-velocity contour plots created from point velocity measurements collected at RM 0.3 in Big Springs Creek. Approximate locations of submerged and emergent vegetation are illustrated. Figure taken from Willis *et al*. (2012).

5.2. Big Springs Creek

Water temperature conditions in Big Springs Creek have undergone substantial changes since they were characterized during the 2008 baseline assessment, which occurred prior to any restoration activity. Furthermore, special studies have improved understanding of local temperature characteristics. These special studies have focused on two key elements that affect heating in Big Springs Creek: stream geometry and aquatic vegetation. Though the previous section identified groundwater-fed springs and meteorological conditions as factors that define the thermal regime of Big Springs Creek, they are not factors that are easily manipulated to change water temperature conditions. Stream geometry and aquatic vegetation can be more easily managed as part of a restoration strategy to improve water temperature conditions. This section will describe the evolution of water temperature conditions in response to restoration actions as well as identify local trends and the key heating reach as of 2011. Knowing where water temperatures can rapidly increase can help identify effective future restoration actions. The lessons learned from the special studies of stream geometry and aquatic vegetation were used to evaluation future restoration alternatives, which are discussed in section 6.

5.2.1.1. *Water Temperature Response to Restoration Activities*

Restoration activities have had a quantifiable effect on water temperatures in Big Springs Creek. Though water temperatures were monitored from the headwaters to the mouth of Big Springs Creek, for the purposes of this analysis, water temperatures at the mouth of Big Springs Creek are examined. The period of interest is generally between April 1 and October 1, when daily maximum water temperatures can exceed project goals depending on seasonal climate conditions and regional water use.

Maximum water temperatures decreased by an average of 2.9°C from 2008 to 2011 (Figure 12). Before for restoration actions began in 2009, a baseline assessment of Big Springs Creek determined that daily maximum water temperatures at the mouth were generally higher than 20°C and at times exceeded 25°C. In 2011, maximum water temperatures were generally lower than 20°C, but still occasionally exceeded 20°C; daily mean and minimum temperatures generally ranged between 10°C and 15°C.

While there were still days in 2011 when daily maximum water temperatures exceeded the target of 20°C, the number of days and number of consecutive days when temperatures exceeded the target decreased after restoration activities were implemented (Table 4). The number of days in excess of the target (20°C) in 2008 was 95 days. This was reduced to 80 days, 32 days, and 16 days in 2009, 2010, and 2011, respectively – a reduction of 15.8%, 66.3%, and 83.1%, respectively. Further, the number of consecutive days over the target in 2008 included a remarkable 30-day stretch that started in June and extended into July. In 2011, the highest number of consecutive days over the target was five – a reduction of 83.3%.

Table 4. Number of days and consecutive days (parenthesis) per month that Big Springs Creek above Shasta River exceeded the 24-month 20°C criteria.

Month	2008	2009	2010	2011
April	6 (2)	8 (5)	0 (0)	0 (0)
May	19 (22)	25 (18)	1 (1)	3 (3)
June	25 (14)	16 (9)	17 (10)	13 (5)
July	29 (21)	30 (24)	14 (10)	0 (0)
August	16 (8)	1 (1)	0 (0)	0 (0)
Total	95	80	32	16
Longest Continuous Series	30*	25*	10*	5
Maximum Seasonal (April-August)	25.3°C	23.9°C	22.3°C	21.1°C

*Longest series of days with maximum daily temperatures over 20°C extended from
- June 22 to July 21, 2008
- July 10 to August 1, 2009
- June 21 to August 1, 2010, and August 9-18, 2010

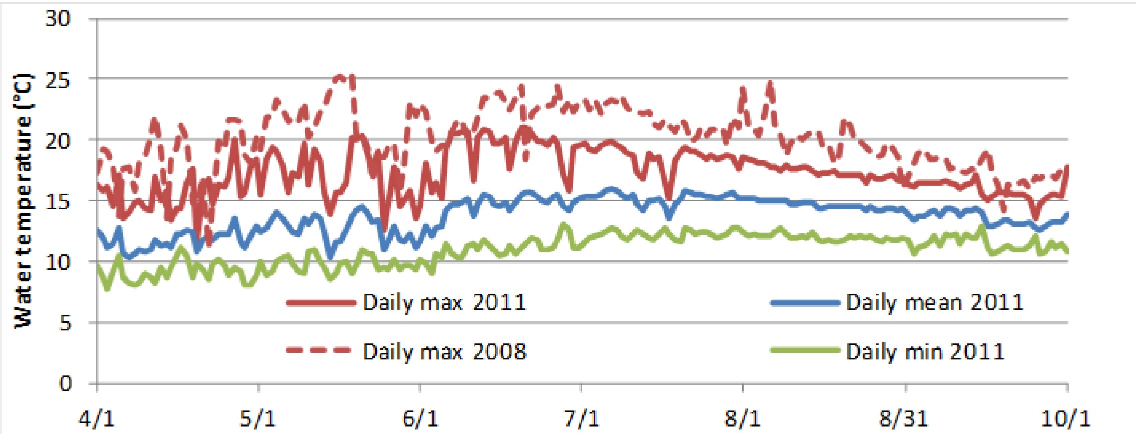

Figure 12. Daily maximum, mean, and minimum water temperatures in Big Springs Creek (BSC) above its confluence with the Shasta River (SR) (BSC abv. SR) during 2011. The daily maximum water temperatures during 2008 are provided for comparison to current conditions.

Another point to consider is that upon examining water temperatures approximately one mile upstream from the mouth (the lowest drivable bridge on Big Springs Creek), the 20.0°C temperature target was met 100% of the time, with a maximum daily temperature of 18.1°C in 2011 (Table 5). This temperature is only 0.1°C above the 5-year target of 18.0°C. Similar information are presented for 2008-2010 in Table 5 as well.

Table 5. Number of days and consecutive days (parenthesis) per month that Big Springs Creek, aprroximately one mile upstream of the mouth (the Lowest Drivable Bridge) exceeded the 24-month 20°C criteria.

Month	2008	2009	2010	2011
April	1 (1)	1 (1)	0 (0)	0 (0)
May	15 (8)	7 (3)	0 (0)	0 (0)
June	18 (9)	0 (0)	0 (0)	0 (0)
July	22 (14)	7 (4)	0 (0)	0 (0)
August	16 (8)	0 (0)	0 (0)	0 (0)
Total	72	15	0	0
Longest Continuous Series	20*	4	0	0
Maximum Seasonal (April-August)	25.4°C	21.5°C	19.6°C	18.1°C

*Longest series of days with maximum daily temperatures over 20°C extended from June 25 to July 14.

Water temperatures were also characterized using metrics that are commonly applied when assessing conditions for salmonid habitat (Welsh *et al*., 2001; Stenhouse *et al*., 2012). The mean weekly maximum temperature (MWMT), maximum weekly average temperature (MWAT), and absolute maximum water temperature were calculated for each year from 2008 through 2011 (Table 6). Each metric illustrates a rapid response to restoration actions beginning in 2009 and continuing through 2011. From 2008 to 2011, MWMT decreased approximately 4°C, from 24.2°C to 20.3°C; MWAT decreased approximately 1.5°C, from 17.1°C to 15.6°C; and absolute maximum water temperatures decreased approximately 4°C, from 25.3°C to 21.1°C. These metrics are not included herein to be used to guide fisheries management actions, but rather to illustrate different methods of characterizing temperature changes in Big Springs Creek in response to restoration activities.

Table 6. Maximum weekly maximum temperature (MWMT), maximum weekly average temperature (MWAT), and absolute maximum water temperature in Big Springs Creek at the mouth during 2008-2011.

	MWMT* (°C)	Period When MWMT Was Observed	MWAT* (°C)	Period When MWAT Was Observed	Absolute Maximum Water Temperature (°C)	Date of Absolute Maximum Water Temperature
2008	24.2	May 13-19	17.1	Jul 7-13	25.3	May 19
2009	22.8	May 16-22	17.4	Jul 16-22	23.9	May 17
2010	21.6	Jun 24-30	16.4	Jul 9-15	22.3	Jun 13
2011	20.3	Jun 15-21	15.6	Jul 2-8	21.1	Jun 19

*MWMT = Maximum weekly maximum temperature, MWAT = Maximum weekly average temperature

A comparison of water temperatures in Big Springs Creek to the mainstem Shasta River illustrated that the restorations activities, opposed to meteorological conditions, resulted in reduced water temperatures in Big Springs Creek. If water temperature reductions were due to meteorological conditions, this would have affected both the Shasta River and Big Springs Creek. Big Springs Creek experienced cool water temperatures during the summer, when other waterways experienced elevated water temperatures (Figure 13). Before restoration actions were implemented in Big Springs Creek, peak water temperatures in the creek and the Shasta River were similar (i.e., between 20°C and 25°C). However, following the implementation of restoration actions in 2009, water temperatures measured in the Shasta River above the confluence with Big Springs Creek generally exceeded those at the mouth of Big Springs Creek from July through October. Maximum water temperatures peaked in the Shasta River at approximately 24°C to 25°C; during these times, water temperatures in Big Springs Creek were approximately 3°C to 5°C lower, ranging between 18°C and 21°C. During the winter and spring (approximately November through March), water temperatures in Big Springs Creek are generally warmer than those in the Shasta River. Minimum water temperatures in the Shasta River decreased to approximately 3°C to 5°C; at the same time, water temperatures in Big Springs Creek were approximately 3°C to 5°C warmer, ranging between 7°C to 8°C. These declining trends are readily available by examining both the seasonal maximum and reduced diurnal range in Figure 13.

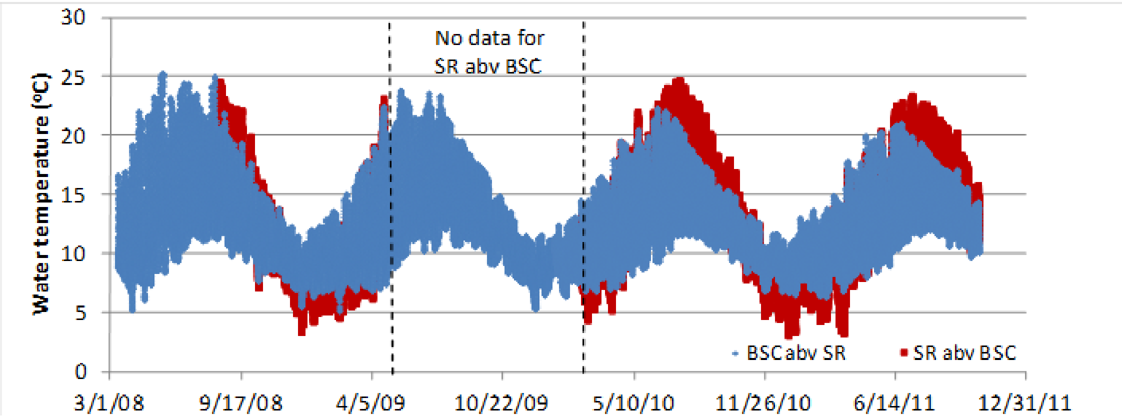

Figure 13. Water temperatures measured in Big Springs Creek above its confluence with the Shasta River (BSC above SR) and in the Shasta River above its confluence with Big Springs Creek (SR above BSC). Periods when water temperatures in the Shasta River exceed or fall below water temperatures in Big Springs Creek are illustrated. No data is available between 4/15/2009-5/1/2010 for SR above BSC.

The changes in Big Springs Creek temperature trends, relative to the Shasta River, illustrate that the restoration activities have had a major impact on water temperatures in Big Springs Creek. The restoration activities, such as riparian fencing, have led to increased growth of seasonal aquatic vegetation which is a major factor behind water temperature conditions in Big Springs Creek. Water temperatures can be categorized by two periods: one from November through June, when aquatic vegetation is submerged (providing no shade to the water surface), and one from July through October, when aquatic vegetation has emerged above the water surface (providing shade to the water surface and impeding water column mixing) (Figure 14). When aquatic vegetation is submerged, water temperatures are driven largely by ambient meteorological conditions as waters flow from the groundwater-fed spring dominated inflow area in the upper creek to downstream reaches and the Shasta River. However, once aquatic vegetation emerges above the water surface, the effects of meteorological conditions are buffered, and maximum water temperatures generally decrease between July and October. When the emergent aquatic vegetation begins to senesce in late fall/early winter, meteorological conditions again drive the heating and cooling process in Big Springs Creek.

The spring season (April through June) is the period during which elevated water temperatures above 20°C are more likely. During this period, days are longer (resulting in prolonged exposure to solar radiation), warm ambient conditions are possible, and vegetation has not emerged past the water surface to provide shade from solar radiation; thus, elevated water temperatures are a result of the combined effect of meteorological conditions that favor heating, little cover, and wide and shallow channel geometry. In 2011, water temperatures at the mouth of Big Springs Creek occasionally exceeded 20°C between April and early July, after which maximum water temperatures generally declined through late summer (September) (Figure 14). The period during which maximum water temperatures began to decline coincided with the period during which dense, emergent aquatic vegetation provided cover (i.e., shade) to about 52% of Big Springs Creek (Willis and Deas, 2011b).

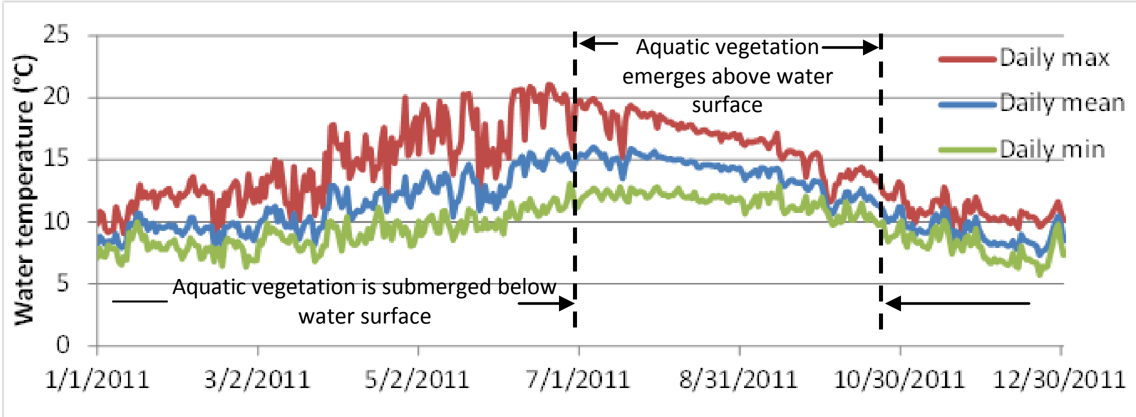

Figure 14. An example of seasonal water temperature trends measured in Big Springs Creek above its confluence with the Shasta River. The dashed lines bound the period during which aquatic vegetation emerges past the water surface and provides shade to portions of the creek.

Water temperatures in Big Springs Creek have demonstrated a rapid response to restoration actions. Elevated water temperatures at the mouth still leave the majority of the creek with water temperatures within project goals; however, Nichols *et al*. (2010) have illustrated how water temperatures in Big Springs Creek strongly influence water temperatures in the Shasta River downstream of the confluence. Therefore, to maintain desirable water temperatures in the Shasta River downstream of Big Springs Creek, further improvements to water temperatures at the confluence of may be desired. Whether the creek may eventually recover through passive restoration to meet project goals is uncertain due to the seasonal dynamics of aquatic vegetation growth and senescence. Furthermore, the time it would take for the creek to reach these goals through passive restoration may be longer than desired. To reduce water temperatures on a shorter timeframe, active restoration alternatives may be considered. The following section identifies locations where active restoration may reduce heating rates (and maximum water temperatures) in Big Springs Creek.

5.2.1.2. Key Heating Reach: the Football Field

As previously described, water temperatures in Big Springs Creek are fundamentally defined by cool (10°C to 12°C) groundwater-fed springs that emanate from discrete sources in the 0.8 km (0.5 mi) reach downstream of Big Springs Dam. However, though maximum water temperatures in Big Springs Creek have substantially improved since restoration actions began in 2009, they occasionally exceed the project goal (i.e., water temperatures exceed 20°C at the mouth)[1]. To meet this goal, additional restoration actions may be considered for stream reaches where rapid heating still occurs. This section provides an overview of the stream reach where the highest heating rates were observed in Big Springs Creek. Understanding the local thermal characteristics of this reach can help identify effective future restoration actions to address water temperature goals.

[1] Although a project goal of 20°C is occasionally exceeded at the mouth of Big Springs Creek, there is extensive habitat upstream and direct connectivity between the mouth and these upstream habitats exists. Thus, the restoration efforts have resulted in broad habitat and provided opportunity for redistribution of fish in response to short-term events (e.g., hot spells).

Directly downstream of the reach in which the majority of the springs are located is a particularly wide and shallow-gradient channel, commonly called the “football field” (Figure 15). The football field extends approximately 0.6 river kilometers (0.4 river miles) downstream, and largely a function of the constriction at the water wheel (which is a combination of natural bedrock constriction and the construction of the water wheel). The channel width in this reach is about 100 m or three times the approximate width in the rest of the stream. Whether this channel geometry is natural or developed as a result of long-term in-stream grazing is unknown; regardless, it contains considerable thermal variability and is also the reach where the highest heating rates were observed.

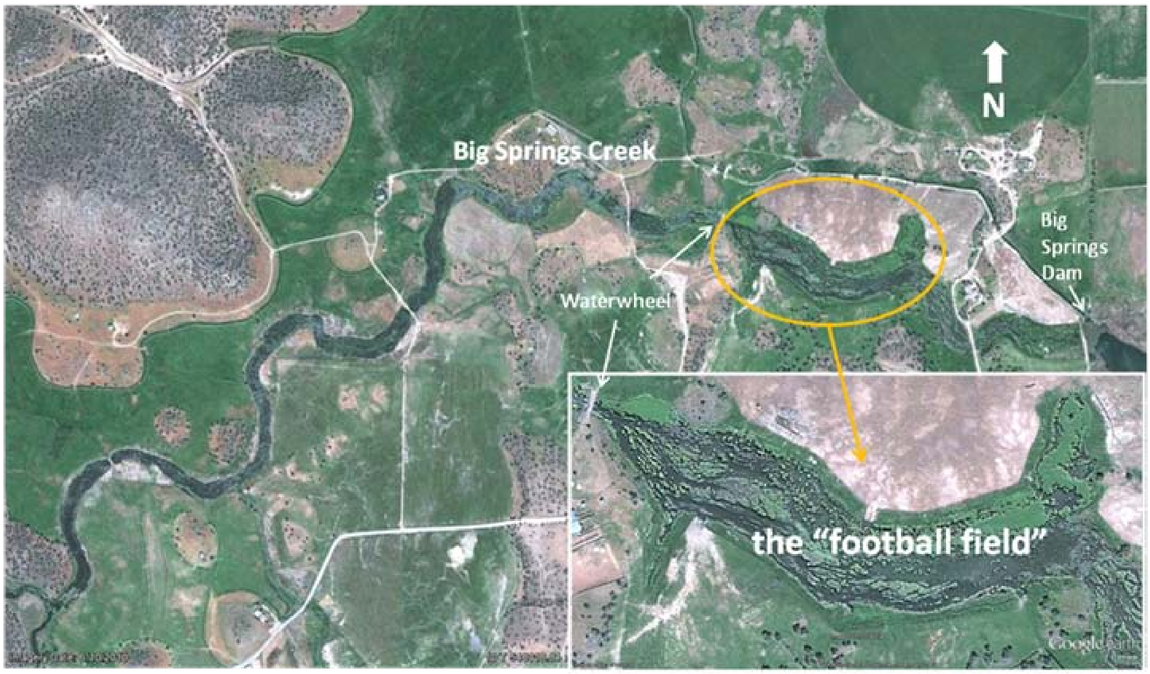

Figure 15. A map of Big Springs Creek and the 0.4 mile reach called “the football field,” where the highest heating rate is observed.

Thermal variability in the football field is illustrated by diurnal and seasonal water temperature trends. Prior to this study, an aerial survey of water temperatures in Big Springs Creek was completed (Watershed Sciences, 2009). The objective of this survey was to characterize water temperatures in the morning (after water temperatures cooled during the night) and afternoon (after water temperatures heating during the day). An image of the football field shows that water temperatures in this reach have a distinct diurnal pattern of approximately uniform temperatures during the cool period of the day (night and early morning hours), and distinct lateral (and longitudinal) variation during the warmer period of the day (Figure 16). The thermal images clearly identify spring sources, preferential flow paths of cool water through the football field, and the fate of this water as it traverses this wide shallow reach. However, this survey only captured a snapshot of these dynamic thermal processes. A special study was designed and implemented to better characterize this trend through time.

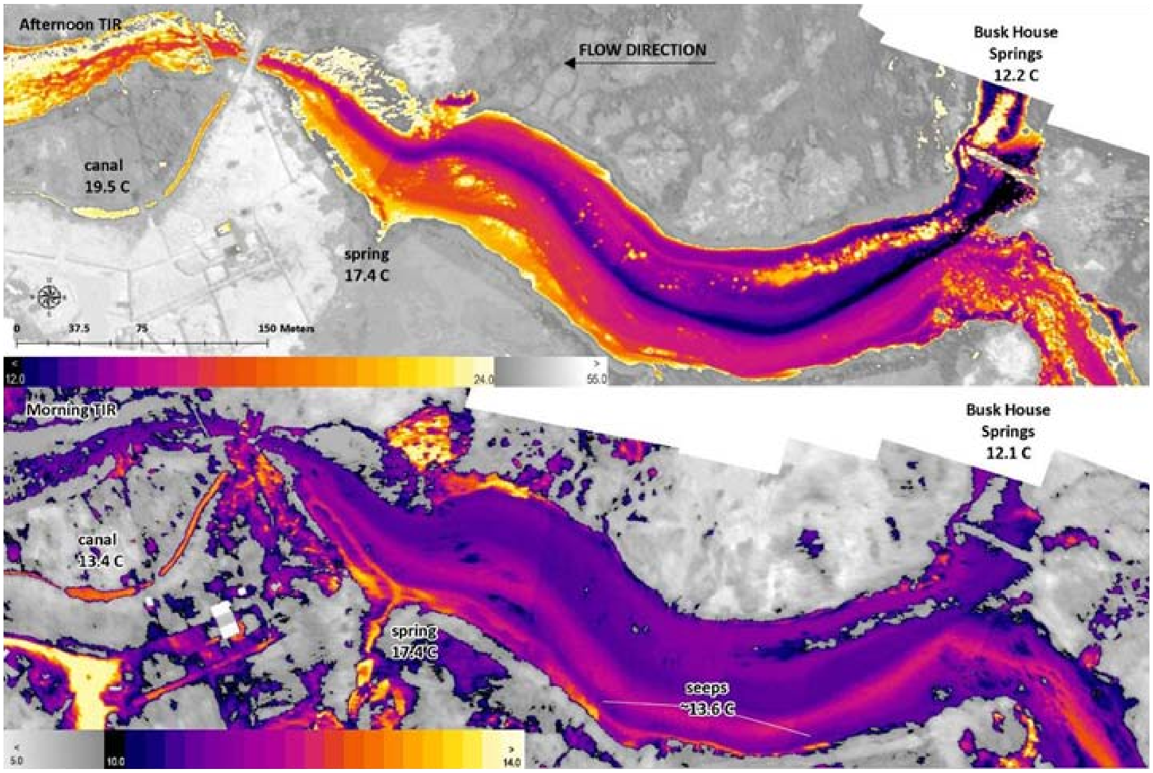

Figure 16. Surface water temperatures in the football field are illustrated using aerial thermal infrared (TIR) imagery. Images taken on July 16, 2008 (afternoon) (top) and July 17, 2008 (morning) (bottom).

Three water temperature monitoring transects were established in the football field to monitor the lateral and longitudinal trends between August 2010 and October 2011 (Figure 17). Each transect consisted of five temperature loggers placed approximately 15 m (50 ft), 30 m (100 ft), 45 m (150 ft), 61 m (200 ft), and 76 m (250 ft) from the north (or river right) bank ("river left" and "river right" always describe a location relative to the downstream view of a waterway). These water temperature monitoring transects were maintained in addition to previously established, long-term water temperature monitoring locations.

Figure 17. Water temperature monitoring transects in the football field. The transects were established as part of a short-term special study. Other locations were monitored as part of the previously established, long-term water temperature monitoring program.

Data collected from each transect was plotted to examine maximum water temperature characteristics over the special study period (e.g., Transect 3 in Figure 18). While the images taken in 2008 show a diurnal shift between laterally well-mixed and laterally stratified water temperature conditions, the data collected in 2011also illustrate a seasonal shift in the extent of mixing or stratification. In October 2010, maximum water temperatures across the transect generally ranged between 12°C and 13°C, with no substantial water temperature difference between monitoring sites. By January 2011, some lateral stratification was apparent, with cooler water temperatures (9°C to 10°C) observed on river left and warmer water temperatures (12°C to 13°C) on river right. This lateral pattern continued through the summer, with the difference between maximum water temperature increasing and the location of warmer and cooler waters shifting. In August 2011, maximum water temperatures ranged from 13°C to 17°C across the transect. The relative position of warmer and cooler waters also shifted, with the warmest temperatures located on river left and cooler water temperatures located on river right. Similar dynamics occurred in Transects 1and 2.

The seasonal growth of aquatic vegetation may account for this shift, as dense, emergent aquatic vegetation was located between the river right and center of the stream channel, while between the center and river left, relatively little emergent aquatic vegetation grew. A special study of the shade characteristics of aquatic vegetation was completed in August 2011, which concluded that emergent aquatic vegetation can block approximately 88% to 94% of solar radiation (Willis and Deas, 2011b). The detailed velocity transects described in Willis *et al*. (2012) also illustrate that stream flow moves with far slower velocities through vegetated areas than through non-vegetated areas. The results of those two studies suggested that the emergent aquatic vegetation located in the football field may have restricted and directed stream flow from the springs through the vegetated areas while also providing shade to reduce heating as spring water moved downstream. When the aquatic vegetation senesced in the fall, water from the various springs could more easily comingle with waters across the transect. The free exchange of waters across the transect, combined with the reduced heating that occurs in late fall, resulted in almost fully mixed conditions across the transect again in October 2011.

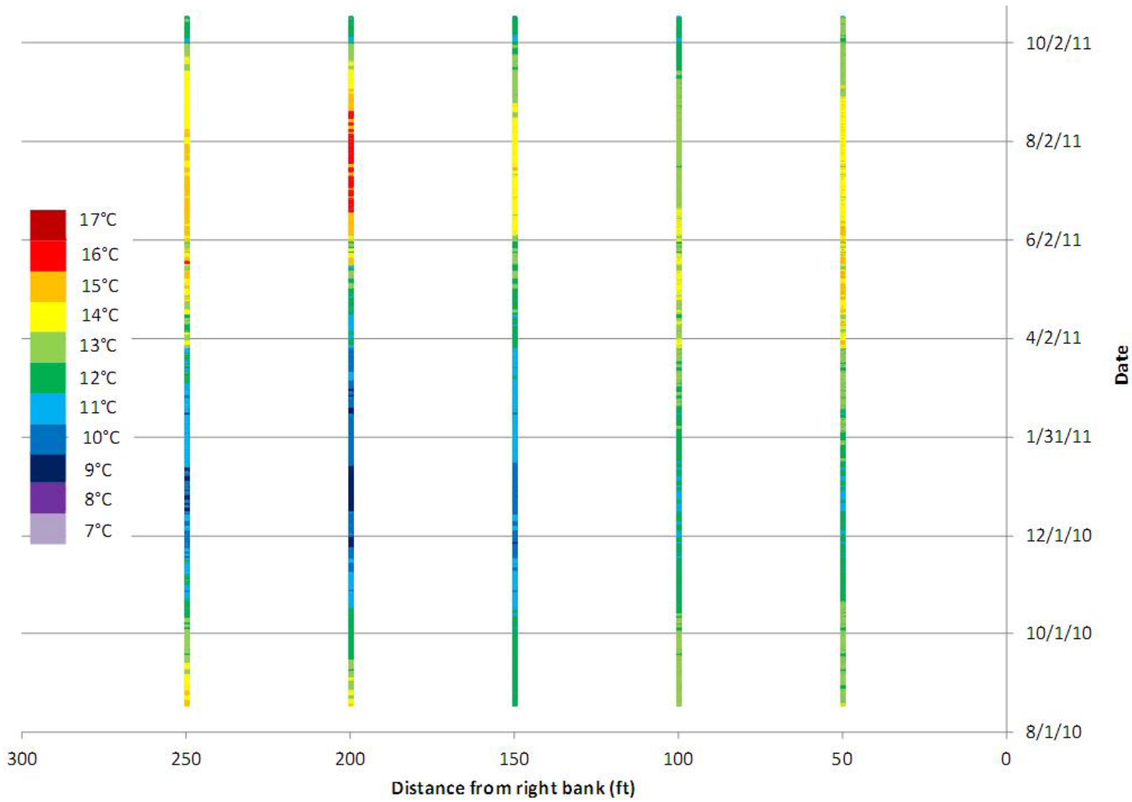

Figure 18. Water temperatures at each monitoring site in Transect 3 from August 2010 to October 2011.

The football field contains thermal diversity as a result of its proximity to spring sources, transport of water from Big Springs Dam, channel geometry, and seasonal vegetation growth. As previously described, heating rates through this reach are generally higher than for other reaches in Big Springs Creek (Figure 9), particularly during the summer, and have remained high despite several years of passive restoration. Daily and seasonal temperature trends illustrate a pattern of mixing and stratification that occasionally limit the extent of cool water in this reach, both in time and space. To preserve and extend cool water areas in this reach, active restoration options may be considered. Active restoration alternatives are explored later in this report.

5.3. Other Waterways and Special Studies

Though Big Springs Creek was the focus of water temperature monitoring during this project, other waterways that are located on Shasta Big Springs Ranch were also monitored to provide preliminary characterizations of water temperatures throughout the ranch. These other waterways include portions of the Shasta River, Parks Creek, Hole in the Ground Creek, and Little Springs Creek (Figure 1). Detailed maps of the 2011 monitoring locations on these waterways are provided in Figure 19 to facilitate interpretation of the data (with the exception of Little Springs Creek monitoring locations, which are shown in Figure 2, Figure 3, and Figure 4). Generally, due to limited project resources, these waterways were monitored as part of short-term special studies; thus, limited data for these waterways is available and may not cover the entire monitoring period between 2009 and 2011. A brief overview of the results of these special studies is presented here. Details describing the objective, methods, and results of these special studies have been documented in technical memoranda, which are referred to in each waterway's description (Appendix C). Electronic versions of these memoranda have been provided to TNC.

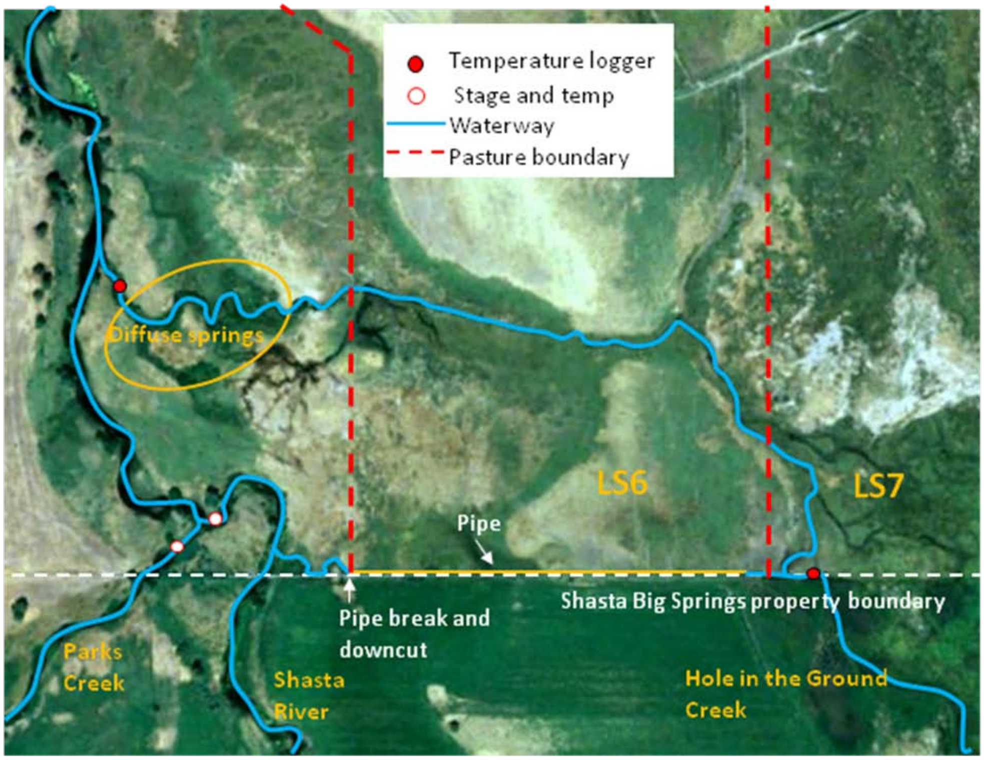

Figure 19. A map of monitoring locations on Hole in the Ground Creek, the Shasta River, and Parks Creek near the upstream Shasta Big Springs Ranch property boundary.

5.3.1. Shasta River and Parks Creek

The Shasta River and Parks Creek are two waterways that influence stream flows and water temperatures on Shasta Big Springs Ranch upstream of Shasta River confluence with Big Springs Creek. Monitoring locations were selected to characterize water temperatures in these two waterways as they flow across the ranch's property boundaries. By monitoring these locations, ranch and natural resource managers could better understand baseline conditions of these waterways as they entered the property, thereby identifying whether downstream water temperature conditions were a result of processes that took place in the stream reaches on Shasta Big Springs Ranch or were inherited from upstream reaches. Because of the long-term importance of addressing water temperatures in these waterways, permanent monitoring sites were established that provide data in real-time via remotely accessible monitoring stations (see Willis and Deas (2010a), Willis and Deas (2010c), and Willis and Deas (2011a) for details on the remote monitoring network). An overview of 2011 water temperature conditions in each waterway is presented here for the reaches located on Shasta Big Springs Ranch. For a more detailed discussion of water temperatures in the Shasta River, please refer to Nichols *et al*. (2010). As of this writing, a comprehensive assessment of water temperatures in Parks Creek has not yet been documented.

As the stream enters Shasta Big Springs Ranch, Shasta River flow volumes are generally defined by releases from Dwinnell Dam, groundwater accretions, and diversions by upstream water users; uncontrolled flows due to spill from the dam occur infrequently (approximately once every ten years). Parks Creek can contribute large volumes of water to the Shasta River reach upstream of Big Springs Creek, but flows generally decrease and water temperatures generally increase throughout the summer. Seasonal growth and senescence of in-stream vegetation makes rating either waterway challenging (Andrew Nichols, personal communication, 6/15/2012). Continuous flow records for these waterways were not available for this analysis.

During the 2011 water year (WY2011), which begins on October 1, 2010 and ends on September 30, 2011, water temperatures in the Shasta River and Parks Creek on Shasta Big Springs Ranch showed generally similar trends (Figure 20 and Figure 21). During the fall and early winter (October through January), maximum, mean, and minimum water temperatures are generally similar, though daily water temperatures in Parks Creek tend to vary more than those in the Shasta River. In late winter and early spring (February through March), water temperatures remain relatively stable, though daily variability increases. Beginning in late spring (April) and continuing through early summer (July), water temperatures increase, at which time they generally remain stable or decrease beginning in the fall (September).

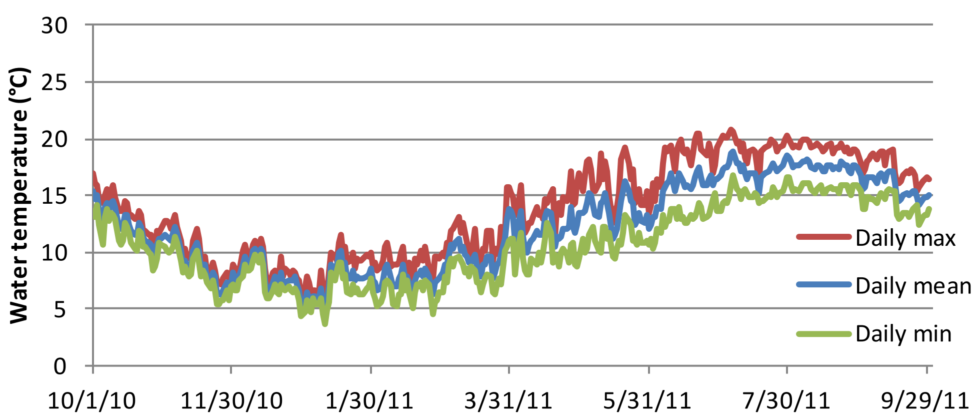

Figure 20. Daily maximum, mean, and minimum water temperatures during WY2011 measured in the Shasta River above Parks Creek as it flows onto Shasta Big Springs Ranch.

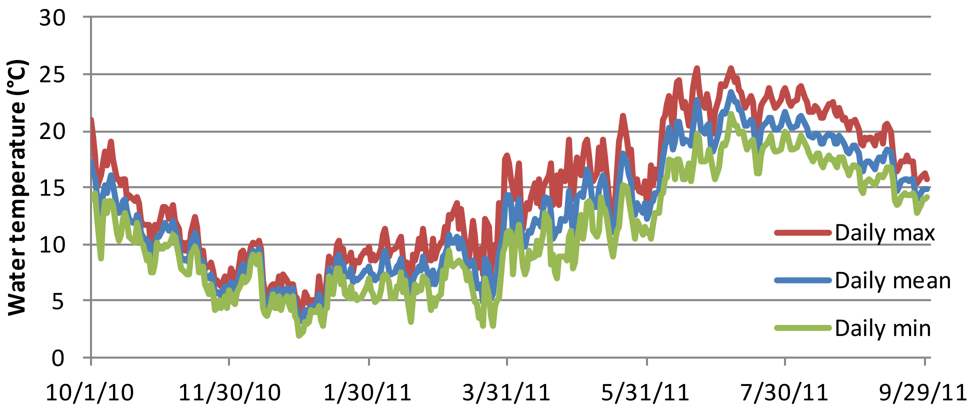

Figure 21. Daily maximum, mean, and minimum water temperatures during WY2011, measured at the mouth of Parks Creek where it flows onto Shasta Big Springs Ranch.

Peak maximum, mean, and minimum water temperatures tended to occur during early summer during 2011. Such conditions can vary to some degree based on water year type (wet, normal, or dry) and local meteorological conditions. Maximum water temperatures near the points where the Shasta River and Parks Creek flowed on to Shasta Big Springs Ranch peaked at 20.8°C and 25.6°C, respectively. Mean water temperatures peaked at 18.9°C and 23.5°C. Minimum water temperatures peaked at 15.9°C and 21.5°C. A summary of magnitude and timing of peak maximum, mean, and minimum water temperatures in each waterway is presented in Table 7.

Table 7. Peak maximum, mean, and minimum water temperatures in the Shasta River and Parks Creek during WY2011, measured where each flows onto Shasta Big Springs Ranch.

Location (RM)	Peak Max (°C)	Date	Peak Mean (°C)	Date	Peak Min (°C)	Date
Shasta River above Parks Creek (RM 35.0)	20.8	7/6/2011	18.9	7/7/2011	16.7	7/7/2011
Parks Creek mouth (RM 0.0)	25.6	7/7/2011	23.5	7/7/2011	21.5	7/7/2011

Water temperature management options for both waterways on Shasta Big Springs Ranch are limited and would require cooperation and collaboration with upstream landowners and water resource managers. Though the potential benefit of water temperature management options has not been quantified, the contributions of the Shasta River above Parks Creek and Parks Creek are typically small flows in the summer period.

5.3.2. Hole in the Ground Creek

Hole in the Ground Creek is a waterway that offers off-channel habitat to the Shasta River upstream of Big Springs Creek. A portion of the creek can be diverted for irrigation on Shasta Big Springs Ranch, however, the mouth of the creek near the confluence with the Shasta River receives water from groundwater contributions, though whether these groundwater sources are springs or upwelling due to recharge from local irrigation is unknown (Figure 19). A special study was completed that compared the water temperatures of the creek as it flowed onto Shasta Big Springs Ranch with the water temperatures from the diffuse spring flow near the creek's confluence with the Shasta River (Willis and Deas, 2010b). Though this study was completed in 2009, monitoring continued through 2011.

The results of subsequent monitoring have supported the findings of the original study: during irrigation season (April 1 to September 30), the surface water in Hole in the Ground Creek is generally unsuitable for cold-water species. However, when the surface water is diverted for irrigation and stream flow consists of groundwater accretions near the mouth of the creek, Hole in the Ground Creek can provide an off-channel thermal refugia. This condition occurred in much of 2009 (Figure 22); after approximately June 1 in 2010 (Figure 23); and after June 1 in 2011, but with sporadic releases to the river in mid-June, late-July, late-August, and mid- and late-September (Figure 24). Hole in the Ground Creek water temperatures at the Shasta Big Springs Ranch property boundary can exceed 20°C, and sometimes 25°C. When these surface water comingle with groundwater accretions near the mouth of Hole in the Ground Creek, water temperatures at the mouth mimic the surface water temperature trends, though peak water temperatures at the mouth are generally lower than those at the property boundary. For example, when surface water was allowed to comingle with groundwater accretions between April and June 2010 and 2011, water temperatures at the mouth followed a similar trend as those at the property boundary. However, once surface water was diverted for irrigation, water temperatures near the mouth of the creek illustrated a more stable diurnal signal and generally ranged between 13°C and 17°C.

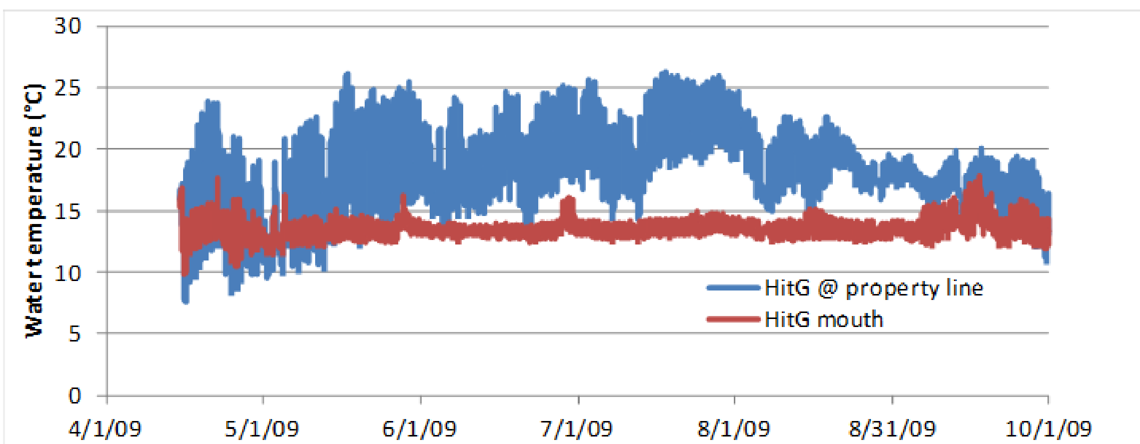

Figure 22. Water temperatures in Hole in the Ground Creek during the 2009 irrigation season.

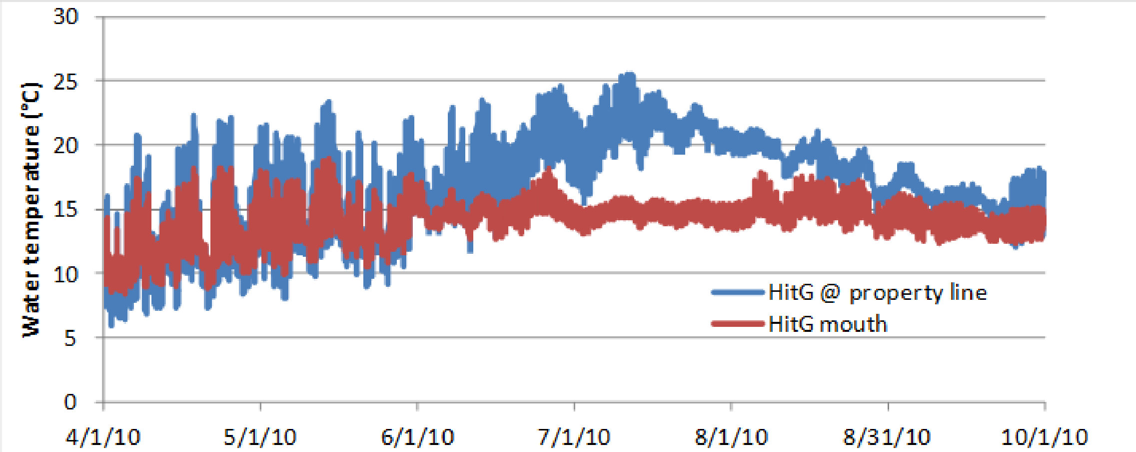

Figure 23. Water temperatures in Hole in the Ground Creek during the 2010 irrigation season.

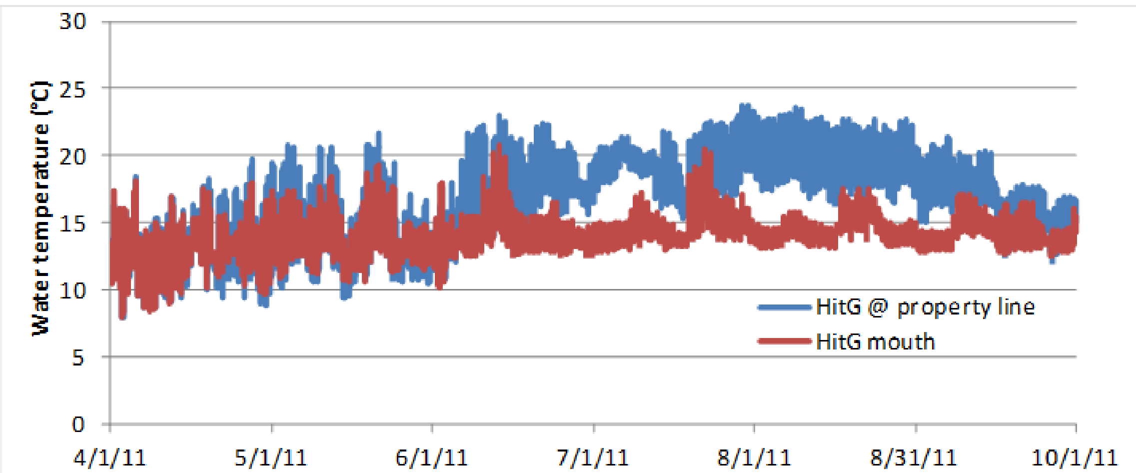

Figure 24. Water temperatures in Hole in the Ground Creek during the 2011 irrigation season.

Management activities are currently focused on limiting the comingling of the surface and groundwater in Hole in the Ground Creek by diverting the appropriated water for irrigation and returning the remaining surface water to the Shasta River at an alternative location. As this creek flows across adjacent properties, additional access would need to be provided to the upstream reaches to further characterize water temperatures and the potential benefit of additional management actions.

5.3.3. Little Springs Creek

Water temperatures in Little Springs Creek were characterized in 2009 as part of a special study (Willis *et al.*, 2010a). However, as restoration actions have been implemented on this waterway, including cattle exclusion (and considering the rapid response similar waterways have had to these actions (e.g., Big Springs Creek)), new studies should be completed to accurately characterize water temperatures in Little Springs Creek. Some short-term special studies have been planned for 2012 in collaboration with the National Fish and Wildlife Foundation, which will improve understanding, though not fully characterize, Little Springs Creek.

5.4. Water Temperature Summary

Four controlling factors were identified that define water temperature conditions in Big Springs Creek: groundwater-fed springs, channel geometry, meteorological conditions, and aquatic vegetation. Monitoring each of these factors allowed for a comprehensive assessment of water temperature conditions in Big Springs Creek. Groundwater-fed springs and channel geometry form the foundation of the water temperature regime in Big Springs Creek. The seasonal and inter-annual water temperature characteristics are defined by the meteorological conditions and strongly influenced by the presence or absence of aquatic vegetation.

Water temperatures in Big Springs Creek have demonstrated a rapid and substantial response to restoration actions that supported the re-establishment of aquatic vegetation – specifically, the construction of a riparian fence to exclude cattle from riparian and in-stream grazing. Maximum water temperatures have declined approximately 4°C since restoration actions were implemented. Despite this decline, water temperatures still occasionally exceed project goals (i.e., water temperatures exceed 20°C at the mouth of Big Springs Creek). These elevated water temperatures tend to occur between April and June, when aquatic vegetation is submerged beneath the water surface and does not provide shade or reduce in-water column mixing. The key heating reach in Big Springs Creek, the "football field," is located where the creek is wide and shallow and the slope is minimal.

Some work has been completed to examine water temperature conditions in reaches of the Shasta River, Parks Creek, and Hole in the Ground Creek on Shasta Big Springs Ranch. Due to limited project resources, this work consisted of special studies that examined water temperature conditions over short periods. These special studies helped identify or monitor the effects of management actions that were implemented to address water temperature objectives. Because of the limited scope of these studies, the current water temperature conditions in these waterways may not be fully characterized, particularly in reaches where restoration actions have been implemented since the original study (e.g., Little Springs Creek) or where limited access prevented a full characterization of the waterway (e.g., Parks Creek). Nonetheless, important gains in understanding of the thermal conditions in these waterways have been achieved through these special studies.

6. Potential Future Conditions

Given the rapid response of Big Springs Creek to restoration actions, assumptions made in 2009 regarding potentially effective restoration actions were reassessed given current (i.e., 2011) conditions. Though water temperature conditions for cool-water fish species have substantially improved, the original project goal of maintaining water temperatures below 20°C at the mouth of Big Springs Creek is occasionally exceeded. The monitoring program that was implemented from 2009-2011 has provided extensive data that characterizes current water temperature conditions in space and time in considerable detail. As well as characterizing on-the-ground conditions, this data was used to update an existing, numerical water temperature model of Big Springs Creek, called the Big Springs Model (TBSM –see Appendix A for details regarding model updates). Using

TBSM, a range of potential restoration activities can be re-evaluated for their effectiveness and remaining resources can be directed to high-value actions.

After TBSM was updated to represent 2011 water temperature conditions in Big Springs Creek, two alternative restoration actions were simulated. The first examined the long-term potential of peak water temperature reductions by estimating future conditions given completed restoration actions – specifically, riparian planting. The second alternative examined the strategy of water rights management associated with Shasta Big Springs Ranch and Nelson Ranch to identify any potential effects on water temperatures. Simulations were run under 2011 meteorological conditions when the most comprehensive data sets were available, which illustrated the effects of these actions during conditions that reflect a relatively wet winter and spring period. Simulations using relatively cool, wet conditions are assumed conservative in this case, identifying the potential lower bound to water temperature benefits given the assumed restoration actions. All results refer to changes in maximum water temperatures at the mouth of Big Springs Creek, as this location corresponds to the compliance point for the overall project goal. However, for simulations that target water temperature conditions in upstream reaches (e.g., the active channel restoration scenarios), changes at both the mouth and the specified upstream reach are discussed. Changes that were smaller than what could be measured by conventional water temperature data loggers (<0.2°C) are considered negligible; in this report, they are indicated as ND (non-detect).

6.1. Alternative Actions and Potential Outcomes

The alternative actions simulated using TBSM were identified based on completed and potential restoration actions considered for Big Springs Creek. Completed actions include riparian fencing, riparian planting, and tailwater control. Potential actions include active channel restoration in reaches where the highest heating rates are currently observed and water management of water rights associated with the Shasta Big Springs Ranch and Nelson Ranch. An overview of each restoration action and a summary of the results for each alternative are discussed below.

6.1.1. Long-Term Potential Response to Completed Actions

The recovery of Big Springs Creek is on-going, and while substantial reductions in water temperature have been achieved since the implementation of restoration actions in 2009, continued reductions may occur as the creek continues to respond. The short-term recovery has largely been due to cattle exclusion via riparian fencing. In addition to cattle exclusion, riparian planting of seral (e.g., *Schoenoplectus sp.*, *Sparganium sp.*, *Typha sp.*) and woody (e.g., *Salix sp.*, *Betula sp.*) vegetation was also implemented, as well as tailwater reduction. The effects of riparian planting are expected to manifest themselves over decades and will depend on the survival rate and distribution of the plantings. The potential long-term water temperature reduction due to this action was evaluated using TBSM. Estimates of current survival rates and vegetation mapping were provided by TNC.

TBSM represented riparian planting through a combination of shade and roughness features that were assigned to specific areas. Shade characteristics of seral and woody vegetation were estimated based on the results of a special study that was completed in 2011 (Willis and Deas, 2011b). The results of this shade study suggested that when aquatic vegetation and willows were fully leafed-out, they blocked an average of 88% and 93% of solar radiation, respectively. Percent solar radiation reduction was used as a surrogate for shade provided for each vegetation type. Though seral vegetation was not examined in this special study, shade provided by this type of vegetation was estimated to be approximately 90% (i.e., between the amount of shade provided by aquatic and woody vegetation), which is consistent with previous studies on the Shasta River (Abbott, 2002). Roughness estimates were provided by the U.C. Davis Center for Watershed Science as part of their work under the National Fish and Wildlife Foundation Keystone Initiative grant. This work suggested that in-stream aquatic vegetation produced a depth-averaged channel roughness of approximately 0.31 to 1.63 (Andrew Nichols, personal communication, 12/13/2011). Because willows (*Salix sp.*) were planted on stream banks, they provided shade, but no in-stream roughness; the roughness for an area that was shaded by a willow was set to the same roughness as a non-vegetated area (i.e., 0.02). The density and location of vegetation in TBSM is assigned using survival and distribution surveys provided by TNC. TNC estimated that the survival of riparian plantings was approximately 75%, and that the remaining plantings provided coverage to approximately 50% of the stream banks located on Shasta Big Springs Ranch (Ada Fowler, personal communication, 6/20/2012). A summary of shade, roughness, and distribution of riparian plantings are provided in Table 8 and Figure 25.

Table 8. A summary of the shade and roughness characteristics used to simulate the effects of riparian plantings and in-stream vegetation in TBSM.

Vegetation Type	Shade (%)	Roughness
Aquatic vegetation	88	0.310
Seral growth (tule (*Schoenoplectus sp.*)/bur-reed (*Sparganium sp.*), cattail (*Typha sp.*))	90	0.310
Willow	93	0.020*

*Because willows were planted on stream banks, they provided shade, but no appreciable increase in in-stream roughness was assumed; the roughness for an area that was shaded by a willow was set to the same roughness as a non-vegetated area.

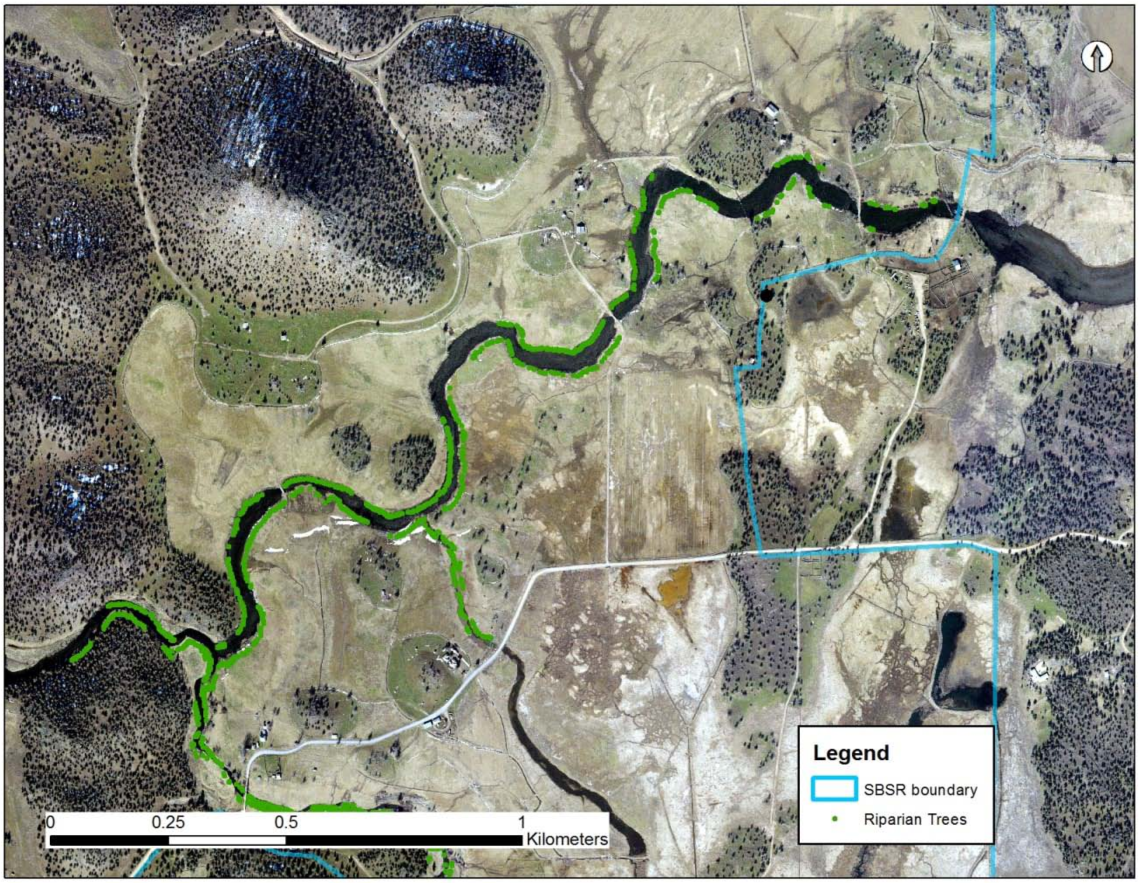

Figure 25. A map of riparian planting locations on Big Springs Creek and parts of other waterways on Shasta Big Springs Ranch (SBSR). Figure provided by The Nature Conservancy.

The results of the long-term potential riparian planting simulations suggested that riparian growth will reduce peak water temperatures in Big Springs Creek, particularly during the early summer when aquatic vegetation has not yet emerged above the water surface (Table 9). From April through June, peak water temperature reductions were more than 0.5°C. From July through September, when aquatic macrophytes provide shade to the water surface of Big Springs Creek, peak water temperature reductions due to riparian plantings were not detectable.

Table 9. A summary of potential water temperature changes at the mouth of Big Springs Creek due to the long-term effects of riparian planting.

Scenario	Apr-Jun	Jul-Sept	Average
Riparian planting	0.5°C	ND	0.2°C<ΔT<0.5°C

6.1.2. Water Management

The other alternative restoration action that was examined focused on managing water rights associated with Shasta Big Springs Ranch to determine if placing adjudicated water rights in-stream effected water temperatures. TNC's purchase of Shasta Big Springs Ranch included the acquisition of water rights associated with the property. These water rights vary in volume and location, and can be used to irrigate the ranch during irrigation season (April 1 to September 30). A summary of all of TNC's water rights, including their source, volume, diversion numbers, and priority date, are presented in Table 10.

Table 10. A summary of the water rights associated with Shasta Big Springs Ranch.

Source	Diversion Number	Water Right (cfs)	Priority Date
Shasta River*	247, 248	2.3	3/18/1914 3/21/1899
Hole in the Ground Creek	167, 168, 169, 170	1.5	4/1/1893 2/15/1898 4/1/1898 4/1/1900
Little Springs Creek	243, 244, 245, 246	7.6	6/15/1891 4/1/1893 4/11/1892 4/1/1900
Big Springs Creek	241	~6.71**	4/1/1872
Total		**18.11**	

*Water right is associated with TNC's Nelson Ranch, the property located directly downstream of Shasta Big Springs Ranch on the Shasta River.
**Diversion shared with Busk Ranch. Shasta Big Springs Ranch takes 10 cfs for 7 days of a 10-day rotation.

Management strategies of Big Springs Creek and Little Springs Creek water rights were simulated using TBSM; Shasta River and Hole in the Ground Creek water rights were based on the Shasta River TMDL model. Simulations included individual and combined in-stream dedications of water rights. The detailed results of the water management modeling were presented to TNC and the California Department of Fish and Game (CDFG) and are documented in a separate report (Willis and Deas, 2012). An overview is presented herein.

These results represent a Phase I scoping analysis to identify potential scenarios and feasibility. For example, for this initial scoping exercise, the model was not recalibrated. Therefore, results are qualitatively evaluated. The results of the water management scenarios suggested that in-stream water right dedications fell into one of three general categories. :

1. Increased or did not change water temperatures,
2. Changed water temperatures locally, but not on a reach-scale, or
3. Changed water temperatures both locally and on a reach-scale.

Local water temperatures changes were defined as changes that occurred in the vicinity where the water right was physically returned to the stream (or in certain cases not diverted). For example, Little Springs Creek flows into Big Springs Creek; a local water temperature change was defined as a temperature change that occurred in Big Springs Creek at the confluence with Little Springs Creek. Reach-scale water temperature changes were defined as changes that could be detected at a downstream location where water temperature trends may also be affected by other factors. For example, to examine reach-scale effects of Little Springs Creek, water temperatures were examined at the mouth of Big Springs Creek, prior to its confluence with the Shasta River. Water rights that illustrated a reach-scale effect were combined with others to see if benefits would extend further downstream given combined in-stream dedication volumes.

Generally, the effectiveness of an in-stream dedication depended on year-type, and the source, timing, relative volume, and relative temperature of the water right to the receiving body of water. Little Springs Creek water right affected water temperatures on both a local and reach-scale. Big Springs Creek and Hole in the Ground Creek water rights affected local water temperatures, but not reach-scale water temperatures. The Shasta River water right had no effect on water temperatures. A summary of each water right in-stream dedication scenario is presented in Table 11.

Table 11. A summary of results for water management alternatives that focus on in-stream dedications of water rights associated with Shasta Big Springs Ranch and Nelson Ranch.

Scenario	Local Effect	Reach-Scale Effect
Hole in the Ground Creek	Yes*	No
Big Springs Creek	Yes	No
Little Springs Creek	Yes	Yes
Big Springs Creek and Little Springs Creek	Yes	Yes
Shasta River	Yes	No

*Examined empirically; see section 5.3.2

The results of the water management modeling were used to identify potential empirical experiments that would further characterize the effects of these dedications on water temperatures. These experiments are planned for 2012 and are performed in partnership with the National Fish and Wildlife Foundation as part of a project funded through a U.S. Department of Agriculture, Conservation Innovation Grant.

6.2. Summary

TBSM was used to examine how water temperatures in Big Springs Creek might respond to long-term or potential water management actions. The long-term effects of already-implemented restoration actions (e.g., riparian planting) may result in further reductions (<0.5°C) to peak water temperatures. However, the timeframe for achieving these reductions is projected to take several years to decades. Further, long-term projections include some uncertainty as the channel form and vegetation assemblage and distribution continue to respond to already-implemented restoration actions. Generally, the effectiveness of water management alternatives depended on year-type, and the source, timing, relative volume, and relative temperature of the water right to the receiving body of water.

7. Conclusions

Water temperatures in Big Springs Creek have shown a substantial and rapid response to restoration actions that were implemented from 2009 through 2011. The most effective action was riparian fencing which resulted in cattle exclusion from the channel. This allowed for the recovery of in-stream aquatic vegetation that reduced travel time through the stream and shaded the water surface during the mid-to-late summer. Though peak water temperatures have steadily decreased since restoration began in 2009, the project target is still occasionally exceeded. Recall, project target temperatures were:

1. In the first 24 months of restoration, daily maximum temperatures at the mouth of Big Springs Creek should not exceed 20^{o}C.

2. After five years of restoration activity, daily maximum temperatures should not exceed 18^{o}C.

While daily maximum temperatures in excess of 20^{o}C historically (pre-restoration) were commonplace from April through August, the number of days when temperatures in excess of 20^{o}C were observed have been reduced in magnitude and frequency since restoration activities were implemented. Specifically, the seasonal maximum daily water temperature was 25.3^{o}C in 2008, which was reduced to 21.1^{o}C in 2011, a 79.2% reduction towards target. In addition to the reduction in the seasonal daily maximum water temperature, the number of days in excess also decreased – from 95 days in 2008 to only 16 days in 2011 (an 83.1% reduction). Of those 95 days in 2008, there was a continuous stretch of 30 days when temperatures exceeded 20°C. By 2011, the longest stretch of continuous days above 20°C was reduced to 5 days.

A review of Figure 13, which illustrates water temperature at the mouth of Big Springs Creek and the Shasta River upstream of the confluence, indicates that the reduction in water temperatures is not entirely the result of variable meteorological conditions (i.e., 2008 being a warm year and 2011 being a cool year). Rather, the seasonal high water temperatures have been steadily declining in Big Springs Creek from 2008 to 2011, while seasonally high water temperatures in the Shasta River above the confluence have remained approximately the same (23^{o}C to 25^{o}C, which was similar to Big Springs Creek prior to restoration). A summary of these conditions is included in Table 4 and Table 5.

A comparison of water temperatures at the mouth and at a location upstream of the confluence (about one mile), indicated that water temperatures are already nearing the 5-year goal of 18°C. Given that under the restored condition there are no impediments to access through this one-mile reach (from the lowest drivable bridge to the mouth), and that there is sufficient physical habitat at the lowest drivable bridge and in adjacent upstream reaches, juvenile fish could readily re-distribute upstream during warm periods and avoid adverse impacts due to short-term periods when water temperatures at the mouth become less desirable. This condition illustrates the immeasurable value of Big Springs Creek as a reach-scale feature that provides a diversity of persistent, interconnected, cold water habitats during the late spring through early fall period. For example, compare this to a typical thermal refugia, where habitat is constrained to a small area and there is little or no opportunity to relocate if conditions degrade. In 2008, the pool immediately below Big Springs Dam represented such a thermal refugia. After several years of restoration, cold water habitats and physical habitats are widespread on the reach-scale, connecting not only reaches within Big Springs Creek, but also providing access to and from the mainstem Shasta River.

To examine possible ways to meet the project goal, the Big Springs Model (TBSM) was used to evaluate several alternative actions. Of all the potential restoration actions that were evaluated using TBSM, none resulted in the same magnitude of water temperature reduction as has already been observed in Big Springs Creek. Though the range of additional restoration actions that were examined using TBSM was not exhaustive, the results of this analysis suggested that the restoration effort has entered a period of diminishing returns, where large investments of restoration resources will be required for relatively smaller reductions in water temperature. Additional alternatives or combinations of alternatives may yield greater benefits, particularly for local habitat enhancement; however, evaluating these options was beyond the scope of this project.

Despite the potentially modest returns that may result from future actions in Big Springs Creek, the current condition of the creek demonstrates clear and measureable success in a larger effort: the recovery of a federally and state-listed threatened species, coho salmon, in the Shasta Basin. Elevated water temperatures were identified as the key impairment to the survival and recovery of juvenile coho salmon. Concurrent studies with this water temperature assessment have illustrated that Big Springs Creek influences water temperatures in the Shasta River for tens of kilometers downstream of the two streams' confluence (Nichols *et al.*, 2010). The reductions in Big Springs Creek's water temperatures, combined with its influence on downstream reaches, has resulted in a wider distribution of juvenile coho salmon than was observed prior to the implementation of restoration actions on Big Springs Creek (Willis *et al.*, 2012). The result has been the increase in available over-summering habitat from tens of square meters in 2008 over a distance of tens of meters to thousands of square meters over a distance of several kilometers in 2011. With continued maintenance and monitoring, Big Springs Creek will continue to function as one of the highest-value cold-water streams in the Shasta Basin, as well as in the entire Klamath Basin.

8. Recommendations

To maintain the substantial improvements that have been achieved in Big Springs Creek, as well as to plan for potential future actions, several recommendations should be considered. These recommendations include:

1. Maintain and improve current restoration and monitoring activities.
    - Maintain riparian fence, as initial cattle exclusion has resulted in rapid and highly effective reductions in maximum water temperatures in Big Springs Creek. Consider developing a riparian management plan for managing the lands between the fence line and the stream.
    - Maintain the remotely-accessible monitoring network to track the progress of the restoration response as well as identify any future impairment.

- Continue to improve water management activities, such as improved irrigation efficiency, which will help restore the balance between agricultural water use and aquatic ecosystem demands.

2. Use TBSM to explore active channel restoration alternatives.
    - These simulations should include alternative channel design configurations as well as consider altering the channel slope within this reach. A particular area of focus should be upstream of the waterwheel, where cold water springs are located and the highest rates of currently heating occur. Modified channel design configurations could include local narrowing, shading, mid-channel islands, in-stream emergent vegetation planting.
    - Complete additional simulations using various meteorological and hydrological data from different year types to assess temperature impacts under a range of conditions.
3. Consider additional analyses and studies to identify reach specific temperature targets in Big Springs Creek to further refine the 5-year target of 18^{o}C in spatial and temporal scales that incorporate interconnected nature of Big Springs Creek and the Shasta River, as well as available physical habitat for coho salmon. Consider assessment of short-term redistribution of fish to avoid adverse condition in the lower-most reach of the creek, or possibly an ability of fish to be able to cope with slightly elevated temperatures due to low nighttime temperatures (e.g., providing a period for fish to recover).
4. Examine opportunities to partner with agencies, other stakeholders, and nearby landowners to improve water temperatures in locations other than Big Springs Creek. This would possibly lead to additional habitats and create potentially more diverse environments to support coho salmon, as well as other aquatic system benefits. Examples could include assessing restoration or water management options for Little Springs Creek, upstream Shasta River and Parks Creek, and other tributaries in the region. Outcomes could lead to improved water use efficiency, maintaining multiple uses of water, and supporting aquatic system needs.

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Appendices

Appendix A. The Big Springs Model (v5) Update

To evaluate the long-term potential of restoration actions that were implemented on Big Springs Creek from 2009 through 2011, and to evaluate the potential effects of future restoration actions, Watercourse Engineering, Inc. (Watercourse) updated and applied the Big Springs Model (TBSM). TBMS was developed in 2009 as a two-dimensional flow and water temperature model to represent Big Springs Creek in its pre-restoration (i.e., 2008) condition. The development and application of TBSM (v1) was documented in Jeffres *et al*. (2009). As Big Springs Creek experienced a rapid response to restoration, baseline conditions in 2008 were no longer representative of baseline conditions in 2011. Therefore, TBSM had to be updated to represent 2011 conditions before it could be applied to evaluate alternative restoration scenarios. In this section, updates that were incorporated into TBSM to represent 2011 conditions in Big Springs Creek are identified. The current version of the model is TBSM (v5).

A.1. TBSM Updates

There were several characteristics in Big Springs Creek that were represented in greater detail in TBSM (v5). These characteristics included aquatic vegetation, groundwater-fed springs, local meteorological conditions, and bed conduction. Aquatic vegetation was simulated through a combination of seasonal growth mapping, channel roughness, and shade. Groundwater-spring sources were simulated using refined discharge volume estimates and water temperature data. Meteorological conditions were represented using data collected at the study site. Finally, bed conduction was added to TBSM. In this section, a detailed description of the updated representation is provided.

A.1.1. Aquatic Vegetation

The results of the Big Springs Creek water temperature monitoring program illustrated that seasonal aquatic vegetation growth had a strong influence on water temperatures. Thus, to develop a model that accurately simulated water temperature in Big Springs Creek, aquatic vegetation had to be well-represented. Among the conclusions regarding the effects of aquatic vegetation on water temperatures were:

1. The effects of aquatic vegetation could be categorized into two periods: one when aquatic vegetation was submerged beneath the water surface and provided roughness, but no shade; and the second, when aquatic vegetation emerged above the water surface and provided roughness and shade.

2. Aquatic vegetation contributed substantial channel roughness that affected water depths and velocities throughout Big Springs Creek.

3. Aquatic vegetation contributed substantial shade to Big Springs Creek when it emerged above the water surface during the late growing season (approximately July-September), which mitigated the effects of ambient meteorological conditions.

These conclusions were used to guide the development of aquatic vegetation features in TBSM.

The seasonal growth cycles of aquatic vegetation, and the effects of those cycles on water temperatures, meant that an accurate spatial representation of aquatic vegetation had to be determined. One of the features of TBSM is a graphical interface where spatial details of a stream system, such as aquatic vegetation, can be defined. This graphical interface is called a geometry file (Figure A-1). Each geo file consists of an element array. Each element is assigned a type, and each type represents a specific combination of roughness and shade features. For TBSM, two geo files were developed: one that illustrated the spatial distribution of aquatic vegetation during early seasonal growth (April-June), and one that illustrated late-season growth (July-September). These periods were selected to distinguish the time when aquatic vegetation transitioned from submerged to emergent. Cover surveys provided by The Nature Conservancy (TNC) and field photos taken by Watercourse were used to estimate the spatial distribution of in-stream and riparian vegetation. Roughness values were determined using detailed velocity surveys taken across two vegetated transects in Big Springs Creek by U.C. Davis Center for Watershed Science. Watercourse conducted shade experiments in July and August 2011 to determine the relative shade contributions of aquatic and woody vegetation; seral vegetation shade was estimated.

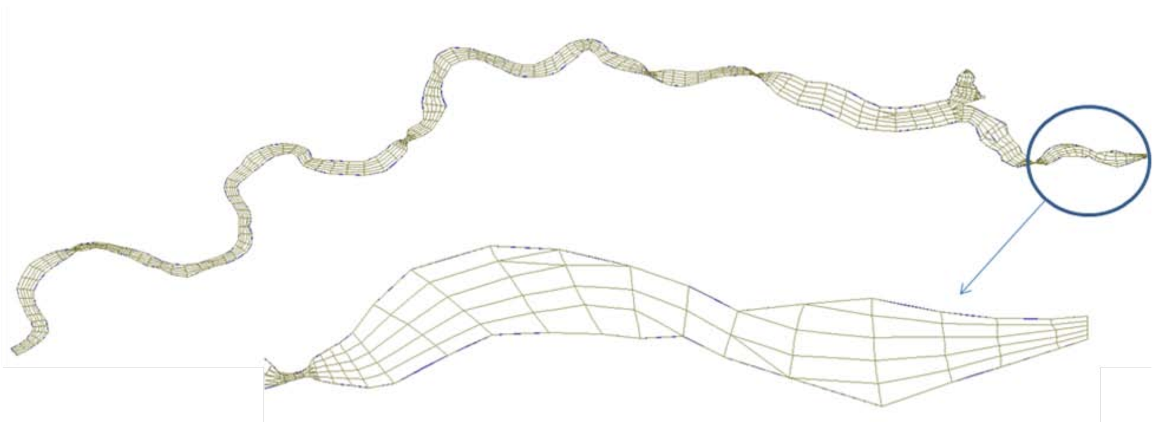

Figure A-1. A graphical illustration of a geo file representing Big Springs Creek. The grid consists of an array of elements, which are each assigned a "type" that represents a specific combination of roughness and shade features. An enlarged portion of the grid is shown to more clearly illustrate individual elements.

Ten elements types were defined for TBSM, of which six types represented vegetation (Table A-1). These six element types distinguished between vegetation types (e.g., aquatic vegetation, seral vegetation, and willows), as well as variations within a group of vegetation. For example, aquatic vegetation was distinguished by its seasonal growth cycle (i.e., submerged versus emergent) and by its location (i.e., in the football field versus in the rest of the creek – for a description of the football field, please see section 5.2.1.2). The decision to distinguish aquatic vegetation by its location was based on the results of the model's calibration. Water depths and velocities in the football field were sensitive to the model's representation of channel geometry and roughness in that reach.

To best represent observed conditions in that reach, unique roughness values were assigned to aquatic vegetation elements located there.

Table A-1. A summary of element types that are defined in TBSM.

Element Type	Description	Roughness (n)	Shade (% Solar Radiation Reduction)
1	Open channel	0.070	0%
2	Aquatic vegetation (submerged)	0.310	88%
3	Aquatic vegetation (emergent)	0.310	88%
4	Seral vegetation	0.310	90%
5	Willow	0.020	93%
6	Rock berm	0.500	100%
7	Bedrock (exposed)	0.020	0%
8	Bedrock (not exposed)	0.020	100%
9	Aquatic vegetation (submerged, in football field*)	0.410	88%
10	Aquatic vegetation (emergent, in football field*)	0.410	88%

* For a description of the football field, please see section 5.2.1.2

A.1.2. Groundwater-Fed Springs

Groundwater-fed springs were another critical characteristic of Big Springs Creek that needed to be well-represented in TBSM. The location, discharge rate, and water temperature of each spring needed to be well-represented to accurately simulate boundary conditions in TBSM. The spatial distribution of discrete groundwater-fed springs had been previously defined in TBSM (v1) (see Jeffres *et al.* (2009) for details). The water temperature monitoring program provided an opportunity to monitor water temperatures in discrete groundwater-fed springs in Big Springs Creek over a three-year period. In addition, a concurrent monitoring program, funded by the National Fish and Wildlife Foundation, provided an opportunity to monitor monthly accretion volumes in the reach where the groundwater-fed springs were located. Data from these two monitoring programs allowed for a more refined representation of flow and water temperature characteristics of discrete groundwater-fed spring sources in Big Springs Creek.

Five discrete groundwater-fed springs were defined in TBSM, which corresponded to the five springs that were identified in section 5.1.1. Monthly discharge measurements, taken by U.C. Davis Center for Watershed Science, were used to estimate the total monthly average accretion contributed by the springs. Though individual springs could be identified in this reach, the diffuse nature of each spring's flow contributions made quantifying flow accretions by individual springs challenging. Instead, field observations were used to estimate the relative percent contribution of each spring, which was then applied to the total flow measurement to determine flow volumes for each spring (Table A-2). Water temperatures were defined using hourly water temperature data measured at each spring (please refer to section 5.1.1 for details regarding water temperatures measured at discrete springs).

Table A-2. A summary of the estimated flow volumes defined for discrete groundwater-fed springs in Big Springs Creek.

Site #	Spring Description	Flow Contribution (Estimated as a Percentage of Total Spring Inflow)
1	North alcove spring	18%
2	East alcove spring	27%
3	Blw. Busk bridge, RR	23%
4	Blw. Big Springs island, RL	8%
5	Blw. Busk bridge, RL	23%

A.1.3. Meteorological Data

Another feature of TBSM that was re-evaluated during the model update was the source of meteorological data. Meteorological data is a key component used to calculate water temperatures in TBSM. One of the special studies completed during the 2009-2011 monitoring program examined whether using local meteorological data (i.e., data gathered at the study site), rather than regional meteorological data (i.e., data gathered approximately nine miles south from the study site, at Weed Airport) improved model performance (Willis and Deas, 2010d). The special study concluded that local meteorological data did improve model performance; as a result, a meteorological station was installed at the study site (Figure A-2), and data from this station was used to define all meteorological characteristics in TBSM.

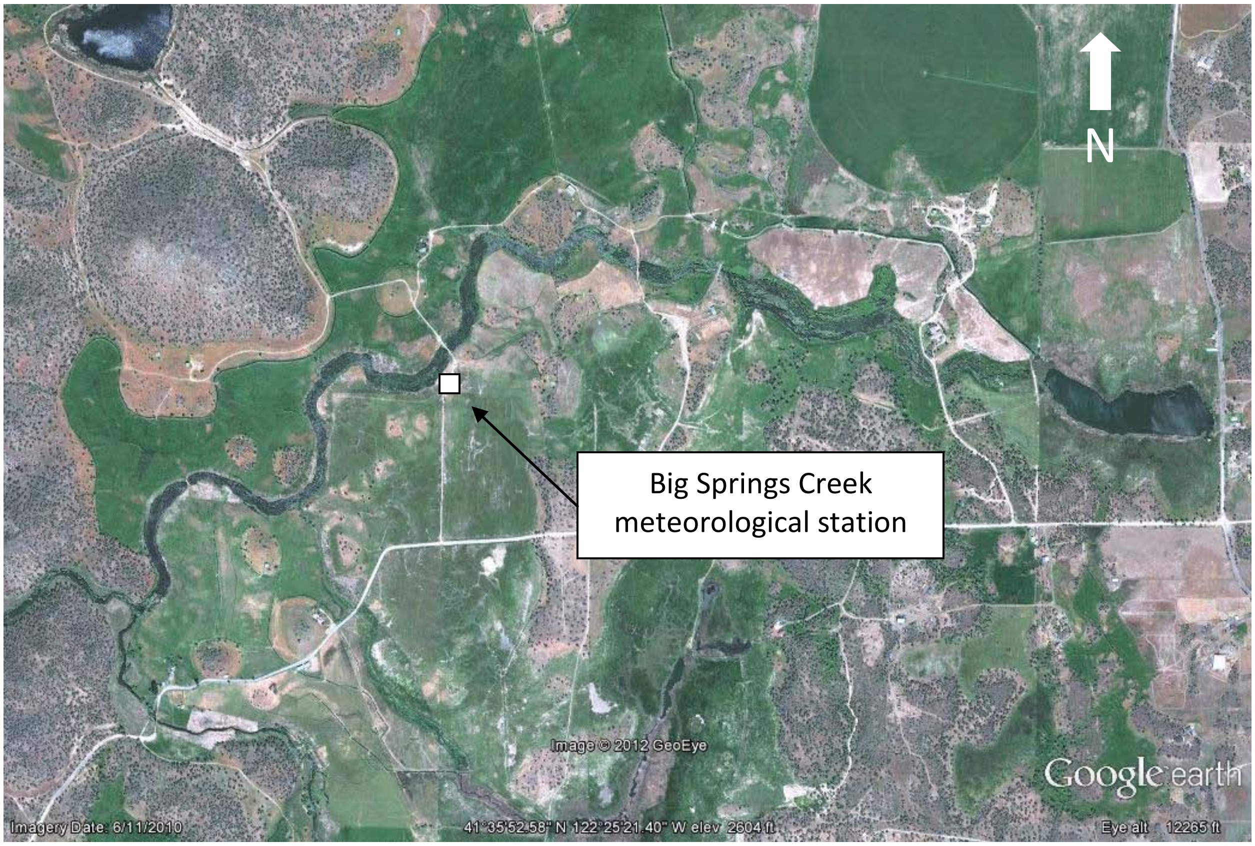

Figure A-2. A map of the local meteorological station installed near Big Springs Creek.

A.1.4. Bed Conduction

Finally, bed conduction was incorporated into TBSM. Bed conduction refers to the heat transfer that takes place between the stream bed and water body. Generally, bed conduction is not a significant term in the overall heat budget of a stream; however, due to the relatively wide and shallow geometry of Big Springs Creek, as well as the substantial groundwater accretions that occur through some reaches, bed conduction played a larger role than usual. In TBSM, bed conduction was used to limit the diurnal range of water temperatures by acting as a heat source or sink to the water. A monthly average bed temperature was estimated for the April through September period of analysis; values were determined through calibration (Table A-3).

Table A-3. A summary of bed temperatures estimated for the bed conduction feature in TBSM.

Month	Bed Temperature (°C)
April	16.0
May	15.0
June	15.0
July	17.0
August	16.0
September	17.0

A.2. TBSM (v5) Performance

After each update was incorporated into TBSM, model performance greatly improved, particularly its representation of peak water temperatures. Model performance was determined by comparing how closely TBSM simulated water temperatures that represented observed conditions in both space and time. Ten locations were selected throughout Big Springs Creek at which simulated water temperatures were compared to observed water temperatures (Figure A-3). The comparison consisted of examining the mean bias, mean absolute error (MAE), and root mean square error (RMSE) of the results.

Figure A-3. A map of the sites at which TBSM results were compared to measured water temperature data.

Mean bias indicated whether TBSM simulated results that were generally warmer or cooler than observed conditions – a positive bias indicated that the model simulated generally warmer simulations, and a negative bias indicated generally cooler simulation. MAE is used to determine whether the bias is systematic (i.e., all calculated results are consistently warmer or cooler). If the value of the MAE is similar to the mean bias, then the bias is systematic; if the two values differ, then the bias is not systematic (i.e., some results may be warmer, some cooler, and the mean bias simply indicates which one is more prevalent). Finally, the RMSE is examined to generally quantify the model's accuracy. For a water temperature model, a MAE and RMSE of less than 1°C is desirable.

The results at each of the ten calibration locations suggest that TBSM (v5) performs well; the model generally simulates water temperatures within 1°C of observed water temperatures (Table A-4). A comparison of mean bias and MAE results suggests that

TBSM has a systematic error at upstream locations (e.g., sites 1 through 4), but non-systematic error at downstream locations (e.g., sites 5 through 10). Thus, results at key locations, such as the mouth of Big Springs Creek, should be closely examined to fully understand their implications, particularly when TBSM is being applied to determine the potential cooling response of specific alternative restoration actions.

Table A-4. A summary of performance statistics for TBSM (v5).

Site #	Location Description	Mean Bias	MAE	RMSE
1	Big Springs Dam	0.0	0.0	0.0
2	Busk bridge	-0.8	0.8	1.0
3	Football field, upstream	0.3	0.5	0.7
4	Football field, downstream	0.5	0.8	1.0
5	Below waterwheel	0.4	0.8	1.0
6	Corral crossing	0.3	0.8	0.9
7	Lowest drivable bridge	0.3	0.8	1.0
8	Above Little Springs Creek	0.2	0.9	1.1
9	Lowest bridge crossing	0.1	0.8	1.1
10	Mouth	0.1	0.9	1.1

A.3. Conclusion

TBSM was updated to improve its representation of water temperatures in Big Springs Creek. The current version of the model is TBSM (v5). Four features were refined using data collected as part of the on-going water temperature monitoring program. These features included the spatial distribution and seasonal characteristics of aquatic vegetation, discharge volume and water temperature characteristics of groundwater-fed springs, local meteorological data, and bed conduction. Improving representation of these four features resulted in significant improvements to model performance; TBSM (v5) simulates water temperatures throughout Big Springs Creek within approximately 1°C of observed water temperatures. Given the level of accuracy simulated by TBSM (v5), this model can be used to evaluate local and reach-scale water temperature changes due to a range of alternative restoration actions. However, given the on-going response of Big Springs Creek to already-implemented restoration actions, baseline conditions should be monitored to determine whether additional updates are necessary for future applications of this model.

Appendix B. Monitoring Plan

The full monitoring plan was submitted separately from this document and can be found in Shasta Big Springs Ranch Restoration Monitoring Plan_revised.doc

Appendix C. Technical Memoranda

Technical memoranda were submitted as pdf files separately from this document. A complete list of the technical memoranda submitted as part of this project is provided in the table below.

Technical Memorandum List	
Title	**Date Submitted**
1. Springs Temperature Monitoring in Big Springs Creek	12/29/2009
2. Remote Sensor Temperature Monitoring at Shasta Big Springs Ranch	1/29/2010
3. Little Springs Creek Temperature Monitoring	1/29/2010
4. Hole in the Ground Temperature Monitoring	3/30/2010
5. Air Temperature Monitoring Analysis	6/30/2010
6. Interannual Water Temperature Data Analysis	6/30/2010
7. Remote sensor network planning, installation and operation	12/17/2010
8. Temperature response to restoration memo	12/17/2010
9. 2011 Temperature special studies	3/21/2011
10. Remote sensor network expansion	6/24/2011
11. Preliminary investigation of macrophyte shade in Big Springs Creek	9/6/2011
12. Big Springs Lake	7/12/2012