Longitudinal Baseline Assessment of Salmonid Habitat Characteristics of the Shasta River, March through September, 2008

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Report prepared for:

United States Bureau of Reclamation
Klamath Basin Area Office

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Acknowledgements

The authors would like to acknowledge the following people who provided support, either directly or indirectly, to the Longitudinal Baseline Assessment of Salmonid Habitat Characteristics of the Shasta River. We would like to thank the U.S. Bureau of Reclamation Klamath Basin Area Office for their support of this research. This project would not have been possible if not for private land owners granting permission for researchers to study the Shasta River on their property. For access we would like to thank Dave Fontius, The Nature Conservancy, California, the Freeman Family, Bob and Laurie Manley, and Dave Webb for facilitating access. Bill Chesney, and Chris Adams and the California Department of Fish and Game for sharing their expertise on coho sampling, habitat assessment, and general life history, and fish collection in the Shasta River. We would also like to thank Joe Kiernan and Sue Maurer for study design and data collection; Ben Lamb for sample collection and tireless laboratory work; Robyn Suddeth, Nickilou Krigbaum, and Bruce Hammock for field data collection. Finally, we also appreciate Stacy Tanaka for her valuable editing suggestions.

Recommended Citation: Nichols, A.L., C.A Jeffres, A.D. Willis, N.J. Corline, A.M. King, R.A. Lusardi, M.L. Deas, J.F. Mount, and P.B. Moyle. 2010. Longitudinal Baseline Assessment of Salmonid Habitat Characteristics of the Shasta River, March to September, 2008. Report prepared for: United States Bureau of Reclamation, Klamath Basin Area Office.

1.0 Executive Summary

Introduction

The Shasta River in Siskiyou County, California may be one of the Klamath River's more exceptional tributaries (CDFG 2004, Deas 2004, NRC 2004) with regards to salmonid fish production. The river receives more than half of its annual flow from spring complexes that sustains year-round baseflow, and in summer provides cold water to support over-summering lifestages for coho salmon. These springs, fed by groundwater recharge from rainfall and snowmelt on Mount Shasta, are unique in that they are nutrient-rich and fuel highly productive aquatic food webs (Jeffres et al. 2009). These naturally occurring conditions provide a level of resilience to the Shasta River, suggesting a high potential for significant and immediate response to restoration and conservation actions supporting salmonids.

Beginning in 2007, the University of California, Davis Center for Watershed Sciences (UC Davis), in cooperation with Watercourse Engineering, Inc. (Watercourse), completed a Year-In-The-Life physical and biological assessment of the Shasta River on The Nature Conservancy's (TNC) Nelson Ranch (Jeffres et al. 2008). While this study concluded that the Shasta River had high potential to support salmonid populations, its observations were limited to a single, 8 kilometer river reach. This limited spatial assessment provided little indication of whether additional river reaches could also function as viable salmonid habitat, nor could it identify the potential range of underlying causes regarding the key impairment in the system: elevated water temperatures. This report extends the aforementioned baseline study of the Shasta River on the Nelson Ranch to five additional stream sites (Figure 1), including the principal cold-water, spring-fed tributary, Big Springs Creek. Findings are presented from data gathered over the 2008 field season (March through September). With two sites above and three sites below Nelson Ranch, this study presents the longitudinal physical and biological characteristics of the Shasta River and is the most comprehensive study to date of one of the more resilient tributaries in the Klamath River basin.

The goal of this study was to provide the baseline information necessary to guide and evaluate restoration efforts designed to improve salmonid populations in the Shasta River. This research occurred concurrently with two important events in the watershed. First, the work was coincident with the 2008 cohort of coho salmon, the largest of the three brood years. This relatively large cohort provided the unique opportunity to record meaningful observations regarding seasonal usage of key habitat types by juvenile coho salmon. Second, TNC secured an option on, and later purchased, the Shasta Big Springs Ranch (formerly Busk Ranch), which allowed access to Big Springs Creek. This unprecedented access provided the opportunity for the first ever baseline assessment conducted on the Big Springs Creek (Jeffres et al. 2009). The Big Springs Creek baseline assessment identified the creek as a principal contributor of streamflow, and the main source of both cold and warm water to the Shasta River. Further, this comprehensive work determined that historic land and water management practices on the ranch had degraded the quality and quantity of coho rearing habitat within Big Springs Creek and for a significant portion of the Shasta River downstream (Jeffres et al. 2008 and Jeffres et al. 2009). The baseline studies at Nelson Ranch and Shasta Big Springs Ranch provided a detailed foundation upon which to build this longitudinal assessment of at the basin scale. Sites assessed in this study include the Fontius Ranch above Lake Shastina (RKM 76.8), Shasta Big Springs Ranch (RKM 54.2), Nelson Ranch (RKM 44.0), Shasta River at Freeman Ranch (RKM 30.8), Manley Ranch (RKM 18.8), and Shasta River canyon (RKM 2.3). Sites on the Shasta Big Springs Ranch included characterization Big Springs Creek and the Shasta River above Big Springs Creek (including Parks Creek) to quantify the role of Big Springs Creek on downstream Shasta River reaches.

The comprehensive baseline assessment included detailed field observations of hydrology, geomorphology, water temperature, water quality, aquatic macrophytes, benthic macroinvertebrates, and salmonid habitat utilization. This integrated suite of physical, chemical, and biological observations provides a robust characterization of the necessary elements required to assess salmonid conditions in the Shasta River, as well as identify potential directions for restoration and maintenance of salmonids in the basin. A summary of findings and conclusions for each of these baseline elements is included herein. Important in this presentation, and throughout the report, is that although presented as discrete elements, these physical, chemical, and biological elements are actually highly integrated, with clear inter-dependencies.

Geomorphology:

Findings:

- Channel gradient in the Shasta River exhibited four morphologically distinct channel segments largely determined by underlying geology. Steep headwaters (0.25 to 0.02 m/m) transition into a moderate gradient channel segment (0.02 to 0.003 m/m) throughout the southern portions of the Shasta Valley upstream of Big Springs Creek. Channel gradient is reduced to a relatively constant gradient below Big Springs Creek (0.001m/m), as the Shasta River meanders through the central and northern portions of the Shasta River Valley. Near Yreka, the Shasta River descends into a bedrock canyon, and gradient increases rapidly to a moderate slope (0.008 m/m).

- Cross sectional channel morphologies throughout the Shasta River basin largely reflect differences in hydrologic regime. Trapezoidal cross-section morphologies and the presence of lateral and mid-channel gravel bars in the Shasta River above Lake Shastina reflect a hydrologic regime dominated by a precipitation (rain and snow) driven hydrograph. Rectangular cross-sectional geometries with elevated width-to-depth ratios in Big Springs Creek and the Shasta River below reflect hydrogeomorphic processes dominated by stable, groundwater-derived baseflows. Cross-sectional channel morphologies throughout Big Springs Creek are remarkably wide and shallow.

- Channel bed material size distributions throughout the Shasta River correspond well with downstream changes in channel gradient. Higher gradient Shasta River channel segments above Lake Shastina and below the Montague-Yreka road exhibited larger surface particle sizes during the project period compared to low-gradient reaches below the Shasta River confluence with Big Springs Creek.

Conclusion: Geomorphology

Patterns of channel morphology throughout the Shasta River appear largely driven by downstream differences in hydrologic processes and channel gradient. Channel forms and large bed material sizes above Lake Shastina are principally driven by elevated channel gradients and a hydrologic regime driven by rainfall and snowmelt runoff. Below the confluence with Big Springs Creek, a reduced channel gradient and transition to a hydrologic regime dominated by spring-fed baseflows lead to, on average, wider and shallower channel morphologies, decreased bed material sizes, and an absence of mid-channel or lateral gravel bars. Bed material size increased concurrent with channel gradient steepening through lower portions or the Shasta River.

Hydrology:

Findings:

- Streamflow in the Shasta River above Lake Shastina during the project period exhibited characteristics of Mediterranean-montane hydrologic systems, with elevated discharge magnitudes in response to late winter rainfall and spring snowmelt (maximum = 274 ft^3/s), followed by a spring snowmelt recession to low summer baseflows (minimum daily average = 9 ft^3/s). Temporally variable streamflow diversions during the irrigation season (March 1 to November 1) reduced discharge magnitudes throughout the project period.

- Unimpaired (i.e. non-irrigation season) streamflow in Big Springs Creek averaged approximately 83 ft^3/s during the project period. Due to stable, groundwater-derived sources of baseflow, non-irrigation season streamflow was minimally variable. During the irrigation season (April 1 to October 1), temporally-variable surface water diversions and presumable seasonal groundwater pumping reduced streamflows in Big Springs Creek (mean = 52 ft^3/s; minimum = 40 ft^3/s). Streamflow rebounded rapidly to unimpaired baseflow conditions following the cessation of the irrigation season (September 30). During the summer and fall, Big Springs Creek, along with several other discrete and diffuse springs, provide the majority of streamflow to the Shasta River below.

- Streamflow in the Shasta River below Big Springs Creek was affected by the varying hydrologic regimes of contributing tributaries, both upstream and downstream, and water resources development activities. During the late winter and early spring, large groundwater-derived baseflows (~120 ft^3/s) were augmented by winter rainfall runoff from numerous tributaries, including Parks Creek, Little Shasta River and Yreka Creek. During the late spring, snowmelt runoff derived from the aforementioned tributaries increased discharge magnitudes throughout the Shasta River, peaking at 208 ft^3/s as measured at the Shasta River canyon site. The longitudinal discharge magnitudes in the Shasta

River below Big Springs Creek during irrigation season progressively decreased downstream in response to diversion. Baseflow rapidly rebounded to approximately spring-fed magnitudes in early October following the cessation of the irrigation season.

Conclusion: Hydrology

Rainfall and snowmelt-derived streamflow in the Shasta River above Dwinnell Dam was stored in Lake Shastina, with minimal (<10 ft^3/s) releases to the Shasta River below. These diversions are to fulfill water rights between Dwinnell Dam and Parks Creek, and do not significantly contribute to baseflow in downstream reaches. Large, groundwater-derived baseflows sourced from discrete (principally Big Springs Creek) and diffuse groundwater spring sources provided the majority of streamflow to the Shasta River below Dwinnell Dam. Spring-fed baseflows were periodically augmented by tributary inflows derived from surface runoff in the Parks Creek, Little Shasta River, and Yreka Creek tributary sub-basins. Streamflow in the Shasta River progressively decreased during the irrigation season, only to rapidly rebound to spring-fed baseflow conditions at the end of the irrigation season.

Water Temperature

Findings

- The Shasta River illustrates several thermal paradigms as it flows from its headwaters to the confluence with the Klamath River. The most significant shift occurs downstream of Big Springs Creek. Above Big Springs Creek, observed water temperature trends largely mimic thermal signals typical of rivers in Mediterranean climates, with spring and summer water temperatures largely increasing as discharge derived from precipitation and snowmelt runoff decreases to baseflow conditions. Downstream of Big Springs Creek, water temperatures in the Shasta River are strongly defined by streamflow temperatures contributed by Big Springs Creek for tens of kilometers before the Shasta River returns to equilibrium temperature.

- The springs sources of Big Springs Creek represent the largest source of cool water for the Shasta River; the creek's spring sources emerge between 10^{o}C and 12^{o}C. However, rapid heating rates in the creek during the 2008 study period resulted in the creek being a source of warm water for the Shasta River, with maximum daily temperatures in the creek exceeding 25^{o}C at times.

- During spring and summer, local meteorological conditions yield equilibrium temperatures in the downstream reaches (i.e. the Canyon Reach) that are not compatible with over-summering life stages of anadromous fish. Preserving the cold water contributed by Big Springs Creek as well as management of processes that contribute to elevated water temperature are the best methods for creating favorable habitat conditions for salmonids within the watershed. This is paramount during critical spring, summer, and early periods, though these effects will be limited to the downstream Shasta River reaches influenced by Big Springs Creek contributions.

Conclusion: Water Temperature

Initially, water temperatures in the Shasta River reflect its rainfall and snowmelt-based hydrology. These water temperatures are characterized by a gradual increase during the spring, followed by a more rapid increase during the summer as rainfall and snowmelt runoff recede and the river is reduced to seasonally low baseflow. A significant change occurs where Big Springs Creek enters the Shasta River, and for tens of kilometers downstream. Specifically, the Shasta River water temperatures are strongly influenced by the water temperatures contributed by Big Springs Creek because of the disparity in both flow and water temperature between the two streams; Big Springs Creek having considerably more flow and often colder than the Shasta River above the confluence. The thermal signal of Big Springs Creek extends a considerable distance downstream, though eventually other factors interfere with this thermal pattern (e.g., variable flow regime, significant diversions and return flows, diffuse upstream springs source waters, and other factors) and cause it to break down. Because Big Springs Creek is the most significant source of cool water during critical over-summering life stages of anadromous fish, preserving the creek's cold water is the most important action to expanding the available over-summering habitat for salmonids in the Shasta River.

Water Quality

Findings

- Unlike most rivers, where elevated nitrogen and phosphorous levels are caused by anthropogenic sources, elevated inorganic nitrate (0.39 mg/l) and inorganic orthophosphate (0.16 mg/l) levels in Big Springs Creek are naturally derived from geologic sources along the groundwater flowpath (i.e. from source or recharge area to the Big Springs complex). Thus, spring flows provide notable inorganic nutrient sources that can support extensive primary production.

- A longitudinal attenuation of nitrate in the Shasta River was observed during the spring and summer months as distance increased from the spring source. This decrease was inversely proportional to the abundance of aquatic macrophytes in the channel, as determined from macrophyte biomass samples collected throughout the sampling period. A similar rate of downstream attenuation was not observed in orthophosphate, suggesting nitrogen limitation in Shasta River reaches downstream from Big Springs Creek.

Conclusion: Water Quality

Unique water chemistry in Big Springs Creek includes large, dispersed springs of constant temperature with notable inorganic nitrogen and phosphorus concentrations. These high nutrient levels result in unusually high primary production within Big Springs Creek and the Shasta River downstream, forming a critical base of the aquatic food web. This food web is an important element of ecology of Big Springs Creek and the Shasta River, and is capable of supporting juvenile salmonids.

Aquatic Macrophytes

Findings

- Aquatic macrophytes in the Shasta River exhibited seasonal and longitudinal variability in biomass accumulation. This variability is related to flow regime, substrate, available nutrients, species composition, site specific conditions (e.g., riparian shading, land use), and other factors.

- Big Springs Creek exhibited the highest biomass, with biomass decreasing in the downstream direction (an exception was the canyon site). These findings are consistent with elevated nutrient concentrations in spring sources and diminishing concentrations downstream due to uptake by aquatic vegetation.

- Extensive aquatic macrophytes, as well as other aquatic vegetation (e.g., epiphyton) provide a food and habitat source to support large macroinvertebrate populations.

- Aquatic macrophytes function as an important habitat for rearing salmonids. They provide cover from predators, velocity refuge, and a habitat for invertebrates.

Conclusions: Aquatic Macrophytes

Aquatic vegetation in the Shasta River and Big Springs Creek illustrated seasonal and longitudinal variability. In certain environments the role of aquatic vegetation was critical to anadromous fish production. This was particularly true in the reaches where summer water temperatures were amendable (i.e. cool) to over-summering anadromous salmonids, such as coho salmon. The reaches in and immediately downstream of Big Springs Creek (~ 10 km) experience these cool water temperatures, have sufficient nutrients to support extensive aquatic vegetation Aquatic macrophytes serve an important role in regulating both the physical (geomorphology, nutrients, and physical structure), and ecological (carbon source, invertebrate and fish habitat) components of the Shasta River ecosystem.

Benthic Macroinvertebrates

Findings

- During the summer sampling period, densities of aquatic macroinvertebrates in Big Springs Creek (48,000 invertebrates/m^2) were considerably larger than densities measured in other five locations within the Shasta River (mean =21,977 invertebrates/m^2). The aquatic macroinvertebrate community in Big Springs Creek was composed primarily of *Hyalella* sp. (scuds) and *Baetis* sp. (mayflies), both of which are collector-gatherers.

- Collector-gatherer insects dominated the macroinvertebrate assemblage at all sites in Big Springs Creek and the Shasta River during the spring sampling period, at times accounting for nearly 98 percent of the entire assemblage. During the summer sampling period, all sample sites except those in Big Springs Creek and the Nelson Ranch showed a greater overall abundance of scrapers relative to the spring sampling period. The increase in scrapers was due primarily to the increase in *Optioservus* sp. (riffle beetle) at all locations. This suggests that epilithon may be an important carbon source for macroinvertebrates during summer in these reaches.

Conclusion: Benthic Macroinvertebrates

Invertebrates are an important linkage in the food web as an energy transfer from primary producers (plants) to fish. Throughout the Shasta River, invertebrate abundances show that ample food is available for rearing salmonids, particularly in Big Springs Creek where abundances are very high. The high proportion of collector-gathers in the system suggests there is a large amount of fine particulate organic matter (FPOM) in the Shasta River, derived principally from aquatic vegetation production.

Salmonid Habitat Utilization

Findings

- Several age classes of steelhead were observed at all study site/survey locations. The most common age class was 0+ fry (fry that emerged in the spring of 2008). Steelhead densities were highest at the Nelson Ranch and Big Springs Creek study sites, where water temperatures cooled at night due to the proximity of cold-water spring sources. At the canyon reach study site, numbers of observed steelhead declined sharply following an increase in water temperatures during May 2008.

- When sampling first began in April 2008, almost all of the Chinook observed in the Shasta River were on the Manley Ranch and Canyon reach. This is likely similar to the distribution of suitable spawning habitat the previous fall when adults returned. When water temperature increased in May, Chinook numbers throughout the river decreased rapidly as rearing Chinook likely left the Shasta River. In the canyon reach, a second group of fish was observed in mid-late June, likely migrating out of the Shasta River toward the ocean. After June the juvenile Chinook were not observed in the Canyon Reach throughout the rest of the summer.

- During the late fall/early winter 2007, 249 adult coho returned to the Shasta River. This is the largest of the three cohorts of coho remaining in the Shasta River. In April through mid-May 2008, juvenile coho were only observed at Big Springs Creek, Nelson Ranch, and in the canyon reach study sites. This corresponds to the primary spawning locations of the previous year's adults (Upper Shasta/Big Springs-Parks Creek area and lower Shasta/canyon reach and Big Springs Complex).

- The primary factor that influences coho distribution in the Shasta River was water temperature. In May 2008, warm weather and degraded habitat led to a warm-water event that redistributed coho from rearing habitats in the mainstem Shasta River into the few remaining cool water refugia in Big Springs Creek, Upper Shasta River, and Parks Creek (Chesney 2010). Fish present below the GID diversion dam during this warm-water event likely migrated out of the Shasta River into the Klamath River in search of suitable over-summering habitat. This event highlights how a single early season warm temperature can have direct and severe consequences for juvenile Shasta River coho.

- Abundant physical habitat and food resources were available for rearing salmonids at all sampling locations during the project period. Water temperature appeared to be the limiting factor for salmonids in the Shasta River.

<u>Conclusion: Salmonid Habitat Utilization</u>

A fish's life history strategy and physiological tolerances ultimately determine which species will be affected by anthropogenic alteration of the environment. Current alteration of the Shasta River has resulted in reduced stream flows and increased water temperatures. Chinook salmon are able to much better tolerate these conditions than coho because they have higher thermal tolerances and leave the Shasta River for the ocean during spring just as temperature begin to reach undesirable levels. Steelhead on the other hand have even a higher thermal tolerance relative to coho salmon and are able to make use of the abundant habitat and food resources that the Shasta River provides, even under severally altered conditions. During summer 2008, only a few isolated locations provided suitable over-summering habitat for coho salmon. Suitable habitat and food resources are present in Big Springs Creek and the Shasta River immediately downstream of Big Springs Creek, but throughout the remaining downstream reaches water temperature was the principal limiting factor for the Shasta River coho population.

Summary

The Shasta River has been identified as one of the most important tributaries for salmon habitat in the Lower Klamath River basin, largely due to the contribution of cold, nutrient rich streamflow from several groundwater springs complexes. From March to September 2008, a baseline study was completed at multiple locations in the Shasta River and Big Springs Creek, in order to extend earlier baseline studies conducted on the Nelson Ranch. This comprehensive baseline assessment has greatly improved the understanding of spatial and temporal trends in physical, chemical and biological conditions throughout the Shasta River, and is a critical step in supporting the restoration of anadromous fish in the basin.

The goal of this study was to provide the baseline information necessary to guide and evaluate restoration efforts designed to improve salmonid populations. Critical system attributes, including geomorphology, hydrology, water temperature/quality, aquatic vegetation, macroinvertebrate assemblages and salmonid habitat usage were defined during the critical spring/summer irrigation-season, lending considerable insight into understanding basin-wide factors limiting salmonid production, as well as identifying high priority areas and potential processes important to restoration and maintenance of anadromous salmonids and other aquatic system function throughout the Shasta River basin.

Findings of this work indicate that while most physical and biological habitat conditions in the Shasta River are sufficient to support robust anadromous salmonid populations, elevated spring and summer water temperatures remain the key impairment to the aquatic ecosystem. As such, maintaining sufficient, cold-water baseflows is critically-important for the successful migration and rearing of salmonids throughout the system, and particularly the over-summering of juvenile coho salmon. Furthermore, these nutrient-rich spring sources provide the necessary foundation for an enormously productive aquatic food web, as well as drive the extensive growth of aquatic vegetation, thus providing the primary physical habitat structure for rearing juvenile salmonids. This unique combination of physical, chemical, and biological factors in the Shasta River results in high anadromous fish production potential. By focusing on these factors, with special attention focused on maintaining cold-water spring sources, targeted restoration activities can be formed to restore and maintain anadromous fish in the Shasta River basin.

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2.0 Introduction

In their comprehensive review of threatened and endangered fishes of the Klamath River watershed, the National Research Council (NRC 2004) noted the importance of lower Klamath River tributary habitat to the recovery of salmonids, particularly coho salmon, within the Southern Oregon/Northern California Coasts Evolutionary Significant Unit (SONCC ESU). The committee suggested a range of factors limiting salmonid production in the tributaries, with high water temperatures figuring most prominently, particularly during the spring and summer irrigation season. However, the committee also noted the surprising lack of information about limiting factors and tributary conditions year-round and suggested that over-wintering habitat, along with other seasonally-related changes in habitat and food production may be important. This observation was also noted in the Recovery Strategy for California Coho Salmon (CDFG 2004).

Beginning in 2007, the University of California, Davis Center for Watershed Sciences (UC Davis), in cooperation with Watercourse Engineering, Inc. (Watercourse), completed a Year-In-The-Life physical and biological assessment of the Shasta River on The Nature Conservancy's (TNC) Nelson Ranch (Jeffres et al. 2008). The Shasta River was identified as one of the most important tributaries for salmon habitat in the Klamath River basin, largely due to the contribution of several springs and springs complexes. While this study concluded that the Shasta River had high potential to support salmonid populations, its observations were limited to a single, 8 km reach. This limited spatial assessment provided little indication of whether additional river reaches could function as salmonid habitat, nor could it identify the potential range of underlying causes regarding the key impairment in the system: elevated water temperatures. This report extends the study of the Shasta River to five additional study sites, including one on the principal cold-water tributary, Big Springs Creek, and presents findings from data gathered over the 2008 field season (March through September). With two sites above and three sites below Nelson Ranch, this study presents the longitudinal physical and biological characteristics of the Shasta River and is the most comprehensive study to date of one of the more resilient tributaries in the Klamath River basin.

The goal of this study was to provide the baseline information necessary to guide and evaluate restoration efforts designed to improve salmonid populations. This research occurred concurrently with two important events in the watershed. First, the work was coincident with the 2008 coho cohort, the largest of the three brood years. This relatively large cohort provided the unique opportunity to record meaningful observations regarding seasonal usage of key habitat types by juvenile coho salmon. Second, TNC secured an option on, and later purchased, the Shasta Big Springs Ranch (formerly Busk Ranch), which allowed access to Big Springs Creek for the first baseline assessment conducted on the primary source of water to the Shasta River during irrigation season (Jeffres et al. 2009). The Big Springs Creek baseline assessment identified the creek as a principal contributor of streamflow, and the main source of cold water to the Shasta River. Further, this work determined that historic land and water management practices on the ranch had degraded the quality and quantity of coho rearing habitat within Big Springs Creek and for a significant portion of the Shasta River downstream (Jeffres et al. 2008 and Jeffres et al. 2009). The baseline studies at Nelson Ranch and Shasta Big Springs Ranch provided a detailed foundation upon which to build this assessment of downstream reaches.

3.0 Background

The Shasta River is the fourth largest tributary to the Lower Klamath River (below Iron Gate Dam) and flows approximately 95 kilometers northwestward across the Shasta Valley in Siskiyou County, California (Figure 1). Bounded by the Scott Mountains to the west, Siskiyou Mountains to the north, and the Cascade Volcanic Range to the south and east, the Shasta River drainage basin exhibits considerable spatial variability in geologic and dependent geomorphic and hydrologic characteristics. The steeper upper Shasta River and its tributaries drain the eastern slopes of the Scott and Siskiyou Mountains, a region comprised of well-indurated Paleozoic and Mesozoic rocks of the Eastern Klamath Belt geologic province (Hotz 1977). Consequently, streamflow in the upper Shasta River is generated principally by surface runoff derived from rainfall and snowmelt. In contrast, northerly and westerly flowing tributaries to the lower Shasta River drain the northern slopes of Mount Shasta and the western slopes of the Cascade Volcanic Range, regions underlain by porous volcanic rocks of the Tertiary-aged Western Cascade volcanic province and the Quaternary-aged High Cascades geologic province (Wagner and Saucedo 1987). The Shasta River flows for most of its length along the floor of the Shasta Valley, an area underlain principally by a complex assemblage of volcaniclastic rocks included within the High Cascades geologic province (Crandell et al. 1984). The relatively porous volcanic rocks allow numerous groundwater springs to discharge to the Shasta River throughout the eastern portions of the Shasta Valley. These groundwater spring sources, dominated by the Big Springs Complex, contribute large baseflows to the Shasta River, and are the principle source of streamflow in the lower Shasta River during the summer and fall.

The construction of Dwinnell Dam and impoundment of Lake Shastina in 1928 at river kilometer (RKM) 65 largely separated the Shasta River into its current upper and lower segments. The dominantly runoff-derived streamflow in the upper Shasta River is regulated by operations of Dwinnell Dam, while streamflow in the lower Shasta River is principally comprised of streamflow contributions from Lake Shastina, Parks Creek (RKM 56.2), and Big Springs Creek (RKM 54.2). Currently, approximately 95 percent of summer baseflows in the lower Shasta River originates from the Big Springs Complex, comprised of groundwater springs in the vicinity of Big Springs Creek. However, anthropogenic impacts to the natural hydrograph have had a substantial impact on the flow volumes in the Shasta River. During late spring, summer, and early fall, the Shasta River is impacted by water withdrawals for agriculture. Several diversions and return flow channels exist along the Shasta River, including the Grenada Irrigation District (GID)-Huseman ditch, the Shasta River Water Association, and Oregon Slough. At times, up to approximately 90 percent of the streamflow is diverted during irrigation season (April 1 –September30) downstream of the spring sources. This creates a longitudinal gradient of water quality in the Shasta River, from relatively cool and abundant water near the spring sources to warm low-flow conditions near the confluence with the Klamath River.

Beginning in 2006, the UC Davis Center for Watershed Sciences and Watercourse began a baseline assessment of salmonid habitat conditions on the Shasta River at the Nelson Ranch (RKM 44-52). This work, funded by TNC, California (owners of the Nelson Ranch), and the U.S. Bureau of Reclamation, provided the first-of-its-kind comprehensive evaluation of factors that impact salmonid spawning and rearing habitat and the use of that habitat at a single location on the Shasta River over the course of an entire year. The methods used included year-round: 1) geomorphic assessments and habitat typing; 2) flow, temperature, and water quality monitoring; 3) fish, invertebrate, and aquatic macrophyte monitoring; and 4) isotopic studies of aquatic food webs. The initial results of this study provided a window into the unique complexity and seasonal variability of Shasta River aquatic communities and provided a critical inventory of the ecosystem. Complete findings are included in Jeffres et al. (2008), but several key preliminary findings of this work were:

- High water temperatures were the most significant limiting factor for anadromous fishes at the Nelson Ranch.
- Streamflow fluctuations associated with upstream irrigation management significantly impacted habitat availability and thermal conditions. Resident and anadromous fish altered habitat usage in response to these streamflow and water temperature fluctuations.
- Food web and aquatic macrophyte studies, along with fish growth rate observations, indicated that the Shasta River is exceptionally productive with high quality food sources for anadromous fishes.

These Nelson Ranch studies have been augmented through additional funds from U.S. Bureau of Reclamation to expand the spatial extent of the comprehensive evaluation outlined above. Five additional study sites, both upstream and downstream of the Nelson Ranch were sampled to increase the understanding of spatial and temporal differences in physical, chemical and biological processes throughout the Shasta River basin. This longitudinal, seasonal baseline dataset provided insight for prioritization and quantification of restoration activities within the watershed.

4.0 Project Area

Project work was conducted throughout the Shasta River and the tributary Big Springs Creek, between March and September 2008. The approximately 80-kilometer portion of the Shasta River studied as part of this project extends from near Edgewood, CA (RKM 80) to the Shasta River confluence with the Klamath River, wherein six sites were selected for study (Figure 1). Study sites were determined based on spatial distribution within the watershed and accessibility. Furthermore, study sites were chosen in order to capture hypothesized longitudinal differences in hydrologic, geomorphic, water quality, and ecological conditions along the Shasta River. General descriptions of the study sites, identified from upstream to downstream, are provide herein (RKM designation refers to the upstream and downstream boundaries of the identified study site):

- Fontius Ranch (RKM 76.8 to 76.1); representing the upper Shasta River above Dwinnell Dam;

- Shasta Big Springs Ranch (RKM 54.2); representing Big Springs Creek, the main cold water tributary and principal source of summer baseflow to the lower Shasta River below Dwinnell Dam;
- Nelson Ranch (RKM 51.7 to RKM 44); representing the geomorphic and hydrologic transition between the higher gradient, runoff-dominated segments of the upper Shasta River and the lower gradient, spring-dominated segments of the lower Shasta River below the confluence with Big Springs Creek;
- Freeman Ranch (RKM 32.7 to 30.8), representing the low gradient channel segments of the lower Shasta River through the central portions of the Shasta River valley;
- Manley Ranch (RKM 21.1 to 18.8); representing the low to moderate gradient segments of the northern portions of the lower Shasta River; and
- Canyon (RKM 2.6 to 2.3); representing the lower Shasta River canyon above the confluence with the Klamath River

Each site is discussed in more detail below.

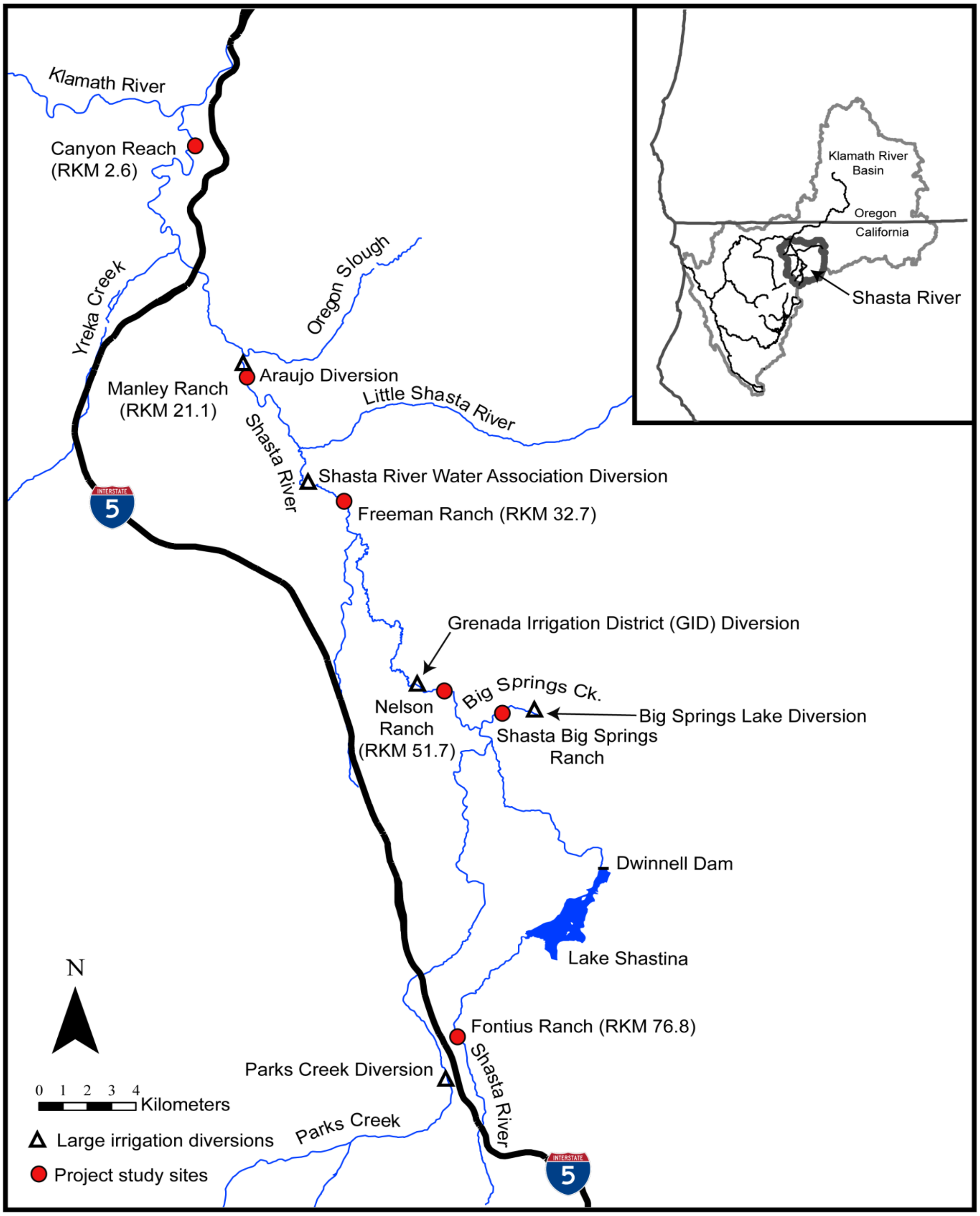

Figure 1. The Shasta River and major tributaries in the project area. Project study sites along the Shasta River and Big Springs Creek are identified.

4.1 ***Study Sites***

The six study sites are a representative sample of different channel segments throughout the Shasta River. The individual site descriptions include an overview of the distinct stream characteristics at that site, the identity of the main water source as well as upstream tributaries, and diversions or return flows that potentially affect conditions at that site. The sites are presented from upstream to downstream.

Fontius Ranch

Located along the Shasta River from RKM 76.8 to 76.1, the Fontius Ranch is the only study site above Dwinnell Dam and Lake Shastina. Located in the southern end of the Shasta Valley near Edgewood, CA, the Fontius Ranch falls within the topographic transition from the steep headwater reaches of the Shasta River to the lower-gradient reaches of the Shasta Valley proper. Hydrological conditions in the Shasta River at the Fontius Ranch are largely driven by rainfall and snowmelt runoff, with small streamflow contributions from the upstream, spring-fed tributaries Beaughton and Boles Creeks. Furthermore, the study site is located approximately 1.7 kilometers downstream from the Montague Water and Conservation District (MWCD) Parks Creek Diversion canal, through which MWCD conveys water from Parks Creek to the upper Shasta River between October 1 and June 15 of the following year for storage in Lake Shastina (priority of water rights varies during this period) (Shasta River decree, 1932). During the irrigation season (March 1 to November 1 for all diversion locations in the Shasta River and its tributaries above the confluence with Big Springs Creek, numerous upstream irrigation diversions can affect the magnitude and variability of streamflow in the Shasta River at the Fontius Ranch.

Shasta Big Springs Ranch

Big Springs Creek flows westward approximately 3.7 kilometers through the Busk and Shasta Big Springs Ranches and joins the Shasta River at RKM 54.2, approximately 11 kilometers below Dwinnell Dam and Lake Shastina. Streamflow in Big Springs Creek emanates from a large groundwater spring complex at 10-12^{o}C, and is the major source of both baseflow and cold water to the Shasta River downstream. The easternmost portions of the spring complex are impounded behind Big Springs Dam in Big Springs Lake, and releases from Big Springs Dam are regulated for surface water diversions during the irrigation season (April 1 to October 1 for all diversion locations in Big Springs Creek and the Shasta River downstream). Several diffuse and unregulated springs join Big Springs Creek immediately downstream from Big Springs Dam (Jeffres et al. 2009). Groundwater-derived baseflows result in minimal streamflow variability in Big Springs Creek outside of the irrigation season. Over the course of the entire irrigation season, discharge can vary by as much as 37 ft^3/s due to operations of Big Springs Dam, tailwater return, regional groundwater pumping, and other factors.

Nelson Ranch

Located on the Shasta River from RKM 51.7 to 44.0, the Nelson Ranch study site is located approximately 2 km downstream from the confluence between the Shasta River and Big Springs Creek. As such, the Nelson Ranch is the first downstream study site to show the effects of Big Spring Creek on the hydrology, geomorphology, water quality and ecology on the Shasta River. The Shasta River through the Nelson Ranch exhibits hydrologic conditions that are affected by varying hydrologic regimes and management of upstream tributaries, including:

- Baseflows derived from upstream, groundwater-fed springs complexes (principally Big Springs Creek);
- Rainfall and snowmelt derived streamflow in Parks Creek (modified by upstream diversions to the upper Shasta River and other users), and
- Small (<10 ft^3/s) streamflow releases to the Shasta River from Dwinnell Dam and Lake Shastina. Dam releases are minimal most years except when reservoir spill occurs.

Streamflow in the Shasta River at the Nelson Ranch changes concurrently with upstream irrigation diversions and regional groundwater pumping, though no data were available to quantify those activities. Furthermore, the GID and Huseman Ditch can divert up to 52 ft^3/s from a single diversion point located within the study site at RKM 49.5.

Freeman Ranch

The Freeman Ranch study site is located along the Shasta River between RKM 32.7 and 30.8, approximately 5 km south of Montague, CA. The site is located in the wide and low-gradient portions of the central Shasta River valley, and is characterized by a slow-moving, single-thread meandering channel. There are numerous, relatively small inflows, outflows, and diversions between the downstream boundary of Nelson Ranch and Freeman Ranch. The Shasta River Water Association irrigation diversion, with an adjudicated water right of 42 ft^3/s, is located immediately downstream from the Freeman Ranch study site. The Little Shasta River, a major tributary originating in the Cascade Mountains bounding the Shasta Valley to the east, enters the Shasta River between the Freeman Ranch and the Manley Ranch at approximately RKM 26.3.

Manley Ranch

The Manley Ranch study site is located between RKM 21.1 and 18.8 along the Shasta River. This site is located along a topographic transition in Shasta River where the low gradient valley segments transition into the moderate gradient canyon segment immediately above the Klamath River. Oregon Slough, a channel conveying a small (likely < 5 ft^3/s) yet largely unquantified volume of baseflow, irrigation return flow, and seepage from upstream sewage settling ponds, joins the Shasta River at RKM 18.2. The Araujo Irrigation Diversion is located within the Manley Ranch study site at RKM 20.5.

Canyon Reach

The Canyon Reach study site is located along the Shasta River between RKM 2.6 to 2.3, above the confluence with the Klamath River. The study site falls within the lower portions of the Shasta River Canyon, an approximately 14-km, moderate gradient canyon incised into the bedrock of the Siskiyou Mountains. The canyon extends from the Interstate 5 crossing near Yreka to the Klamath River. Yreka Creek enters the Shasta River at RKM 12.4. No other appreciable inflows or diversions are located within the lower Shasta River Canyon.

5.0 Baseline Assessment Overview

At each study site, a defined methodology was applied to describe several key physical and biological elements. These elements include geomorphology, hydrology, water temperature, water quality, aquatic vegetation, benthic macroinvertebrates, and salmonid habitat usage. These elements were chosen to develop a comprehensive assessment of baseline conditions at each site in sufficient detail to define key aquatic system processes, as well as identify elements that may present limiting spatial and temporal factors for salmonids.

The advantage of a comprehensive baseline approach is the spatial and temporal representation of a wide range of physical, chemical, and biological attributes. This rich data set provides the important process of intra- and inter-site comparison, allowing assessment of upstream conditions on downstream reaches, and anadromous fish implications regarding habitat conditions and potential movement both upstream and downstream. Further, this comprehensive baseline approach identifies which site or sites have higher relative restoration potential, provides insight into targeted restoration actions and priorities, and identifies which sites can only be improved as long as upstream progress is made. Such an approach results in the efficient and effective use of restoration funds and resources.

The following sections present a synopsis of each baseline assessment element at each study site over the spring and summer of 2008: geomorphology, hydrology, water temperature, water quality, aquatic vegetation, benthic macroinvertebrates, and salmonid habitat use. Examining each element's spatial and temporal patterns identifies not only the source of system impairments, but also the timing. As the timing of impairments is examined in the context of life stage histories of anadromous fish populations, this report illustrates both the key locations in the Shasta River basin and temporal periods that are high priority for restoration action.

6.0 Geomorphology

Geomorphic studies identify key characteristics of physical stream processes and channel structure upon which ecological communities develop and function. Quantifying and documenting geomorphic conditions and processes is a critical step in identifying factors which may maintain, enhance, or limit ecological processes in riverine systems. Furthermore, geomorphic data provide a foundation from which to design and evaluate river restoration projects.

During the project period, geomorphic surveys were conducted at each project study site (Figure 1) to document longitudinal variations in geomorphic conditions, including: channel pattern, channel slope, bed material size distribution, and channel cross-section morphologies. These data provided a foundation from which to analyze and understand concurrent observations of water quality and ecological community structure and function, as well as, identify the need for maintenance or restoration.

6.1 ***Methods***

Channel morphology at each study site was characterized through interpretation of remotely sensed geographic data (aerial photographs and digital elevation models) and local field surveys. Localized topographic surveys of channel morphology were conducted using a TOPCON HiperLite Plus Real-Time Kinematic (RTK) survey unit. Along reaches where researchers could safely wade, channel bed and water surface elevation longitudinal profiles were conducted along the channel thalweg. To understand basin-wide trends in channel gradient, elevation data along the entire longitudinal profile of the Shasta River was extracted from a 10-meter resolution digital elevation model provided by the USGS using the geographic information system (GIS) ArcMap 9.2. Channel cross-section surveys were conducted across the channel bottom at each survey site. Elevations of channel bankfull conditions were estimated for each cross-section based on observed topographic breaks in the channel bank, and where evident, indicators of bankfull channel inundation such as overbank deposits of fine sediment and high-water debris lines along riparian and marginal emergent vegetation. Channel width-to-depth ratios for each surveyed cross-section were calculated by dividing the bankfull channel width by mean bankfull depth. Pebble counts (Wolman 1954) were conducted along each surveyed channel cross-section (excluding Big Springs Creek due to extensive aquatic macrophyte growth) to estimate bed material size distributions.

Channel gradient, cross section morphology, and bed material data were collected for mainstem Shasta River sites (Fontius, Nelson, Freeman and Manley Ranches, and Canyon Reach) per the project work plan. In addition, channel gradient and cross-section data was collected from Big Springs Creek, and are included herein.

6.2 ***Channel Gradient***

Shasta River

The Shasta River exhibits considerable longitudinal variation in channel gradient. Steep headwater channel segments descend into moderate gradient channel segments throughout the southern portion of the Shasta River Valley above the Shasta River confluence with the tributary Big Springs Creek. Downstream from Big Springs Creek, low-gradient channel segments extend along the northern portions of the Shasta Valley, ultimately transitioning into moderate gradient segments of the lower Shasta River Canyon above the confluence with the Klamath River.

The longitudinal profile of DEM-derived elevation data (Figure 2) identify high channel gradients (0.25 to 0.02 m/m) throughout headwater reaches of the Shasta River in the Scott Mountains. Channel gradient rapidly declines as the Shasta River enters the southern end of the Shasta Valley (RKM 84), exhibiting moderate gradients (0.008 to 0.003 m/m) along channel reaches between the Interstate-5 (I-5) Shasta River crossing near Edgewood, CA (RKM 81) and the confluence with Big Springs Creek (RKM 54). Lake Shastina is located along this channel segment between RKM 70 and 65. Downstream from Big Springs Creek, channel gradient declines to approximately 0.001 m/m and remains consistently low (0.001 to 0.003 m/m) as the Shasta River meanders through the central and northern portions of the Shasta River Valley (RKM 54 to RKM 14). At the I-5 Shasta River crossing near Yreka, CA channel gradient rapidly increases to a moderate 0.008 m/m as the Shasta River enters a bedrock controlled canyon. The lower Shasta River Canyon is the steepest channel segment currently accessible to anadromous fish. Site specific channel gradients derived from local topographic surveys at each project study site are summarized in Table 1. Channel gradient data collected at each study site corresponded with channel gradients calculated from USGS digital elevation models.

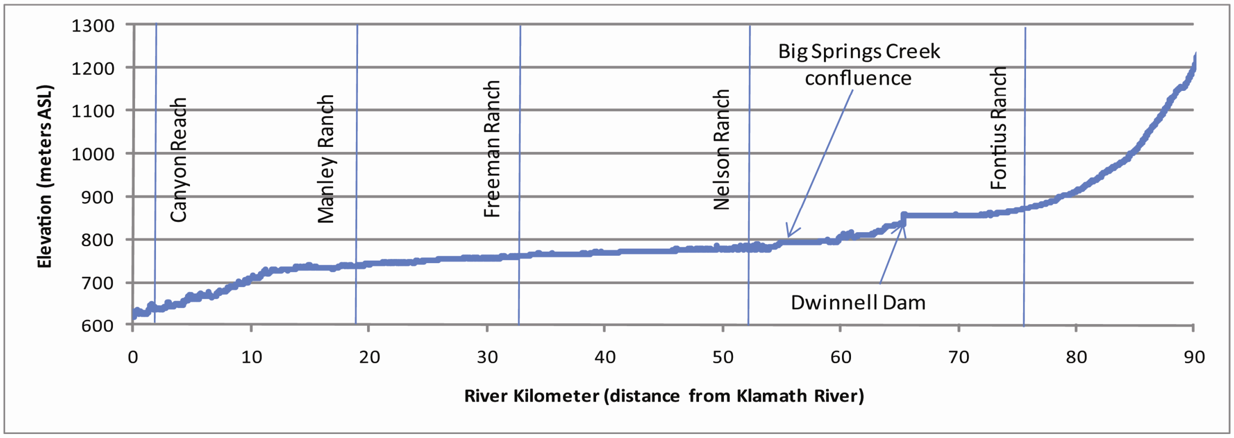

Figure 2. Longitudinal profile of the Shasta River (derived from 10-m resolution digital elevation model). Project study sites and locations of the Big Springs Creek confluence with the Shasta River and Dwinnell Dam are provided for reference.

Table 1: Summary of channel gradient at each project study site. Bed gradient is represented as the slope of the linear regression of channel bed surface elevations surveyed at each study site, and as such does not encompass the entire range of observed channel gradients.

	Upper Shasta River	Big Springs Creek	Nelson Ranch	Freeman	Manley	Canyon
Shasta River Location (river kilometer)	76.61	N/A	51.5	32.54	19.62	2.59
Bed Gradient	0.0054	0.0033	0.001	0.002	0.0034	0.0087

Big Springs Creek

Channel gradient along Big Springs Creek ranges from 0.0003 to 0.006 (Jeffres et al. 2009), with long channel reaches of relatively homogenous slope. Discrete longitudinal differences in channel slope (Figure 3) are largely dependent on external geologic conditions such as the presence/absence of erosion-resistant basaltic bedrock outcrops on the channel margins and channel bed. However, apparent geologic controls on channel slope in upper Big Springs Creek are locally overridden by a flow-through impoundment known as the “waterwheel”, a concrete and rock structure located approximately one kilometer below Big Springs Lake. For approximately 300 meters upstream from the waterwheel, Big Springs Creek exhibits a remarkably stable and shallow gradient of

0.0003 (Figure 3). Below the waterwheel structure, channel gradient ranges from 0.006 to 0.003.

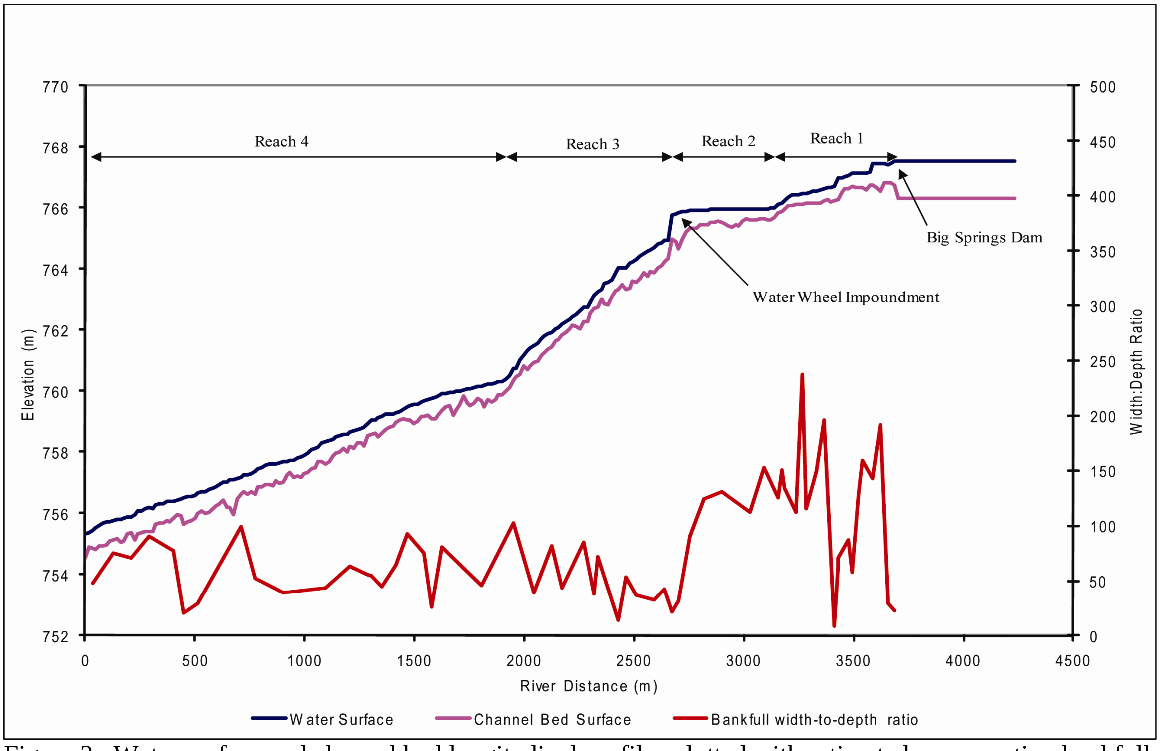

Figure 3. Water surface and channel bed longitudinal profiles plotted with estimated cross-section bankfull width-to-depth ratios along Big Springs Creek (from Jeffres et al. 2009).

6.3 ***Channel Cross-section Morphology***

Shasta River

Downstream trends in cross-sectional channel morphology are apparent in the Shasta River. Above Dwinnell Dam, surveyed channel cross-sections at the Fontius Ranch study site exhibited trapezoidal geometries and width-to-depth ratios (mean = 16) typical of streams deriving the majority of streamflow from surface and shallow subsurface runoff (Whiting and Moog 2001) (Figure 4). The stream channel throughout the study site also exhibited considerable lateral variability in morphology, including the presence of both lateral and mid-channel gravel bars.

The Shasta River below Big Springs Creek exhibited channel morphologies more typical of spring-fed rivers that derive the majority of streamflow from discrete or diffuse groundwater sources. Spring-fed rivers typically experience low seasonal variability in flow, and, as a result, exhibit remarkably homogenous channel morphologies conspicuously absent of channel bars or other bedforms typical of runoff-dominated rivers. Furthermore, spring-fed rivers are often characterized by elevated bankfull width-to-depth ratios and rectangular cross-sectional channel geometries (Whiting and Moog 2001).

Channel cross-section morphologies throughout the Nelson Ranch study site were deep and narrow, with mean width-to-depth ratios of 11. Such low bankfull width-to-depth ratios may be related to the presence of relatively cohesive channel bank sediments, which may inhibit channel widening (Chitale 1973). Surveyed cross-sections exhibited largely rectangular geometries, with homogenous bedforms devoid of lateral or mid-channel bars. Cross-section morphologies became wider and shallower at the downstream Freeman and Manley Ranch study sites, with mean bankfull width-to-depth ratios of 29 and 28, respectively. Channel bars continued to be absent throughout these downstream channel reaches, and channel geometry remained rectangular, typical of spring-fed streams.

Channel cross-section morphologies through the Shasta River canyon study site remained wide and shallow, with a mean bankfull width-to-depth ratio of 23 (Table 2). Channel geometries remained largely rectangular, with limited lateral variability in morphology. While qualitative observations indicated that locations along the Shasta River throughout the 14-kilometer canyon near Yreka (i.e. channel reaches located outside of the project study site) can exhibit lateral and mid-channel gravels bars (e.g. at “Salmon Heaven”; RKM 9), it is hypothesized that such conditions may be derived from localized conditions, such as small tributary or hillslope sediment inputs, spawning gravel restoration, or reductions in channel gradient promoting deposition of available sediment.

Table 2: Summary of mean bankfull width-to-depth ratios at each project study site.

	Upper Shasta River	Big Springs Creek	Nelson Ranch	Freeman	Manley	Canyon
Shasta River Location (river kilometer)	76.61	N/A	51.5	32.54	19.62	2.59
Mean bankfull width:depth ratio	16	84	11	29	28	23

Big Springs Creek

Cross-sectional channel morphologies throughout Big Springs Creek were remarkably wide and shallow. Width-to-depth ratios ranged from less than 9 at laterally-confined road crossings to 237 (Figure 3). The mean bankfull width-to-depth ratio throughout Big Springs Creek was 84 (including road crossings), with a standard deviation (σ) of 50. Width-to-depth ratios remained relatively stable between the mouth of Big Springs Creek and the water wheel (RKM 2.5) (mean = 61; σ = 21) (Figure 3), but are nearly double this value in reaches above the water wheel (mean = 117; σ = 54). Average ratios measured in Big Springs Creek were significantly greater than those measured in selected spring-fed streams in Oregon and Idaho, where average width-to-depth ratios were 34 (σ = 24) (Whiting and Moog 2001). Reasons for elevated width-to-depth ratios in Big Springs Creek compared to spring-fed creeks in Idaho and Oregon are uncertain, but may be related to the presence of numerous spring seeps along the channel bed, particularly in channel reaches upstream from the waterwheel. Spring seeps within the channel bed may inhibit bank formation, thus increasing the width of the channel where such seeps are present.

Longitudinal trends in cross-sectional channel form were apparent in Big Springs Creek. Throughout the 2.5 river kilometers from the mouth of Big Springs Creek to the water wheel impoundment, channel geometries were largely rectangular with minimal lateral asymmetry. Excluding channel road crossings, width-to-depth ratios were high (mean = 61) and moderately variable ($\sigma = 21$) (Figure 3). Water depths were shallow through this reach, with a mean depth during the summer 2008 of 0.58 meters ($\sigma = 0.15$ meters). Large deviations from the mean water depth principally occurred across shallow, bedrock-dominated riffles and at deeper bridge crossings (Figure 3).

The impoundment structure at the waterwheel forced a unique set of localized geomorphic conditions for over approximately 400 m upstream (Figure 3). While channel width remained largely stable across this reach, the gradual reduction in mean water depth in the upstream direction from the waterwheel resulted in a large increase in width-to-depth ratios (Figure 3).

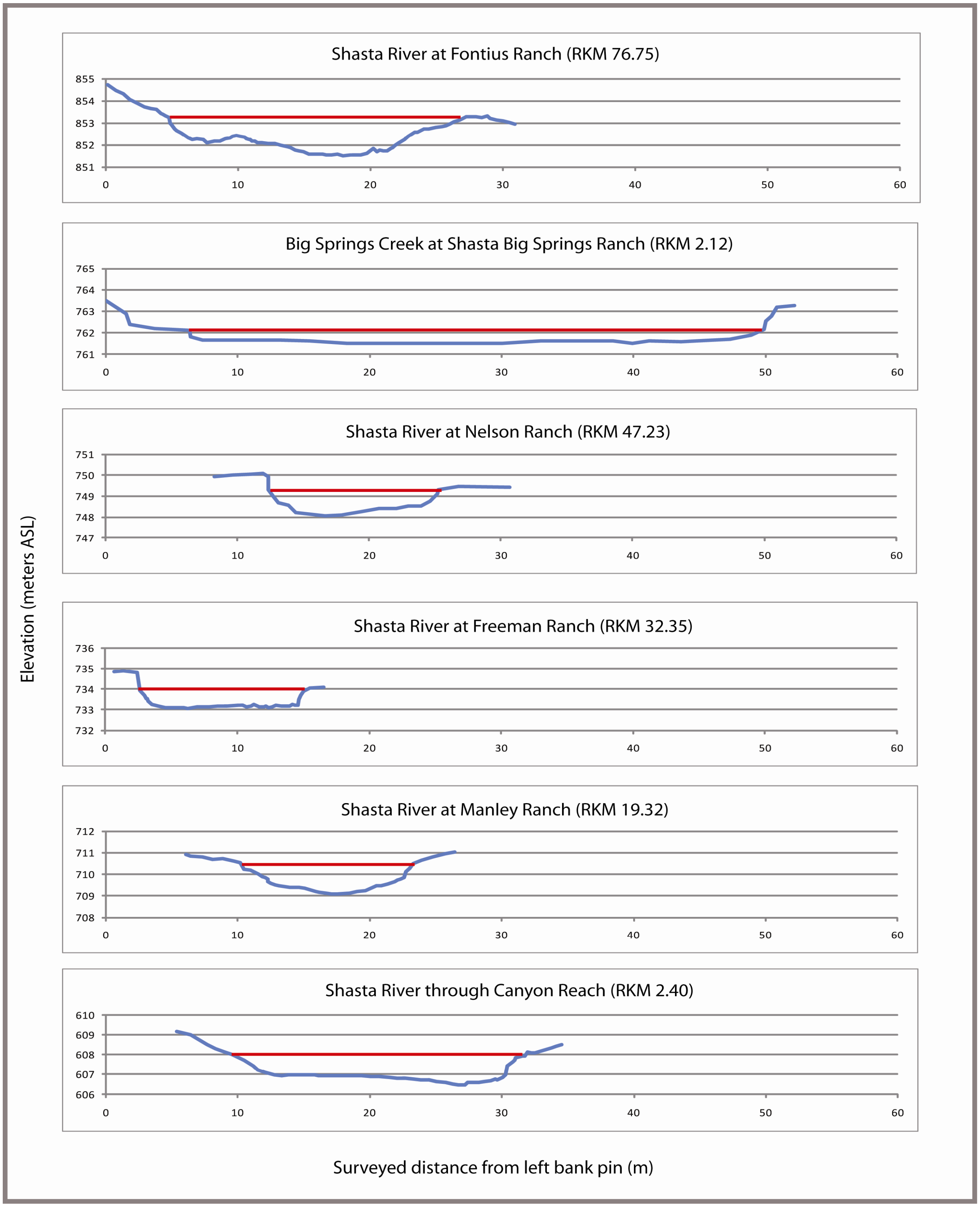

Figure 4. Representative channel cross-sections surveyed at each study site. Big Springs Creek exhibits remarkably high bankfull width-to-depth ratios compared to channel cross-sections surveyed along the Shasta River. (Red = estimated channel bankfull inundation; Blue = topography of the surveyed channel cross-section.)

6.4 ***Bed Material***

Bed material size distributions provided useful indicators of spawning habitat quality at each study site, excluding Big Springs Creek. Cumulative frequency distributions of bed surface sediments (Figure 5) identified longitudinal segregation of particle sizes throughout the Shasta River that corresponded principally with channel slope (see Table 1). D_{50} particle sizes, or the particle size at which 50 percent of the sampled sediments are finer, was largest at the Fontius Ranch study site (38 mm; slope = 0.0054) and smallest at Nelson Ranch study site (13 mm; slope = 0.001). While mean D_{50} particle sizes remained low at the Freeman Ranch study site near Montague (15 mm; slope = 0.002), mean D_{50} particle sizes increased substantially at the Manley Ranch study site (36 mm; slope = 0.0034), concurrent with a measured gradient increase in the Shasta River towards the northern end of the Shasta Valley. Mean D_{50} particle sizes were remarkably small at the Canyon Reach study site (16 mm; slope = 0.0087), and did not correspond with the elevated slope through the study reach or the lower Shasta River Canyon in general. Qualitative observations suggest D_{50} particle sizes based on surface sediment sampling in the Canyon Reach strongly underestimated D_{50} particle sizes. Sediment sampling locations throughout the Canyon Reach study site appeared skewed towards lower gradient portions or the study reach (slope ~ 0.001), which appeared to explain this discrepancy.

Bed material sizes throughout the Shasta River appear to correspond well with changes in channel slope. As discussed above, increased bed surface material sizes were found at study sites above Dwinnell Dam (Fontius Ranch) and below Yreka-Montague Road (Manley Ranch, Canyon Reach). Conversely, study sites located throughout the low-gradient Shasta Valley (Nelson Ranch, Freeman Ranch) exhibited much smaller bed materials. These data generally correspond with historical qualitative observations of spawning gravel quality (i.e. larger gravel sizes) throughout the Shasta River (Wales 1951, Ricker 1997). Wales (1951) also identified salmon and steelhead spawning in Big Springs Creek, suggesting that gravel distributions appropriate for salmonid spawning historically existed in the spring-fed tributary. Qualitative observations made by UC Davis personnel identified suitable spawning gravels throughout Big Springs Creek during the study period, particularly in the lower 2.5 river kilometers.

Table 3: Summary of mean D_{50} particle size at each project study site.

	Upper Shasta River	Big Springs Creek	Nelson Ranch	Freeman	Manley	Canyon
Shasta River Location (river kilometer)	76.61	N/A	51.5	32.54	19.62	2.59
Mean D_{50} particle size (mm)	38	--	13	15	36	16

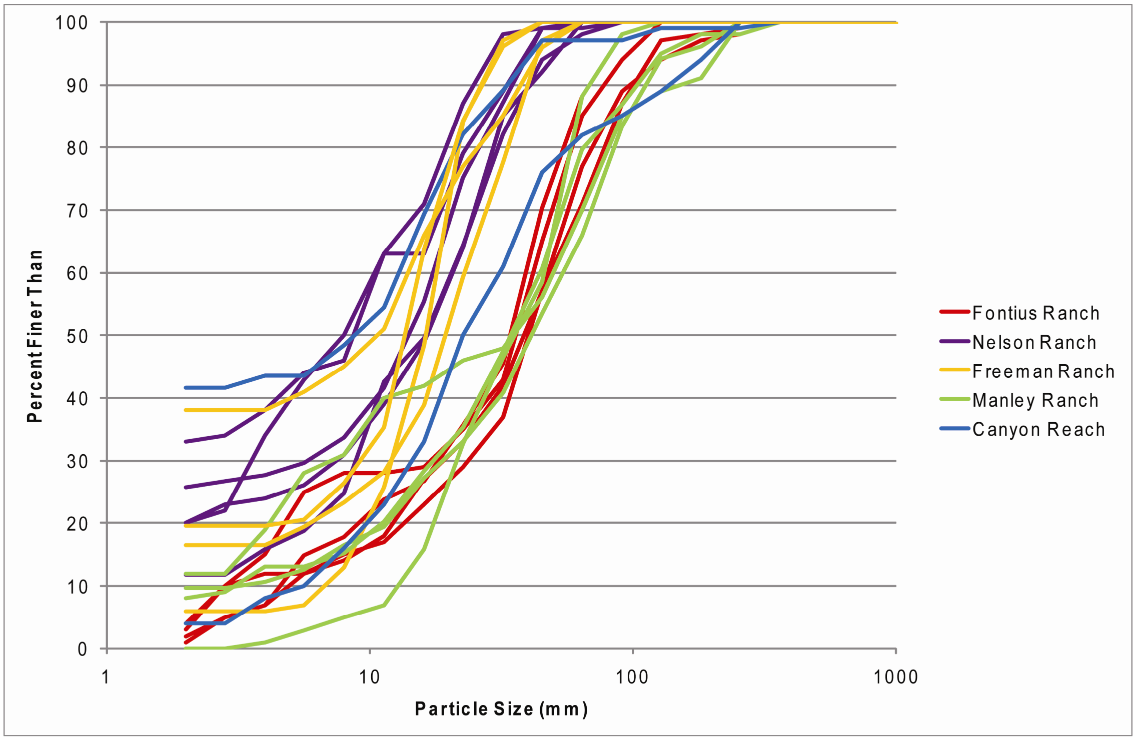

Figure 5 – Cumulative particle size distributions from surface sediment samples collected at each study site (excluding Big Springs Creek).

6.5 *Summary*

The Shasta River exhibited longitudinal (i.e. downstream) patterns in geomorphologic characteristics that were largely driven by spatial differences in hydrologic regime and channel gradient. Along the Shasta River above Dwinnell Dam, trapezoidal cross-section channel geometries and gravel to cobble-sized bed materials reflect elevated channel slopes and a hydrologic regime dominated by snowmelt and rainfall runoff. In contrast, rectangular cross-section channel geometries, elevated width-to-depth ratios and sand to small gravel-sized bed materials in both Big Springs Creek and the Shasta River below principally reflect hydrogeomorphic processes dominated by shallow channel gradients and stable, groundwater derived baseflows. Elevated channel gradients and larger bed materials were identified in the lower Shasta River canyon near Yreka.

7.0 Hydrology

The Shasta River exhibits downstream differences in discharge magnitude and variability as a result of spatial differences in streamflow generation, tributary inputs, dam regulation, and seasonal in-stream irrigation diversions and associated return flows. The upper Shasta River, exhibits hydrologic characteristics of a runoff-dominated stream (Whiting and Moog 2001, Nichols 2008), with sharp ascending and descending hydrograph limbs during rainfall runoff events, as well as a more prolonged spring-time snowmelt recession derived from surface runoff in the Scott and Siskiyou Mountains. Following the rainfall and snowmelt runoff in the winter and spring, flows in the Upper Shasta River consist of Boles, and Beaughan Creeks (spring creeks that during irrigation season are diverted for use), the upper Shasta River, and diversions from Parks Creek via the Montague Water Conservation District canal. The regulated lower Shasta River receives no appreciable quantities of streamflow from Lake Shastina (releases of up to 10 ft^3/s may occur during irrigation season to meet water right holders to the Shasta River below the dam). Hydrologically, the lower Shasta River exhibits characteristics of a "spring-dominated" stream (Whiting and Moog 2001, Nichols 2008) periodically influenced by winter/spring flood events sourced from rainfall and snowmelt derived from the Parks Creek tributary. The spring-dominated hydrologic characteristics of the lower Shasta River are largely derived from discrete spring-fed tributary inputs, principally from Big Springs Creek (Jeffres et al. 2009). Both discrete (e.g. Big Springs Creek) and diffuse (i.e. unnamed springs and seeps) groundwater sources provide seasonally-independent baseflow discharges throughout the lower Shasta River.

The Shasta River is largely appropriated, allowing riparian land owners and local irrigation districts to divert in-stream flow in accordance with adjudicated water rights established in 1932. Water diversions from the upper Shasta River and Parks Creek occur between March 1 and October 31, while diversions from the lower Shasta River occur between April 1 and September 30. Furthermore, unquantified and unadjudicated groundwater pumping occurs throughout the Shasta River basin, including the area surrounding Big Springs Creek (Jeffres et al. 2009). Irrigation diversions strongly reduce discharge magnitudes throughout the Shasta River during the irrigation season (Jeffres et al. 2008, Jeffres et al. 2009), while the effects of groundwater pumping remain unquantified. However, examination of river discharge records and known irrigation withdrawals along Big Springs Creek (Jeffres et al. 2009) suggest that local groundwater pumping may reduce groundwater spring production, and thus reduce discharge magnitudes in Big Springs Creek. More investigation is needed to identify and quantify linkages between local groundwater pumping and streamflow throughout the Shasta River basin.

Quantifying discharge at locations throughout the Shasta River basin is a critical step in understanding abiotic and biotic responses to downstream (i.e. longitudinal) changes in streamflow magnitude and variability, particularly during the spring/summer irrigation season. For large diversions (e.g., irrigation district withdrawals), water right values were employed in the assessment of data. Individual diversions, return flows, reach losses due to evaporation and evapotranspiration, local groundwater exchange, and other factors were not quantified unless noted.

7.1 ***Methods***

Streamflow during the project period was either monitored directly by the UC Davis Center for Watershed Sciences or acquired from publicly available data sources maintained by the United States Geological Survey (USGS) and the California Department of Water Resources (DWR). Discharge was gauged at five locations throughout the Shasta River basin: Shasta River at Edgewood (Fontius Ranch), Big Springs Creek at Water Wheel (SBSR), Shasta River above GID (Nelson Ranch), Shasta River at Montague, and Shasta River at Yreka (Table 4). Locations of streamflow gauges and prominent irrigation diversion points are identified in Figure 6.

Table 4. Streamflow gauging locations, river kilometer, and data source for the Shasta River

Site Name	River Kilometer	Data Source
Shasta River at Edgewood (Fontius Ranch)	76.6	DWR/UCD[1]
Big Springs Creek at Water Wheel (SBSR)	2.6	UCD[2]
Shasta River above GID (Nelson Ranch)	51.5	UCD[3]
Shasta River at Montague	15.5	USGS
Shasta River at Yreka	0.9	USGS

[1]River stage continuously monitored by DWR; Discharge rating curve developed by UC Davis Center for Watershed Sciences.
[2]Stream gauge is located approximately 2.6 kilometers upstream from the confluence with the Shasta River
[3]Discharge estimated through summation of rated upstream gauges (Parks Creeks, Upper Shasta River, Hole in the Ground Creek, and estimates of spring-flow contributions from Little Springs Creek and unidentified diffuse springs.

At stream gauge locations maintained by the UC Davis Center for Watershed Sciences, river stage data were collected at 10-minute sampling intervals using Global Water WL-16 submersible pressure transducers. DWR continuously monitored river stage in the Shasta River at Edgewood (Table 1, RKM 76.6) at 15-minute sampling intervals. Streamflow at the UC Davis and DWR gauge locations were periodically measured using standard methodologies (Rantz 1982). Point velocities were measured within vertical bins across river cross-sections at 0.6 of the stream depth using a Marsh McBirney Flo-Mate electromagnetic velocity meter attached to a top-set wading rod. Vertical bin widths typically did not exceed 5% of the channel cross-section wetted width. Discharge measurements were calculated using the USGS mid-section velocity-area methods (Rantz, 1982). Streamflow rating curves were subsequently developed for the UC Davis and DWR stream gauges to estimate continuous streamflow magnitudes at each location.

Due to difficulties developing reliable discharge rating curves for a previously established stream gauge on the Shasta River above the GID diversion at RKM 49.5 (gauge located RKM 51.5) (Jeffres et al. 2008, Jeffres et al. 2009), discharge magnitude at this location was estimated through the summation of gauged and rated upstream tributaries (Shasta River below Dwinnell Dam, Parks Creek, Hole in the Ground Creek and Big Springs Creek) (see Jeffres et al. 2009) and estimated contributions from discrete (Little Springs Creek; 5 ft^3/s) and unidentified diffuse (10 ft^3/s) spring sources. Streamflow estimations for the Shasta River above the GID diversion correlate with measured discharges at this location during the project period ($r = 0.73$).

At streamflow gauges maintained by the USGS (Shasta River at Montague (Station ID 11517000) and the Shasta River at Yreka (Station ID 11517500)) (Figure 6), river stage was sampled at 15-minute intervals, from which a continuous record of discharge was developed by the USGS. Available data collected during the project period was reported by the USGS as mean daily discharge (i.e. the mean of all continuous streamflow magnitudes for each date).

To facilitate the comparison of longitudinal differences in streamflow characteristics, herein mean daily discharge is reported for each streamflow gauge. Mean daily discharge magnitudes were calculated from continuous streamflow data from the stream gauges operated by UC Davis or DWR. Streamflow statistics (mean, median, maximum, minimum, standard deviation) were subsequently calculated for each stream gauge during the project period using mean daily discharges.

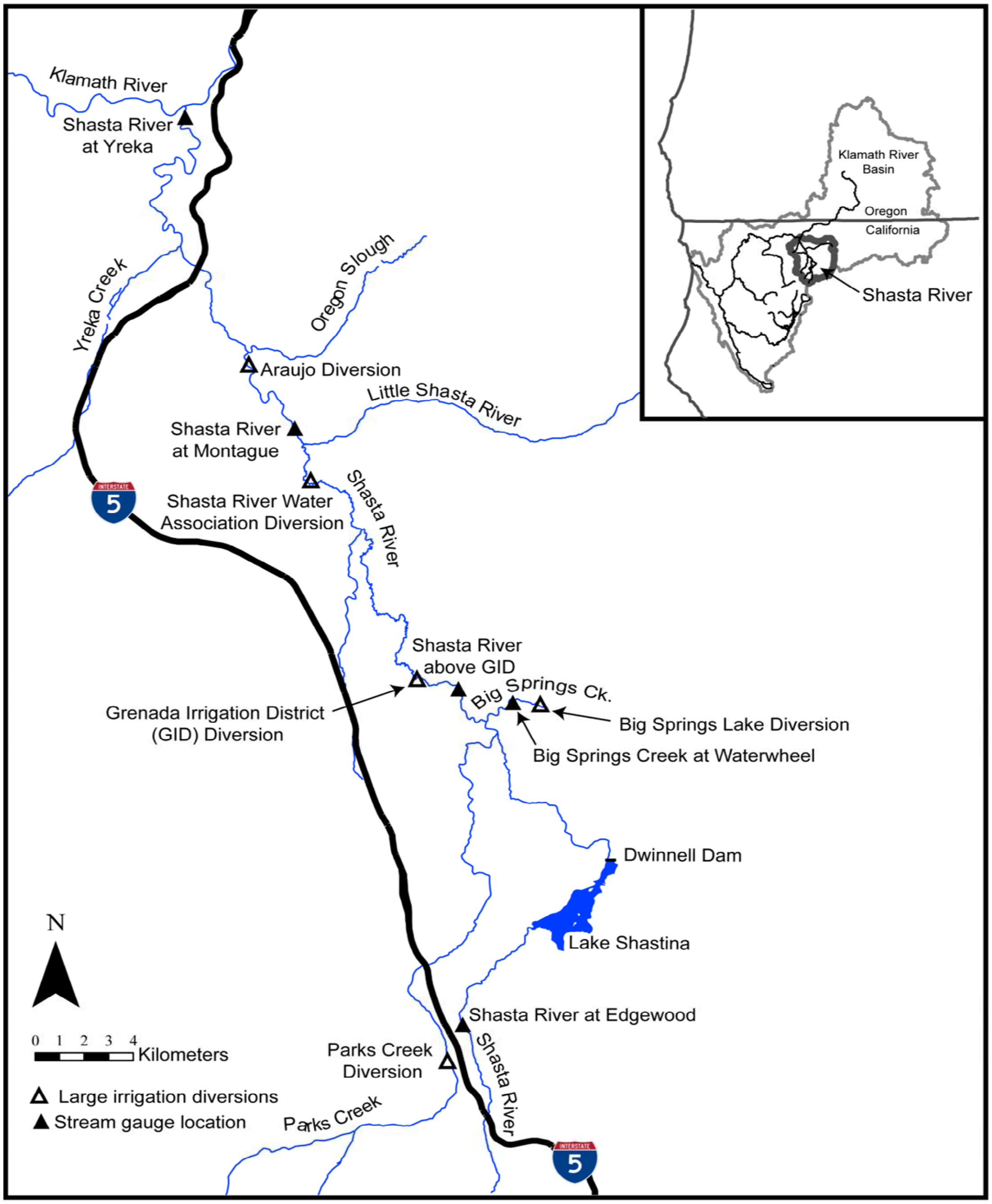

Figure 6: Streamflow gauge locations and major irrigation diversion points along the Shasta River and Big Springs Creek.

7.2 ***Data Analysis***

A review of hydrologic observations from March through October, 2008 is presented for each of the stream gauge locations along the Shasta River and Big Springs Creek (Table 2).

7.2.1 *Shasta River at Edgewood (Fontius Ranch)*

During the entire project period, water was continuously diverted for irrigation purposes from river reaches upstream from the Shasta River at Edgewood gauge (Figure 6). Furthermore, streamflow measured in the Shasta River at Edgewood was stored in Lake Shastina approximately 7 kilometers downstream, and periodically released to the Shasta River below Lake Shasta to: 1) provide water to landowners whose irrigation diversion points along the Shasta River were inundated or dewatered by the construction of Dwinnell Dam and the impoundment of Lake Shastina; and 2) the Montague Water and Conservation District (MWCD) canal for delivery to irrigation district customers. Other unquantified outflows from Lake Shastina include evaporation and seepage.

Beginning in early April 2008, discharge magnitude progressively increased in the Shasta River at Edgewood in response to surface and shallow subsurface runoff derived from the continuous spring snowmelt (Figure 7). Progressive increases in discharge were augmented by sharp yet short hydrograph peaks in response to surface runoff derived from rapid snowmelt and/or rainfall, with a maximum measured discharge magnitude of 274 ft^3/s during the project period (Table 5). Following the spring snowmelt, discharge progressively decreased from June 2008 through August 2008, with minimum discharge magnitudes approaching 9 ft^3/s (Table 5, Figure 7). Streamflows in the Shasta River at Edgewood gradually increased through September and October 2008, presumably in response to decreased upstream irrigation diversions. Potential reductions in evapotranspiration during the fall period may have also promoted a seasonal increase in groundwater-derived baseflows during the fall period.

7.2.2 *Big Springs Creek at Water Wheel (Shasta Big Springs Ranch)*

Big Springs Creek is hydrologically characterized by fairly stable baseflow derived from discrete and diffuse groundwater sources. Jeffres et al. (2009) identified two large natural spring complexes within the upper 1.5 kilometers of Big Springs Creek. The stream gauge along Big Springs Creek at the Water Wheel is located immediately downstream from the spring complexes, that together produced a mean unimpaired (i.e. non-irrigation season) discharge of 83 ft^3/s ($\sigma = 9$) in 2008 (Jeffres et al. 2009). During the April 1 to September 30 irrigation season, the large spring complex at the head of Big Springs Creek was periodically impounded behind Big Springs Dam to facilitate irrigation diversions to adjacent properties. These temporally variable surface water diversions, as well as currently unquantified groundwater pumping, imposed substantial hydrologic variability upon Big Springs Creek during the irrigation season. As a result, mean irrigation season discharge in Big Springs Creek was 52 ft^3/s ($\sigma = 9$), while minimum discharges were approximately 40 ft^3/s (Table 5). Discharge magnitudes in

Big Springs Creek rebounded rapidly to unimpaired baseflow conditions in early October 2008 following the cessation of upstream irrigation diversions (Figure 7).

7.2.3 *Shasta River above GID Diversion (Nelson Ranch)*

Streamflow in the Shasta River above the GID diversion represents the combined streamflow contributions from the Shasta River below Lake Shastina, Parks Creek, Hole in the Ground Creek, Big Springs Creek, Little Springs Creek (a tributary of Big Springs Creek located below the Big Springs Creek Waterwheel gauge), and numerous groundwater springs and seeps that were not formally measured (e.g., unquantified). Streamflow data for each of the aforementioned tributaries was summarized for the project period by Jeffres et al. (2009). Data presented herein for the Shasta River above the GID diversion are the summation of: 1) the aforementioned measured tributary inflows (Jeffres et al. 2009); and 2) estimated streamflow contributions from Little Springs Creek (5 ft^3/s) and unquantified springs and seeps (~10 ft^3/s).

During the project period, principal sources of streamflow in the Shasta River above the GID diversion varied seasonally. Between April and early June 2008, groundwater-derived baseflows were augmented by streamflow from snowmelt and rainfall-derived runoff in the Parks Creek sub-basin. Runoff-derived streamflows were moderated by irrigation diversions in the Shasta River, Parks Creek, Hole in the Ground Creek, Big Springs Creek and Little Springs Creek. Between April and early June 2008, maximum discharge in the Shasta River above the GID diversion was 138 ft^3/s, while minimum discharge was 79 ft^3/s (Table 5). From mid-June 2008 through September 2008, discharge magnitude steadily decreased as the snowpack was depleted, and both irrigation diversions and groundwater pumping continued throughout the watershed. From June 1 to September 30, 2008 mean discharge magnitude in the Shasta River above the GID diversion was 80 ft^3/s, with minimum streamflows approaching 67 ft^3/s.

7.2.4 *Shasta River at Montague*

Similar to the Shasta River above the GID diversion, the Shasta River at Montague gauge measures groundwater baseflows derived from spring sources in the vicinity of Big Springs Creek that are 1) augmented by seasonal streamflow increases from snowmelt and rainfall runoff, including those derived from the tributary Little Shasta River; and 2) reduced by upstream water diversions for irrigation between April 1 and September 30. From April 1 to April 12, 2008 discharge in the Shasta River at Montague was reduced from 143 ft^3/s to 43 ft^3/s (~70 percent), signifying the large and rapid reduction of groundwater-fed baseflows throughout the basin in response to irrigation diversions and groundwater pumping. For comparison, discharge in the Shasta River above the GID diversion was reduced from 134 ft^3/s to 94 ft^3/s (~27 percent) during this same period, highlighting the considerable streamflow diversions from the Shasta River between the two locations.

From April through early June 2008, runoff derived from snowmelt and rainfall periodically augmented streamflows in the Shasta River at Montague, with maximum discharge approaching 147 ft^3/s. Minimum discharge during this period was 29 ft^3/s. Following spring snowmelt, around mid-June, discharge varied between 16 ft^3/s and 37 ft^3/s until the reduction in volume of upstream irrigation diversions in late September 2008. Beginning October 1, 2008 streamflows rapidly rebounded to near baseflow conditions as irrigation withdrawals ceased.

7.2.5 *Shasta River at Yreka*

Streamflow conditions in the Shasta River at Yreka largely mimicked those observed in the Shasta River at Montague during the project period. Exceptions included elevated maximum discharge magnitudes in response to runoff-derived streamflow from the Yreka Creek tributary, and reduced minimum streamflows in response to additional irrigation diversions between the two monitoring stations. During the project period, maximum discharge in the Shasta River at Yreka was 251 ft^3/s, while minimum discharge was 11 ft^3/s. Mean discharge magnitude during the entire project period was 90 ft^3/s ($\sigma = 68$), while mean discharge during the irrigation season was 62 ft^3/s ($\sigma = 46$). From July 1 to September 30, 2008, mean discharge was 26 ft^3/s.

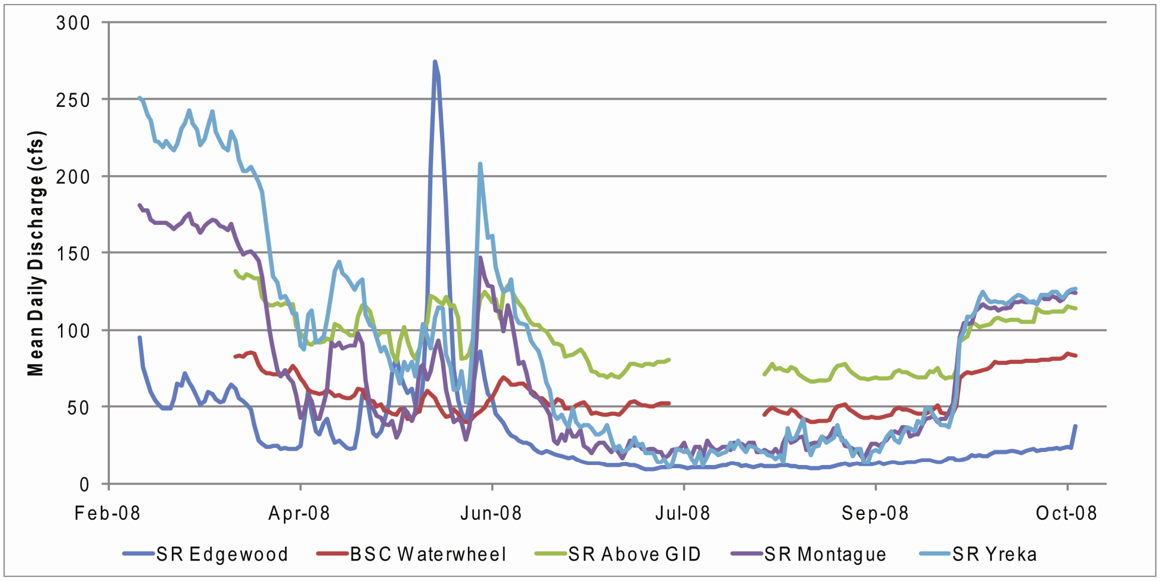

Figure 7 – Hydrograph identifying streamflow magnitudes measured in the Shasta River during the project period (SR = Shasta River; BSC = Big Springs Creek).

Table 5 – Streamflow statistics for mean daily discharge values calculated more measured discharges at gauges located along the Shasta River and Big Springs Creek. All measurements units are cubic feet per second (ft^3/s). Streamflow in the Shasta River above the GID diversion represents the combined streamflow contributions from the Shasta River below Lake Shastina, Parks Creek, Hole in the Ground Creek, Big Springs Creek, Little Springs Creek (tributary to Big Springs Creek), and numerous unnamed groundwater springs and seeps.

	Shasta River at Edgewood	Big Springs Creek at Waterwheel	Shasta River above GID	Shasta River at Montague	Shasta River at Yreka
All Data (March 1, 2008 to October 31, 2008)					
Mean	33	57	93	70	90
Median	21	52	93	46	82
Max	274	85	138	181	251
Min	9	40	67	16	11
Standard Deviation	36	13	20	51	68
Irrigation Season (April 1, 2008 to September 30, 2008) [1]					
Mean	33	52	89	47	62
Median	21	50	84	34	40
Max	274	77	134	147	208
Min	9	40	67	16	11
Standard Deviation	36	9	19	30	46

[1]Irrigation season in the Shasta River above Lake Shastina was March 1, 2008 to October 31, 2008

7.3 ***Summary***

The Shasta River exhibited longitudinal differences in hydrologic characteristics, largely stemming from spatial differences in streamflow generation processes. Streamflow in the Shasta River above Lake Shastina exhibited characteristics of Mediterranean-montane hydrologic systems, with elevated discharge magnitudes in response to late winter rainfall and spring snowmelt, followed by a spring snowmelt recession to low summer baseflows. Rainfall and snowmelt-derived streamflow in the Shasta River above Dwinnell Dam was stored in Lake Shastina, with minimal releases to the Shasta River below. In contrast, groundwater derived streamflow in Big Springs Creek provided voluminous and stable baseflows to the Shasta River approximately 11 kilometers below Dwinnell Dam. These spring-fed baseflows were periodically augmented by tributary inflows derived from surface runoff in the Parks Creek, Little Shasta River and Yreka Creek tributary sub-basins. Streamflow throughout Shasta River and Big Springs Creek progressively decreased during the spring and summer irrigation season, only to rapidly rebound to spring-fed baseflow conditions at the end of the irrigation season.

8.0 Water Temperature

Water temperature is the key limiting factor for rearing salmonids in the lower Shasta River and Big Spring Creek (Jeffres et al. 2008, Jeffres et al. 2009). Several factors that affect water temperatures in the Shasta River include, but are not limited to: temperature of source waters and tributaries (particularly Big Springs Creek), channel morphology, flow volume, solar radiation, atmospheric conditions, shade elements (i.e. riparian and emergent vegetation), aquatic macrophytes, and water management activities (e.g. diversions, tailwater, and return flows). The relative importance of the specific factors that affect water temperature throughout the Shasta River basin depend largely on the location within the watershed and season.

The key location where the Shasta River's water temperature paradigm shifts is the confluence of the Shasta River with Big Springs Creek. Upstream of this location, observed water temperature trends largely mimic thermal signals seen in rivers within Mediterranean climates, with spring and summer water temperatures largely increasing as discharge derived from precipitation and snowmelt runoff decreases to baseflow conditions. Downstream of Big Springs Creek, water temperatures in the Shasta River are strongly defined by streamflow temperatures contributed by Big Springs Creek for tens of kilometers before the Shasta River returns to equilibrium temperature[1]. During spring and summer, local meteorological conditions yield equilibrium temperatures in the downstream reaches that are not compatible with over-summering life stages of anadromous fish. Preserving the cold water contributed by Big Springs Creek as well as management of various heating elements are the best methods for creating favorable habitat conditions for salmonids within the watershed during critical periods of the year.

8.1 *Methods*

Water temperature field monitoring occurred primarily through the direct deployment of temperature loggers. HOBO® Pro v2 Water Temperature Data Loggers from Onset Computer Corporation were used to collect information at 30-minute intervals throughout the project area. These loggers have a resolution of approximately 0.03^{o}C (0.02°C at 25°C) and an accuracy of ±0.2°C over the range from 0°C to 40°C, and a 90 percent response time of 5 minutes in water (Onset 2009). Loggers were deployed at each study site; additional locations were included to provide detail for some reaches (Figure 8).

[1] Equilibrium temperature is the water temperature that would result from exposure to a specific set of meteorological conditions, i.e., the water temperature is in equilibrium with meteorological condition. In reality, equilibrium temperature is a moving target over the period of a day in response to varying meteorological conditions. Nonetheless, the theoretical construct of an equilibrium conditions is a useful tool to interpret water temperature information.

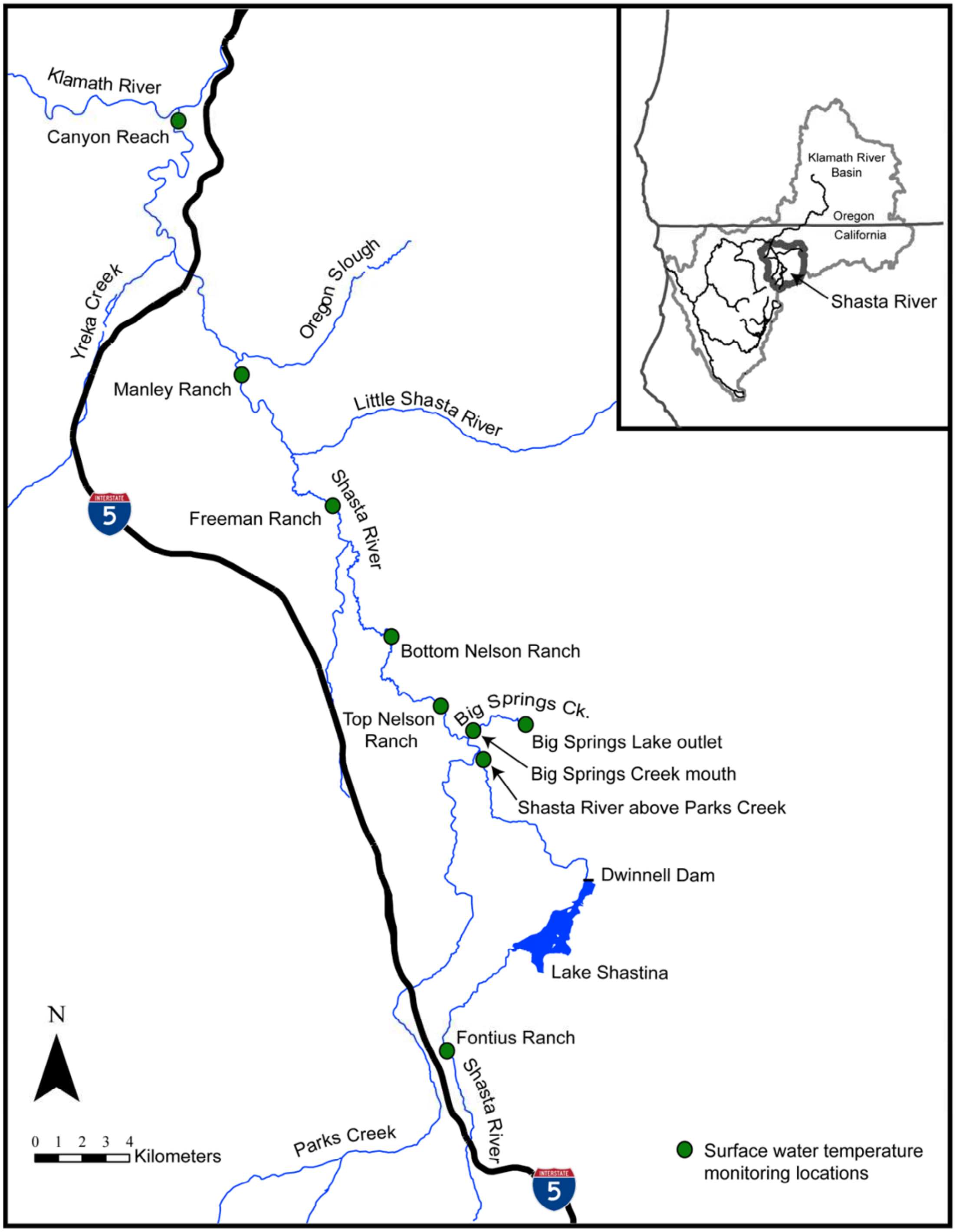

Figure 8. Temperature monitoring locations in the Shasta River and Big Springs Creek.

8.2 *Data Analysis*

Longitudinal water temperature trends in the Shasta River varied considerably from upstream to downstream locations during the project period. These variations were in response to seasonal meteorological conditions, seasonal variations in riparian and emergent aquatic vegetation shading, cool spring water inflows (most notably from Big Springs Creek), diversion and return flow, and other factors that were not uniformly distributed throughout the system. Above Big Springs Creek, Shasta River water temperatures steadily increased throughout the summer and began to cool in the fall. Below Big Springs Creek, Shasta River water temperatures reflected the creek's considerable spring inflow but still followed this seasonal trend. Imposed upon this trend was a unique pattern of maximum and minimum diurnal variation at specific locations downstream of Big Springs Creek. This pattern was consistent with the advective heating and cooling patterns of streams with steady flows and near-constant source water temperatures under stable meteorological conditions (Lowney 2000). Specifically, such conditions can produce longitudinal temperature patterns wherein diurnal variation (as represented by the daily maximum minus minimum temperature) is suppressed downstream of constant temperature sources. While Lowney (2000) examined a system more conducive to identifying predictable thermal trends (i.e., the Sacramento River downstream of Keswick Reservoir), such signals occur in the Shasta River downstream of Big Springs Creek. Although factors interfere with this diurnal pattern of suppressed diurnal range (e.g., variable flow regime, significant diversion and return flow, diffuse upstream springs source waters, and other factors) the concepts are similar and useful when interpreting the thermal regime of the Shasta River.

Because the groundwater springs' source temperature in Big Springs Creek is relatively constant (10-12^{o}C), streamflows are relatively steady on a seasonal basis, and seasonal meteorological conditions are generally stable, water temperatures reflect minimal diurnal variation at downstream locations. These occurrences, referred to here as minima, were observed on Nelson and Freeman Ranches and indicate that water temperature trends in the Shasta River are more defined by Big Springs Creek than by the upstream Shasta River for tens of kilometers below the confluence. Eventually, the Shasta River water temperature signal associated with the cold water pulse from Big Springs Creek breaks down and the pattern resumes the seasonal thermal signal observed upstream of Big Springs Creek.

Water temperatures during the project period are illustrated using box and whisker plots (Figures 9-16). Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Filled circles show the maximum instantaneous temperature during the month and non-filled circles show the minimum instantaneous temperature during the month. Charts illustrating temperature trends over the study period for each study site are presented. Separately, the longitudinal temperature profile is presented for each month during the study period to illustrate the strong influence of Big Springs Creek on downstream Shasta River water temperatures. For the purposes of the longitudinal charts, the Big Springs Lake outlet is defined as the main flow source of the downstream Shasta River during the study period; consequently distances are presented as distance downstream from this cold-water spring source. Additional temperature monitoring locations are included in the longitudinal temperature plots to provide more detail describing the diurnal heating and cooling patterns observed in the Shasta River downstream of Big Springs Creek. The first two locations represent the Big Springs Dam outlet (distance from source springs: 0.0 km) and the mouth of Big Springs Creek (distance from source springs: 3.7 km), respectively. The next two locations represent the upstream and downstream boundaries of the Nelson Ranch (distance from source springs: 6.2 km and 13.9 km, respectively). The remaining locations are downstream boundaries of the Freeman (distance from source springs: 25.2 km) and Manley Ranches (distance from source springs: 36.8 km), and the Canyon Reach (distance from source springs: 55.3 km).

8.2.1 *Fontius Ranch*

Water temperature data at the Fontius Ranch illustrated water temperature trends typical of rainfall- and snowmelt-based runoff. Seasonally, during the project period, water temperatures rose in the spring, reaching a maximum in mid-summer, and then decreasing through the fall. The initial temperature increase was interrupted by increased runoff and cooler water temperatures associated with the spring snowmelt (Figure 9). Once the snowpack was exhausted, the rate of heating increased. The increased rate of heating continued until July, when maximum temperatures were approximately 26°C, but water temperatures in excess of 20°C did occur from June through August. Heating rates declined starting in August, and cooling continued into the fall as solar radiation was reduced and atmospheric conditions cooled. A similar temperature pattern was illustrated in the Shasta River above Parks Creek at RKM 56.2; however, there was no snowmelt signal (Figure 10).

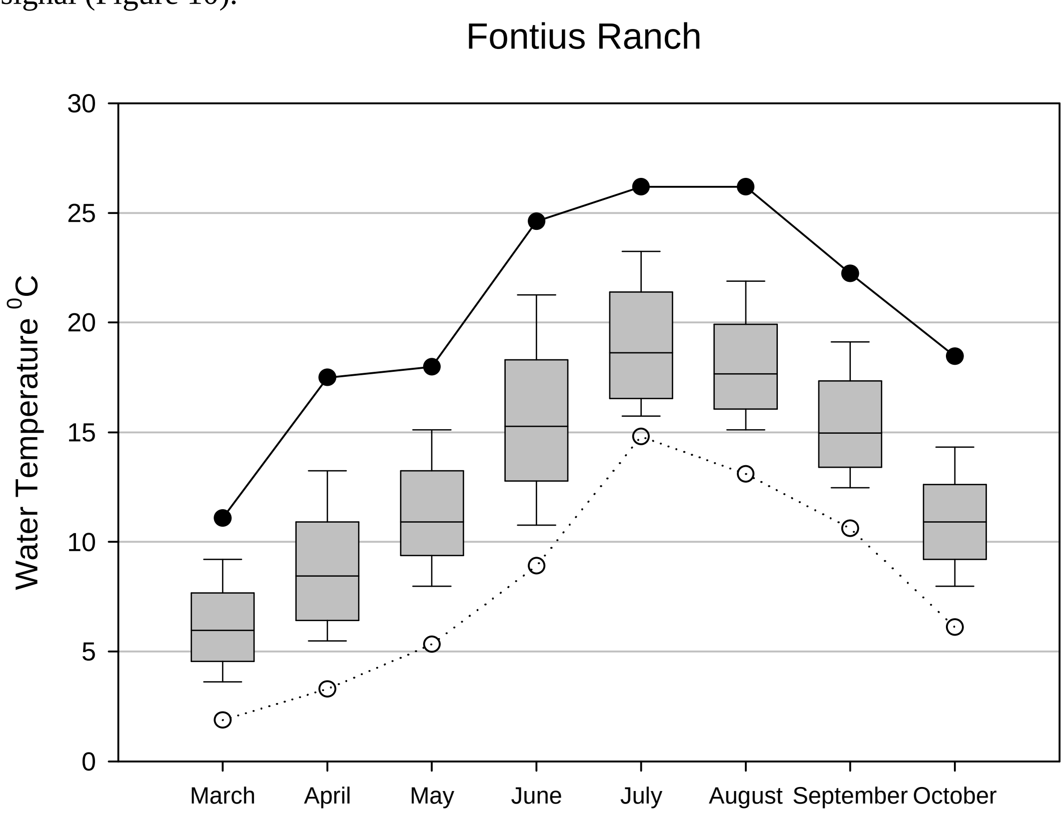

Figure 9. Monthly water temperature trends in the Shasta River at Fontius Ranch (RKM 76.6). Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

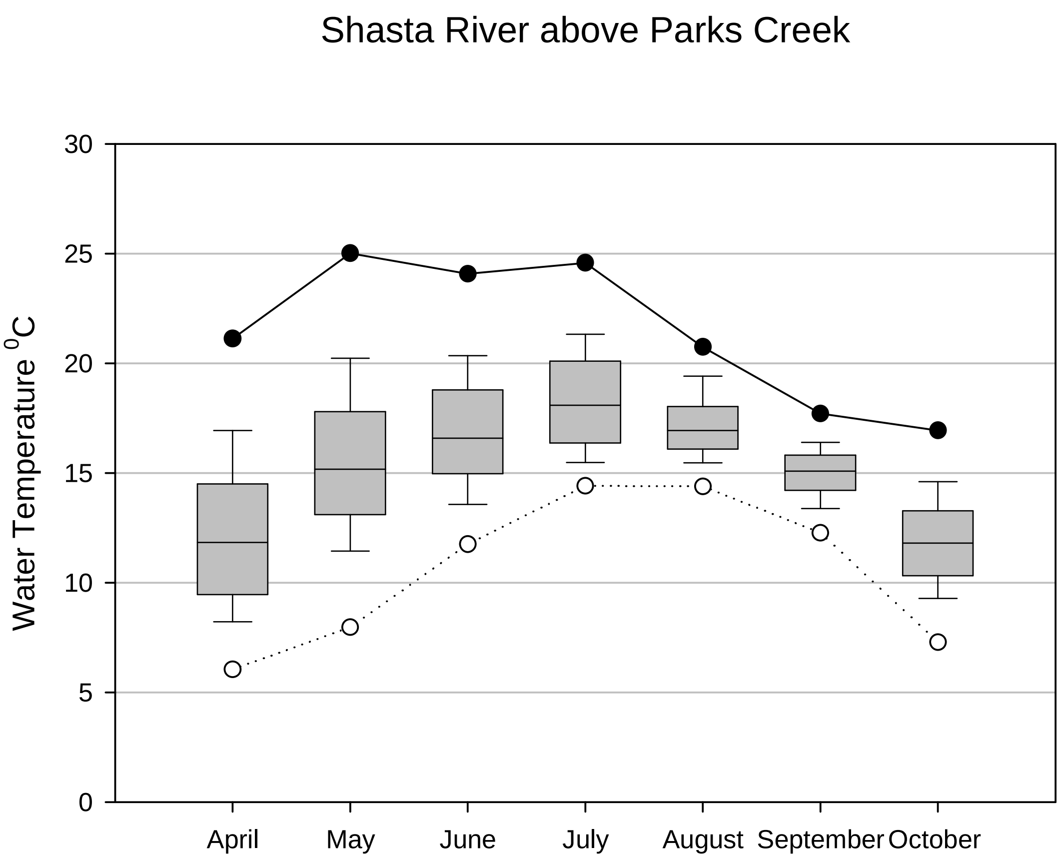

Figure 10. Monthly water temperature trends in the Shasta River above Parks Creek (RKM 56.3). Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

8.2.2 *Big Springs Creek*

Big Springs Creek water temperature trends differed from the rainfall and rainfall-snowmelt based temperature signals in the Shasta River above Big Springs Creek. The nearly constant water temperature of the spring sources was reflected by the minimal seasonal variation in stream temperature below the Big Springs Lake outlet (Figure 11). While the temperatures of the discrete springs in Big Springs Lake are unknown, temperature monitoring of springs downstream of Big Springs Lake show that they emerge between 10-12°C (Willis and Deas 2009). Throughout the study period, monthly average temperature at the lake outlet ranged from 10.7-14.5°C. The difference between monthly maximums and minimums ranged between 4.4°C to 6.6°C; maximum and minimum diurnal variations were 4.6°C and 0.6°C. The variation illustrated in the Big Springs Lake outlet temperature was likely due to heating, cooling, and mixing that occurs in Big Springs Lake as the water travels approximately 0.5 km from the source springs to the lake outlet (Jeffres et al. 2009).

While the springs contributed near-constant water temperature to Big Springs Creek during the project period, water temperatures increased rapidly between the lake outlet and the mouth of Big Springs Creek, approximately 3.7 km downstream (Figure 17,

Figure 18, and Figure 19). Maximum water temperatures at the mouth exceeded 25^oC in May, representing a 13^oC increase from maximum temperatures at the source. However, as submerged and emergent aquatic macrophytes grew, providing both shade and reduced travel times, maximum water temperatures decreased throughout the remainder of the study period.

This heating was caused principally by meteorological conditions, with several contributing factors. As discussed in section 6.3, cross-sectional channel geometries throughout Big Springs Creek are wide and shallow, exhibiting elevated width-to-depth ratios. Such channel geometries resulted in extended travel times and a large air-water interface increasing the potential for heating. These heating conditions were further exacerbated by reduced streamflows during irrigation season. During the study period, streamflow ranged between 85 ft^3/s and 40 ft^3/s; minimum flows of 40 ft^3/s were observed during irrigation season (April 1 to October 1). Finally, historic cattle grazing in the channel eliminated emergent and woody vegetation that had probably provided shade. This increased exposure also contributed to increased heating. During the 2008 project period, cattle grazing practices and ranch operations were modified and considerable instream vegetation colonized the channel throughout the summer, increasing depth, and decreasing travel times. These conditions resulted in notably cooler water entering the Shasta River as the summer progressed.

This thermal signal of Big Springs Creek water was observed in the downstream Shasta River, though the impact of this thermal signal changed as travel times changed in response to increased channel roughness resulting from increased aquatic vegetation growth and decreased streamflow magnitudes. When travel times increased, the aforementioned minimum diurnal temperature variation (minima) in the Shasta River was observed near Nelson Ranch; when travel times were reduced, the minima was observed near the Freeman Ranch. These conditions are discussed further in subsequent sections.

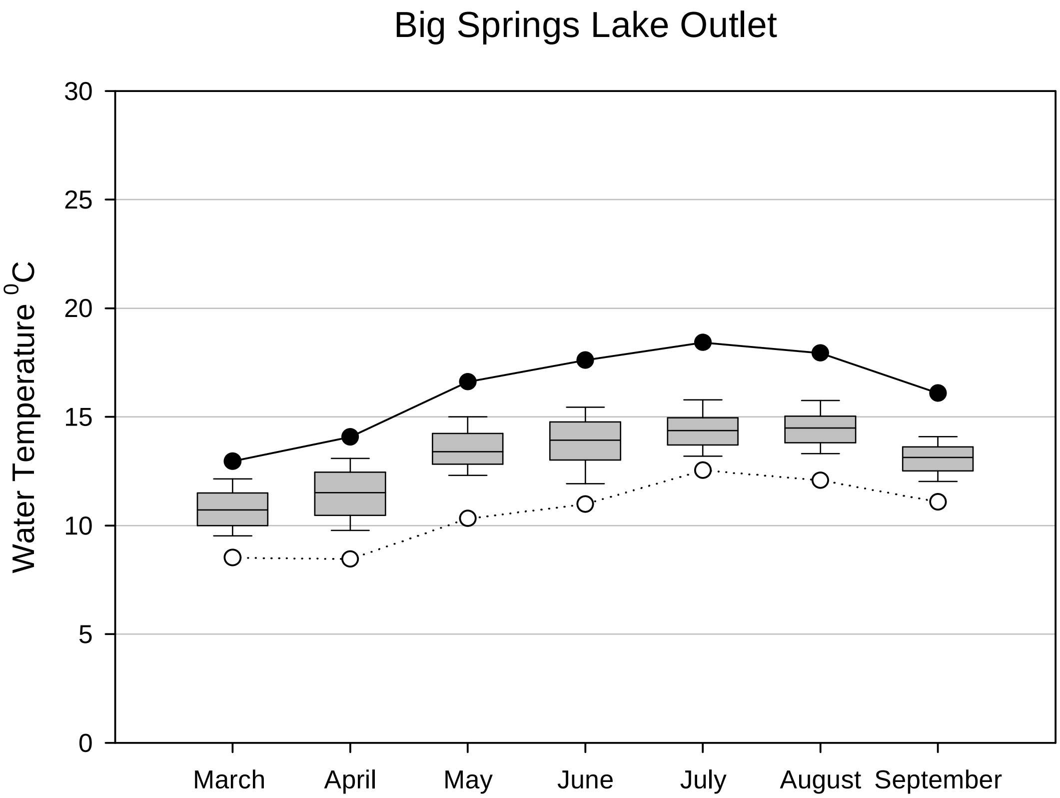

Figure 11. Monthly water temperature trends at the Big Springs Lake outlet. Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

8.2.3 *Nelson Ranch*

Nelson Ranch is the first location where the combination of Big Springs Creek and Shasta River water was monitored. Maximum water temperatures at the upstream boundary of Nelson Ranch were often comparable to those at the mouth of Big Springs Creek, indicating that the Big Springs Creek temperature signal strongly overlays the inherited Shasta River and Parks Creek thermal signal. Except for March and September, monthly maximum water temperatures exceeded 20^{o}C during the study period (Figure 12), though maximum water temperatures at the top of Nelson Ranch were cooler than those at the mouth of Big Springs Creek for all months except May. Monthly maximum water temperatures peaked in May, exceeding 25^{o}C. Factors that contributed to this peak include elevated water temperatures contributed by Big Springs Creek as well as upstream Shasta River.

Maximum water temperatures at the downstream boundary of the Nelson Ranch were consistently lower than those at the upstream boundary. This occurred because of the upstream thermal signature of water from Big Springs Creek. Water temperatures at the downstream boundary of the Nelson Ranch in June and July illustrated traces of the original thermal signal from Big Springs Creek (Figure 13). The difference in maximum and minimum water temperatures during June and July were 8.3^{o}C and 5.8^{o}C, approximately reflecting the minimal diurnal variation observed at the Big Springs Lake outlet.

At this point, though, the original thermal signal was degraded due to the addition of Shasta River water as well as flow diversions at the GID-Huseman ditch. The addition of the Shasta River shifts water temperatures from Big Springs Creek proportionally with discharge volume and heat load in the upstream Shasta River. Travel time through Nelson the Ranch was affected by the GID-Huseman ditch diversion (as well as by impoundment), which, as explained in section 7.0, can divert up to 52 ft^3/s from the Shasta River. Travel times through the Nelson Ranch were proportional to the diversion volume and thus affect the location of the Big Springs thermal signal. The relatively large temperature range detected at the downstream boundary during June and July suggests that flow conditions place the minima at a different location (e.g., between the Nelson Ranch and Freeman Ranch).

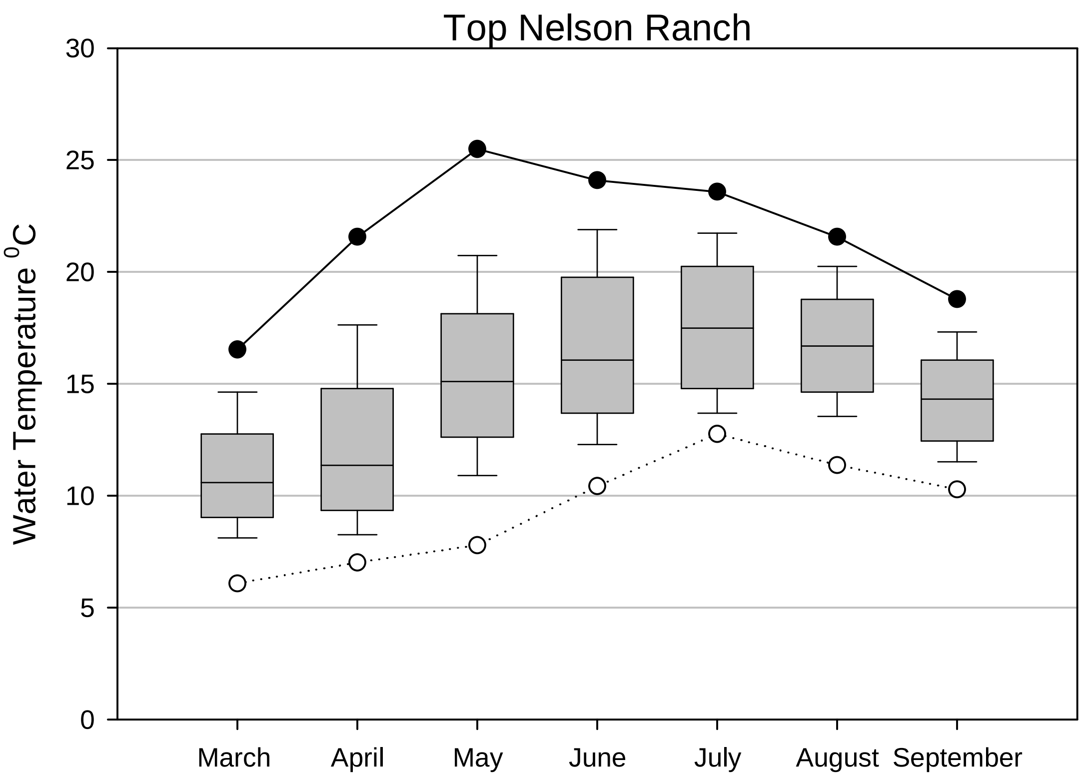

Figure 12. Monthly water temperature trends at the upstream boundary of Nelson Ranch (RK 51.7). Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

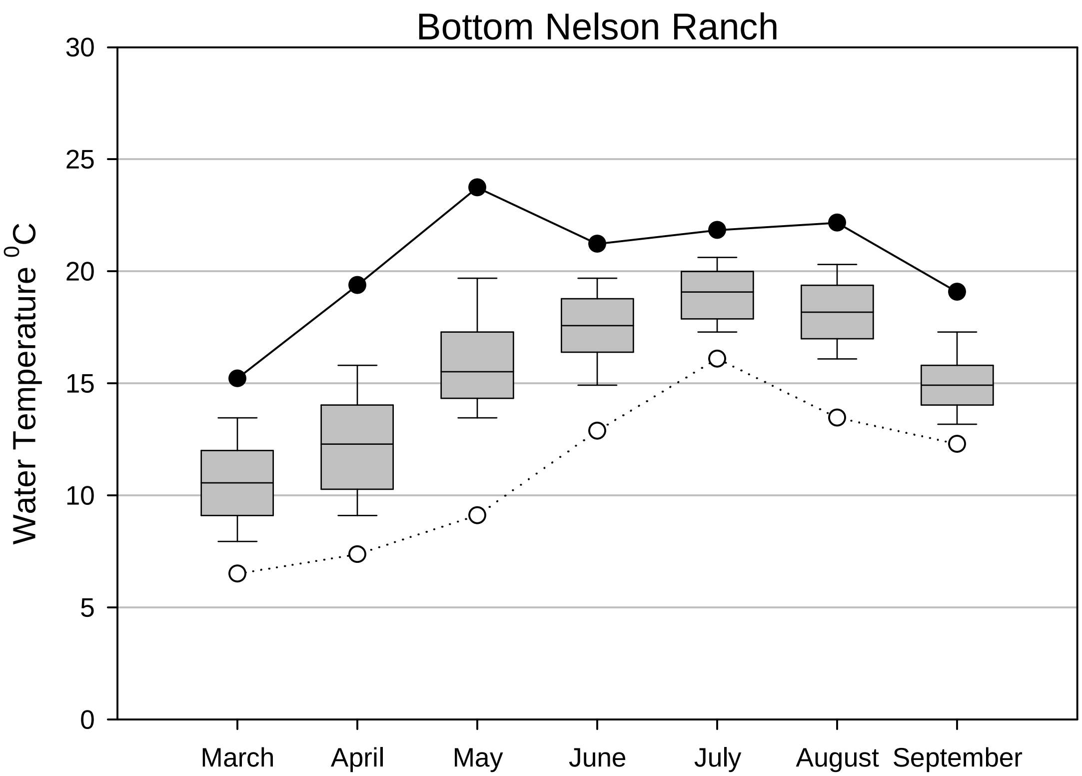

Figure 13. Monthly water temperature trends at the downstream boundary of Nelson Ranch (RK 44.0). Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

8.2.4 *Freeman Ranch*

Water temperatures on the Freeman Ranch were a result of water temperatures inherited from upstream reaches with additional water management activities that occurred between April 1 and October 1 superimposed on the thermal regime. Monthly maximum water temperatures exceed 20°C from May through August (Figure 14). The peak monthly maximum water temperature occurred in May at 24.6°C.

During March, August, and September 2008, Freeman Ranch illustrated the recovered thermal signal that occurred when constant-temperature water sources traveled though a cycle of daytime heating and nighttime cooling (Figure 17, Figure 18, and Figure 19). During those months, diurnal water temperatures rarely ranged greater than 3°C; the monthly instantaneous minimum and maximum temperatures were less than 6°C apart for those months. This illustrates that the effects of contributions from Big Springs Creek affect Shasta River water temperatures downstream for over 20 km.

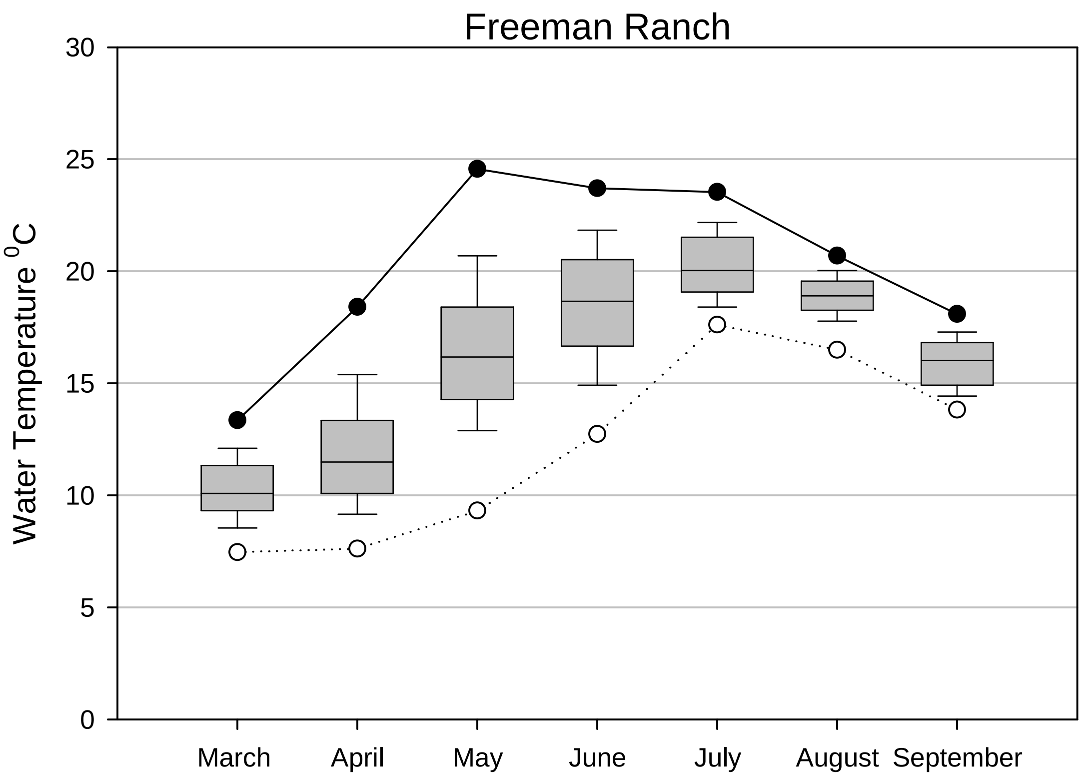

Figure 14. Water temperature trends at the downstream boundary of Freeman Ranch (RK 30.8). Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

8.2.5 *Manley Ranch*

Water temperatures measured at the Manley Ranch indicate that the Shasta River transitions from the pattern reflecting Big Spring Creek's thermal signal toward a system dominated by local equilibrium conditions. Equilibrium temperatures are a function of flow volume, channel geometry, hydrologic operations (diversion and return flow), riparian shading, meteorological conditions, and other factors. As well as inheriting water temperatures from the upstream river reaches, tributaries such as the Little Shasta River and Oregon Slough also enter this reach, and flows were reduced by the Shasta River Water Association diversion upstream. The addition of tributary flows and their associated water temperatures, as well as other factors, further diminishes the water temperature pattern observed at the Freeman and Nelson Ranch sites. The channel morphology at this site represents a transition from the low gradient, valley bed profile to the steeper canyon reach. This increased bed slope also reduces travel time through the reach, changing the heating potential. Monthly maximum temperatures exceeded 20^{o}C from May through September and peaked in June and July at 26.2^{o}C (Figure 15).

From March through May, average temperatures at the Manley Ranch were similar to the upstream Freeman Ranch, but instantaneous maximum and minimum temperatures at Manley Ranch exceed those on Freeman Ranch; this wide range of instantaneous monthly maximum and minimum temperatures occurred concurrent with diversions by the Shasta River Water Association (Figure 17, Figure 18, and Figure 19). However, while maximum and minimum temperatures varied from those observed at the upstream Freeman Ranch, the similar average temperatures indicated that the Shasta River was near equilibrium. From June through September, mean monthly temperatures at the Manley Ranch were consistently warmer than at the Freeman Ranch, indicating that the Shasta River was still heating in the downstream direction (i.e. has not completely transitioned to an equilibrium condition) .

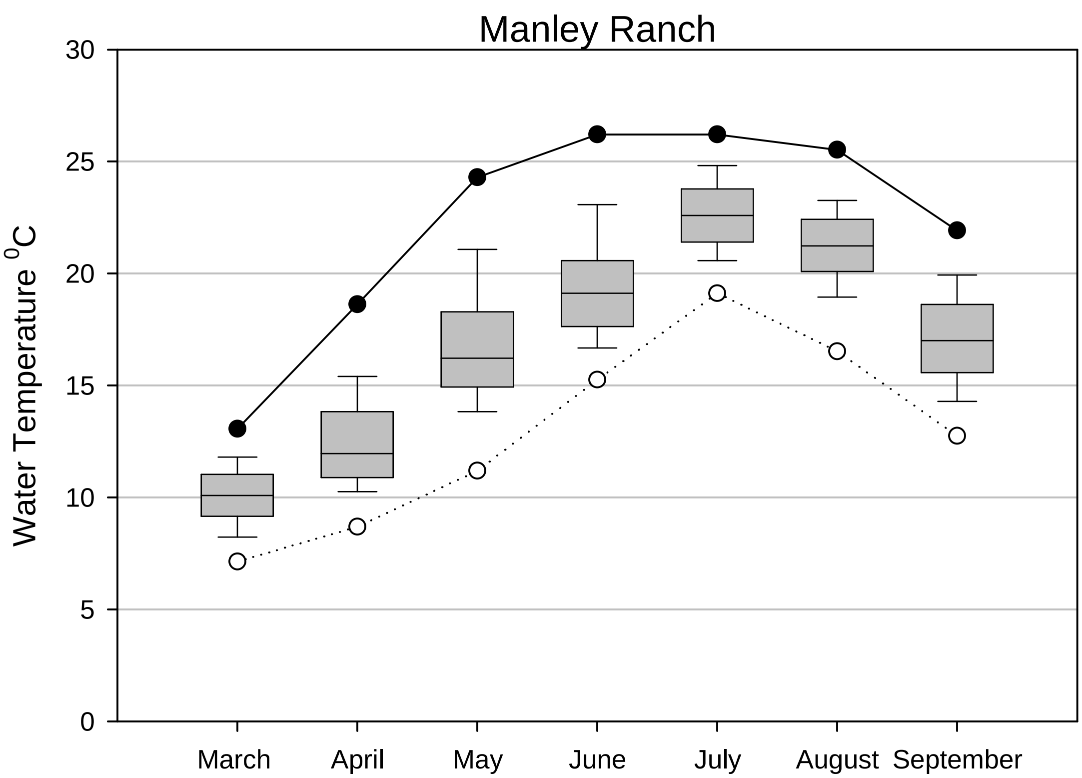

Figure 15. Monthly water temperature on Manley Ranch (RK 18.8). Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

8.2.6 *Canyon Reach*

In the Canyon Reach, stream temperatures appear to have reached or were close to equilibrium temperatures. Water temperatures in this reach represent the culmination of all upstream activities, including significant tributary contributions (i.e. Big Springs Creek), and the effect of upstream water resources development. Additional streamflow was also contributed by Yreka Creek, located at RKM 12.4; flow and temperature monitoring of Yreka Creek was beyond the scope of this project. The steeper bed slope in this reach also decreased travel time, reducing potential heating. Maximum water temperature exceeded 25°C in May through August and 20°C in September; the peak maximum water temperature occurred in July at 28.7°C (Figure 16).

Equilibrium temperatures shift relative to source temperatures depending on the season. In March, equilibrium temperatures were cooler relative to the source temperatures at Big Springs Creek, with average water temperatures at the mouth 1.4°C cooler than at the Big Springs source (Figure). In April, equilibrium temperatures were comparable to the source temperatures, with average water temperatures at the mouth 0.5°C warmer than those at the source. Beginning in May and continuing throughout the study period, equilibrium temperatures in the Shasta River canyon were warmer than source temperatures (Figure 17, Figure 18, and Figure 19). Average temperature differences from the Big Springs source to the Shasta River canyon range between 3.6°C and 8.9°C, with the greatest temperature difference occurring in August. Additional field data from subsequent monitoring has confirmed these thermal conditions and were consistent with previous studies (Abbott and Deas 2003). Specifically, that Big Spring Creek is a relatively warm water source in the winter (although no winter data was collected as part of this project) and a relatively cold water source in the summer, and during periods in the spring and fall has little thermal effect beyond adding flow (mass) to the river system.

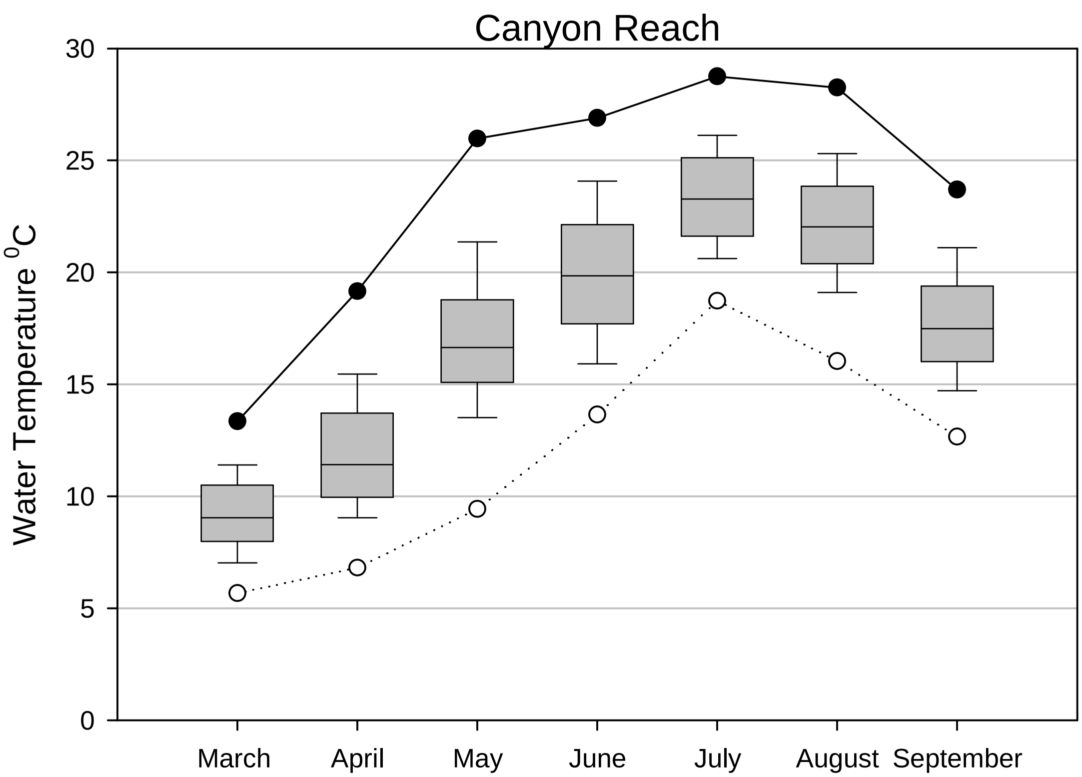

Figure 16. Monthly water temperature trends at RK 0.2 in the Canyon Reach. Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

8.2.7 *Longitudinal Profile*

Viewing the monthly longitudinal temperature profile of Big Springs Creek and the Shasta River more clearly illustrated the transition that the Shasta River makes from a rainfall and snowmelt-based thermal regime to a river strongly influenced by spring accretions, and then finally to equilibrium temperature. Box and whisker plots of monthly water temperatures at several monitoring locations are presented in Figure 17, Figure 18, and Figure 19. Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Filled circles show the maximum instantaneous temperature during the month and non-filled circles show the minimum instantaneous temperature during the month. As Big Springs Creek is the main source of streamflow to the Shasta River during the study period (as well as a significant thermal influence), source temperatures are defined as the headwaters of Big Springs Creek rather than in the Shasta River above Big Springs Creek.

As described in the previous sections, Big Springs Creek's source springs emerge at relatively constant temperatures (10-12^{o}C). However, factors such as the creek's geometry, water and ranch management activities, and initial absence of emergent vegetation resulted in rapid heating, causing the creek to be the source of both warm and cool water to the Shasta River, depending on the diurnal cycle. The influence of Big Springs Creek on the Shasta River is illustrated at the third location on the longitudinal profile: the upstream boundary of Nelson Ranch. The box and whisker plots, as well as the instantaneous monthly maximum and minimum temperatures, were similar at the mouth of Big Springs Creek and the upstream boundary of the Nelson Ranch. These similarities illustrate the strong influence water temperatures at the mouth of Big Springs Creek have on the Shasta River downstream of the confluence.

Big Springs Creek's thermal influence continues for tens of kilometers downstream of the Nelson Ranch and is apparent as far down as the Freeman Ranch (distance from source springs: 25.2 km). The clearest example is presented in the August plot (Figure 18). As discussed in section 8.2.4, diurnal water temperatures rarely ranged greater than 3°C; the monthly instantaneous minimum and maximum temperatures were less than 6°C apart**.** These differences are comparable to those observed at the springs source in Big Springs Creek, where diurnal water temperatures differences were 2.3^{o}C, on average, and the difference between the monthly maximum and minimum was 6.6^{o}C. The suppressed diurnal variation observed on Freeman Ranch was consistent with the advective heating and cooling patterns of streams with steady flows and near-constant source water temperatures under stable meteorological conditions (Lowney 2000), and illustrates that Big Springs Creek influences the Shasta River's water temperature for tens of kilometers downstream of the confluence.

Other factors interfere with this thermal pattern of suppressed diurnal range (e.g., variable flow regime, significant diversion and return flow, diffuse upstream springs source waters, and other factors) and cause it to break down. By the time the Shasta River reaches the Canyon Reach (distance from the source springs: 55.3 km), it begins to achieve equilibrium; a thermal state defined more by seasonal meteorological conditions than by inherited water temperatures. Compared to the cool-water source in Big Springs Creek, equilibrium temperatures in the Shasta River were comparable in the spring and warmer in the summer and early fall. Upon having transitioned toward equilibrium conditions, the Shasta River confluences with the Klamath River.

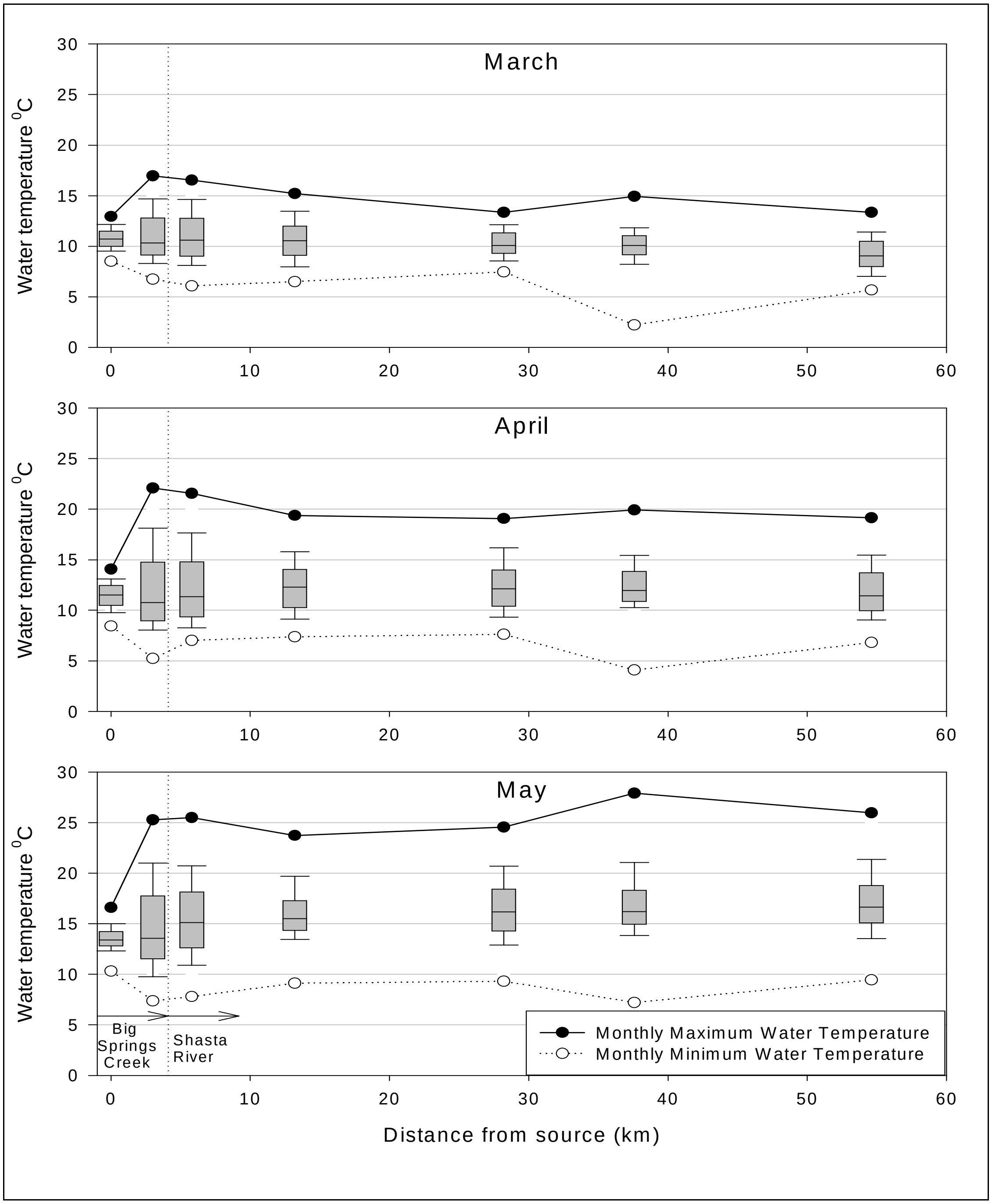

Figure 17. Box and whisker plots of water temperature downstream from Big Springs Lake outlet into the Shasta River and down to the Klamath River (57.2 km downstream). Boxes show 25^{th} and 75^{th} percentiles and whiskers are at the 10^{th} and 90^{th} percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

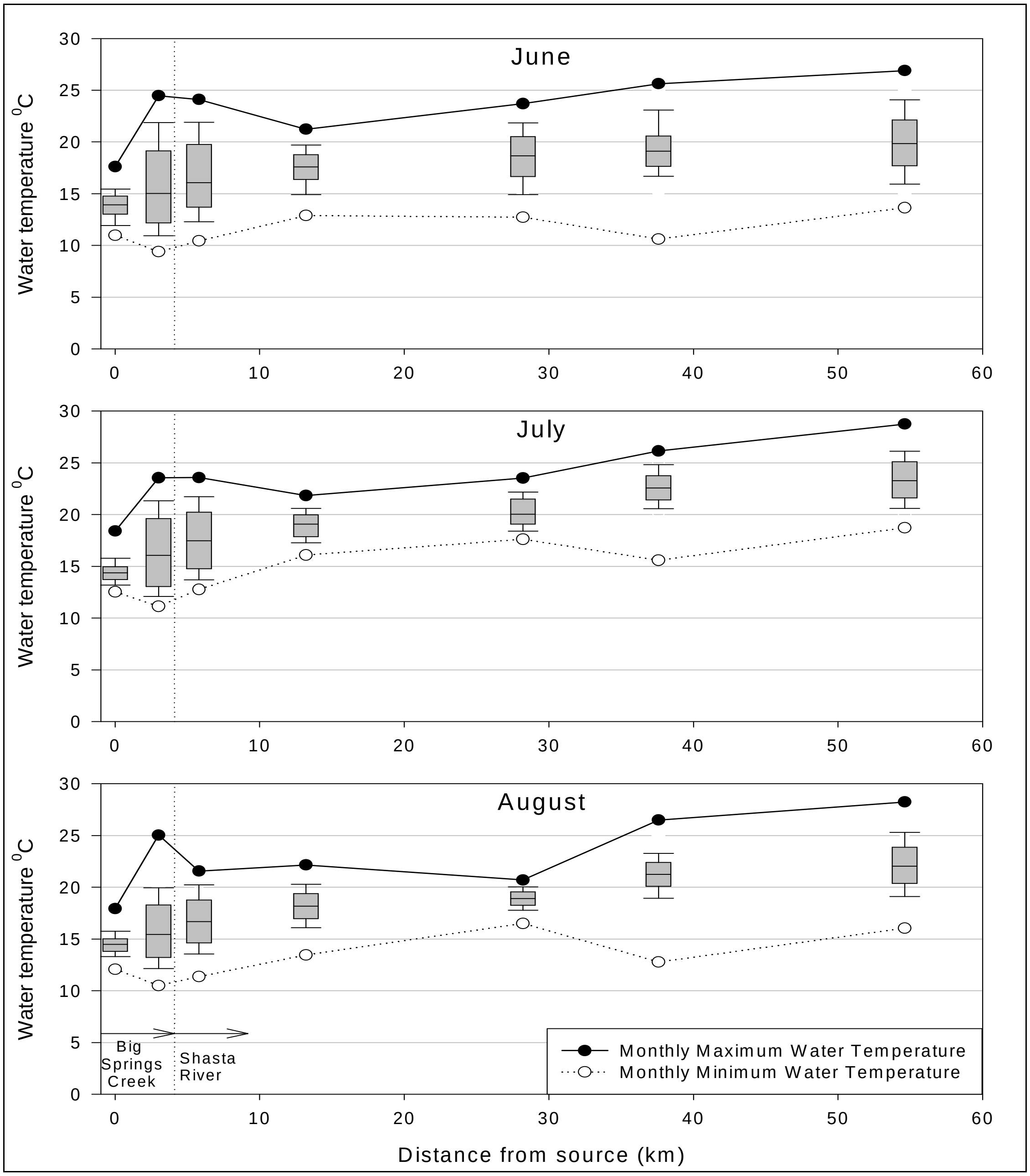

Figure 18. Box and whisker plots of water temperature downstream from Big Springs Lake outlet into the Shasta River and down to the Klamath River (57.2 km downstream). Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

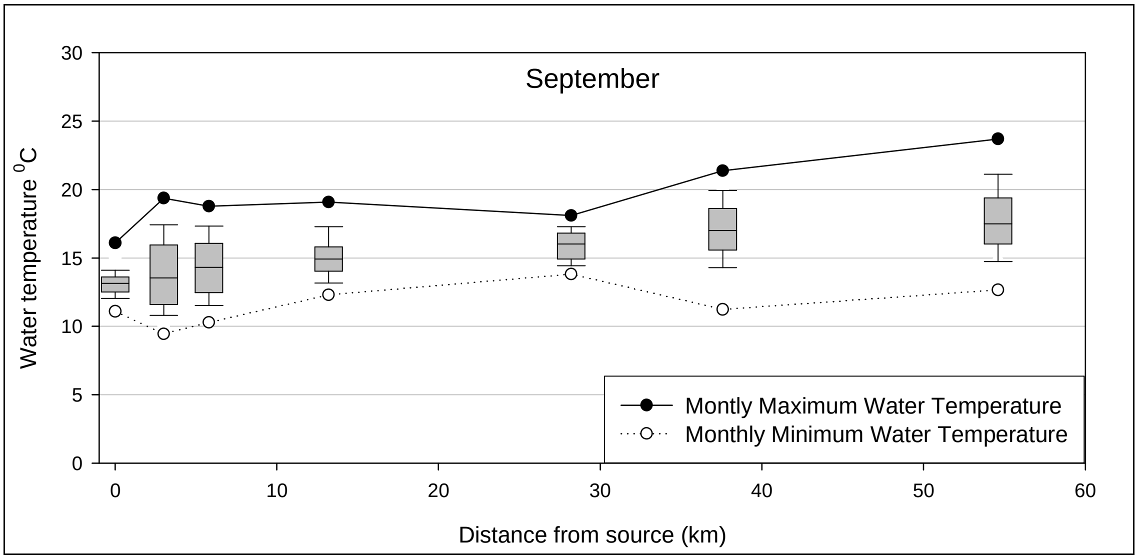

Figure 19. Box and whisker plots of water temperature downstream from Big Springs Lake outlet into the Shasta River and down to the Klamath River (57.2 km downstream). Boxes show 25th and 75th percentiles and whiskers are at the 10th and 90th percentiles of data collected at 30-minute intervals throughout the month. Distance is measured from the Big Springs Lake outlet.

8.3 *Summary*

The Shasta River illustrated several thermal patterns as it flowed from its headwaters to the confluence with the Klamath River during the project period. Above Big Springs Creek, water temperatures in the Shasta River were influenced by the rainfall and snowmelt runoff-based hydrology, with spring and summer water temperatures largely increasing as discharge derived from precipitation and snowmelt runoff decreased to baseflow conditions. However, below the confluence between Big Springs Creek, the Shasta River temperature paradigm shifted to one largely defined by the creek's cool spring sources. As data from study sites downstream of Big Springs Creek illustrated, water temperature trends in the Shasta River below Big Springs Creek were defined more by Big Springs Creek than by the Shasta River upstream of the confluence. Significant, discrete spring inflows supply a constant inflow of at least 40 ft^3/s with source temperatures of 10-12^oC. This relatively constant source temperature was detected in the Shasta River downstream of Big Springs Creek, where minimal diurnal variation occurred between Nelson Ranch and Freeman Ranch; the location of the recovered Big Springs thermal signal varied depending on flow volume, channel roughness, and water management practices. The heating and/or cooling effects of diversions, as well as tributary, tailwater, and return flows, were superimposed on the thermal signal of the Big Springs Creek pulse. The thermal signal from Big Springs Creek becomes less apparent as water flows towards the mouth of the Shasta River, where temperatures trend toward equilibrium.

9.0 Water Quality

Water quality throughout the Shasta River varies considerable in response to geology, hydrology, land use, and aquatic system processes. Surface water samples were collected and analyzed for pH, electrical conductivity, nitrogen species, phosphorus species, dissolved organic carbon, turbidity, and major cations and anions. Discussions herein are focus on nutrients: nitrogen, phosphorus, and carbon because of their biological importance in aquatic systems and the potential role of these constituents in restoration actions. Water quality constituent data from the sampling program are included in the appendix.

9.1 *Methods*

Water samples were collected in acid-washed 125 ml high-density polyethylene bottles at 19 locations throughout the Shasta Valley on a biweekly to monthly basis. A sample subset consisting of seven longitudinal sampling locations was selected for discussion in this report (Figure 1). Bottles were rinsed with the local water three times prior to collection of the sample. Samples were placed in a cooler and transported back to University of California Davis where samples were refrigerated throughout completion of processing. Samples were analyzed for pH, electrical conductivity (EC), total nitrogen (TN), nitrate nitrogen (NO_3^-N), ammonia nitrogen (NH_4^+-N), total phosphorus (TP), soluble-reactive phosphorus (SRP as PO_4^{3-}), dissolved organic carbon (DOC), turbidity, and major cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) and anions (Cl^-, SO_4^{2-}).

9.2 *Data Analysis*

Downstream changes in water quality attributes of the Shasta River are largely borne out of basin-wide differences in geologic conditions and resultant streamflow generation processes. More specifically, above Lake Shastina, streamflow is derived principally from surface runoff in the Scott and Siskiyou Mountains, with minor contributions from groundwater springs. Below Lake Shastina, groundwater-fed spring complexes provide the majority of streamflow to the Shasta River below. These springs complexes emanate along a roughly north-south trending line traversing the eastern portion of the Shasta Valley. This line largely signifies the geologic contact between the permeable basalt flows of the High Cascades (principally the Plutos Cave Basalts) and the less permeable rocks of an underlying Pleistocene debris avalanche. Furthermore, the groundwater flow paths of these spring waters appear to intersect both the surficially-exposed volcanic rocks of the High Cascades (a primary source of inorganic phosphorous as PO_4^{3-}), as well as the underlying Cretaceous marine sediments of the Hornbrook Formation (a primary source inorganic nitrogen as NO_3^-) Specifically, the combination of ancient marine sediments overlain by volcanic rock in the Shasta Valley allows for natural sources of nitrogen (N) and phosphorus (P) to be incorporated into the groundwater that eventually emerges as streamflow from the springs complexes. The project team has investigated several springs, including the headwater of Big Springs Creek and found elevated levels of nitrate and orthophosphate (Figure 20). Although some of the variability in the concentration, particularly nitrate, may be from irrigation operations, there are clearly elevated levels of both nutrients present.

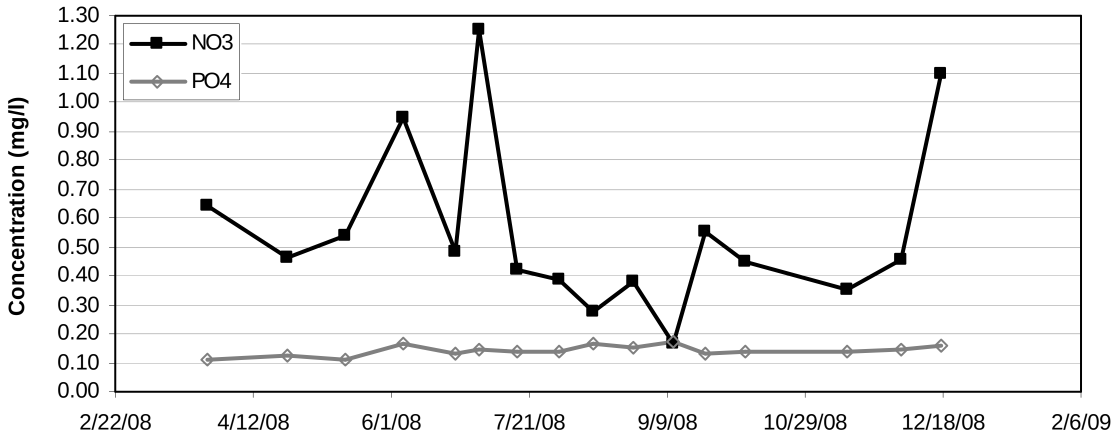

Figure 20. Nitrate and orthophosphate concentration in Big Springs Creek at the Waterwheel, 2008.

Nitrogen and phosphorous are key components of primary productivity and one or the other are often limiting in natural aquatic ecosystems (when both limit primary productivity, the condition is termed colimitation). When nitrogen and phosphorous are available in sufficient quantities, primary production in aquatic systems can be appreciable. System status in terms of nitrogen, phosphorus, and carbon, as well as nutrient limitation is presented below on a site-by-site, seasonal, and longitudinal basis. For purposes of this discussion the following abbreviations are used:

- SR-F: Shasta River at Fontius Ranch
- SR-abP: Shasta River above Parks Creek
- BSC: Big Springs Creek at the lowest crossing (near mouth)
- SR-TN: Shasta River at the top of the Nelson Ranch
- SR-TF: Shasta River at the top of the Freeman Ranch
- SR-TM: Shasta River at the top of the Manley Ranch
- SR-Cyn: Shasta River Canyon site

9.2.1 *Nitrogen*

Nitrogen is an essential nutrient for plant growth, yet is often described as a pollutant (e.g., from fertilizers and animal wastes) in many freshwater systems and is subject to total daily maximum loads (TMDLs) due to its role in eutrophication. In rivers with elevated nutrient levels (N & P), abundant primary productivity often results in a high biological oxygen demand (BOD), which can lead to undesirable dissolved oxygen concentrations. Both total nitrogen (organic and inorganic) and inorganic nitrogen are examined herein. Inorganic nitrogen is available for uptake by aquatic plants and consists of ammonium, nitrite, and nitrate. Because nitrite is largely absent under aerobic conditions, total inorganic nitrogen is calculated herein as ammonium plus nitrate.

Total nitrogen (TN) and inorganic nitrogen (TIN) in the Shasta River from Fontius Ranch to the Canyon varied considerably (Figure 21 and Figure 22, respectively) during the project period. TN concentrations were lowest at Fontius for all seasons of the year. Generally concentrations increased in the downstream direction in the winter and spring, were mixed in the summer, and decreased in the fall. The role of fall and winter senescence of benthic algae (periphyton, filamentous forms, rooted aquatic vegetation) and seasonal rainfall runoff contributions to TN are not completely understood, but undoubtedly played a role in the observed longitudinal response during fall and winter. Land use activities throughout the year probably contributed to TN concentrations as seasonal rainfall provided overland and sub-surface stormflow to the river, and spring and summer irrigation practices resulted in point and non-point sources contributions to the river. Elevated winter values at the lowest site (Canyon) may be the result of contributions from Yreka Creek and associated urban activities in that sub-watershed.

TIN concentrations indicated a considerably different response than TN (Figure 22). During winter periods, concentrations showed a general increase from upstream to downstream, while in the spring and summer, there was considerable depletion of TIN due to extensive macrophyte growth. As the spring season extended through the summer, systematic, significant reductions of TIN were observed at sampling locations between Big Springs Creek and the Klamath River. During fall, concentrations recovered in response to decreased demand from plant uptake and fall senescence of seasonal algal standing crop. Winter and fall concentrations suggest that upstream of Big Springs Creek the background TIN concentrations were on the order of 0.1 mg/l, while downstream of Big Springs Creek background concentrations were on the order of 0.2 to 0.25 mg/l. These concentrations are assumed to represent the approximate levels of available nutrients when primary production is at an annual minimum and fall senescence has abated.

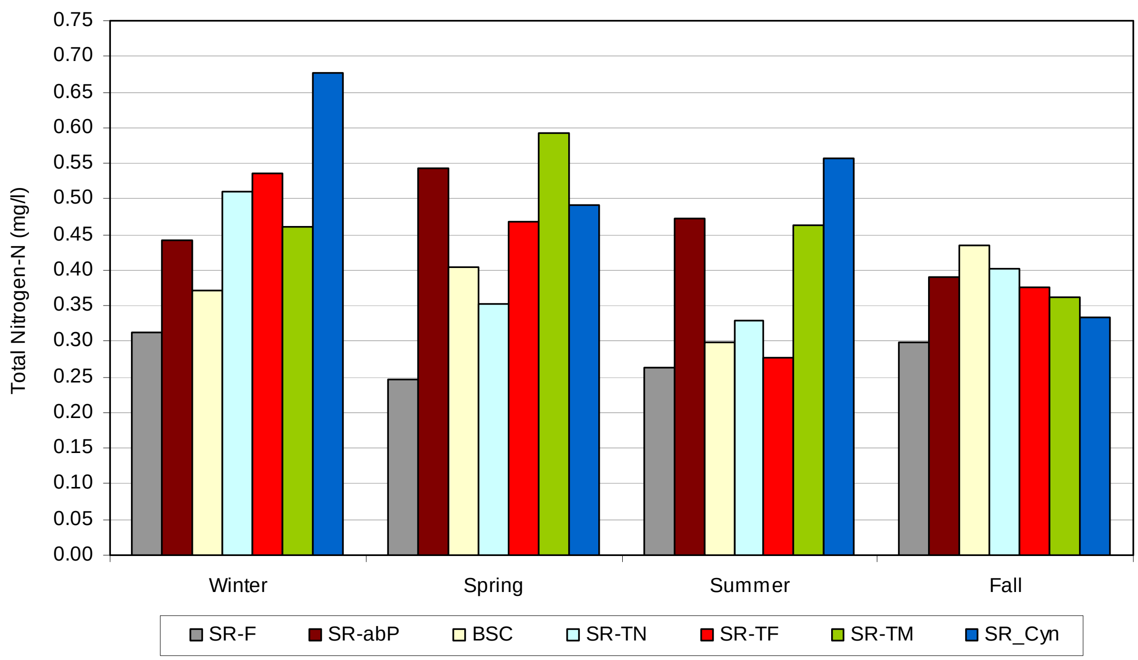

Figure 21. Total nitrogen concentration by location and season in the Shasta River and Big Springs Creek, 2008. Data are arranged within each season from upstream to downstream (left to right).

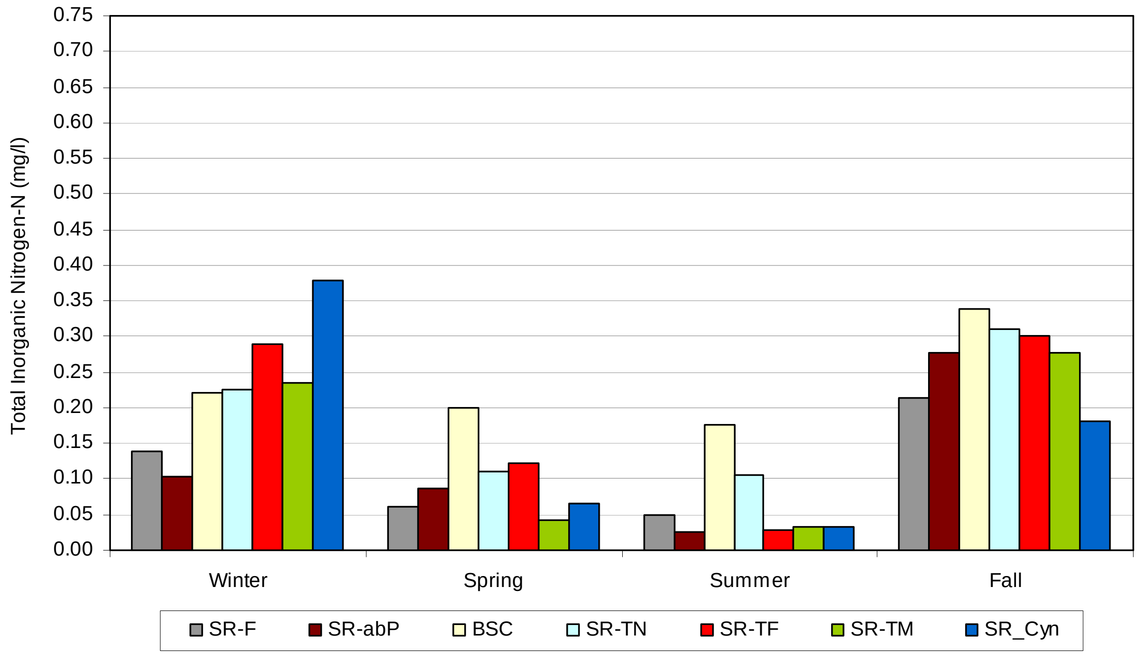

Figure 22. Total inorganic nitrogen concentration by location and season in the Shasta River and Big Springs Creek, 2008. Data are arranged within each season from upstream to downstream (left to right).

9.2.2 *Phosphorus*

Like nitrogen, phosphorus is an essential nutrient for plant growth, and is often described as a pollutant (e.g., from fertilizers, pesticides, detergents) in many freshwater systems and is subject to total daily maximum loads (TMDLs) due to its role in eutrophication. As noted above, in combination with nitrogen, phosphorus can lead to abundant primary productivity, which can lead to undesirable dissolved oxygen concentrations. Both total phosphorus (organic and inorganic) and inorganic phosphorus are examined herein. Inorganic phosphorus is available to uptake by aquatic plants and consists of orthophosphate.

Total phosphorus (TP) and inorganic phosphorus (TIP) in the Shasta River from Fontius Ranch to the Canyon varied remarkably little at all sites except above Dwinnell Dam and Lake Shastina (Figure 23 and Figure 24, respectively). At Fontius, TP concentration increased from winter and spring through summer and peaked in the fall. TP concentrations at sample locations downstream from Dwinnell Dam were almost unchanged, varying between 0.15 and 0.2 mg/l.

TIP concentrations followed a similar pattern with low concentrations at Fontius Ranch and stable/moderately elevated (~ 0.15 mg/l) concentrations throughout the entire year in Big Springs Creek and all Shasta River sites downstream of Dwinnell Dam. These data suggest that the waters above Dwinnell Dam are dominated by precipitation/surface runoff-driven hydrology, while those downstream of Dwinnell Dam are dominated by groundwater. Note how TIP concentrations in the Shasta River at the Fontius Ranch increased steadily from winter through fall as the baseflow component associated with precipitation diminished. By late summer and fall, most baseflow in the upper Shasta River was provided by Boles and Beaughan Creeks – both spring fed creeks with elevated phosphorus. Immediately downstream of Dwinnell Dam (and above Parks Creek), streamflow is primarily generation by groundwater springs presumably similar in chemical make-up to downstream Big Springs complex. Below Big Springs Creek, the Shasta River baseflow is dominated by groundwater inputs from the creek. These data, coupled with the seasonal nitrogen depletion suggest nutrient limitation plays a pivotal role in the Shasta River.

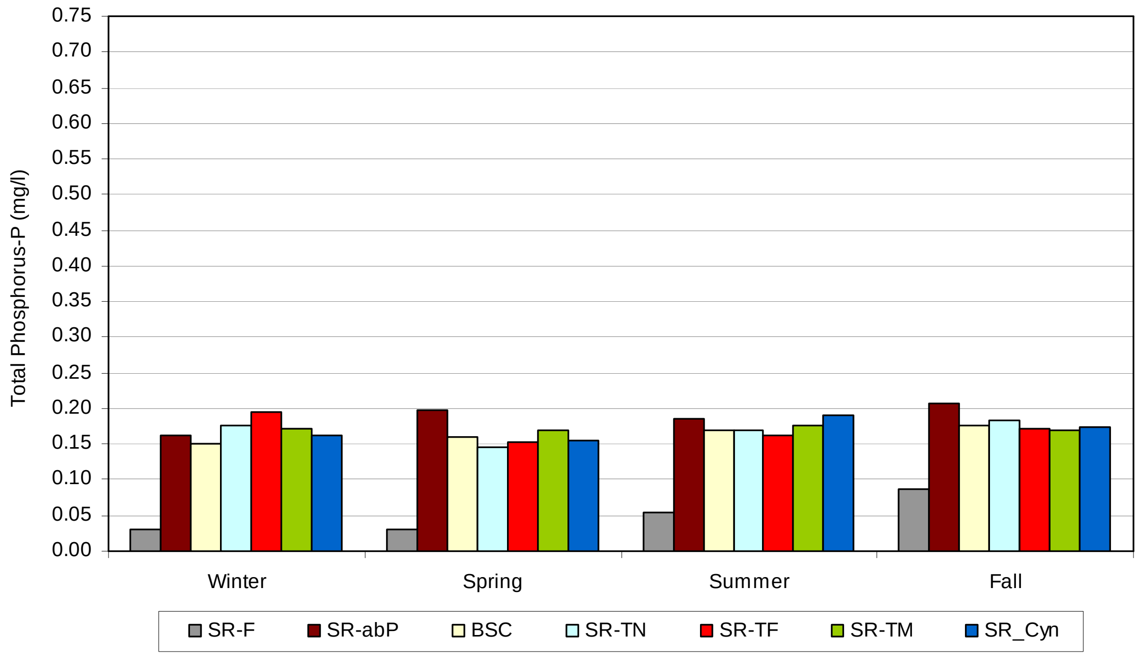

Figure 23. Total phosphorus concentration by location and season in the Shasta River and Big Springs Creek, 2008. Data are arranged within each season from upstream to downstream (left to right).

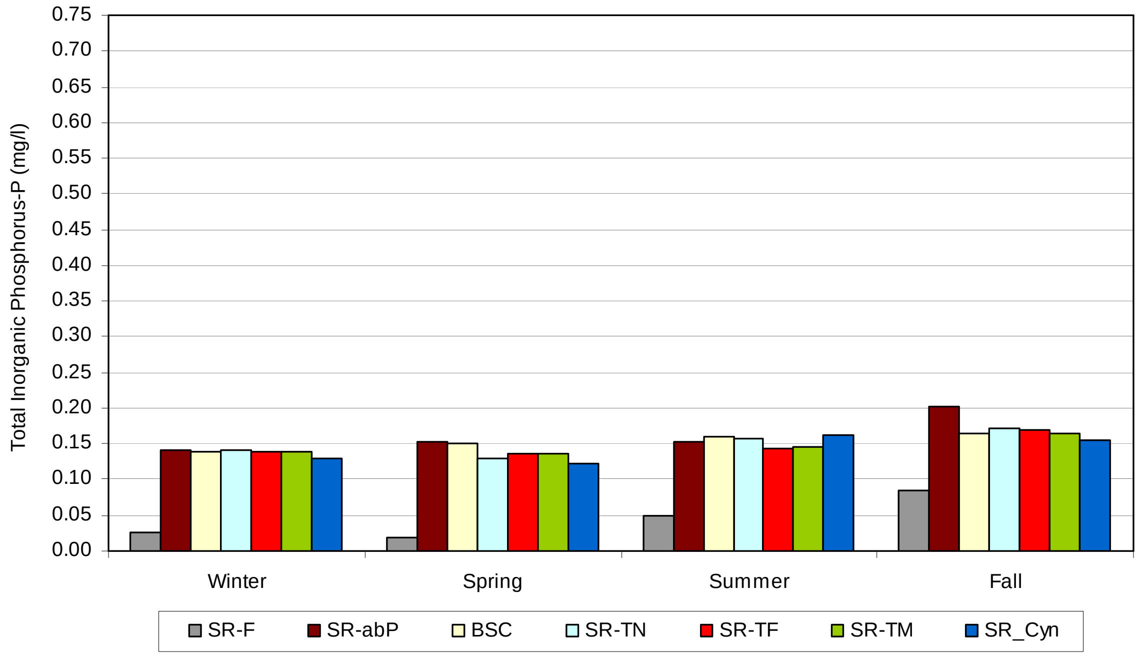

Figure 24. Total inorganic phosphorus concentration by location and season in the Shasta River and Big Springs Creek, 2008. Data are arranged within each season from upstream to downstream (left to right).

9.2.3 *Nitrogen:Phosphorus Ratio*

Nitrogen, and phosphorus in algal tissues typically occur in a 16:1 molar ratio (or 7:1 by mass), known as the Redfield ratio (Redfield 1934). Carbon can be limited, but due to the ubiquitous nature of carbon (e.g., CO_2), such limitation is generally transitory versus systematic over periods such as a season. Generally, a ratio less than 7:1 by mass is associated with a nitrogen limitation and grater than 7:1 translates to phosphorus limitation (Kalff 2002), although local conditions can lead to deviations in these ratios.

Using inorganic forms (i.e. those available for plant uptake) the nitrogen to phosphorus ratio (by mass) was calculated for each location by season (Figure 25). Throughout the project area the TIN:TIP ratio was well under 7, indicating nitrogen limitation. Fontius Ranch, above Dwinnell Reservoir illustrated the highest numbers during winter (4.6), but all other locations throughout the year were less than 2.5. During spring and summer, the TIN:TIP ratio diminished with downstream distance, reaching values less than 0.2 in the summer at Shasta River sampling locations between the Freeman Ranch and the Klamath River – indicating evident nitrogen limitation. This is consistent with diminishing TIN concentrations downstream of Big Springs Creek during the spring and summer (Figure 22), while TIP concentrations were essentially unchanged during these periods at all locations below Big Springs Creek (Figure 24).

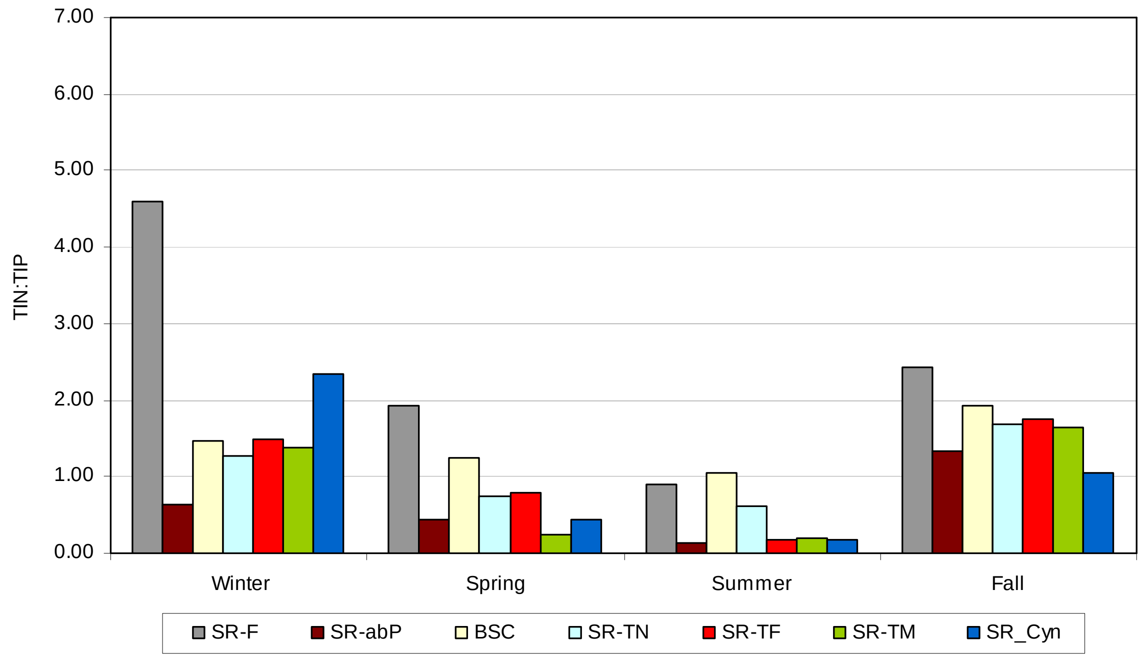

Figure 25. Total inorganic nitrogen to total inorganic phosphorus ratio (TIBN:TIP) by location and season in the Shasta River and Big Springs Creek, 2008. Data are arranged within each season from upstream to downstream (left to right).

To further illustrate the nitrogen limitation, available nitrate (ammonia values were consistently near or at the detection limit) data were examined longitudinally over a 58-km distance extending from upper Big Springs Creek, which is a principal nutrient source, downstream to the Shasta River confluence with the Klamath River. When sampling began in March 2008, little aquatic vegetation was present throughout the river and nitrate levels were relatively similar throughout Big Springs Creek and the Shasta River downstream. As spring progressed, aquatic macrophyte standing crop progressively increased in response to longer day length, reduced seasonal flows, and readily available nutrients. This increasing level of macrophyte uptake systematically reduced nitrate levels from the water column, a trend particularly evident in the downstream direction. To explore the longitudinal response in space and time, concentration data were plotted longitudinally throughout the year (Figure 26). In March, nitrate concentrations in upper Big Springs Creek were approximately 0.45 mg/l, but in the Shasta River below Big Springs Creek ranged between approximately 0.2 and 0.3 mg/l. In May, concentrations in upper Big Springs Creek were over 0.5 mg/l, but concentrations diminished rapidly in the downstream direction, such that at the confluence with the Shasta River (approximately 3.7 km downstream), nitrate concentrations had been reduced by approximately 50 percent. Downstream reductions in nitrate continued throughout the Shasta River downstream from Big Springs Creek, with measured concentrations well below 0.1 mg/l in downstream reaches. This pattern was repeated into September, when day length began to shorten rapidly and standing crops of aquatic macrophytes began to diminish. Under these conditions, demand for nitrate dropped off rapidly and nitrate concentrations with the water column increased in response. By November 2008, longitudinal trends in nitrate concentration were roughly similar to those observed in March 2008.

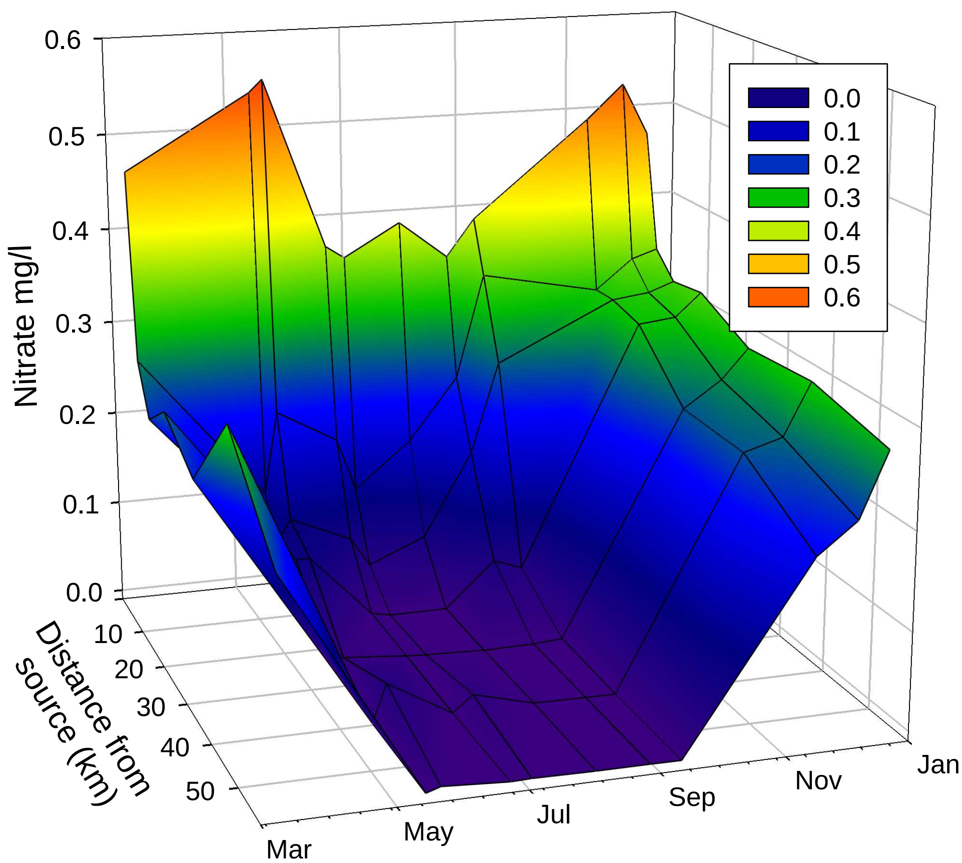

Figure 26. Seasonal and longitudinal fluctuation in Nitrate (NO_3^-) from the spring source in Big Springs Creek (0 km) to the confluence with the Klamath River (58 km).

9.2.4 *Carbon*

Carbon is an essential nutrient for plant growth and an important factor in macroinvertebrate production, and the parameter lends insight into the fate and transport of organic matter in a riverine system. Dissolved organic carbon (DOC) in the Shasta River from Fontius Ranch to the Canyon varied considerably by season and location (Figure 27). Above Dwinnell Dam at the Fontius Ranch site DOC was fairly constant from winter through summer, with measured values of approximately 2.5 mg/l. In the fall, measured DOC concentrations were less than 2 mg/l, perhaps as land use activities abated and instream metabolic processes associated with primary and secondary production diminished.

Big Springs Creek illustrated low values of DOC, ranging from approximately 1.0 mg/l in the winter and fall, to 1.5 and 1.7 mg/l in the spring and summer, respectively. Organic carbon values are expected to be low in spring systems because groundwater sources are typically low in organic nutrients (contamination being an exception). DOC concentrations would likely be even lower, were it not for the contribution of organic matter (and organic carbon) from Big Springs Lake and upstream creek reaches. Further, some of this seasonal increase may be due to land use practices in the Big Springs Creek watershed, as well as, increases in primary production in summer and fall.

In the Shasta River, DOC values varied considerably. In general, winter and fall experienced the lowest values, while spring and summer produced higher values. The Shasta River above Parks Creek produced some of the higher values measured throughout the project area, with concentrations exceeding 3 mg/l in the winter and 5 mg/l in the summer. Land use practices in this reach probably contributed the majority of DOC to the stream as winter overland flow associated with precipitation events, subsurface storm flow or subsurface return flow, and return flow. This elevated concentration was largely diluted by Big Springs Creek contributions. Interestingly, the Nelson and Freeman Ranch study sites exhibited modest, stable concentrations of DOC throughout the year, on the order of 1.5 to 2.5 mg/l. During spring and summer, the Manley Ranch and Canyon study sites exhibited increases. These lower valley reaches experienced considerable return flow (surface and/or subsurface) from irrigated lands adjacent to the stream, as well as inputs from Oregon Slough. These inputs appear to contribute notably to DOC at the Manley Ranch study site, which translated into elevated values at the Canyon study site. The highest DOC values occurred in summer at the Canyon site, but reasons for this are not clear at this time. Possibilities include additional contributions below the Manley Ranch or contributions from Yreka Creek.

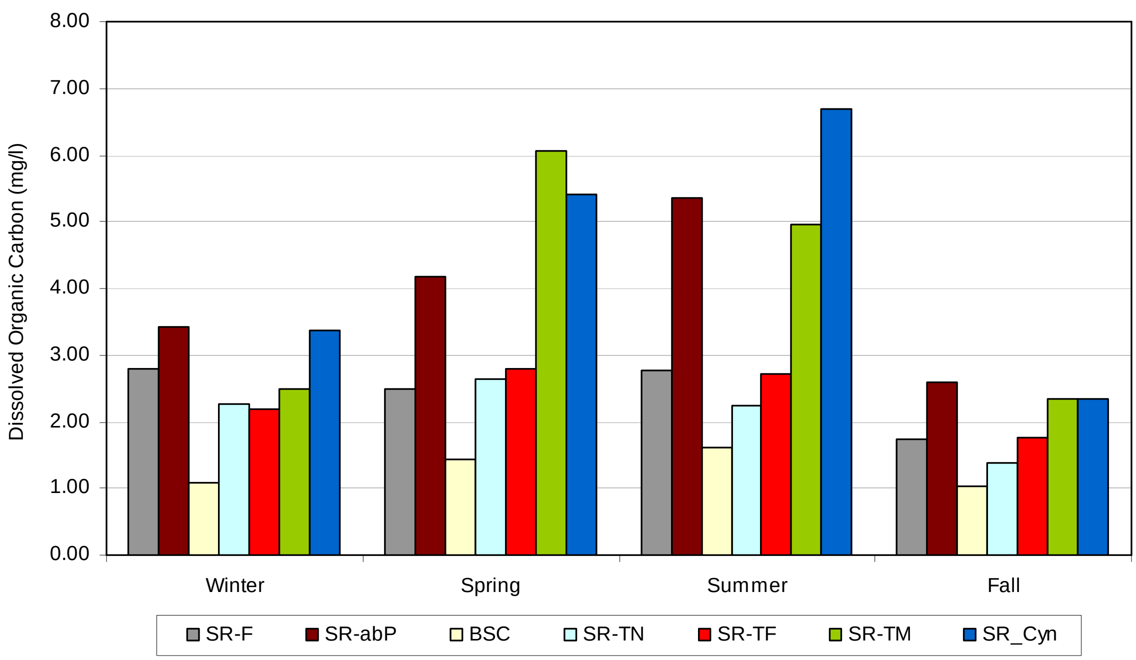

Figure 27. Total dissolved organic carbon concentration by location and season in the Shasta River and Big Springs Creek, 2008. Data are arranged within each season from upstream to downstream (left to right).

9.3 *Summary*

As data from study sites in the Shasta River and in Big Springs Creek illustrate, water quality conditions in the Shasta River below Big Springs Creek are defined more by Big Springs Creek than by the Shasta River upstream of the confluence. Above Dwinnell Dam, water quality is governed by local hydrology and land use and background levels of nitrogen and phosphorous are relatively low. Below Dwinnell Dam, where spring inputs become an important component of baseflow, particularly below Big Springs Creek, nitrogen and phosphorus are notably higher. Field data identify that the springs that form a vital portion of the Shasta River baseflow are natural sources of these nutrients. These nutrients provide enhanced growth rates at ever higher trophic levels in the food web from primary producers up through salmonids. In summary, spring contributions

- form a vital aspect of baseflow, and associated habitats, in Big Springs Creek and the Shasta River,
- provide relatively warm water in the winter and cool water, thermal refugia in the summer; and
- provide nutrients that drive a highly productive food web that are critical to salmonid production.

As such, restoration prescriptions in the Shasta River should consider each of these factors, recognizing that actions that do not maintain spring baseflows may be considerably less effective than those that retain these essential, unique, and interrelated processes.

10.0 Aquatic Vegetation

Aquatic vegetation is a vital element in aquatic ecosystems and consists of periphyton, filamentous algae, and vascular macrophytes. This section of the report focuses on those plants that live within the stream margins, whether on the bed or attached to the bed, and extending into the water column and possibly above the water surface. Aquatic vegetation serves many ecosystem functions in the Shasta River both physically and ecologically. Both emergent and submergent aquatic vegetation uptake and seasonally retain nutrients, as well as provide a food source and habitat for macroinvertebrates and other secondary consumers. Vegetation also increases channel/bed roughness, creating significant hydraulic diversity typically characterized by reduced flow velocities through vegetation patches (resulting in a trapping of fine sediment), and increased flow velocities through flow corridors adjacent to macrophyte patches (where fine sediment is often scoured away, leaving gravels suitable for spawning salmonids). Aquatic vegetation also functions as habitat for fish. It provides cover as well as a bioenergetically favorable feeding location where fish are able to rest in slow water and feed on food drifting in the adjacent high velocity corridor. The seasonal growth and senescence process of aquatic vegetation is one of the most important factors in restoration of the Shasta River.

10.1 ***Methods***

We characterized the aquatic plant assemblage during the spring and summer of 2008. Samples were collected during the last week of March and last week of June, 2008. On each date, six sample sites were randomly selected within each study reach (Figure 1). A square PVC-frame quadrat was used to delineate an area of 0.37 m^2 and all above-ground biomass within the quadrat was removed. Harvested plant material was vigorously agitated in the stream to reduce the presence of clinging macroinvertebrates (epibiota) and other detrital material prior to being placed in individually labeled bags and returned to the laboratory. In the laboratory, samples were separated by species and the individual fractions were dried to a constant mass at 65ºC for at least 72 hours (h) and weighed. Samples were then ashed in a muffle furnace for four hours at 475ºC, cooled to a constant mass and reweighed to derive ash free dry mass (AFDM). Mean standing stock for macrophytes and filamentous algae is reported as grams ash-free mass dry per square meter ($g\ AFDM \cdot m^{-2}$).

10.2 ***Filamentous Algae***

Spring

Filamentous algae were the dominant aquatic vegetation in the two most downstream reaches during the spring sampling period (Figure 28). The two lowest reaches, Manley Ranch and Canyon, are geomorphically different than the reaches upstream and consist of relatively wide open channels with more gravel and cobble substrate (Figure 4). The relatively wide and shallow channel morphology along with larger substrate for attachment at these two locations allowed for adequate light during the late winter season to grow algae. The filamentous algae were also dependent on a lack of high flow events that would potentially result in loss of biomass due to channel bed scour. Along with light availability, suitable substrate, and a lack of high flows, nutrients were available to the filamentous algae during the winter and spring months due to aquatic macrophyte senescence and resultant minimal utilization of the abundant nutrients in the water column. Because filamentous algae are neither rooted nor vascular, they are dependent on nutrients in the water column. The combination of channel morphology, water quality, and minimal high flows favored the filamentous algae growth leading up the time of the spring sampling effort.

Despite abundant nutrients in Big Springs Creek and the Nelson Ranch during the winter and spring, little filamentous algae were present in these locations. Filamentous algae need stable substrate to attach (i.e. cobbles), and bed materials within Big Springs Creek and the Shasta River above the Manley Ranch largely consisted of a sand-dominated bed materials which were constantly in motion, particularly during higher flows of the winter months. Until aquatic macrophytes were available later in the year to act as a substrate, little substrate were available in these reaches for filamentous algae attachment. The absence of filamentous algae at the Fontius Ranch study during the spring sampling period can be explained by the fact that the coarse bed materials at the study site underwent active coarse sediment transport during the previous winter, limiting colonization.

Summer

Filamentous algae biomass was slightly higher in the upper reaches during the summer months, yet lower in the two lowest reaches. The increase of biomass in the upper reaches is likely due to the increased abundance of macrophytes that function as substrate upon which the filamentous algae could attach. In the lowest two reaches, biomass was significantly reduced in the summer compared to the spring sampling period. During the summer, little water column nitrate was available in the downstream reaches and likely limited the growth of filamentous algae (Figure 26). Shading from macrophyte growth throughout the river may also prohibit abundant filamentous algae growth during the summer months.

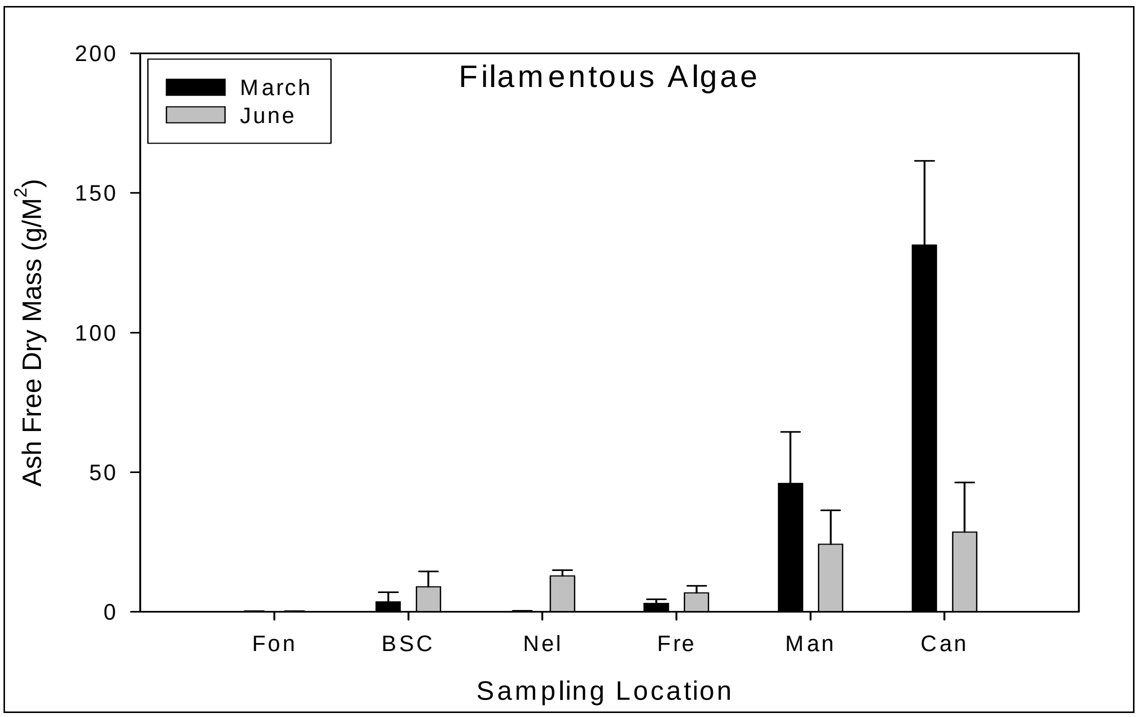

Figure 28. Filamentous algae abundance as measured in grams ash free dry mass (AFDM) per meter squared during spring and summer longitudinally in the Shasta River at Fontius Ranch (Fon), Shasta Big Springs Ranch (BSC), Nelson Ranch (Nel), Freeman Ranch (Fre), Manley Ranch (Man), and Canyon (Can).

10.3 ***Aquatic Macrophytes***

Spring

During spring, macrophyte biomass throughout the watershed was found in relatively low abundance due to conditions during the previous winter months (low temperatures and low light conditions) that limited growth (Figure 29). The exception to this naturally low abundance was in Big Springs Creek, even as the aquatic macrophytes had largely been removed by cattle browsing throughout the winter. Due to the proximity to relatively warm springs, water temperatures did not cool during winter months in Big Springs Creek and thus allowed macrophytes to continue to grow as submergent vegetation throughout the winter, albeit at a reduced rate and biomass compared to the summer growing period.

Summer

As water temperatures warmed and day length increased, aquatic macrophytes became the dominant type of aquatic vegetation in Big Springs Creek and the Shasta River. Big Springs Creek showed the most dramatic increase in macrophyte biomass between the spring and summer sampling periods. This was likely due to the exclusion of cattle from the river during the summer months and abundant nutrients sourced from proximal, nutrient-rich spring sources. Sampling locations downstream in the Shasta River also yielded increased biomass of macrophytes relative to the spring sampling event. Macrophyte biomass decreased in the downstream direction with the exception of the canyon reach. The reduction in biomass was likely related to the longitudinal attenuation of nitrate available for plant uptake from the water column (Figure 26). The canyon reach was the exception to the longitudinal decreasing macrophyte biomass. A possible explanation for the continued growth of macrophytes in the lower Shasta River canyon, even with low measured nitrate concentrations in the water column, may be that as rooted vascular plants, the aquatic macrophytes in the canyon reach were able to assimilate nutrients from the bed sediments, eve as water column nitrate concentrations were reduced (Birgand et al. 2007). The roots of the macrophytes may have been able to utilize sources of nitrate from the breakdown of the organic material trapped in the interstitial spaces of larger substrates found in the canyon reach. This may help to explain why aquatic macrophyte growth took place throughout the summer in the canyon reach, despite little to no nitrate measured in the water column

The role of macrophytes in Big Springs Creek cannot be understated. Seasonal increases in macrophyte standing crop resulted in remarkable increases in roughness, leading to fine sediment deposition in slower water areas behind macrophytes patches, and notably higher velocities in narrower and deeper channels adjacent to macrophyte patches. This process lead to a lateral diversity of streamflow velocities and depths, creating extensive and diverse habitat for juvenile salmonids. Further, the narrower, deeper channel leads to a smaller air-water interface and a shorter travel time, resulting in reduced rates of stream heating. Some of the emergent aquatic vegetation also provided shade to Big Springs Creek. Finally, higher velocities in the narrowed channel mobilized fine sediments, exposing gravels for spawning anadromous salmonids.

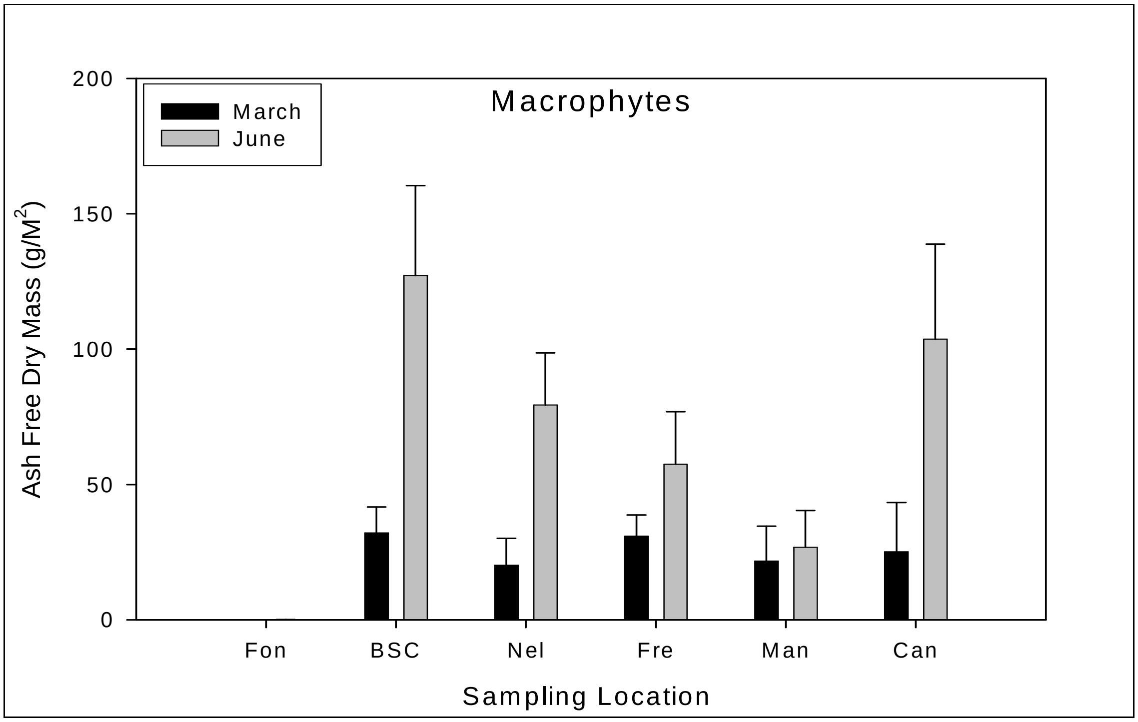

Figure 29. Macrophyte abundance as measured in grams ash free dry mass (AFDM) per meter squared during spring and summer longitudinally in the Shasta River at Fontius Ranch (Fon), Shasta Big Springs Ranch (BSC), Nelson Ranch (Nel), Freeman Ranch (Fre), Manley Ranch (Man), and Canyon (Can).

10.4 ***Summary***

Aquatic vegetation in the Shasta River and Big Springs Creek illustrated seasonal and longitudinal variability. This variability was most likely related to flow regime, substrate, available nutrients, local conditions, and other factors. In certain environments the role of aquatic vegetation was critical to anadromous fish production. This was particularly true in the reaches where summer water temperatures were amendable to over-summering anadromous salmonids, such as coho salmon. The reaches in and downstream of Big Springs Creek experience these cool water temperatures, have sufficient nutrients to support extensive aquatic vegetation, yet are upstream of the extreme nutrient limitation. The changes in Big Springs Creek that are favorable to anadromous fish are also important drivers of habitat. Thus, consideration of longitudinal and seasonal distribution of aquatic vegetation and the role it plays in anadromous fish production is an important factor in the Shasta River.

11.0 Benthic Macroinvertebrates

Invertebrates are an important linkage in the food web as an energy transfer from primary producers to fish. The primary food source for rearing salmonids is benthic macroinvertebrates, so an understanding of invertebrate populations is necessary to understanding the Shasta River ecosystem. Aquatic macroinvertebrates were collected from Big Springs Creek and Shasta River during March and June of 2008 (spring and summer) to determine community compositions and temporal changes in the assemblages. Multiple sample sites were selected in an effort to understand the spatial arrangement of macroinvertebrates in Big Springs Creek and the Shasta River.

11.1 ***Methods***

Macroinvertebrate samples from Big Spring Creek and five locations throughout the Shasta River (Figure 1) were collected using a modified 21.6 cm diameter Hess sampler (335 µm mesh). We used a tape measure and number tables to randomly select the location for a single transect line during each sample period. Five subsamples were then collected at evenly spaced intervals across the length of the transect. For each sample, substrate within the area delineated by the Hess sampler was vigorously disturbed to a depth of 5 cm for one minute. The five resultant subsamples were combined in a bucket and elutriated to remove sand, silt, and gravel. The composite sample was passed through a 250 µm sieve and all retained material was preserved in 95 percent ethyl alcohol and returned to the laboratory for processing and identification.

11.2 ***Taxonomic Determination***

In the laboratory, macroinvertebrate samples were evenly distributed over a standardized sorting grid and randomly subsampled to reach a minimum count of 500 organisms. The remainder of the sample was then searched for large and rare taxa (i.e., invertebrate taxa not found in the subsample, but present nonetheless). Large and rare taxa were excluded from subsequent quantitative analyses, but included in the taxonomic list generated for each sample period (see appendix).

Aquatic macroinvertebrates were identified using Merritt et al. (2008), Thorp and Covich (2001), Smith (2001), Wiggins (1996), as well as various taxonomic-specific references. Ostracoda, Oligochaeta, and Arachnida were identified to class, while Chironomidae were identified to family. Specimens in poor condition or in very young instars were left at the next highest taxonomic level. We selected 12 common macroinvertebrate metrics that included various measures of taxonomic richness, functional feeding group membership, and organism tolerance values. Tolerance values are a measure of an organism's ability to survive and reproduce in the presence of known levels of stressors. Tolerance values range from zero (highly intolerant) to 10 (highly tolerant). Functional feeding group designations are based on how an organism acquires food and include: (*i*) *collectors* which gather or filter fine particulate organic matter; (*ii*) *shredders* which consume coarse particulate organic matter; (*iii*) *scrapers* (grazers) which consume epilithon; (*iv*) *predators*, which capture and feed on other consumers (*v*) *omnivores*, which consume both plant and animal matter; and (*vi*) *parasites* which live in or derive nourishment from other aquatic animals.

11.3 ***Invertebrate Abundance***

Invertebrate abundance was calculated using the known area sampled by the Hess sampler and extrapolating to invertebrates per meter squared. During the spring sampling period all of the sites were relatively similar in abundance, with the Manley Ranch having the highest abundance and the Fontius Ranch with the lowest (Figure 30). During the summer sampling period the Big Spring Creek sample was considerably larger than the other locations, which were fairly similar. The Big Springs Creek summer sample had greater than 48,000 invertebrates/m^2. This sample was composed primarily of *Hyalella* sp. and *Baetis* sp. (see appendix for species distribution). Throughout the Shasta River, invertebrate abundances show that ample food is available for rearing salmonids, particularly in Big Springs Creek where abundances are very high.

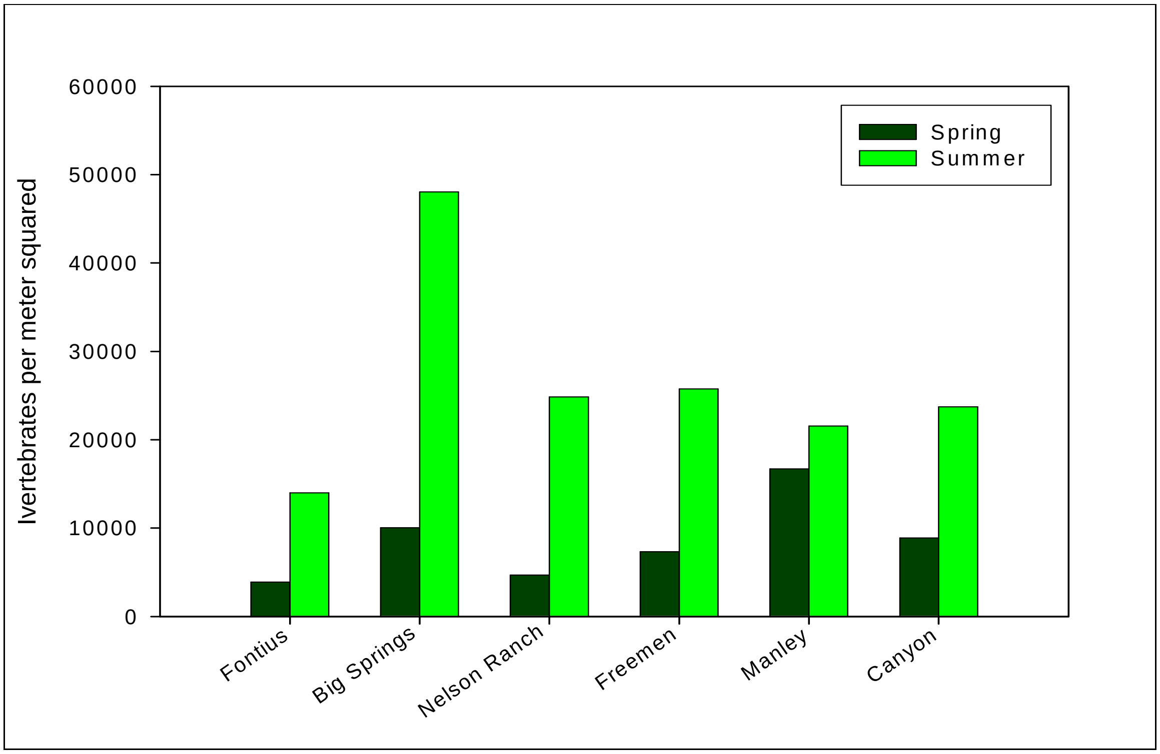

Figure 30. Abundance of invertebrates measured by number per meter squared sampled longitudinally throughout the Shasta River in the spring and summer 2008.

11.4 ***Functional Feeding Groups (FFG)***

Macroinvertebrates have evolved several different functional feeding strategies in order to exploit various carbon sources, both allochthonous and autochthonous in origin. The abundance or absence of particular functional feeding groups provides direct insight into the types of organic matter available for uptake by particular macroinvertebrates.

Collector-gatherer insects dominated the macroinvertebrate assemblage at all sites during the spring sampling period (Figure 31), at times accounting for nearly 98 percent of the entire assemblage (Fontius Ranch and Big Springs). Even though the collector-gatherer FFG was dominant during the spring sampling period throughout all sampling sites, the species composition varied throughout the sites. The Fontius sample was dominated by the Chironomidae family, the Big Springs Creek sample by *Hyalella* sp. and the rest of the reaches by *Baetis* sp. This highlights how different species have adapted to the abundant carbon sources during the spring. During the summer sampling period, all sample sites, except Big Springs Creek and Nelson Ranch showed a greater overall abundance of scrapers relative to the spring sampling period (Figure 31). The increase in scrapers was due primarily to the increase in *Optioservus* sp. at all locations. This suggests that epilithon may be an important carbon source for macroinvertebrates during summer in these reaches. The epilithon was likely using the increased duration and intensity of sunlight during the summer months and growing on both aquatic macrophytes and larger substrate that was stationary throughout the summer season.

Shredding and predatory macroinvertebrates were rare in all samples collected during all seasons, never accounting for more than 0.9 percent of the entire macroinvertebrate assemblage for each reach. The ubiquitous nature of collector-filterers, coupled with an absence of shredders, implies that coarse particulate organic matter (CPOM)-fine particulate organic matter (FPOM) breakdown processes and transport may not follow traditional pathways associated with the river continuum (Vannote et al. 1980). Rather, shredder-mediated breakdown of CPOM may be replaced by sources of FPOM from annual senescence of aquatic macrophytes or other unexplained sources. The absence of predatory macroinvertebrates is also unexplained. Generally, invertebrate communities contain approximately 15 percent predatory individuals. The lack of predators may be due to sampling bias and the unique nature of the Shasta River system. Abundant Ondonata (damselflies and dragonflies) have been observed in the Shasta Valley as adults, yet are virtually absent in our samples. Odonates are often found in margin habitat with slower water velocities and emergent habitat, which was not sampled with our technique.

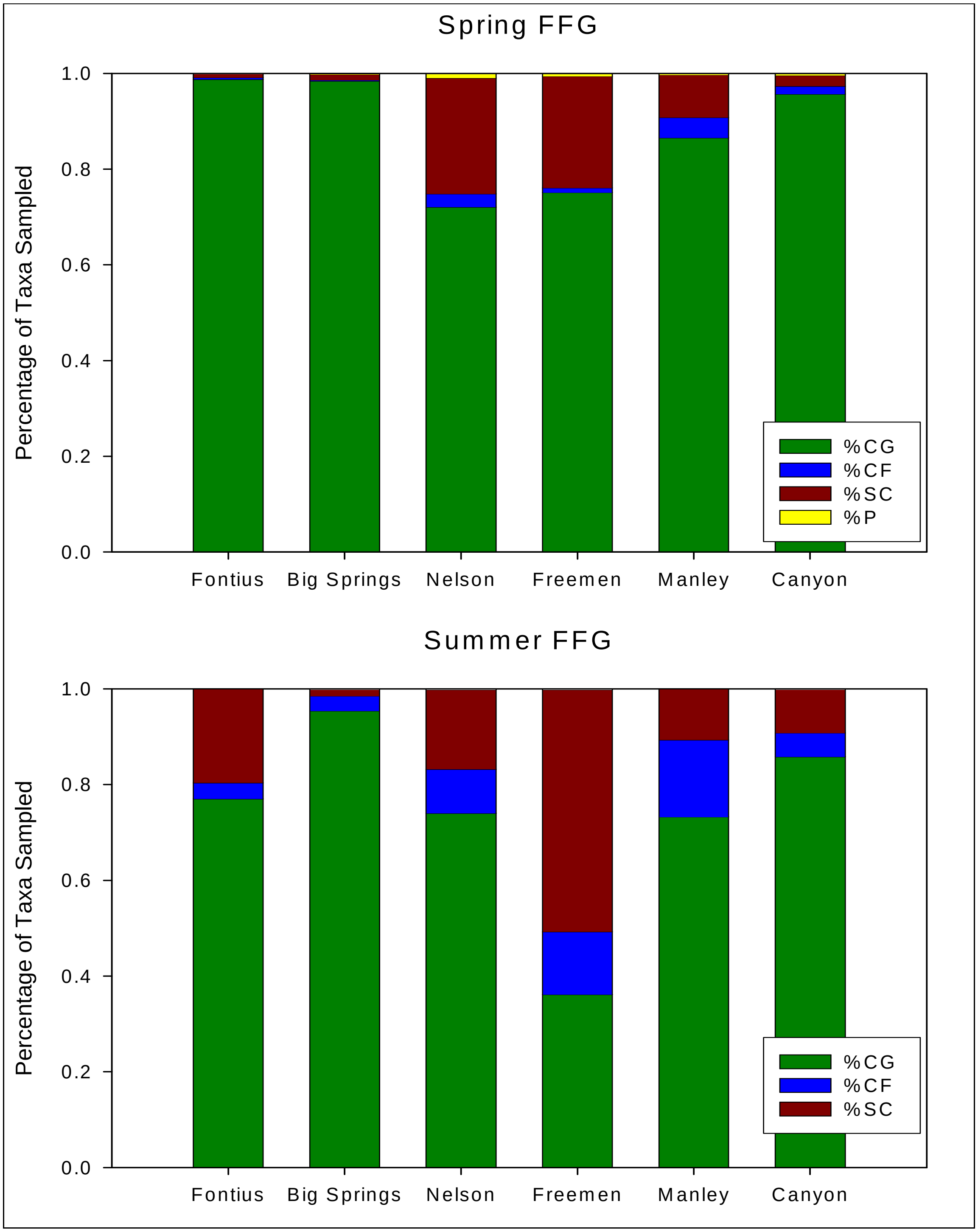

Figure 31. Functional feeding groups (FFGs) of benthic macroinvertebrates sampled throughout the Shasta River in spring and summer, 2008. Collector-gatherer (CG), collector-filterer (CF), scraper (SC), predator (P)

11.5 ***Summary***

Aquatic invertebrates are an important component of the aquatic ecosystem. Aquatic invertebrates utilize aquatic macrophytes as a seasonally available habitat. The high percentage of collector/gathers present correlates with the large amount of FPOM found in the Shasta River. The large amount of FPOM is likely resultant from the breakdown of aquatic macrophytes and organic material from allochthonous sources delivered from tailwater return to the river. When invertebrates process organic material they act as an energy transfer from primary producers to rearing salmonids. The density of aquatic invertebrates in the Shasta River and tributaries can provide amble food resources for rearing salmonids, providing other factors are not limiting (e.g. water temperature).

12.0 Salmonid Habitat Usage

Adult salmonids returning to spawn in the Shasta River utilize two broad areas of stream with suitable spawning habitat. The downstream spawning area consists of the 7 km immediately above the confluence with the Klamath River (Figure 1). The canyon reach has been the location of spawning habitat enhancement through the installation of boulder weirs and gravel augmentation. Gravel enhancement was aimed to enhance the production of Chinook salmon, but adult coho salmon and steelhead also utilize the restored gravels. The second spawning area (Big Springs Complex) is 55 km above the Klamath River confluence and consists of Big Springs Creek, Shasta River, and lower Parks Creek (Figure 1).

Steelhead and/or rainbow trout (*Oncorhynchus mykiss*) are the most thermally tolerant year-round salmonid in the Shasta River. Steelhead and rainbow trout are the same species and are not obligated to go to the ocean to mature. Some fish remain in fresh water where they mature and can spawn with other mature fish that return from the ocean environment. Ocean going adults return to the Shasta River to spawn November through March. Resident rainbow trout also participate in spawning activities with the returning sea-run adults. The majority of the steelhead spawning takes place in March. Juvenile steelhead begin to emerge in April where they can either leave the Shasta River during their first year or any year there after to go to the ocean.

Chinook salmon (*Oncorhynchus tshawytscha*) primarily use the Shasta River from September through June each year. The adults return to spawn starting in September and continue to return through November, with the peak of spawning taking place in October. Juveniles emerge from the gravels beginning in late January through March depending on adult spawning timing and proximity to springs where relatively warm temperatures are found during winter. The relatively warm water temperatures increase developmental rates resulting in earlier emergence from the gravels. The juveniles then remain in the Shasta River until April when emigration begins. Juveniles will emigrate through June with only a very small number remaining in the Shasta River to over-summer.

Coho salmon (*Oncorhynchus kitsuch*) have been in decline in the Shasta River and are the principal driver of restoration activities within the basin. Adult coho return to spawn during late fall and winter when flows are at the seasonal high and water temperatures have cooled from summer periods. During fall and winter, there is little difference in the apparent quality of the two spawning locations (canyon reach and Big Springs Complex). Juvenile coho emerge from the gravels in March and April depending on spawning timing and proximity to relatively warm water spring sources. However, in spring, habitat and migration conditions in the two reaches differ considerably. As irrigation season begins, reductions in flow and seasonal thermal loading lead to increased water temperatures, particularly downstream of Big Springs Creek. Further, flashboard dams are installed throughout the Shasta River to support irrigation water diversion, and these features can form migration barriers (Jeffres et al. 2008, Jeffres et al. 2009). While summer water temperatures in the canyon section often exceed 27°C, temperatures remain relatively cool (10-18°C) near the Big Springs Complex source springs. This longitudinal and seasonal gradient ultimately determines if and where juvenile coho will survive.

12.1 ***Methods***

Snorkel surveys were used as a non-invasive method to determine relative abundance and habitat usage and should not be used as a surrogate for population estimates. Because of the presence of coho (a federally threatened species), snorkel surveys were determined to be the method with the lowest level of impact when determining habitat usage by fishes. To conduct snorkel surveys, reaches were selected at each of the study sites. Within each of the reaches, snorkel surveys were conducted among the various habitat/cover types available. Each survey was completed moving upstream and fish were only counted within one meter of each side of the surveyor. In addition to upstream surveys a downstream “Reach Dive” was also conducted to incorporate locations not included in the habitat/cover-type surveys. We conducted snorkel surveys twice per month throughout the study period. Reaches varied between 100 and 200 meters in length. During all surveys, the surveyor identified fish species and age class, and recorded the information on a wrist slate. After a reach survey was completed, instream cover, substrate type and exposed substrate were qualitatively estimated and recorded. Water quality parameters were measured after each survey using a YSI 6820 data sonde. Water quality parameters recorded were temperature, dissolved oxygen, turbidity, pH, and conductivity.

12.2 ***Steelhead***

Steelhead trout are the most abundant year-round salmonid in the Shasta River watershed. Steelhead have a high water temperature tolerance relative to the other salmonids that utilize the Shasta River throughout the year. Several age classes of steelhead were observed at all survey locations. The most common age class was 0+ fry (fry that emerged in the spring of 2008). Steelhead densities were highest at the Nelson Ranch and Big Springs Creek study site where temperatures cooled at night (Figure 32). In the canyon reach, steelhead number declined sharply following an increase in water temperatures during May. The warm temperatures likely forced the rearing fish to seek habitat with cooler temperatures. During this time the majority of steelhead were small 0+ fry and upstream migration was probably not feasible due to the small size of the fish, the large distance fish would have to travel, and the poor conditions en route (e.g., migration barriers, lack of habitat, elevated temperatures). Many of these fry likely moved downstream into the Klamath River.

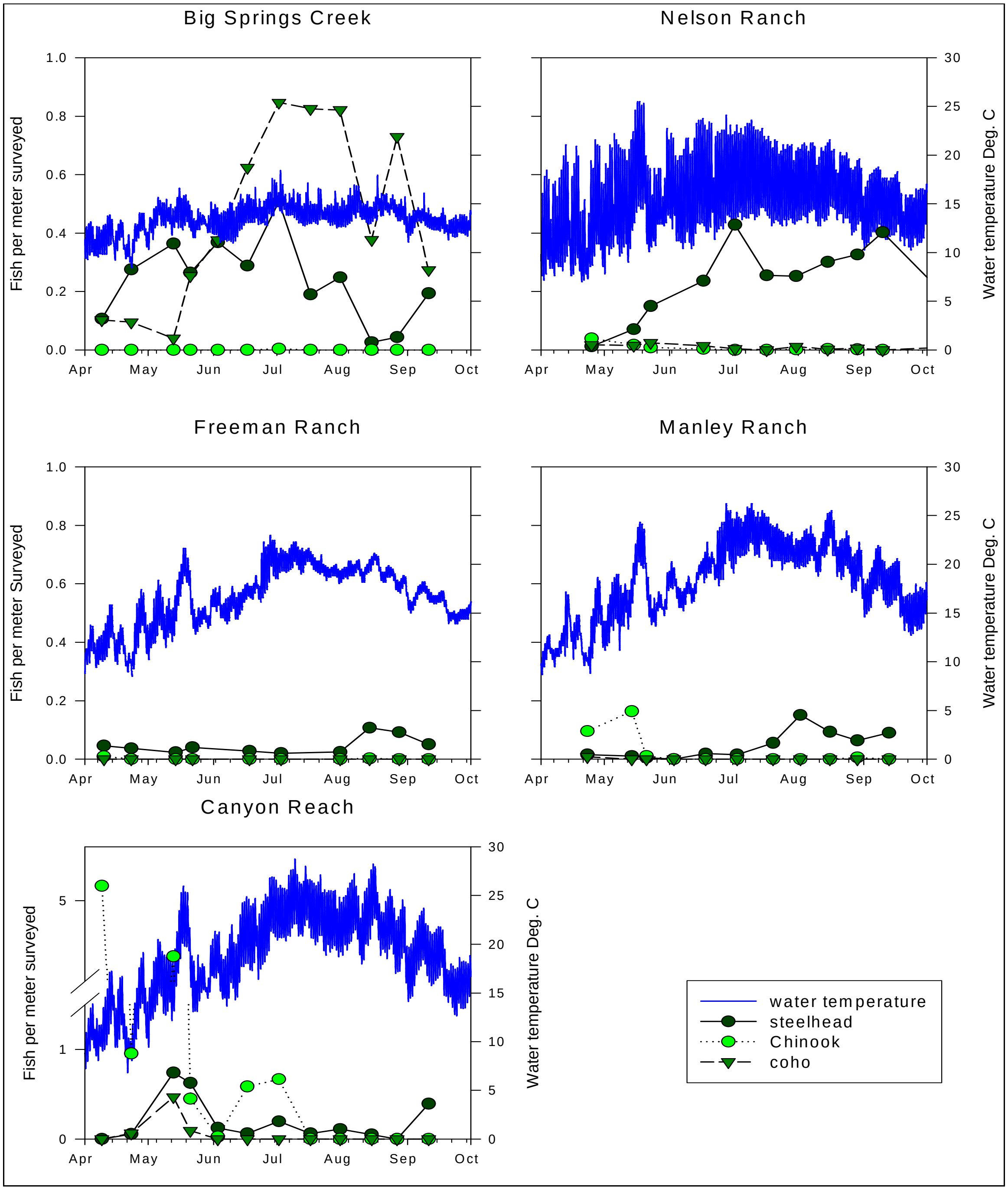

Figure 32. Fish per meter surveyed with temperature at five reaches throughout the Shasta River. Note changes in fish density with rapid increases in temperature in May. At most locations fish left the reach as temperatures increased with the exception of Big Springs Creek and the Nelson reach where temperatures remained relatively moderate throughout the summer.

12.3 ***Chinook***

Historically, the Shasta River was one of the most productive salmon streams in California, with runs of Chinook salmon over 80,000 returning adults in the 1930s (NRC 2004). Since the closure of Dwinnell Dam in 1928, Chinook salmon numbers have decreased dramatically. Between 2001 and 2006, Chinook returns averaged 4,566 adults per year with a high of 11,093 and a low of 978 (CDFG unpublished data). A reduction in spawning habitat is likely one of the primary reasons for the decline of Chinook populations over time. Closure of Dwinnell Dam blocked 33 percent of river but likely a much higher percentage of the high-quality spawning habitat (Wales 1951). Construction of Dwinnell Dam not only cut off access to spawning habitat upstream of the dam, but altered habitat conditions downstream. Through time, the combination of lower summer flows and less frequent and smaller magnitude peak winter flows, resulted in sedimentation of fine material within the gravels and encroachment of riparian vegetation (Ricker 1997). This reduction in stream size resulted in a considerable loss of spawning habitat in the reach from Dwinnell Dam to Big Springs Creek. Although there has been a reduction in the total amount of spawning habitat immediately below Dwinnell Dam, habitat still exists. The spawning habitat below Dwinnell Dam and in Big Springs Creek, although present, has been degraded by historic land use practices.

When sampling first began in April, almost all of the Chinook observed in the Shasta River were in the lower watershed. This is likely similar to the distribution of suitable spawning habitat the previous fall when adults returned. Spawning habitat is available in the upper watershed, but due to cattle having access to large portions of the Shasta River and Big Springs Creek throughout the fall of 2007 and winter 2008, it was not likely to produce large numbers of the fry compared to the canyon reach. When sampling began in April, habitat conditions were not suitable for either spawning or rearing in Big Springs Creek or the Shasta River immediately above Big Springs Creek. Habitat had been degraded (high water temperature, fine sediment, and lack of cover for rearing) by cattle having access to the river channel, resulting in removal of aquatic vegetation and likely trampling of redds. Since cattle were excluded from Big Springs Creek in 2009, habitat conditions have improved considerably and both adult and juvenile Chinook have been observed utilizing this habitat in large numbers.

When water temperature increased in May 2008, Chinook numbers throughout the river decreased rapidly as rearing Chinook likely left the Shasta River (Figure 32). In the canyon reach, a second group of out-migrating Chinook was observed in mid-late June. After June, on three occasions juvenile Chinook were found to be rearing on the Nelson Ranch. A small percentage of Chinook over-summer in the Shasta River, some of which mature during the summer and spawn with returning adults in the fall (see Jeffres et al. 2009).

12.4 ***Coho***

The Shasta River coho salmon population is currently in decline and verging on local extirpation (Figure 33). Coho salmon are particularly susceptible to warm water and habitat degradation due to the obligate over-summer residency in freshwater (Bryant

2009). During summer, water resources are generally placed under greater stress due to increasing demand and a reduction in cold water resources (Carpenter et al. 1992). Unlike other salmonids that are found in anadromous waterways during summer (e.g. steelhead and Chinook salmon), coho are thermally intolerant and have specific habitat requirements (e.g. slower water velocities with cover). Alteration of the natural conditions in the Shasta River basin coupled with habitat and physiological requirements have caused coho salmon populations to decline, which will continue unless habitat conditions are ameliorated.

During the late fall/early winter 2007, 249 adult coho returned to the Shasta River (CDFG unpublished data) (Figure 33). This is the largest of the three cohorts of coho remaining in the Shasta River and provided a good opportunity to observe how juvenile coho utilized limited over-summering habitat in the Shasta River basin under adverse conditions. In April through mid-May, juvenile coho were only observed in Big Springs Creek, the Nelson Ranch, and in the canyon reach. This corresponds to the primary spawning locations of the previous year's adults (canyon reach and Big Springs Complex) (CDFG unpublished data).

The primary factor that influences coho distribution in the Shasta River is water temperature. A single warm water event in the spring can have a large impact on when and where fish will move to find suitable over-summering habitat. In May 2008, warm weather and degraded habitat led to a warm-water event that redistributed coho from rearing habitats in the mainstem Shasta River into the few remaining cool water refugia in Big Springs Creek, Upper Shasta River, and Parks Creek (Jeffres et al. 2009, Chesney 2010). If fish were below the uppermost barrier to migration (GID diversion dam), then they likely migrated out of the Shasta River into the Klamath River in search of suitable over-summering habitat. This led to coho only being observed in a few locations after the May warm-water event, despite many locations with suitable habitat and temperatures after the May event through June (Figure 32). This event highlights how a single early season warm temperature pulse can have severe consequences for juvenile Shasta River coho.

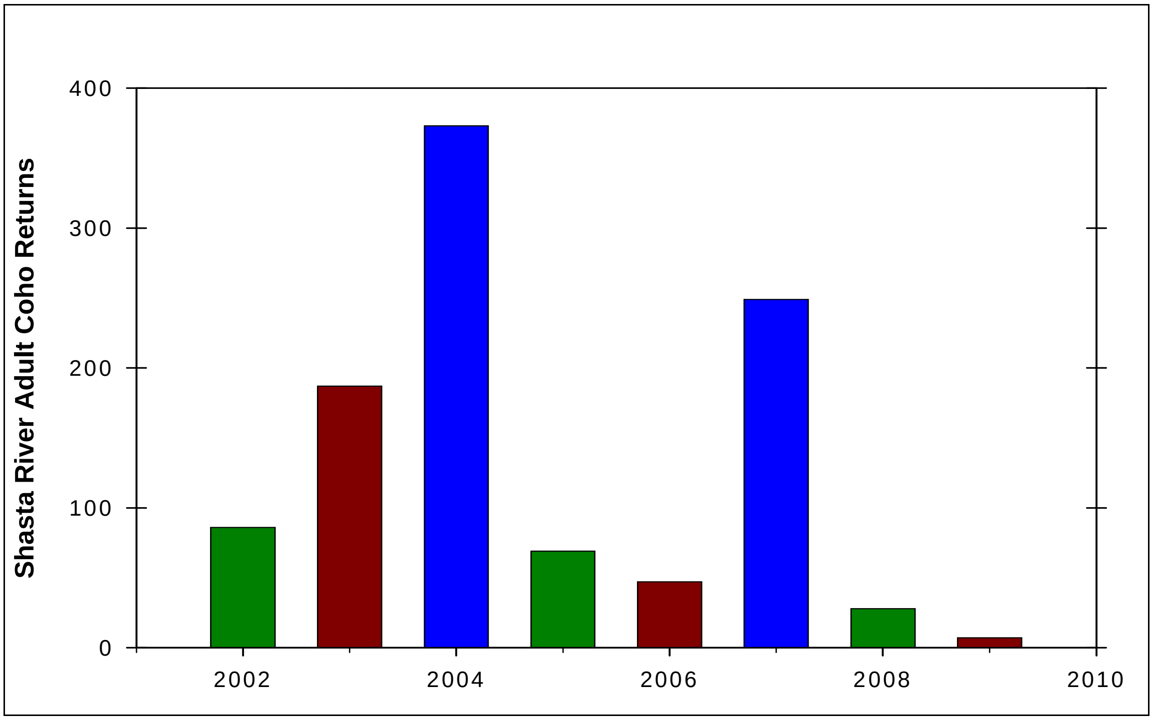

Figure 33. Shasta River adult coho returns from 2002 through 2009 (DFG unpublished data). Each cohort is represented with a unique color.

12.5 ***Summary***

A fish's life history strategy and physiological tolerances ultimately determine which species will be affected the most by anthropogenic alteration of the environment. Current alteration of the Shasta River has resulted in reduced stream flows and increased water temperatures. Chinook salmon are able to much better tolerate these conditions than coho because they have higher thermal tolerances and leave the Shasta River for the ocean just as conditions begin to degrade. Steelhead on the other hand have a high thermal tolerance relative to coho salmon and are able to make use of the abundant habitat and food resources that the Shasta River provides, even under severely altered conditions. During summer 2008, only a few isolated locations provided suitable over-summering habitat for coho salmon. Suitable habitat and food resources are present in Big Springs Creek and the Shasta River downstream of Big Springs Creek, but warm water is currently limiting the Shasta River coho population.

13.0 Conclusion

The Shasta River has been identified as one of the most important tributaries for salmon habitat in the Klamath Basin, largely due to the contribution of several groundwater springs and springs complexes. A baseline study was completed at multiple locations in the Shasta River and Big Springs Creek to extend previous studies on the Nelson Ranch to improve the understanding of spatial and temporal conditions in support of restoring anadromous fish in the basin.

The goal of this study was to provide the baseline information necessary to guide and evaluate restoration efforts designed to improve salmonid populations. Critical system attributes of:

- Geomorphology,
- Flow (including contributions from springs complexes),
- Water temperature,
- Water quality,
- Aquatic vegetation,
- Macroinvertebrates, and
- Salmonid usage

have been defined over considerable length of the Shasta River throughout critical periods of the year that lend considerable insight into high priority areas and potential processes important to restoration and maintenance of anadromous salmonids and other aquatic system function. Specifically, maintaining sufficient, baseflows are important for migration and rearing throughout the system. Cool water reaches, such as those associated with the Big Springs Complex, are likewise critical for over-summering juvenile rearing. Protection of such spring inflows not only provides cool water habitat, but also provides important nutrient inputs to the system that allowing extensive aquatic vegetation growth. In upstream reaches (near Big Springs), where nutrient limitation is less of a factor, this vegetation growth serves multiple purposes, including seasonal sequestering nutrients, modifying channel conditions (e.g., narrowing and deepening) and flow regimes, creating diverse and important habitats for spawning and rearing, and a food source and habitat for macroinvertebrates. This unique combination of physical, chemical, and biological factors results in high anadromous fish production potential in the Shasta River. By focusing on these factors, with special attention focused on the key inter-relationships among processes, targeted restoration activities can be formed to restore and maintain anadromous fish in the Shasta Basin.

14.0 References

Abbott, A. G. and M. L. Deas. 2003. Shasta River Field Studies to Support Flow and Temperature Modeling.

Birgand, F., R. W. Skaggs, G. M. Chescheir, and J. W. Gilliam. 2007. Nitrogen removal in streams of agricultural catchments - A literature review. Critical Reviews in Environmental Science and Technology **37**:381-487.

Bryant, M. D. 2009. Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska. Climatic Change **95**:169-193.

Carpenter, S. R., S. G. Fisher, N. B. Grimm, and J. F. Kitchell. 1992. Global change and freshwater ecosystems. Annual Review of Ecology and Systematics **23**:119-139.

CDFG. 2004. Recovery strategy for California coho salmon. Report to the California Fish and Game Commission. Native Anadromous Fish and Watershed Branch, 1416 9th Street, Sacramento, CA 95814 [on-line] http://www.dfg.ca.gov/nafwb.cohorecovery.

Chesney, W. R., C. C. Adams , W. B. Crombie , H. D. Langendorf ,S. A. Stenhouse , and K. M. Kirkby 2010. Shasta River Juvenile Coho Habitat and Migration Study. California Department of Fish and Game.

Chitale, S. V. 1973. Theories and relationships of river channel patterns. Journal of Hydrology **19**:285-308.

Crandell, D. R., C. D. Miller, H. X. Glicken, R. L. Christiansen, and C. G. Newhall. 1984. Catastrophic Debris Avalanche from Ancestral Mount Shasta Volcano, California. Geology **12**:143-146.

Deas, M. L., P.B. Moyle, J.F. Mount, J. Lund, C. Lowney, and S. Tanaka. 2004. Priority actions for restoration of the Shasta River: a technical report. Prepared for The Nature Conservancy, California

Hotz, P. E. 1977. Geology of the Yreka Quadrangle, Siskiyou County, California. U. S. Geological Survey Bulletin B 1436.

Jeffres, C. A., E. M. Buckland, M. L. Deas, B. G. Hammock, J. D. Kiernan, A. M. King, N. Y. Krigbaum, J. F. Mount, P. B. Moyle, D. L. Nichols, and S. E. Null. 2008. Baseline Assessment of Salmonid Habitat and Aquatic Ecology of the Nelson Ranch, Shasta River, California Water Year 2007. Report prepared for: United States Bureau of Reclamation, Klamath Area Office.

Jeffres, C. A., R. A. Dahlgren, M. L. Deas, J. D. Kiernan, A. M. King, R. A. Lusardi, J. F. Mount, P. B. Moyle, A. L. Nichols, S. E. Null, S. K. Tanaka, and A. D. Willis. 2009. Baseline Assessment of Physical and Biological Conditions Within Waterways on Big Springs Ranch, Siskiyou County, California. UC Davis Center for Watershed Sciences and Watercourse Engineering. Report prepared for: California State Water Resources Control Board.

Kalff, J. 2002. Limnology. Prentice Hall, New Jersey.

Lowney, C. L. 2000. Stream temperature variation in regulated rivers: Evidence for a spatial pattern in daily minimum and maximum magnitudes. Water Resources Research **36**:2947-2955.

Merritt, R. W., K. W. Cummins, and M. B. Berg. 2008. An introduction to the aquatic insects of North America. 4th edition. Kendall/Hunt Publishing, Dubuque, Iowa, USA.

Nichols, A. L. 2008. Geological Mediation of Hydrologic Porcess, Channel Morphology, and Resultant Planform Response to Closure of Dwinnell Dam, Shasta River, California. University of California, , Davis, CA.
NRC. 2004. Endangered and Threatened Fishes in the Klamath River Basin Causes of Decline and Strategies for Recovery. National Research Council, National Academies Press, Washington, DC.
Onset. 2009. HOBO® Pro v2 Water Temperature Data Logger specification. http://www.onsetcomp.com/products/data-loggers/u22-001#tabs-product_page_tabs1-2
Rantz, S. E. 1982. Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge. U.S. Geological Survey.
Redfield, A. C., editor. 1934. On the proportions of organic derivations in sea water and their relation to the composition of plankton. University Press of Liverpool, Liverpool.
Ricker, S. J. 1997. Evaluation of salmon and steelhead spawning habitat quality in the Shasta River Basin, 1997. Administrative Report 97-9, California Department of Fish and Game Region 1 Inland Fisheries Administrative Report 97-9.
Smith, D. G. 2001. Pennak's freshwater invertebrates of the United States. 4th edition. John Wiley and Sons, New York, USA.
Thorp, J. H. and A. P. Covich. 2001. Ecology and classification of North American freshwater invertebrates. 2nd edition. Academic Press, San Diego, CA. USA.
Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences **37**:130-137.
Wagner, D. L. and G. J. Saucedo. 1987. Geologic map of the Weed Quadrangle. California Division of Mines and Geology, Regional Geologic Map Series **Map No. 4A, 1:250,000**.
Wales, J. H. 1951. The decline of the Shasta River king salmon run. Bureau of Fish Conservation, California Division of Fish and Game.
Whiting, P. J. and D. B. Moog. 2001. The geometric, sedimentologic and hydrologic attributes of spring-dominated channels in volcanic areas. Geomorphology **39**:131-149.
Wiggins, G. B. 1996. Larvae of the North American caddisfly genera (Trichoptera). 2nd edition. University of Toronto Press, Toronto, Canada.
Willis, A. D. and M. L. Deas. 2009. Spring Temperature Monitoring in Big Springs Creek. Technical memorandum prepared for The Nature Conservancy.
Wolman, M. G. 1954. A method of sampling coarse river-bed material. Transactions - American Geophysical Union **35**:951-956.