SUMMER STREAM TEMPERATURES EXPERIENCED BY

ADULT SPRING-RUN CHINOOK SALMON

(*ONCORHYNCHUS TSHAWYTSCHA*)

IN A CENTRAL VALLEY STREAM

A Thesis

Presented

to the Faculty of

California State University, Chico

In Partial Fulfillment

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Master of Science

in

Environmental Science

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by

Danielle Joy Cresswell

Winter 2004

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ABSTRACT

SUMMER STREAM TEMPERATURES EXPERIENCED BY

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This study was initiated to identify existing summer stream temperature conditions for spring-run chinook salmon (*Oncorhynchus tshawytscha*) in Big Chico Creek (BCC), and determine if pools occupied by salmon through summer contained thermal refugia. In addition, the stream temperature model, SSTEMP 2.0, was applied to evaluate the potential for changes in riparian tree height and density to affect mean stream temperature in spring-run salmon holding habitat of BCC.

During summer 2003, potential holding pools were evaluated for cold-water habitat. At pools where cooler water was encountered, temperatures were measured in detail along transects, and physical habitat and discharge were characterized. In addition, hourly stream temperatures were measured near the surface and bottom of three pools where spring-run salmon held through summer.

With one exception, cold-water areas found in potential summer holding pools were not of sufficient volume to provide thermal refugia to spring-run salmon. Cold-water areas were found in the organic layer at the water/streambed interface, or at channel margins where subsurface flow entered the channel. In a single pool, a physical barrier separated the pool from main channel flow, allowing stratification to occur.

Between June 1 and October 1, 2003, stream temperature measured at Higgins Hole, Henning Hole, and Salmon Hole indicated adult spring-run salmon holding in these pools were periodically exposed to stressful thermal conditions. Maximum temperatures for the three pools were between 22.9^{o} C and 25.6^{o} C. The percentage of hours that stream temperature $\geq 21^{o}$ C at these pools during the summer of 2003 ranged from 1.6% to 28.5%. Higgins Hole represented a thermal refuge for over-summering spring-run salmon relative to available holding habitat in the foothill zone.

Application of SSTEMP 2.0 indicated management efforts which increase riparian height and density within and above the foothill zone of BCC could result in a decreasing rate of temperature change, and lower mean stream temperatures within the foothill zone during the warmest summer period. Increased riparian tree height and density along the model stream segment within the spring-run salmon holding reach resulted in a decrease in mean stream temperature of less than 0.5^{o}C. By also increasing riparian tree height and density in the 4.4 km upstream of the original model stream segment, mean stream temperature declined further, though still not by more than 1^{o}C.

CHAPTER ONE

INTRODUCTION

Perhaps no other environmental factor has a more pervasive influence on salmonids and other aquatic biota than temperature.

Spence et al., *An Ecosystem Approach to Salmonid Conservation*

Influence of Temperature in a Stream Environment

In the stream environment, the temporal and spatial variation of temperature strongly influences local faunal species assemblages, as well as habitat selection at each life cycle phase (Brett, 1956; Ricker, 1972; Coutant, 1987; Poff and Ward, 1990; Schlosser, 1991; Haro and Wiley, 1992, and Quinn and Hickey, 1990, as cited by Richards et al., 1996; Ebersole et al., 2001). In fishes, water temperature influences survival through effects on metabolism, growth, feeding activity, reproduction, geographic distribution, susceptibility to predation and disease, and community interactions (Brett, 1956; Coutant, 1976; Kaya et al., 1977; Berman and Quinn, 1991; McCullough, 1999).

Temporal and spatial temperature patterns are a significant determinant of availability of stream habitat for Pacific salmon and trout (*Oncorhynchus* spp.) (Coutant, 1976). Stream temperatures vary in time according to diurnal and seasonal cycles, and in space through the longitudinal (Vannote et al., 1980), lateral (Ward, 1989), and transverse dimensions (Poole and Berman, 2001). Thus, salmonids migrating in a stream are presented with a dynamic, four-dimensional thermal environment in which to behaviorally and physiologically adjust in their effort to survive, grow, and reproduce. As salmonids are cold-water fishes (Magnuson et al., 1979), the upper thermal limit for a particular species and life stage is significant when considering potential species distribution relative to the magnitude and distribution of summer temperatures in salmonid streams.

Thermal regimes of temperate stream habitats have been widely investigated by authors with particular interest in summer stream temperatures experienced by salmon and trout (Bilby, 1984; Berman and Quinn, 1991; Li et al., 1994; Matthews et al., 1994; Nakamoto, 1994; Nielsen et al., 1994; Roper et al., 1994; Torgersen et al., 1999; Gaffield, 2000; Ebersole et al., 2001; Ebersole et al, 2003). The health of salmon and trout populations in the western United States is commonly linked to the health of stream ecosystems. As of this writing, 26 of 52 Pacific salmon and steelhead species occurring from southern California to the Canadian border have been listed by the National Marine Fisheries Service (NMFS) as threatened or endangered (National Marine Fisheries Service, 2004). Among the many causes for salmonid decline, direct and indirect alteration of stream conditions, such as temperature, is uniformly cited (Nehlsen et al., 1991; Spence et al., 1996). Past studies of summer stream temperature conditions experienced by salmonids were conducted to: 1) document the distribution of thermal characteristics in current and historic salmonid streams, 2) determine the relationship between stream temperatures and behavioral and physiological observations of salmonid species at differing life stages, and 3) investigate the relative effects of riparian and instream structural elements (e.g., vegetation density, pool depth, large woody debris) on thermal characteristics experienced by threatened and endangered salmonids.

Spring-Run Salmon in the Sacramento River Drainage

Historically, spring-run chinook salmon (*Oncorhynchus tshawytscha*), or "spring-run salmon," inhabited coastal and inland rivers in Washington, Idaho, Oregon, and California (Myers et al., 1998). In California, spring-run salmon occurred in coastal and inland streams, with significant production from the Sacramento and San Joaquin River drainages of the Central Valley (Figure 1). Three other races of chinook salmon (*O. tshawytscha*) occur in the Sacramento River drainage: the fall and late-fall runs, and the winter run. Over the past fifty years, salmon populations of California's Central Valley have significantly declined in abundance (Fisher, 1994; Yoshiyama et al., 1998; Yoshiyama et al., 2000). This decline is attributed largely to migration barriers, historic mining activities, water diversion, over-fishing, and ocean conditions (California Dept. of Fish and Game (DFG), 1998; Myers et al., 1998; Yoshiyama et al., 2000). Spring-run salmon populations were particularly affected due to reduction in access to or quality of habitat in upper watershed reaches. In 1999, Central Valley spring-run salmon were listed by the State of California and the U.S. Dept. of Commerce as a threatened species under state and federal Endangered Species Acts (Federal Register, 1999).

Though Central Valley spring-run salmon once inhabited fourteen tributaries of the Sacramento River, only seven of those tributaries still support regular spawning populations, including Cottonwood Creek, Battle Creek, Antelope Creek, Mill Creek, Deer Creek, Big Chico Creek, and Butte Creek (DFG, 1998). The spring-run salmon

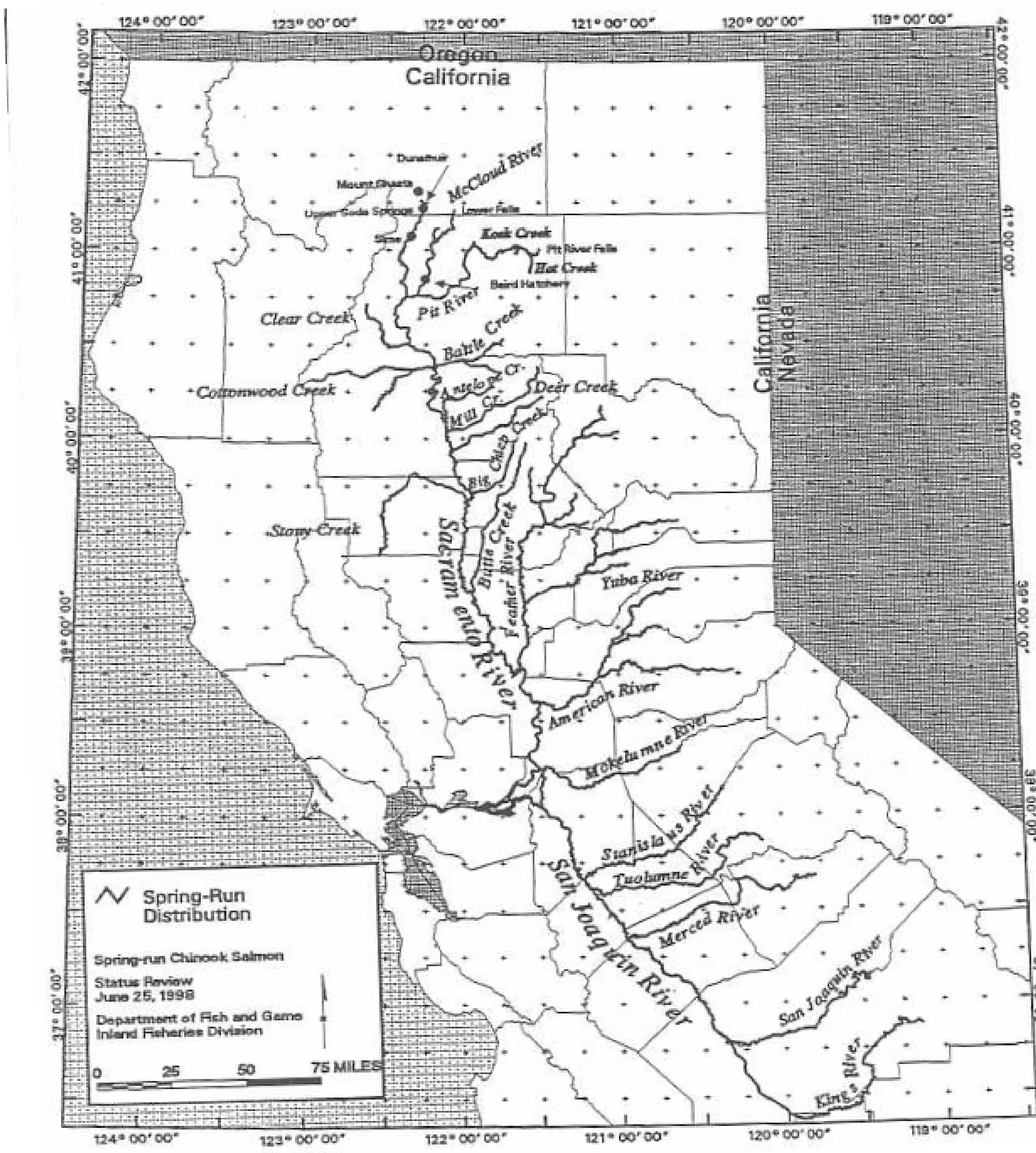


Figure 1. Historic distribution of spring-run chinook salmon in the Central Valley. (Source: California Department of Fish and Game (DFG). 1998. A status review of the spring-run chinook salmon (*Oncorhynchus tshawytscha*) in the Sacramento River drainage. Candidate Species Status Report 98-01.)

population of Big Chico Creek (BCC) is relatively small, with an average of 57 adults observed during snorkel surveys for the period of 1989-2003 (DFG, 1998; DFG, unpublished data). While annual estimates for the BCC spring-run salmon population are not as high as the three major spring-run salmon streams (Table 1), the persistence of spring-run salmon in BCC suggests that adequate habitat is available for them to carry out the freshwater component of their life cycle. Adult migration barriers, both natural and human-caused, and warm summer stream temperatures appear to be significant factors limiting annual spring-run salmon production in BCC (CH2M Hill, 1993; DWR, 2001).

	Mill Ck.	**Deer Ck.**	**Butte Ck.**	**Big Chico Ck.**
1989	561	77	2384	7
1990	844	458	183	0
1991	319	448	150	no estimate
1992	237	209	730	0
1993	61	259	650	38
1994	723	485	474	2
1995	320	1295	7500	200
1996	252	614	1413	2
1997	300	466	635	2
1998	424	1879	20259	369
1999	560	1591	3529	27
2000	544	637	4118	27
2001	1104	1622	9605	39
2002	1594	2195	8785	0
2003	1426	2759	4398	81
Average	618	1000	4321	57

Table 1. Adult spring-run salmon counts from snorkel surveys reported for Mill Ck., Deer Ck., Butte Ck., and Big Chico Ck. (1989-2003). (Sources: DFG. 1998. A status review of the spring-run chinook salmon (*Oncorhynchus tshawytscha*) in the Sacramento River drainage. Candidate Species Status Report 98-01; DFG. 2004. Sacramento spring-run chinook salmon. 2002-2003 biennial report.)

Summer stream temperature data collected in BCC between 1997 and 2001 (DWR, unpublished) indicated daily maximum temperatures exceeded temperatures known to cause mortality in adult spring-run salmon (McCullough, 1999). Presuming that spring-run salmon in BCC are subject to this threshold, their survival through summer may depend on access to cold-water refuges, or thermal refugia. Distribution and use of thermal refugia by adult salmon and steelhead are described for streams of the Pacific Northwest and coastal California (Beschta et al., 1987; Hostetler, 1991; Nakamoto, 1994; Nielsen et al., 1994; Torgersen et al., 1999). However, description of cold-water refugia use by adult spring-run salmon in the semi-arid climate of California's Central Valley is not found in the available body of scientific literature.

Scope of Research

The purpose of this study was to investigate thermal conditions in vacant and occupied holding habitats (e.g., pools with a maximum depth of $\geq$ 1.5 m) of adult spring-run salmon in BCC during summer 2003. Specifically, this research addressed the following questions: 1) did holding habitats for spring-run salmon in BCC exceed thermal tolerance as described in scientific literature, and if so, were thermal refugia available in holding habitats, 2) if thermal refugia were available in BCC holding habitats, what were the sources and landscape processes supporting refugia, and 3) would protecting and encouraging growth of riparian tree species reduce mean summer stream temperature experienced by spring-run salmon in BCC?

Two study elements were employed to address the above research questions. First, a field study was conducted between June 1 and October 1, 2003, to assess stream temperatures of summer holding habitats for spring-run salmon in BCC. The stream temperature model, SSTEMP 2.0 (Bartholow, 2002), was then employed to evaluate the effect of increased riparian tree height and density on mean summer stream temperature in the spring-run salmon holding reach of BCC.

Results from this research indicated summer stream temperatures in the foothill zone of BCC exceeded thermal tolerance of spring-run salmon described in scientific literature. Localized thermal refugia were generally not available for adult spring-run salmon in the foothill region of BCC. Of the three pools commonly used as holding habitat through summer by spring-run salmon in this stream, Higgins Hole provided a thermal refuge relative to other available holding habitats. Application of SSTEMP 2.0 indicated even extreme increases in riparian tree height and density within and above the model stream segment would not significantly lower mean stream temperatures within spring-run salmon holding habitats during the warmest summer period.

CHAPTER TWO

THERMAL REQUIREMENTS OF ADULT SPRING-RUN SALMON

Introduction

Although a suite of physical parameters governs suitability of habitat for spring-run salmon, stream temperature exerts a particularly strong control. Spring-run salmon, like other fish, are poikilothermic vertebrates: internal body temperature of salmon is governed by ambient environmental temperature (Brett, 1956; Coutant, 1976; Reynolds & Casterlin, 1979; Taylor, 1991). Thus, optimal environmental temperatures for salmon are dictated by the thermal requirement of the most sensitive internal tissues, namely tissues of the nervous system (Brett, 1956).

The geographical distribution of streams inhabited by spring-run salmon, as well as timing of their adult freshwater migration, appear to be adaptations which allow spring-run salmon access to over-summer holding habitats suitable to their temperature needs (Myers et al., 1998; Yoshiyama et al., 1998). Adult spring-run salmon enter and migrate in freshwater during spring (March – June), when precipitation and snowmelt runoff provide an adequate volume of water to allow migration to upper watershed reaches. Migration ceases through July and August as spring-run salmon hold through summer in selected habitat units, followed by spawning in fall (August – October).

Summer holding habitats utilized by adult spring-run salmon are typically located in upper watershed reaches where stream temperatures are more tolerable compared to reaches lower in a stream system (Vannote et al., 1980; Yoshiyama et al., 1998;

McCullough, 1999; Torgersen et al., 1999). However, summer habitat for spring-run salmon may also occur in reaches where stream temperatures are naturally warm, or are warmer due to anthropogenic effects.

Temperature Thresholds for Adult Salmon

Salmonids tend to avoid streams or stream habitats that warm beyond functional thresholds (Coutant, 1976; Kaya et al., 1977; Li et al., 1994; Nielsen et al., 1994; Torgersen et al., 1999). In general, adult spring-run salmon exhibit low tolerance for stream temperatures exceeding 21^{o}C (McCullough, 1999). Studies of temperature tolerance in adult spring-run salmon have identified maximum temperature ranges at which specific functions (e.g., migration, holding, and spawning) are impaired or eliminated (Table 2).

Migration appears to be limited or ceases at temperatures $\geq$21^{o}C (Hallock et al., 1970; Stabler, 1981; Bumgarner et al., 1997). Spring-run salmon holding in temperatures over 17^{o}C may experience high mortality rates (Marine and Cech, Jr., 1992). Mortality during the adult holding stage is commonly related to infection by viral or bacterial pathogens, which increase in occurrence at temperatures >15^{o}C (Berman, 1990; McCullough, 1999). Spawning occurs with the onset of declining stream temperature in autumn, and temperatures >16^{o}C may inhibit spawning (McCullough, 1999). In addition, summer holding temperatures affect not only the adult spring-run salmon, but also their gametes and development of fertilized eggs (Berman, 1990; Marine and Cech, Jr., 1992).

Source	Location	Observation	Temperature
Bell (1986)	--	normal migration	3.3-13.3°C
Berman (1990)	Yakima River, WA	mortality due to disease (*Columnaris*)	19°C
Berman (1990)	Yakima River, WA	increased mortality and developmental abnormalities prior to hatch; smaller alevin size	17.5-19°C
Bjornn and Reiser (1991)	--	upper zone of thermal tolerance	22°C
Bumgarner et al. (1997)	Tucannon River, WA	thermal migration barrier	21.1°C
Hallock et al. (1970)	Sacramento-San Joaquin River delta	thermal migration barrier	21°C
McCullough (1999)	--	increasing incidence of freshwater diseases	>15°C
McCullough (1999)	--	spawning ceases	≥16°C
Stabler (1981)	Clearwater River, Idaho	thermal migration barrier	>21°C

Table 2. Selected observations of temperature effects on adult spring-run salmon.

Spring-run chinook salmon do appear to be able to withstand periodic, short-term exposure to elevated, constant temperatures in laboratory tests (Berman, 1990). However, exposure to high temperatures of long duration eventually leads to lethal bacterial infections or metabolic stress (Berman, 1990; McCullough, 1999). It should be noted that the relationship between water temperature and exposure time leading to mortality of spring-run salmon (e.g., a mortality curve) holding in elevated temperatures is not well documented in empirical studies.

Conclusion

Due to their inability to internally regulate their body temperature, spring-run salmon must acclimate or adjust behaviorally to cope with or avoid unfavorable temperature conditions (Reynolds and Casterlin, 1979). Adult salmonids holding in warm stream reaches have been observed utilizing cold-water refuges, referred to as thermal refugia, to cope with warm water temperatures (Berman and Quinn, 1991; Nielsen et al., 1994; Torgersen et al., 1999). Successful reproduction by spring-run salmon that utilize warmer stream reaches may be due to availability of cold-water areas that serve as refugia, or possibly due to adaptation mechanisms.

CHAPTER THREE

PHYSICAL SETTING

Climate

Climate within the Big Chico Creek watershed is characteristic of interior Mediterranean climate zones (Critchfield, 1974), with hot summers which commonly exceed 33^{o}C in the middle and lower watershed. Winters are relatively mild, though temperatures in the upper watershed commonly drop below 0^{o}C (Big Chico Creek Watershed Alliance, 1999). The majority of precipitation occurs as rain falling between November and May, with the annual average ranging between 1780-2030 mm in the mountains to 510 mm at the valley floor (Big Chico Creek Watershed Alliance, 1999).

Geology

Geologic formations in the area reflect the historical volcanic and tectonic activity associated with the Sierra Nevada Range and the Mt. Lassen area of the Cascade Range. The channel bedrock of BCC is formed by the Chico Formation (~75 million years old), sedimentary rock that originated from deposition along an ancient shoreline of the Pacific Ocean. The next layer above is the Lovejoy Basalt (~20 million years old), a hard, fractured layer which emerges along canyon walls in the foothill zone. The uppermost and youngest formation in the BCC basin is the Tuscan Formation (~4 million years old), containing layers of volcanic mudflow and alluvial deposits. A map of geologic formations occurring in the study reach is presented in Appendix A.

Hydrology

Big Chico Creek emerges from western slopes of the Sierra Nevada mountains at approximately 1,645 meters above sea level. From its headwaters, BCC flows 72.4 km (Big Chico Creek Watershed Alliance, 1999) to the Sacramento River in California's northern Central Valley, draining a watershed of approximately 186.5 km^2 (USFWS Anadromous Fish Restoration Program).

The primary holding and spawning habitat for spring-run salmon in BCC occurs in the foothill zone (Big Chico Creek Watershed Alliance, 1999), extending approximately 12.5 km from Brown's Hole to Higgins Hole (Figure 2), with elevations increasing from 200.4 to 313.3 m. Mean summer base flow is approximately 0.9 m^3/s (DWR, 2001). There are no major diversions or impoundments on BCC within or above the foothill zone. Numerous springs occur on the hillslopes of the foothill zone, frequently emerging at contacts between the Lovejoy Formation and Chico Formation or Tuscan Formation and Chico Formation (P. Maslin, unpublished data).

Vegetation

The foothill zone of BCC watershed includes diverse vegetation communities. At a large spatial scale, vegetation types found in the BCC are included within the following broad categories: grassland, wet meadow, riparian, valley oak savanna/woodland, blue oak savanna/woodland, mixed woodland/forest, chaparral, and chaparral/savanna (Big Chico Watershed Alliance, 1999). This diversity makes for a rich biological and physical environment, and likely influences the hydrology and morphology of BCC. Influence of vegetation may be direct and indirect through variation in rates of processes such as

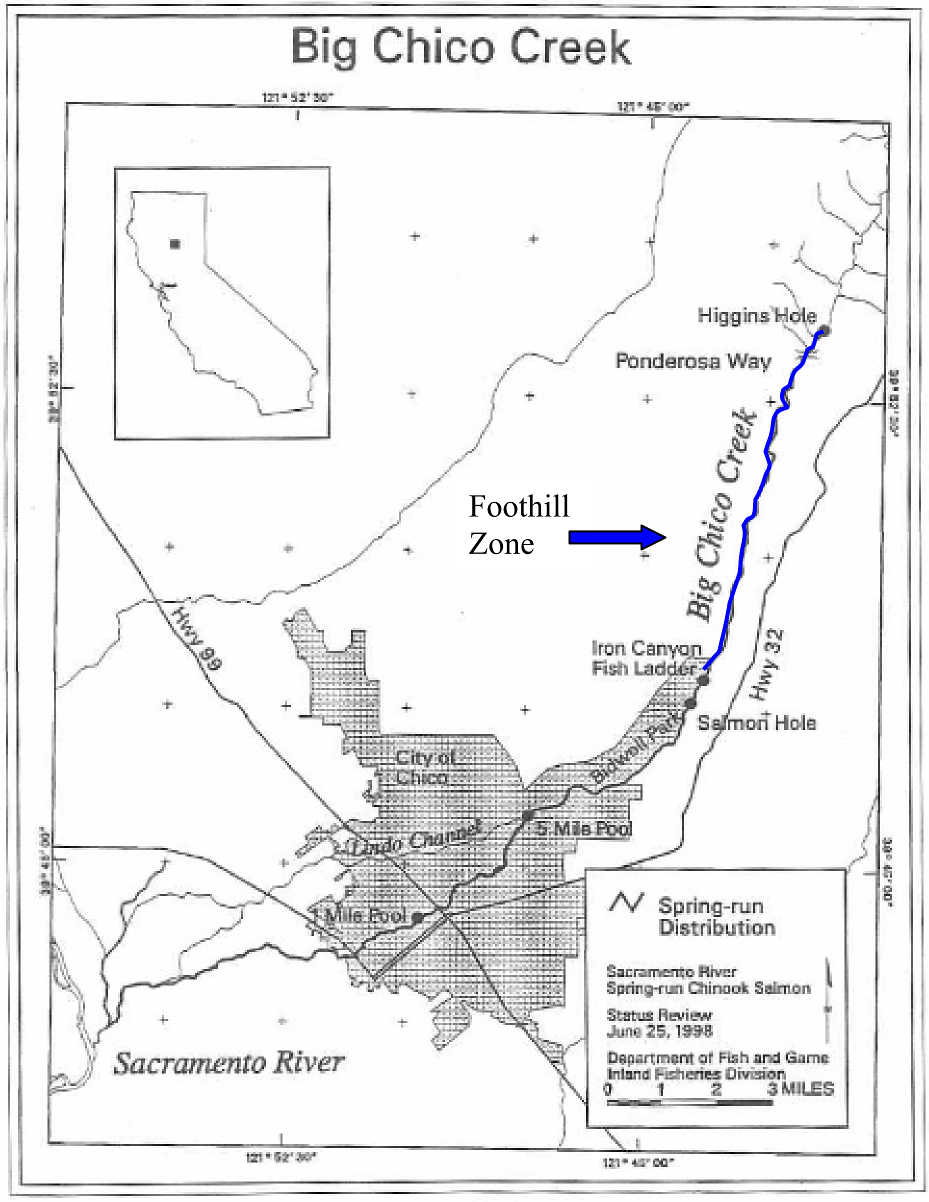


Figure 2. Location of BCC foothill zone. (Modified from: DFG. 1998. A status review of the spring-run chinook salmon (*Oncorhynchus tshawytscha*) in the Sacramento River drainage. Candidate Species Status Report 98-01.)

interception, evapotranspiration, infiltration, and soil erosion. A map depicting vegetation types within the study reach is presented in Appendix B.

Land Use

Throughout its length, BCC travels through a range of land ownership types, both public and private. While much of the middle and upper watershed of BCC is rural and forested, the lower reaches extend through the urban center of the City of Chico, and on through agricultural lands to the west of the city before draining to the Sacramento River. Much of the foothill zone of BCC occurs in Bidwell Park and the Big Chico Creek Ecological Reserve (BCCER). The Park is managed primarily for recreation, while management of the BCCER focuses on conservation, education, and research. Commercial logging occurs in portions of the upper watershed, primarily targeting ponderosa pine (*Pinus ponderosa*). Historical land-use activities (e.g., prior to the 1930s) dominant in the upper watershed included timber harvesting, livestock grazing, and road-building associated with these activities (Big Chico Creek Watershed Alliance, 1999).

CHAPTER FOUR

AVAILABILITY AND USE OF THERMAL REFUGIA BY ADULT SPRING-RUN SALMON

Introduction

Cold-water areas in a stream may serve as thermal refugia for adult spring-run salmon if they provide relief from warmer ambient stream temperature. The fundamental requirements for the formation of potential thermal refugia are: 1) input to a stream of a significant volume of water which is cooler than the receiving waters and 2) physical separation of incoming cooler water from the receiving stream so that turbulence does not result in complete mixing of the two water bodies (Nielsen et al., 1994). The greater the physical separation of the two water bodies, the less the flow of cooler water needs to be to form potential thermal refugia.

Formation of cold-water areas and their use as thermal refugia during summer by adult spring-run salmon is documented for streams of eastern Oregon and central Washington (Torgersen et al., 1999; Berman and Quinn, 1991). In addition, habitat selection by steelhead and rainbow trout (*Oncorhynchus mykiss*) relative to stream temperature patterns is documented for streams in northern California, eastern Oregon, Wyoming, and Wisconsin (Kaya et al., 1977; Matthews et al., 1994; Nakamoto, 1994; Nielsen et al., 1994; Gaffield, 2000; Ebersole et al., 2001). A review of findings from selected studies is given in this chapter, followed by methods and results of a field investigation of cold-water availability and character in Big Chico Creek, California, and a discussion of the implications of these empirical observations.

Review of Relevant Studies

Berman and Quinn (1991) investigated the effect of elevated thermal regimes on habitat selection and migration of adult spring-run salmon in the Yakima River, WA. Summer stream temperatures in the study area ranged from 12-19.5^{o}C. Results from monitoring of internal temperatures indicated that spring-run salmon did locate thermal refugia in order to regulate internal body temperature. Mean difference between internal temperature of salmon and ambient river temperature was 2.5^{o}C, with maximum divergence of 7.2^{o}C.

Nielsen et al. (1994) studied temporal preference for thermally stratified pools by adult and juvenile steelhead in three northern California streams, with summer maximum temperatures exceeding 20-25^{o}C. This study documented main channel cold-water areas formed by tributary inflow, groundwater seepage along the channel bed, downstream intergravel flow, and thermal stratification of deep, still water.

Channel structure strongly influenced development of thermal stratification in pools in low gradient channels of two streams observed by Nielsen et al. (1994). The most common cold-water formation was due to interflow from gravel bars leading into bedrock scour pools, with cold-water areas forming due to physical separation from the main channel combined with cold-water inflow. Stratification was not a function of pool size in this case. Also, large woody debris was not observed to be as effective as gravel bars in isolating cold-water inflow.

There was little apparent influence of structural elements to isolate pools from main flow in the steeper gradient, bedrock channel studied in the third stream observed by Nielsen et al. (1994). Extremely low summer discharge (2 m^3/s at mouth) kept deep pools (often > 4m) from mixing. Stratification was believed to be caused by surface water cooling at night, then settling to the pool bottom as the surface warmed during the day.

A study by Torgersen et al. (1999) of stream habitat used by over-summering spring-run salmon in the Middle and North Forks of the John Day River, Oregon, found that spatial scale was an important consideration in defining thermal refugia. The authors described thermal refugia as relative features which could exist at local or expanded scales, depending on temperatures of the surrounding stream. In the Middle Fork, where maximum daily temperatures exceeded 25^{o}C, and localized refugia (e.g., stratified pools) were not available, examination of population distribution at the reach-scale indicated higher spring-run salmon numbers in reaches exhibiting cool temperatures relative to other accessible stream reaches.

Gaffield (2000) investigated the importance of stream base flow in maintaining high quality cold-water habitat for the trout fishery of the Driftless Area of Wisconsin. Degradation of the trout fishery in the area was attributed to loss of base flow due to European settlement and land use. Gaffield’s study indicated that decreases in base flow were more likely to affect summer stream temperature than flow increases of the same magnitude. This study also found that shade enhanced the effect of cooler, groundwater input to surface streams in summer. Groundwater discharge had more of a cooling effect on a receiving stream when the quantity of groundwater discharge was large relative to total stream discharge. Input of focused groundwater discharge via springs more effectively reduced mean stream temperature in summer, but the effect quickly dissipated with distance downstream from the source. Diffuse groundwater input to a stream resulted in reduced cooling compared to focused input, but the overall effect on stream temperature was more persistent downstream.

Ebersole et al. (2001) explored the relationship between distribution and abundance of rainbow trout relative to water temperature patterns in four northeastern Oregon streams. The authors defined thermal refugia as cold-water areas actually used by fish during times of high ambient water temperatures. Observed cold-water areas were formed by lateral seeps, cold side-channels, floodplain tail seeps, floodplain seeps, and stratified pools, ranging 3-10^{o}C cooler than ambient streamflow. Mean daily maximum stream temperatures ranged from 15.68^{o}C to 25.06^{o}C. Mean maximum pool depth ranged from .45 m to 1.09 m. The coldest temperatures were consistently located at the channel bottom and near a source of upwelling groundwater.

Field Study in the Foothill Zone of Big Chico Creek

From June 1 to October 2, 2003, a field study was conducted to assess the availability, distribution, and sources of cold-water areas in BCC. In addition, observed cold-water areas were evaluated to determine their potential as thermal refugia for adult spring-run salmon.

Three major tasks were completed in the field study. Stream and air temperatures were monitored from June 1 through October 1, 2003, at the three pools known to serve as summer holding habitat for spring-run salmon in BCC. Stream temperature was measured near the channel bottom and just below the water surface at two of the three pools in order to detect occurrence of stratification. Potential holding habitats (i.e., pools with maximum depth $\geq$ 1.5 m) within the foothill reach of BCC were located and explored for cold-water areas. Location of potential holding habitats involved snorkeling and hiking the foothill zone, measurement of maximum pool depths, and recording of pool positions using a geographic positioning system (GPS) unit. A subset of potential holding habitats was systematically explored by divers feeling along the channel bottom of each pool to locate existing cold-water areas. Lastly, detailed thermal profiles were measured at a subset of potential holding habitats in order to determine the vertical and lateral extent of cold-water areas where they were encountered. Stream temperature was measured at multiple points along each profile transect, including measurements at the bottom and top of the stream for each transect point.

Description of Study Reach and Holding Pools

The field study included the foothill zone of BCC where spring-run salmon have historically been observed holding through summer. The reach spanned approximately 14.1 km of free-flowing stream to include the three most commonly used holding pools – Salmon Hole, Henning Hole, and Higgins Hole. Approximately 1.6 km of stream channel above Salmon Hole were not included in this study, as the stream flows through a steep, basalt-confined canyon (~3.3% gradient) that is turbulent and uncharacteristic of salmon holding habitat.

The channel in the study reach is frequently confined on one or both sides by steep bedrock walls or eroding hillslopes. Long, deep pools were common throughout the reach, frequently created by scour around bedrock protrusions. Substrate was predominantly of gravel, cobble, and boulder sizes, with sand and organic material commonly deposited along channel margins. The average stream gradient through the study reach was 0.9%.

Salmon Hole was the furthest downstream in the study reach. It is located in Bidwell Park, easily accessible to the public, and frequently visited by people during summer. The maximum depth in Salmon Hole was approximately 3.5 m. There was relatively little cover available for spring-run salmon holding in Salmon Hole other than depth. The pool inlet allowed some access to more complex boulder habitat upstream, but as discharge decreased through summer, migration potential declined.

Figure 3. A view of Salmon Hole, with BCC entering at top of pool. (Source: http://www.chico.ca.us/common/_mod_resource.asp?p=50&f=139. Accessed April 12, 2004.)

Henning Hole occurs approximately 9.8 km upstream of Salmon Hole, and is located within the Big Chico Creek Ecological Reserve (BCCER). The creek is less accessible on the BCCER, and swimming is prohibited. Maximum depth at Henning Hole was approximately 4.6 m. Henning Hole offered good cover for spring-run salmon, including depth, bedrock protrusions, and instream woody debris.

Figure 4. Looking upstream at Henning Hole. (Source: D. Cresswell.)

Higgins Hole occurs on private property approximately 4.3 km above Henning Hole. The property serves as a part-time residence, and the pool was disturbed relatively infrequently. Maximum depth at Higgins Hole was between 9 and 10 meters. The large volume of this pool effectively provides cover for adult spring-run salmon holding there through summer.

Figure 5. Looking upstream at Higgins Hole. (Source: D. Cresswell.)

Observations

Temperature Evaluation at Known Holding Pools.

Between May 31 and June 3, 2003, temperature-recording data loggers (Onset H8 External Temperature data logger, $\pm$ 0.7^{o} C) were launched at or near the three known holding pools (e.g., Higgins Hole, Henning Hole, and Salmon Hole) to record air and stream temperatures. Prior to launching data loggers, each was calibrated to a National Institute of Standards and Technology (NIST) traceable thermometer following methods set forth in the Stream Temperature Protocol by the Forest Science Project at Humboldt State University (http://www.humboldt.edu/~ifwm/TempPubs.shtml). Each data logger was enclosed in a Hobo/Stowaway Submersible Case to prevent water and weather damage. All data loggers were programmed to record temperatures hourly.

At Higgins and Henning holes, water temperature was monitored at two locations: approximately 60 cm below the water surface and 45 cm up from the channel bottom. Data loggers were maintained within the same water column using an anchor-buoy system. Data loggers recording air temperature were attached to streamside vegetation at each pool. Locations for air temperature monitoring were chosen where direct solar radiation was avoided, but where the units were able to record air temperature within three meters of the water surface.

The temperature monitoring set up for Salmon Hole was modified to avoid tampering by humans that visit Bidwell Park in summer. Data loggers at Salmon Hole were vandalized during previous monitoring efforts, so for this study a surrogate pool approximately 75 m upstream of Salmon Hole was monitored (Figure 6). Stream temperature data collected prior to this study indicated Salmon Hole temperatures were not significantly different from temperatures monitored near the selected surrogate pool (DWR, unpublished data). A single data logger was placed on the channel bottom near the base of a large boulder for camouflage. The depth of this temperature data logger was

Figure 6. Pool monitored as a surrogate for Salmon Hole. (Source: D. Cresswell.)

approximately 2.1 meters from the water surface. The data logger recording air temperature was secured to a small alder branch approximately 30 m downstream of the stream temperature data logger. Ten spring-run salmon were observed using this pool when data loggers were launched at this site on May 31.

Exploration for Cold-Water Areas.

From June 26 to July 8, 2003, a survey was conducted within the study reach to identify and record locations of potential holding habitats. Potential holding habitats were defined as pools with a maximum depth $\geq$ 1.5 m. In a study by Torgersen et al. (1999), researchers observed that vertical mixing within the water column was thorough even in pools >2 m deep. Torgersen et al. (1999) also cited unpublished data from D.M. Price and B.A. McIntosh which indicated that spring-run salmon holding in streams which remain relatively cool in summer will occupy non-pool units more frequently than spring-run salmon in streams that warm significantly in summer. BCC is a relatively warm stream without significant input of cold tributaries in summer to buffer warm water temperature, so it was assumed that salmon would not hold in well-mixed channel units (i.e., shallow pools, riffles, runs). In addition, spring-run salmon in BCC are rarely observed in riffles, runs or shallow pools during summer.

Potential holding habitats were identified during a survey of the study reach, in which stream depths were measured with a telescoping measuring staff at existing pools to determine maximum depth. Positions of pools identified as potential holding habitats were located in the field using a hand-held GPS unit (E-trex model by Garmin), and downloaded using National Geographic Topo! mapping software to display on a topographic map. Each pool was individually labeled with a letter from the alphabet, starting with Pool A at the top of the study reach. Following Pool Z, the top of the alphabet was applied again to remaining pools with double letter coding (e.g., Pool AA). Fifty-two pools were identified during this survey as potential holding habitats (Figure 7). Geographic coordinates and maximum depth for the fifty-two pools identified as potential holding habitats are given in Appendix C.

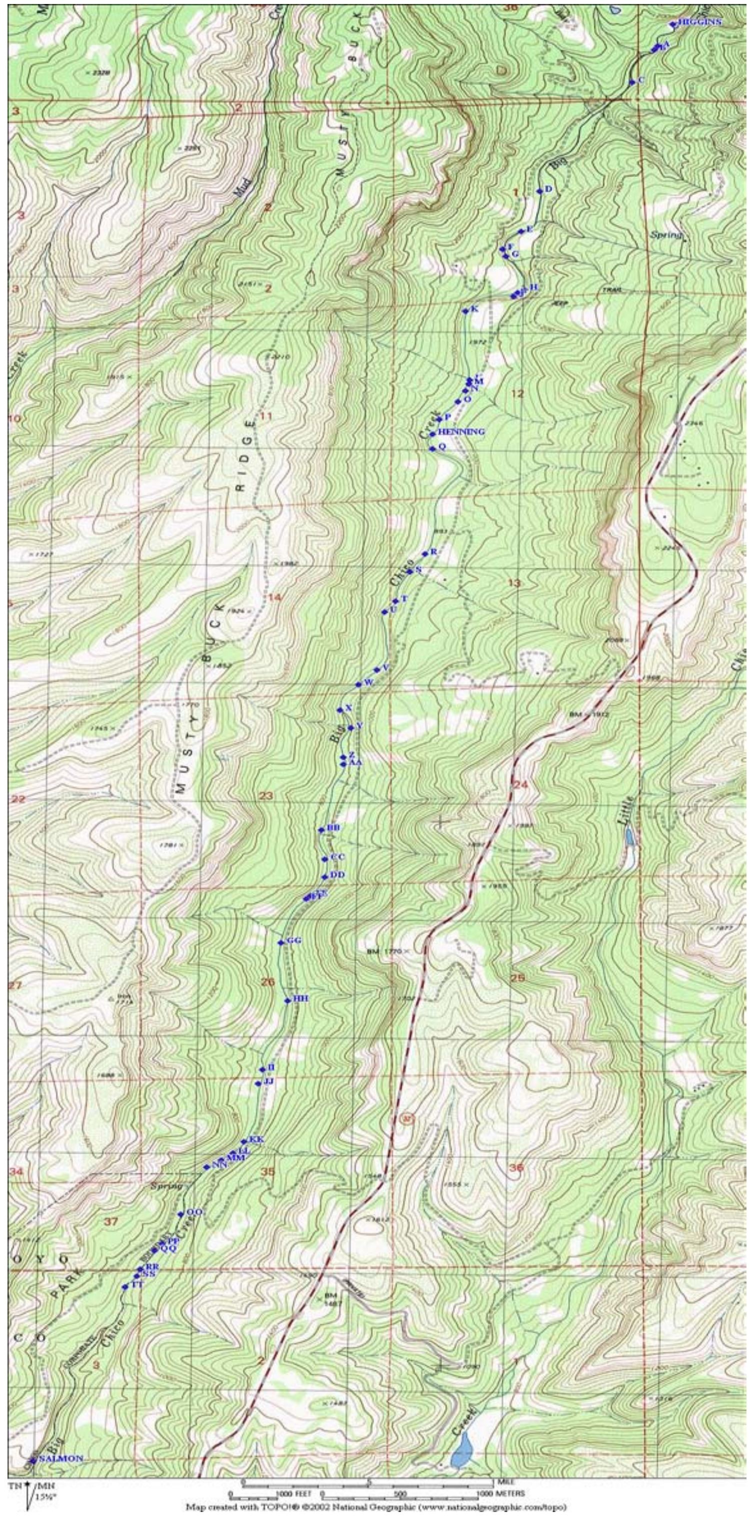


Figure 7. Map of potential holding habitats identified in the study reach.

Between July 17 and August 17, 2003, twenty-two potential holding habitats were re-visited and manually explored for cold-water areas. Cold-water areas were defined as locations within a holding habitat at least 0.2^{o}C below surface water temperature. This temperature difference corresponded to the accuracy of the temperature probe used for thermal profiles (YSI 30 Salinity/Conductivity/Temperature Instrument), as well as the temperature difference reliably detected by divers using their sense of touch during exploration for cold-water areas.

Potential holding habitats were not explored until after 1:00 pm to improve likelihood of detection of cold-water areas. Two divers using their sense of touch to detect temperature difference worked their way longitudinally along the pool, one on each side of the channel, sweeping back and forth along transects from bank to mid-line. Once the initial exploration was complete, divers revisited cooler areas for joint evaluation. If depth at these spots allowed, the temperature was measured with the YSI meter. Of the twenty-two potential holding habitats explored, nine contained cold-water areas (Pools L, R, S, T, AA, BB, CC, II, and JJ) (Figure 8).

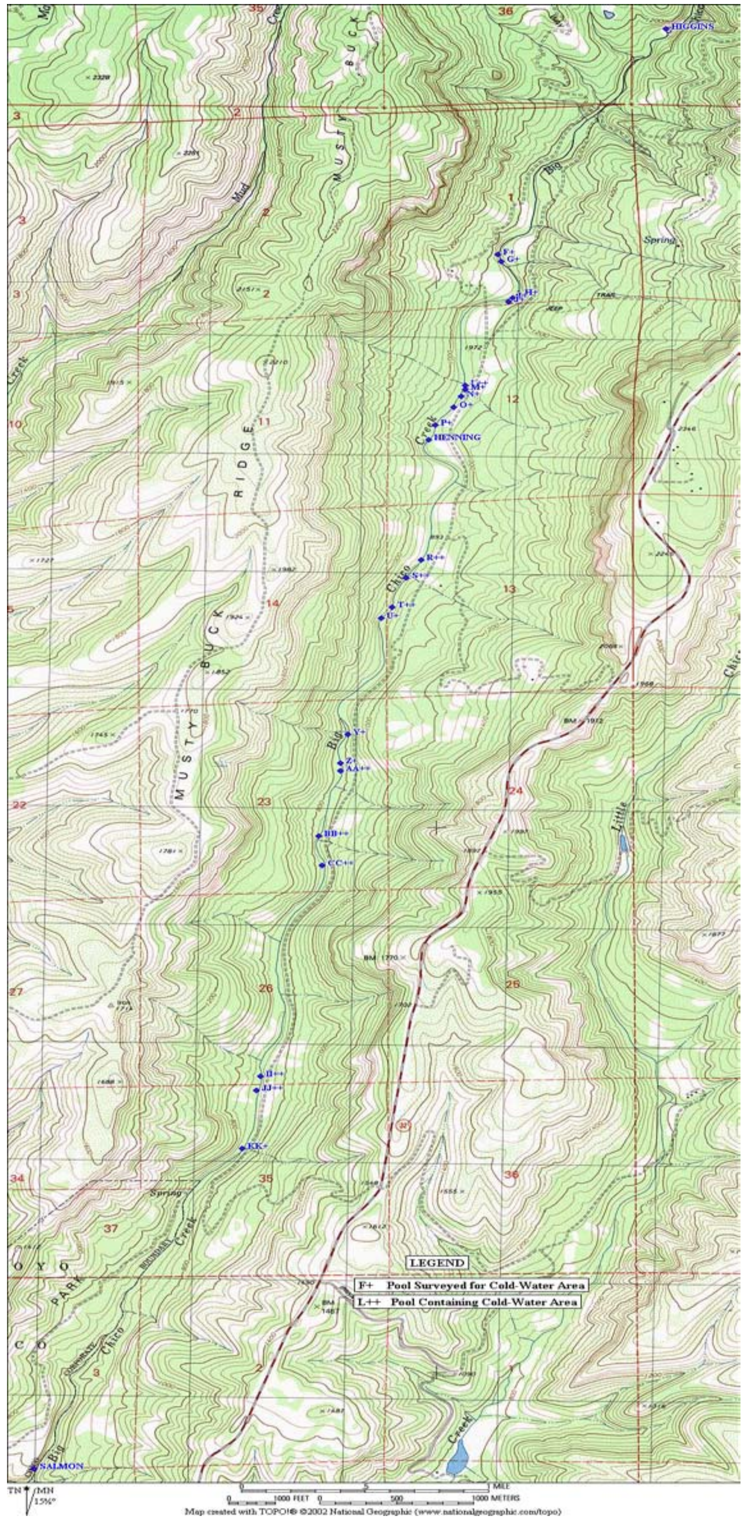


Figure 8. Map of potential holding habitats explored for, and containing, cold-water areas. (+) indicates explored potential holding habitat, (++) indicates potential holding habitat containing cold-water area.

Temperature and Velocity Profiles.

Temperature and velocity profiles were measured at four of the nine pools where cold-water areas were identified during exploration of potential holding habitats (Pools T, CC, II, and JJ). These pools contained larger, mid-channel cold-water areas, compared with small, channel margin cold-water areas in the five non-profiled pools (Pools L, R, S, AA and BB). Pool length and maximum depth were recorded for each pool, as were air temperature, and wetted width for each transect.

Starting at the upstream edge of a pool, stream temperature was measured along lateral transects spaced every five meters along the length of the pool. Along each transect, stream temperature was measured at approximately 1.5 m intervals. At each interval, temperature measurements occurred at one or more points within the water column, including temperature at the channel bottom for each interval. For intervals with shallow water depths (30 – 60 cm), temperature was measured fifteen centimeters below the water surface. For intervals with moderate water depth (61 – 99 cm), a measure was made fifteen centimeters above the channel surface and fifteen centimeters below the water surface. For intervals with greater water depths (1 – 4.5 m), the total depth was divided so that measurements were made every fifteen centimeters. If cooler waters (e.g., temperatures more than 0.2^{o}C below surface water temperature) were detected at the beginning of measurement for any interval (e.g., at the channel bottom), measurements were made every 3 to 5 centimeters until the temperature measured was equal to the surface water temperature. Substrate underlying each interval was also qualitatively noted. Discharge was estimated at the top of riffle units above pools where thermal profiles were measured, following procedure described in Trihey and Wegner (1981).

The vertical and lateral extent of cold-water areas was calculated, as well as maximum and average vertical and lateral temperature differences. In calculating lateral extent, cold-water areas were assumed to be continuous laterally if cold-water areas were measured in adjacent transect intervals.

Analyses

Stream Temperature in Occupied Holding Habitats

Between June 1 and October 1, 2003, stream temperature measured at Higgins Hole, Henning Hole, and Salmon Hole indicated adult spring-run salmon holding in these pools were periodically exposed to stressful thermal conditions (Table 3). Maximum summer temperatures for the three pools measured between 22.9^{o} C and 25.6^{o} C. During the month of July, air and water temperatures peaked at all three pools. Even mean minimum stream temperatures at Salmon Hole exceeded 21^{o}C in July.

	JUNE					JULY				
	Daily Mean (°C)	Mean Daily Max. (°C)	Mean Daily Min. (°C)	Mean Daily Air (°C)	% Hrs. ≥ 21°C	Daily Mean (°C)	Mean Daily Max. (°C)	Mean Daily Min. (°C)	Mean Daily Air (°C)	% Hrs. ≥ 21°C
Higgins Bottom	16.98	18.35	15.76	21.43	0.0	18.36	19.80	17.34	24.80	6.3
Higgins Surface	17.10	18.56	15.73	--	0.0	18.77	20.31	17.34	--	13.8
Henning Bottom	17.96	19.70	16.29	21.30	0.4	19.97	21.92	18.31	23.50	31.9
Henning Surface	18.04	19.86	16.35	--	1.0	20.15	22.18	18.34	--	36.0
Salmon	19.81	20.92	18.46	24.76	15.3	22.18	23.04	21.10	28.12	66.7

	AUGUST					SEPTEMBER				
	Daily Mean (°C)	Mean Daily Max. (°C)	Mean Daily Min. (°C)	Mean Daily Air (°C)	% Hrs. ≥ 21°C	Daily Mean (°C)	Mean Daily Max. (°C)	Mean Daily Min. (°C)	Mean Daily Air (°C)	% Hrs. ≥ 21°C
Higgins Bottom	16.88	17.96	16.21	21.76	0.0	15.11	15.96	14.57	20.12	0.0
Higgins Surface	17.39	18.71	16.18	--	0.0	15.53	16.53	14.57	--	0.0
Henning Bottom	18.28	20.00	16.99	20.60	3.6	16.22	17.69	15.15	18.74	0.0
Henning Surface	18.68	20.36	17.03	--	4.8	16.67	18.05	15.18	--	0.3
Salmon	20.54	21.27	19.56	24.38	24.7	18.36	19.06	17.53	22.21	6.9

Table 3. Monthly summary temperature statistics for occupied holding habitats.

The warmest two-week period in summer occurred between July 21 and August 3, 2003. During that period, maximum duration of stressful temperatures for spring-run salmon occurred (Table 4). However, duration of stressful temperatures varied among pools and for one pool, duration varied significantly as a function of pool depth. During this period at Higgins Hole, the pool bottom exceeded 21^{o}C less than half the time that 21^{o}C was exceeded near the channel surface (14.0% and 30.7%, respectively). In contrast, a relatively small difference was observed at Henning Hole between percentage of time the surface and pool bottom exceeded 21^{o}C during this period (67.3% and 63.1%, respectively). Stream temperatures observed at Salmon Hole exceeded 21^{o}C for 100% of all hours during this warmest two-week period.

6/2-10/2 **(7/21-8/3)**	**Higgins**	**Henning**	**Salmon**
Mean daily air (^{o}C)	21.98 **(25.71)**	20.97 **(25.04)**	24.79 **(28.80)**
Mean diel air flux (^{o}C)	17.33 **(15.25)**	15.79 **(12.74)**	16.65 **(15.39)**
Mean daily water @ surface (^{o}C)	17.16 **(20.56)**	18.35 **(21.94)**	--
Mean daily water @ bottom (^{o}C)	16.80 **(20.17)**	18.07 **(21.70)**	20.19 **(23.95)**
Mean daily maximum water @ surface (^{o}C)	18.49 **(21.82)**	20.09 **(23.60)**	--
Mean daily maximum water @ bottom (^{o}C)	17.97 **(21.28)**	19.80 **(23.30)**	21.04 **(24.76)**
Mean diel water flux @ surface (^{o}C)	2.56 **(2.34)**	3.38 **(3.17)**	--
Mean diel water flux @ bottom (^{o}C)	2.04 **(1.77)**	3.13 **(2.89)**	1.89 **(1.73)**
% Hrs. @ surface $\geq$ 21^{o}C	3.5 **(30.7)**	10.6 **(67.3)**	--
% Hrs. @ bottom > 21^{o}C	1.6 **(14.0)**	9.0 **(63.1)**	28.5 **(100.0)**

Table 4. Summary of temperatures at occupied holding habitats for entire summer and during the warmest two-week period (in bold font).

Of the three occupied pools, Higgins Hole maintained the coolest temperatures throughout summer, and Salmon Hole temperatures exceeded temperatures in both Henning and Higgins Hole. Channel bottom stream temperatures at Henning and Higgins Hole did not exceed 21^{o}C as frequently as surface temperatures. In fact, overall summer mean temperatures at the channel bottom for Henning and Higgins Holes were statistically cooler than temperatures near the water surface (see Table 3; alpha = 0.1, $.05<P<0.1$ at Henning, and $.01<P<.025$ at Higgins). Although differences between bottom and surface temperature means were less than 0.7^{o}C (the stated accuracy of the Hobo data loggers) at both pools, these data loggers reported identical readings during initial calibration, suggesting the differences in reported bottom and surface temperatures were actual.

<u>Distribution and Nature of Cold-Water Areas.</u>

With only one exception, cold-water areas were found in the organic layer at the water/streambed interface, or at channel margins where subsurface flow entered the channel, and were not usable as thermal refugia by adult spring-run salmon.

The single cold-water area not occurring at the streambed or channel margins resulted from physical separation of a pool (Pool T) from the main channel by a large boulder. This physical separation allowed the pool to stratify, with water cooled during night underlying surface water warmed in the day. Although stratification declined during early morning hours, it was maintained through the remainder of the day (Figure 9).

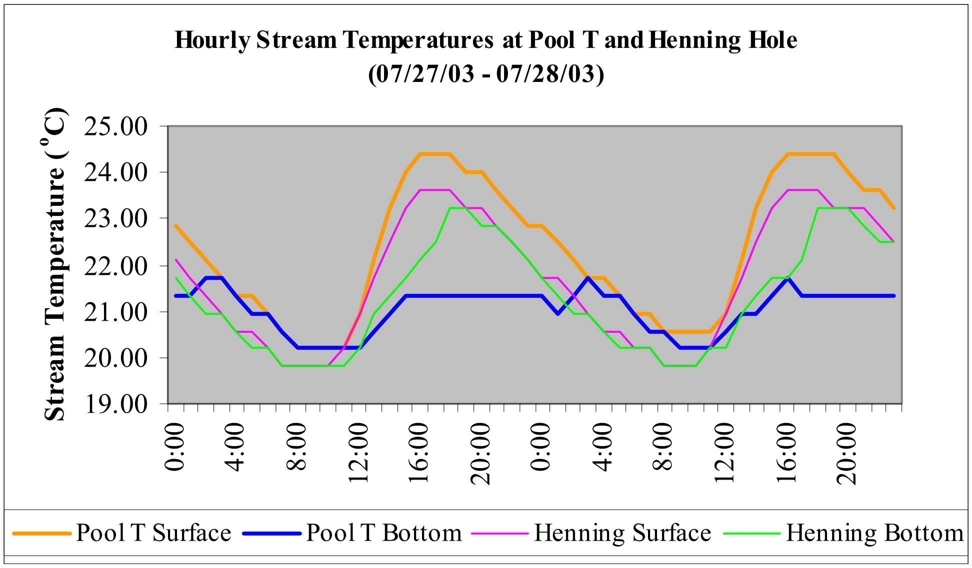


Figure 9. Example of daily stratification that occurred at Pool T (07/27/03 – 07/28/03).

Following discovery of the stratification at Pool T, data loggers were added to monitor surface and bottom temperatures. During the period of 7/26-10/3, average maximum difference between channel bottom and surface water temperatures at Pool T was 2.1°C. Although maximum water temperature at the bottom of Pool T exceeded that of Salmon Hole at times (Figure 10), it was frequently below Henning Hole maximum bottom temperature.

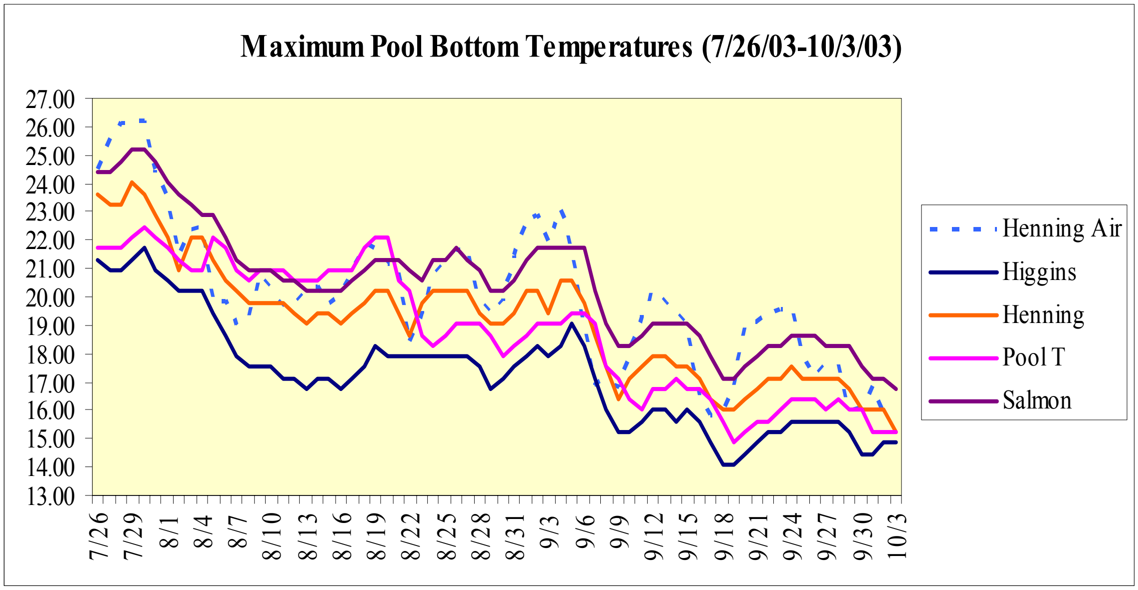


Figure 10. Maximum pool bottom temperatures measured from 7/26/03 to 10/3/03.

<u>Thermal Profiles.</u>

The four profiled pools were relatively deep, with an average maximum depth of 3.15 m. Cold-water areas in these pools were small and discontinuous, comprising an average of 1.7% of total pool area (Table 5). Maximum vertical extent of cold-water areas above channel bottom ranged from 0.16 m to 1.31 m. While average vertical temperature difference within cold-water areas was 0.88^{o}C, maximum vertical temperature differences tended to be nearly twice as large (average maximum vertical temperature difference = 1.68^{o}C). Cold-water areas extended laterally over an average distance of 4.7 m, and an average maximum distance of 8.6 m. Average and maximum lateral temperature differences (calculated using temperatures measured at channel bottom within each interval along individual transects) exceeded vertical temperature differences in all but one case.

Pool	Max. Depth (m)	Vertical Extent of Cold-Water (m)	Vertical Temp. Difference (°C)	Lateral Extent of Cold-Water (m)	Lateral Temp. Difference (°C)	Area of Cold-Water (m^2)	Area of Pool (m^2)	Cold-Water Area as % of Pool Area
T	2.83	0.74 (1.31)	1.6 (2.6)	8.5 (12.0)	1.9 (2.8)	18.81	446.23	4.2
CC	3.50	0.46 (1.10)	0.6 (1.4)	4.5 (9.0)	0.8 (1.6)	12.41	1207.01	1.0
II	3.20	0.09 (0.16)	0.7 (1.8)	3.2 (7.5)	1.1 (1.9)	2.76	576.07	0.5
JJ	3.07	0.14 (0.85)	0.6 (0.9)	2.6 (6.0)	0.8 (1.2)	5.57	633.98	0.9
Average	3.15	0.36 (0.86)	0.88 (1.68)	4.7 (8.6)	1.15 (1.88)	9.89	715.82	1.7

Table 5. Average vertical and lateral extent of cold-water areas measured at four pools. Values in parentheses represent maximums.

Discussion

In the three pools commonly used as holding habitat for spring-run salmon in BCC, water temperatures increased predictably in relation to longitudinal position along the stream channel. Higgins Hole, highest in elevation and stream position, provided the coolest temperatures for spring-run salmon throughout the summer. Temperatures at Henning Hole were intermediate in magnitude and duration, while Salmon Hole temperatures consistently exceeded the other monitored holding pools. In keeping with the notion of Torgersen et al. (1999) that designation of conditions as thermal refugia should consider local and expanded spatial scales, thermal conditions at Higgins Hole can be considered refugia for over-summering spring-run salmon in BCC relative to temperatures in holding habitats downstream. Access to Higgins Hole appears to be important for BCC spring-run salmon, and stream temperatures further downstream in the system may act as a barrier if fish are delayed in their migration. Declining stream flow through spring has presented migration delays at Iron Canyon in Bidwell Park, a concern that local and state agencies are attempting to address through passage improvements (DWR, 2001).

Air temperature at Henning Hole remained cooler than Higgins and Salmon Holes during all months, reflecting the presence of considerable riparian shade at the site. However, the damped air temperature appeared to have little capacity to reduce stream temperature at Henning Hole. Transfer of heat via convection (e.g., transfer of heat energy due to contact between the air overlying a stream and the stream itself) is a minor process in the stream heat budget (Sinokrot and Stefan, 1993; Spence et al., 1996; Boyd and Sturdevant, 1997). While air and water temperature in a stream environment are highly correlated, it is a common misconception that a causative relationship exists (Johnson, 2003). In a model application using empirically-derived stream parameters, Boyd (1996) observed that an increase of air temperature by 20^{o}F (11^{o}C) resulted in an increase in stream temperature of only 0.07^{o}F (0.04^{o}C) – an amount considered immeasurable and insignificant. However, the riparian shade at Henning Hole likely plays an important role as a buffer against solar radiation input, which is known to increase heat load in a stream, and thus stream temperature (Beschta et al., 1987; Sinokrot and Stephan, 1993; Spence et al., 1996; Boyd and Sturdevant, 1997; Poole and Berman, 2001).

Prolonged exposure of spring-run salmon to elevated stream temperatures amplifies the biological effect of those temperatures (Somero and Hofmann, 1996). Salmon may endure stressful stream temperatures (e.g., temperatures $\geq 20^{o}C$) for short periods of time (on the order of hours to days), but as duration of exposure increases, the likelihood of direct or indirect mortality approaches certainty (Berman, 1990). During the warmest two-week period of summer in 2003 (7/21-8/3), stream temperatures at Salmon Hole exceeded $21^{o}C$ for 336 consecutive hours, or 100% of that period. At least thirty adult spring-run salmon were observed in Salmon Hole in mid-July, but none were observed in mid-August by DFG personnel conducting the annual snorkel survey of spring-run salmon in BCC. Although there is no direct evidence of temperature-related mortality, such an outcome would be expected under the observed thermal conditions.

Spring-run salmon holding in Henning and Higgins Holes were also exposed to long durations of potentially lethal temperatures between July 21 and August 3, 2003. Water temperatures exceeded $21^{o}C$ an average of 16 hours per day at the surface of Henning Hole, and an average of 7 hours per day at Higgins Hole surface. Although the extent of cooler waters measured at the channel bottom at both pools is unknown, relatively little refuge would presumably be available at Henning Hole where temperatures exceeded $21^{o}C$ an average of 15 hours each day. Temperatures measured at the bottom of Higgins Hole, however, exceeded $21^{o}C$ an average of only 3 hours per day, indicating a potential for local thermal refuge for holding spring-run salmon.

Cold-water areas observed in BCC were similar to observations made in previous studies (Bilby, 1984; Ebersole et al., 2003), but thermal stratification observed by Nielsen et al. (1994) in deep, unobstructed pools (e.g., >4 m) was generally not observed. In a single pool (Pool T), a physical barrier separated the pool from main channel flow, allowing stratification to occur, similar to the role of gravel bars as described in Nielsen et al. (1994).

Cold-water areas observed in BCC were identified at the channel bottom or margin, with variable extent in vertical and lateral dimensions. Descriptions of cold alcoves and lateral seeps given in Ebersole et al. (2003) match observed cold-water areas located in channel margins of BCC. The likely water source for observed channel margin cold-water areas was local subsurface flow. In addition, mid-channel cold-water areas were observed near the channel bed. The source for these areas may be bedrock seepage, or near-bed stratification of water cooled during the night. All cold-water areas were small, and generally not capable of providing local thermal refugia for adult spring-run salmon (except Pool T).

As the magnitude of discharge observed at cold-water areas in BCC during 2003 was very small, buffering effects of subsurface flows in BCC may be restricted to localized regions of occurrence. It is not known whether subsurface discharge to BCC in the foothill zone was greater historically, thus having a larger effect on BCC summer stream temperatures. Grazing and logging occurred in the BCC foothills at medium to high intensity from the late 19th century through the 20th century (Big Chico Creek Watershed Alliance, 1999), along with the addition of roads. These activities may have altered hydrologic flow paths. These types of land-use activities are known to lead to reduced groundwater discharge, reduced hyporheic flow (e,g, shallow subsurface flow adjacent to or below a stream channel that originates from and reemerges in surface water), and reduced stream and tributary flow during low-flow periods (Poole and Berman, 2001). If such hydrologic effects occurred following historical land-use activities in the BCC watershed, it is possible that summer stream temperatures in the foothill and lower reaches of BCC have increased as a result.

Efforts to maintain or restore thermal refugia may be less effective management actions than improving ambient stream temperature conditions in altered arid-land streams (Ebersole et al., 2001). In the foothill zone of BCC, removing non-native riparian vegetation species, and increasing and protecting large trees such as conifers, oaks, and sycamores within and adjacent to riparian habitats may reduce solar radiation reaching the stream, and thus decrease ambient summer stream temperatures. Also, restoration of connectivity between channels and their floodplains in first and second order tributaries may increase rainy season infiltration, and thereby buffer heat inputs to the main channel in summer through increased subsurface lateral flow.

Managers of the BCCER are implementing policies and activities to improve riparian habitat within the foothill zone of BCC. A stream temperature model was employed in the present study to investigate the effectiveness of these activities at reducing mean ambient stream temperature within spring-run salmon holding habitat located on the BCCER. Description of the model and its application are given in Chapter Five.

CHAPTER FIVE

EFFECT OF RIPARIAN VEGETATION ON STREAM TEMPERATURE

Introduction

Short-wave radiation from the sun is the dominant source of heat energy to a stream (Brown, 1970; Boyd, 1996; Spence et al., 1996). The amount of heat transferred to a stream via solar radiation is a function of the amount of exposed channel surface. Species, density, age and location of riparian vegetation relative to the stream channel, channel width, channel orientation, and topography of the stream valley determine the amount of exposed channel surface (Sinokrot and Stefan, 1993; Spence et al., 1996; Poole and Berman, 2001). Riparian vegetation can reduce the amount of solar radiation reaching the stream by obstructing the channel, and maintaining cohesion within bank materials to reduce erosion and channel widening. Li et al. (1994) examined the cumulative effect of riparian canopy on rainbow trout populations in high elevation stream segments within the John Day River basin, Oregon. They found that stream reaches with dense riparian shade (dominant species included *Alnus* sp., *Salix* sp., and *Pinus ponderosa*) resulted in cooler stream reaches by up to 5^{o}C compared to sparsely shaded reaches of approximately equal sampling elevation, contributing basin, and stream length exposed to the sun.

In this study, the USGS stream temperature model, Stream Segment Temperature Model (SSTEMP) Version 2.0, was applied to evaluate the impact of increasing riparian vegetation height and density on ambient stream temperature. Although riparian vegetation along BCC is relatively healthy, there have been historical impacts including logging, grazing, and fire (Big Chico Creek Watershed Alliance, 1999). In addition, several non-native plant species persist in the riparian of BCC, with Spanish broom (*Spartium junceum*) of particular concern in the foothill zone. Unlike native riparian vegetation, such as white alder (*Alnus rhombifolia*), willow (*Salix* spp.), and big leaf maple (*Acer macrophyllum*), the leafless morphology and shrub habitat of broom is ineffective at providing shade to buffer summer stream temperatures against solar radiation.

Application of SSTEMP in this study focused spatially on the Big Chico Creek Ecological Reserve (BCCER), where managers are undertaking efforts to improve riparian conditions for the benefit of native aquatic species including spring-run salmon. Current riparian efforts on the BCCER include removal of Spanish broom and reduction of fuels that could destroy mature trees.

SSTEMP 2.0 was applied using a 1.7 km stream segment (Henning Hole to Pool T) on the BCCER in which data had been previously collected or was available. A brief introduction, parameter description, and summary of methods and results of this model application are presented below.

SSTEMP 2.0

SSTEMP 2.0 predicts mean daily stream temperatures from a set of inputs describing average channel geometry, steady-state hydrology and meteorology, and stream shading (Bartholow, 2002). SSTEMP and a more complex version of the model, Stream Network Temperature Model (SNTEMP), have been applied in other studies to determine effects of riparian vegetation on mean stream temperature (Blann et al., 2002; Whitledge, 2001; Bartholow, 2000; Theurer et al., 1985). The program employs a heat budget approach in which heat gain or loss from a parcel of water is calculated by simulating heat flux processes as it passes through a user-defined stream segment. Heat flux processes included in the model are short-wave radiation, long-wave radiation, convection, conduction, and evaporation[1] (Figure 11). Although SSTEMP 2.0 is appropriate for examining the effects of changing riparian shade conditions on stream temperature, Bartholow (2002) noted that cumulative effects of adding or subtracting vegetation (i.e., air temperature, relative humidity, wind speed, channel width) are not automatically accounted for during simulation. In order to estimate such cumulative effects, the user must adjust selected model parameters as deemed necessary for conditions at a specific location.

[1] SSTEMP (2.0) is appropriate for single stream segments for a single time period; it does not address heat flux due to advection, e.g., heat flux due to tributary inflow.

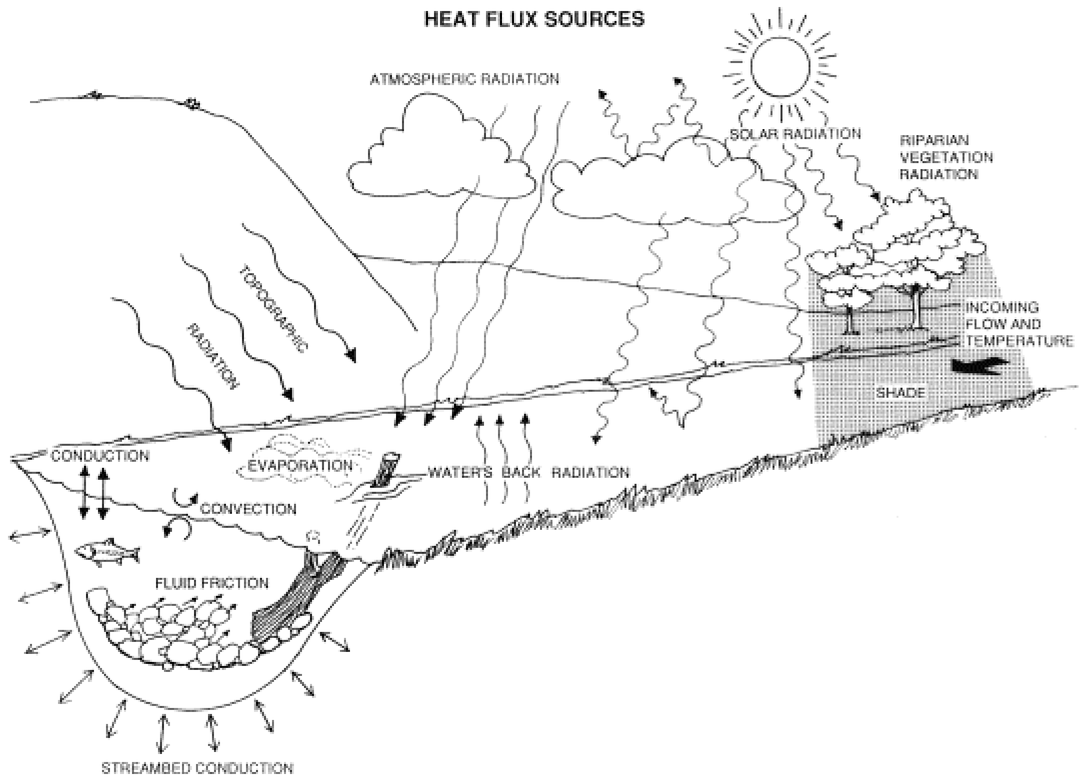


Figure 11. Diagram of heat flux processes acting on a stream channel. (Source: Bartholow, J.M. 2002. SSTEMP for Windows: The Stream Segment Temperature Model (Version 2.0). US Geological Survey computer model and documentation. Available on the Internet at http://www.fort.usgs.gov/.)

Parameterization of the BCC Stream Temperature Model

SSTEMP 2.0 was parameterized to simulate conditions in BCC in the segment from Henning Hole to Pool T during the hottest two-week summer period of 2003 (e.g., 7/21 to 8/3), thus creating a BCC Stream Temperature Model. Parameters describing stream, riparian, and meteorological conditions for the model stream segment between were generated from empirical, referenced, and calculated data. The parameters and their values included in the model are listed in Table 6.

Parameter #	Parameter (units)	Value	Method
1	segment inflow (m^3/s)	1.035	estimated
2	inflow temp (^oC)	21.940	empirical
3	segment outflow (m^3/s)	1.049	empirical
4	accretion temp (^oC)	16.328	estimated
5	latitude (radians)	0.696	USGS topographic map
6	segment length (km)	1.706	USGS topographic map
7	upstream elevation (m)	270.358	USGS topographic map
8	downstream elevation (m)	254.203	USGS topographic map
9	width's A term (s/m^2)	12.820	estimated
10	width's B term where $W=A*Q^B$	0	empirical
11	Manning's n	0.065	Chow (1959); Barnes (1967)
12	month/day	27-Jul	--
13	mean daily air temp (^oC)	25.077	empirical
14	maximum air temp (^oC)	36.130	empirical
15	relative humidity (%)	53.647	Bartholow (2002)
16	wind speed (mps)	2.148	calculated
17	ground temperature (^oC)	15.328	calculated
18	thermal gradient ($j/m^2/s$)	4.960	Gaffield (1999)
19	possible sun (%)	95	The Weather Center
21	solar radiation ($j/m^2/s$)	300	Renewable Resource Data Center
21	azimuth (radians)	0.163	USGS topographic map
22	topographic altitude, east and west (radians)	0.401 (E) and 0.507 (W)	calculated
23	vegetation ht., east and west (m)	15.636 (E) and 13.411 (W)	empirical
24	vegetation crown, east and west (m)	7.315 (E) and 6.401 (W)	empirical
25	vegetation offset, east and west (m)	6.919 (E) and 5.639 (W)	empirical
26	vegetation density, east and west (%)	16 (E) and 26 (W)	estimated

Table 6. Parameters included in the BCC Stream Temperature Model.

Channel Geometry

Latitude, segment length, upstream elevation, downstream elevation, and azimuth were determined from an electronic USGS topographic map on National Geographic's Topo!® computer software. The model stream segment occurs in the Paradise West, CA quadrangle (1:24,000) produced by the United State Geological Survey (USGS).

The width's A and B terms are part of the equation describing the power relationship between wetted width and discharge (e.g., $W = A * Q^B$, where W is a known width, Q is a known discharge, and B is the power relationship). The B term was assumed to equal 0, as flow was not expected to vary significantly during the period of interest. Thus, the A term represented the stream width, and for the model input, was estimated from several width measurements in the model stream segment. Manning's n was determined by comparing results of two methods: calculation of n using Chow's equation (1959) and estimation of n from Barnes (1967). Independent application of each method resulted in the same estimate.

Meteorology

Mean and maximum daily air temperatures were determined from data logger measurements made at Henning Hole during the period of interest. Air temperatures were collected in shaded locations within three meters of the water surface.

Accretion temperature (e.g., the temperature of non-tributary groundwater seepage) was assumed to equal mean annual air temperature. A year-long record of air temperature in the model stream segment was created using the FORECAST function in Microsoft Excel: two weeks of hourly air temperature data at Henning Hole was regressed on air temperature data for the same period at the Cohasset climate station (maintained by the California Dept. of Forestry and Fire Protection). Prediction of values at Henning Hole throughout the year was then made, with the average of those values reported as the mean annual air temperature. Data for the Cohasset climate station were obtained from the

Internet on the California Data Exchange Center (CDEC) web site (http://cdec.water.ca.gov/).

Relative humidity was calculated using the method stated in Bartholow (2002). Values for relative humidity and air temperature at the Cohasset climate station were obtained online from CDEC to estimate relative humidity in the model stream segment. Average hourly wind speed was calculated from wind speed measurements also collected at the CDEC Cohasset climate station.

Mean annual air temperature was substituted for ground temperature. Method for calculation of mean annual air temperature is described above for accretion temperature.

Thermal gradient represents the rate of heat flux between the streambed and water. This parameter was estimated as described in Gaffield (2000).

The value for possible sun was obtained from the The Weather Center (www.weatherwatch.com). The July value of possible sun for Redding, California was reported for the model.

The value for solar radiation was obtained from a report on 30-year means of monthly solar radiation (1961-1990). This report can be found at the Renewable Resource Data Center web site (http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/sum2/state.html).

Hydrology

Mean daily inflow temperature was determined from data logger measurements made at Henning Hole during the period of interest. Predicted mean stream temperatures during model runs were compared to an empirical mean stream temperature value (22.31^{o}C) produced from data logger measurements at Pool T for the period of interest.

Segment outflow was estimated at the riffle above Pool T on 7/23/03 using standard field measurement of velocity and subsequent flow calculation (Trihey and Wegener, 1981). Segment inflow was assumed to be approximately 10% less than the measured segment outflow to account for potential measurement error and subsurface seepage through the model segment.

Shading Conditions

Topographic altitude, vegetation height, vegetation crown, vegetation offset, and vegetation density were measured or estimated for a representative 150 m section of the model stream segment. Topographic altitude was estimated from an electronic USGS topographic map on National Geographic's Topo!® computer software. Vegetation height was calculated by applying trigonometry: vegetation offset and the angle to vegetation top were measured in the field with an electronic range finder, thus forming a triangle for which the vertical leg (e.g., the tree height) was calculated. Vegetation crown and vegetation density were visually estimated.

Sensitivity and Uncertainty Analyses

SSTEMP 2.0 performs a sensitivity analysis one-at-a-time for parameter values entered by the model user. The analysis includes calculations of 10% increase and decrease of parameter values, and indicates the resultant change in mean or maximum stream temperature. A schematic graph is also provided by the model software to indicate the relative influence of each parameter.

The sensitivity analysis for mean stream temperature values in the BCC Stream Temperature Model indicated stream temperature entering the model stream segment most strongly influenced model results, followed by segment inflow, segment outflow, and mean air temperature (Table 7). The model was mildly sensitive to relative humidity, solar radiation, width's A term, and ground temperature.

Variable	Decreased	Increased	Relative Sensitivity
Segment Inflow (m^3/s)	-0.05	+0.50	********
Inflow Temperature (^oC)	-1.8	+1.82	******************************
Segment Outflow (m^3/s)	+0.49	-0.09	********
Accretion Temperature (^oC)	-0.02	+0.02	
Width's A Term (s/m^2)	-0.04	+0.04	*
Width's B term where $W=A*Q^B$	+0.00	+0.00	
Manning's n	+0.00	+0.00	
Air Temperature (^oC)	-0.31	+0.28	*****
Relative Humidity (%)	-0.10	+0.10	**
Wind Speed (mps)	+0.02	-0.02	
Ground Temperature (^oC)	-0.04	+0.04	*
Thermal Gradient ($j/m^2/s$)	+0.02	-0.02	
Possible Sun (%)	+0.01	-0.02	
Solar Radiation ($j/m^2/s$)	-0.11	+0.11	**
Segment Azimuth (radians)	0.00	+0.00	
West Side:			
Topographic Altitude (radians)	+0.01	-0.01	
Vegetation Height (m)	+0.00	0.00	
vegetation Crown (m)	+0.00	0.00	
Vegetation Offset (m)	0	+0.00	
Vegetation Density (%)	+0.01	-0.01	
East Side:			
Topographic Altitude (radians)	+0.01	-0.01	
Vegetation Height (m)	+0.00	0.00	
vegetation Crown (m)	+0.00	0.00	
Vegetation Offset (m)	0.00	+0.00	
Vegetation Density (%)	+0.00	0.00	
Maximum Air Temperature (^oC)	+0.00	+0.00	

Table 7. Sensitivity analysis performed by SSTEMP 2.0 for mean temperature values (10% variation), with original mean predicted temperature of 22.31^{o}C.

SSTEMP 2.0 also performs an uncertainty analysis for given parameter values by applying the Monte Carlo method to create a distribution of values that theoretically represents the inherent variability in environmental phenomena, measurement and extrapolation, and parameter estimation. The user provides absolute or percentage deviations for each input parameter to be incorporated in the Monte Carlo analysis, specifies the number of trials and samples per trial to run, and chooses between a uniform and normal distribution for sampling. The mean stream temperature is calculated from repeated model simulation and reported as the best estimate plus or minus the calculated standard deviation.

One hundred trials were run using the Monte Carlo method, with 11 samples per trial drawn from a normal distribution. SSTEMP 2.0 reported the best estimate of the mean stream temperature as 22.21^{o}C $\pm$ 0.13^{o}C standard deviation. The 95% confidence interval included values from 21.95^{o}C to 22.47^{o}C. This predicted value shows close agreement with the empirical mean stream temperature of 22.31^{o}C measured at the end of the model stream segment (e.g., at Pool T).

Model Application

The BCC Stream Temperature Model was run through several scenarios in order to determine individual and combined effects of riparian vegetation height and density on mean stream temperature in adult spring-run salmon holding habitat, including cumulative effects of upstream riparian vegetation changes. The model was also run to evaluate the effect of riparian vegetation density reduction on mean stream temperature (i.e., due to fire).

Although changes in vegetation height and/or density would likely affect other physical riparian parameters (e.g., vegetation crown, vegetation offset, channel width, and Manning's n), these potential cumulative effects were not addressed in this study.

Effect of Vegetation Height

Vegetation structure within the riparian zone along a stream can strongly affect ambient stream temperatures. In particular, species distribution and age of riparian vegetation influence the proportion of stream channel which receives shade, and thus the amount of short-wave radiation reaching the stream each day.

Dominant shade tree species in the riparian of BCC included white alder (*Alnus rhombifolia*), California bay (*Umbellularia californica*), big-leaf maple (*Acer macrophyllum*), valley oak (*Quercus lobata*), ponderosa pine (*Pinus ponderosa*), and incense cedar (*Calocedrus decurrens*). Based on empirical evaluation of riparian vegetation in the model stream segment, the mean vegetation height to the west and east of the stream channel was 13.4 m and 15.6 m, respectively. Measurements of mature ponderosa pine and incense cedar revealed a mean height of 22 m. Ponderosa pine commonly reach 27 to 40 m (University of California Cooperative Extension, 2004). Based on the observed vegetation species composition, ponderosa pine and incense cedar were estimated to comprise 10 to 15% of riparian tree species.

Model runs were initially focused on the effect of riparian conifer composition on mean stream temperature, assuming a height of 35 m. First, the average height of deciduous trees, x, was calculated for west and east sides of the channel, assuming conifers comprised 10% of the riparian tree species and average vegetation height was 13.4 m (W) and 15.6 m (E):

$$22 + 9x = 134 \text{ (W)} \qquad 22 + 9x = 156 \text{ (E)}$$

$$x = 12.4 \text{ m (W)} \qquad x = 14.9 \text{ m (E)}$$

Average vegetation height was then calculated assuming conifer height of 35 m, again at 10% species composition:

$$(35 + 9(12.4))/10 = 14.7 \text{ m (W)} \qquad (35 + 9(14.9)) = 16.9 \text{ m (E)}$$

Thus, average riparian vegetation height with conifers at a mean height of 35 m comprising 10% of riparian trees species resulted in average vegetation height to the west and east of the channel of 14.7 m and 16.9 m, respectively.

The calculation was repeated for the assumptions of conifer height at 35 m comprising 20 and 30% of riparian tree species, and deciduous trees at the same initial height. Results of these calculations are given in Table 8. The model indicated conifer riparian composition of 30% at a height of 35 m would reduce the mean stream temperature by only 0.02^{o}C.

Conifer Composition (%)	**Vegetation Ht., West (m)**	**Vegetation Ht., East (m)**	**Mean Stream Temp. (^{o}C)**
10	14.7	16.9	22.30
20	17.0	18.9	22.30
30	19.3	20.9	22.29

Table 8. Effect of riparian conifer composition on mean stream temperature at height of 35m.

Model runs with increased mean riparian vegetation height up to 35 m on both sides of the stream channel (e.g., 100% conifer species in the riparian corridor) resulted in a decrease of mean stream temperature at the segment outflow by 0.06°C (Figure 12).

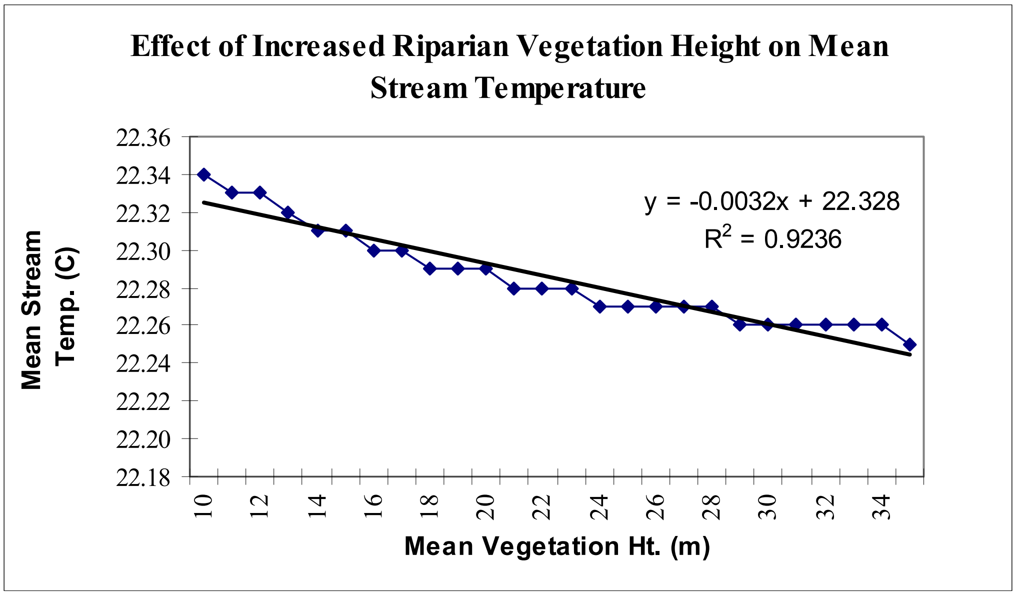


Figure 12. Effect of increased riparian vegetation height on mean stream temperature.

Effect of Riparian Vegetation Density

Model runs with increased riparian vegetation density indicated greater declines in mean stream temperature compared with increased vegetation height. A maximum vegetation density of 95% on both sides of the channel produced a decrease in mean stream temperature at the segment outflow of 0.35°C (Figure 13).

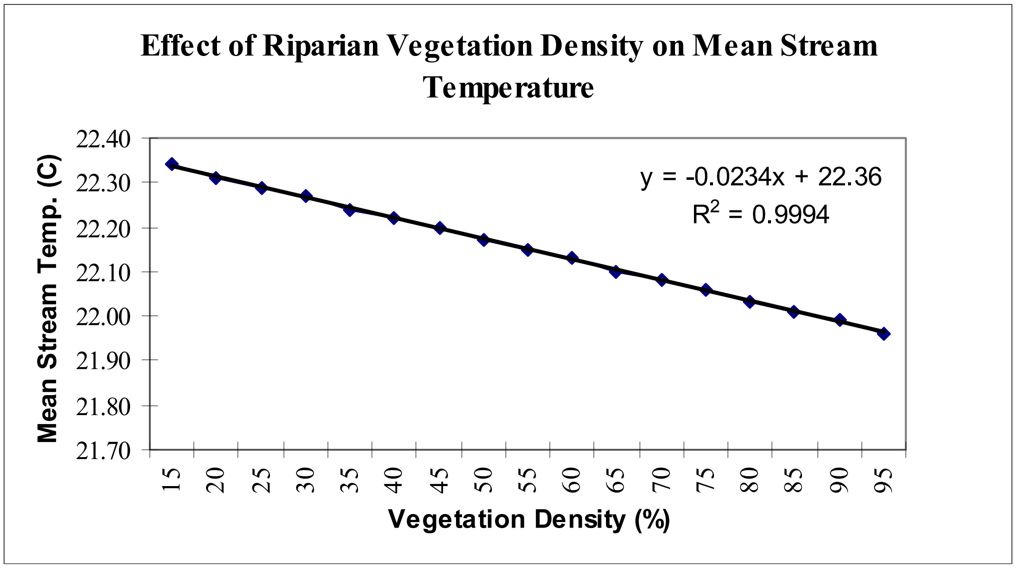


Figure 13. Effect of riparian density on mean stream temperature.

Combined Effect of Vegetation Height and Density

Six realistic vegetation height scenarios (16 m, 17 m, 18 m, 19 m, 20 m, and 21 m) were evaluated with increasing vegetation density values to determine the combined effect of riparian height and vegetation on mean stream temperature. The vegetation height scenarios were calculated based on riparian conifer composition between 10 and 30%.

Mean riparian vegetation height and density had a stronger effect on mean stream temperature then the individual effects of these parameters. Stream temperature reduction was enhanced as vegetation height increased, and the effect of vegetation height increased with vegetation density (Figure 14). A maximum decrease in mean stream temperature at the segment outflow of 0.47^{o}C resulted at 95% riparian vegetation density with conifers comprising approximately 30% of riparian tree species, (e.g., mean vegetation height of 21 m on both sides of the stream channel).

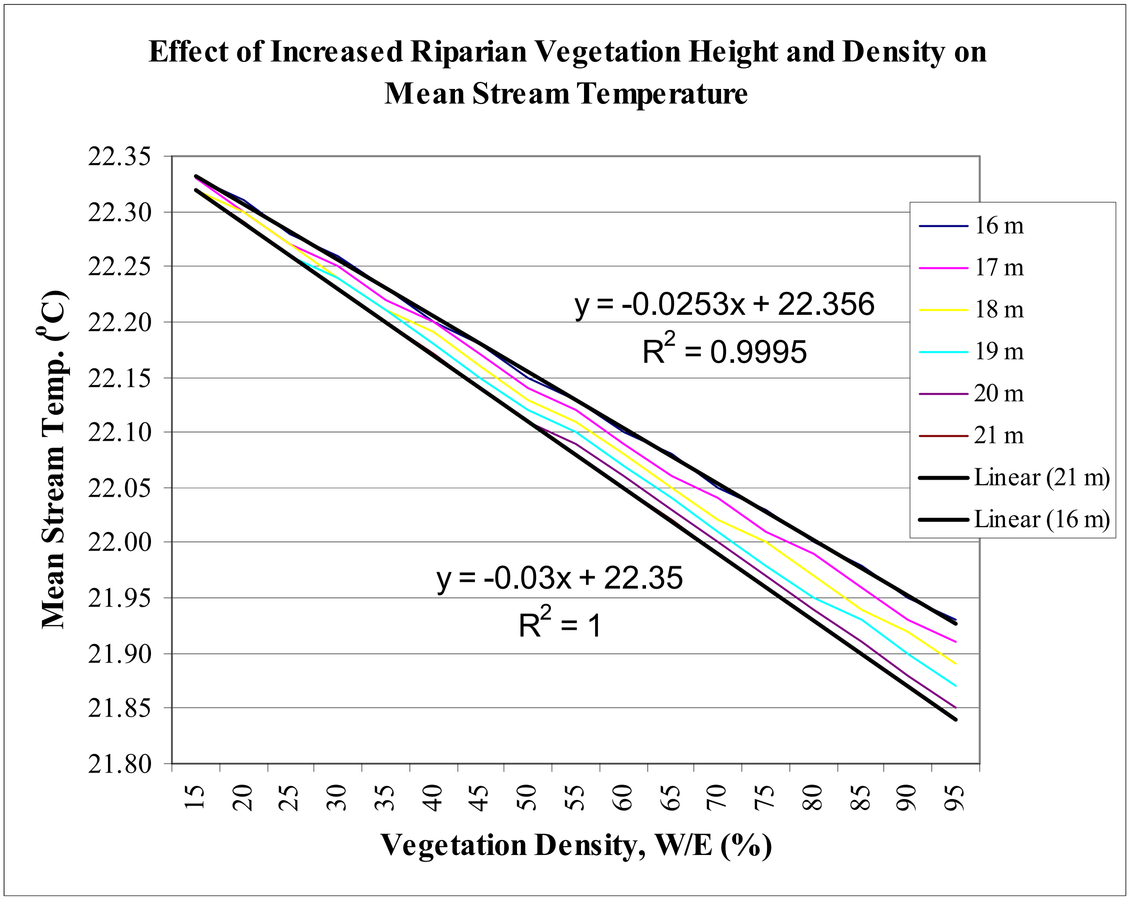


Figure 14. Combined effect of riparian vegetation height and density on mean stream temperature.

An additional analysis was completed to evaluate the cumulative effect on mean stream temperature if the same increase in riparian tree height and vegetation density occurred in the stream segment approximately 4.6 km upstream of the model stream segment (e.g., between Higgins Hole and Henning Hole). SSTEMP 2.0 was parameterized to simulate the upstream segment (Table 9), and run for the same six height scenarios as the original model to predict mean stream temperature that would result at Henning Hole as vegetation density increased from 35% to 95%. Each predicted value for Henning Hole was then entered as the inflow temperature for the stream segment between Henning Hole and Pool T, and the model was re-run to evaluate effect of increased riparian vegetation height and density on mean stream temperature.

Parameter #	Parameter (units)	Value	Method
1	segment inflow (m^3/s)	1.021	estimated
2	inflow temp (°C)	20.556	empirical
3	segment outflow (m^3/s)	1.035	estimated
4	accretion temp (°C)	16.328	estimated
5	latitude (radians)	0.696	USGS topographic map
6	segment length (km)	4.360	USGS topographic map
7	upstream elevation (m)	313.298	USGS topographic map
8	downstream elevation (m)	270.358	USGS topographic map
9	width's A term (s/m^2)	11.278	estimated
10	width's B term where $W=A*Q^B$	0	empirical
11	Manning's n	0.065	Chow (1959); Barnes (1967)
12	month/day	27-Jul	--
13	mean daily air temp (°C)	25.710	empirical
14	maximum air temp (°C)	28.213	empirical
15	relative humidity (%)	53.647	Bartholow (2002)
16	wind speed (mps)	2.148	calculated
17	ground temperature (°C)	15.328	calculated
18	thermal gradient (j/m^2/s)	4.960	Gaffield (1999)
19	possible sun (%)	95	The Weather Center
21	solar radiation (j/m^2/s)	300	Renewable Resource Data Center
21	azimuth (radians)	0.718	USGS topographic map
22	topographic altitude, east and west (radians)	0.401 (E) and 0.507 (W)	calculated
23	vegetation ht., east and west (m)	14.000 (E) and 14.000 (W)	estimated
24	vegetation crown, east and west (m)	7.315 (E) and 6.401 (W)	empirical
25	vegetation offset, east and west (m)	6.919 (E) and 5.639 (W)	empirical
26	vegetation density, east and west (%)	35 (E) and 35 (W)	estimated

Table 9. Estimated parameter values for the stream segment from Higgins Hole to Henning Hole.

This additional analysis indicated increases in riparian vegetation height and density in the reach preceding the model stream segment (e.g., Higgins Hole to Henning Hole) resulted in predicted mean stream temperature up to 0.71°C less than when these same increases occurred solely in the model stream segment from Henning Hole to Pool T (Table 10).

	16 m		17 m		18 m	
Riparian Vegetation Density (%)	Original Predicted Mean (°C)	Cumulative Predicted Mean (°C)	Original Predicted Mean (°C)	Cumulative Predicted Mean (°C)	Original Predicted Mean (°C)	Cumulative Predicted Mean (°C)
35	22.23	22.24	22.22	22.21	22.21	22.19
40	22.20	22.17	22.20	22.14	22.19	22.12
45	22.18	22.10	22.17	22.07	22.16	22.04
50	22.15	22.03	22.14	21.99	22.13	21.97
55	22.13	21.96	22.12	21.93	22.11	21.89
60	22.10	21.89	22.09	21.85	22.08	21.81
65	22.08	21.82	22.06	21.77	22.05	21.74
70	22.05	21.75	22.04	21.71	22.02	21.66
75	22.03	21.68	22.01	21.63	22.00	21.59
80	22.00	21.61	21.99	21.56	21.97	21.51
85	21.98	21.54	21.96	21.49	21.94	21.44
90	21.95	21.47	21.93	21.41	21.92	21.36
95	21.93	21.41	21.91	21.34	21.89	21.28

	19 m		20 m		21 m	
Riparian Vegetation Density (%)	Original Predicted Mean (°C)	Cumulative Predicted Mean (°C)	Original Predicted Mean (°C)	Cumulative Predicted Mean (°C)	Original Predicted Mean (°C)	Cumulative Predicted Mean (°C)
35	22.21	22.17	22.20	22.15	22.20	22.14
40	22.18	22.10	22.17	22.07	22.17	22.06
45	22.15	22.02	22.14	21.99	22.14	21.97
50	22.12	21.94	22.11	21.91	22.11	21.89
55	22.10	21.85	22.09	21.83	22.08	21.80
60	22.07	21.78	22.06	21.75	22.05	21.72
65	22.04	21.70	22.03	21.67	22.02	21.64
70	22.01	21.62	22.00	21.58	21.99	21.56
75	21.98	21.54	21.97	21.51	21.96	21.47
80	21.95	21.47	21.94	21.43	21.93	21.39
85	21.93	21.39	21.91	21.34	21.90	21.30
90	21.90	21.31	21.88	21.26	21.87	21.22
95	21.87	21.23	21.85	21.18	21.84	21.13

Table 10. Comparison of predicted mean stream temperature values at Pool T when riparian vegetation height and density increase in the model stream segment and when increases also occur from Higgins Hole to Henning Hole.

Effect of Riparian Vegetation Density Reduction

The model was also run to determine the effect of riparian vegetation density decrease within the model stream segment on mean stream temperature. Model runs included reduction in riparian vegetation density of 30, 50, and 70%. The predicted mean stream temperature in the model segment increased by up to 0.07^{o}C for this scenario. If vegetation density decreased by the same proportion in the upstream segment from Higgins Hole to Henning Hole, predicted mean stream temperature in the model segment increased by up to 0.34^{o}C.

Discussion

Results from the BCC Stream Temperature Model are intended to be an initial estimate of riparian effects on mean stream temperature on the BCCER. Uncertainty regarding current and projected riparian conditions such as mean vegetation crown and density, and deciduous and coniferous tree heights under current BCCER management should be addressed in order to improve the strength of the model.

In this application, the BCC Stream Temperature Model indicated increases in riparian vegetation height and density produced greater reduction in mean stream temperature than either parameter alone. However, even with conifers at a 35 m height comprising 30% of riparian tree species, and vegetation density of 95%, mean stream temperature was reduced by less than 0.5^{o}C.

Does this mean increases or decreases in riparian vegetation height and density on the BCCER would have negligible results for spring-run salmon in the foothill zone of BCC? Actually, increases in riparian vegetation height and density on the BCCER examined during the model application would result in a negative rate of change in mean stream temperature, an outcome generally considered favorable for salmonids in Central Valley streams. However, the magnitude of mean stream temperature observed in the model applications during the warmest summer period was still higher than values cited as detrimental for reproduction in spring-run salmon (Berman, 1990).

Although decreases in riparian vegetation density, including loss in the upstream segment, resulted in predicted mean stream temperature increase less than 0.5^{o}C, the resulting increase in maximum stream temperature or duration of maximum temperatures is not predictable with any real confidence using SSTEMP 2.0. In studies of stream temperature change in forested watersheds where riparian vegetation was removed by logging, increases in maximum stream temperature exceeded 10^{o}C (Brown and Krygier, 1970; Brown et al., 1971; Claire and Storch, 1977). These studies suggest protection of riparian vegetation from significant loss in density would be an important management activity along salmonid streams, including BCC.

Given that stream temperature measured for a particular stream segment is cumulative, the magnitude of stream temperatures observed during the 2003 field study was a dynamic function of the riparian, watershed, and land-use activities occurring upstream. Recall that the model's sensitivity analysis indicated upstream water temperature was the most significant determinant of mean stream temperature in the model stream segment. Based on hourly stream data measured from July 26, 2003 to August 4, 2003 during this study, rates of increase in stream temperature in three reaches were calculated. The rate of increase in mean stream temperature from Higgins Hole to

Henning Hole was $0.32^{o}C/km \pm 0.03^{o}C$ (SE). In the stream segment from Henning Hole to Pool T (the model stream segment) the rate of increase was $0.11^{o}C/km \pm 0.02^{o}C$ (SE). And from Pool T to Salmon Hole, the rate of increase was lowest at $0.10^{o}C/km \pm 0.05^{o}C$ (SE). Mean stream temperature at these pools during this time period is displayed in Appendix D. The non-linear rate of increase of mean stream temperature with increasing distance downstream demonstrates the effect of variable channel and riparian features (e.g., flow volume, channel width, riparian vegetation structure and composition) on heat flux in a stream (Figure 15). Unfortunately, there is not a data set available to compare the magnitude of current rates of increase in stream temperature with historical values. It is reasonable to assume however, that reduced rates of increase in stream temperature for upstream segments of BCC, including segments with negative rates of increase, would result in lower stream temperatures in spring-run salmon habitat downstream.

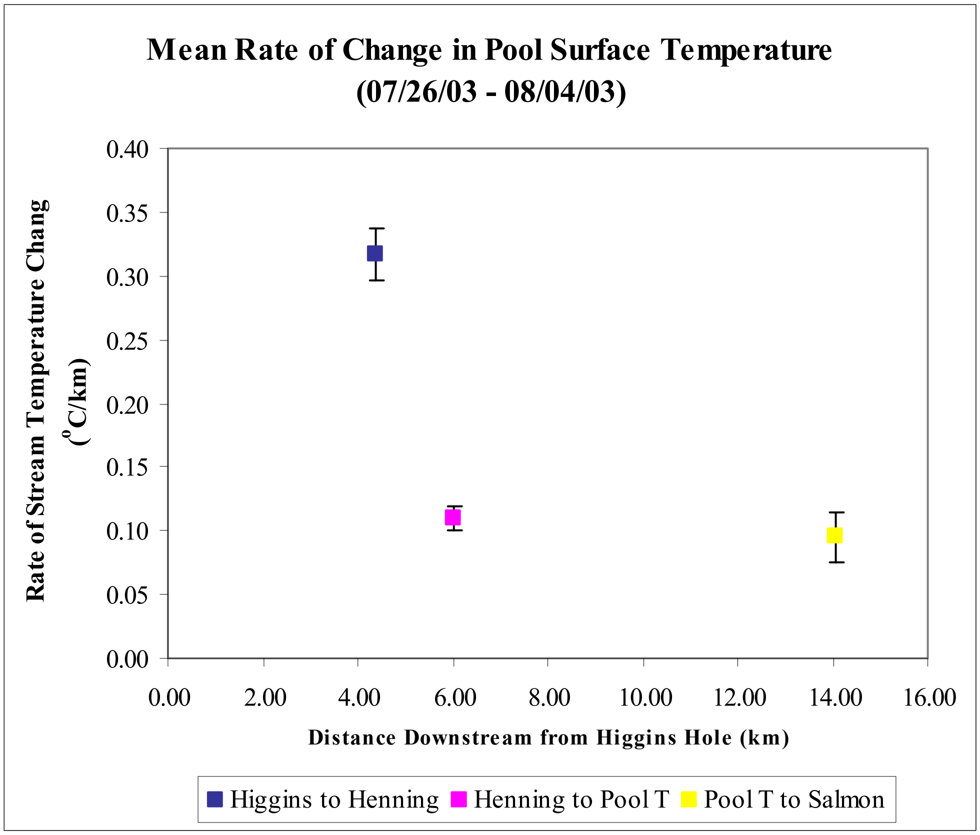


Figure 15. Rates of temperature change in selected BCC stream segments.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

During the summer period, adult spring-run salmon holding in Central Valley streams experience warm temperatures that approach or exceed thermal limits documented in scientific literature for this race of chinook salmon (Moyle, 1976). Of the three pools commonly used as holding habitat through summer by spring-run salmon in Big Chico Creek (BCC), tributary to the Sacramento River, Higgins Hole provides a thermal refuge relative to other available holding habitats. Though many large, deep pools occur as potential holding habitat in the BCC foothill zone, stream temperatures in these pools exceed thermal tolerance documented for adult spring-run salmon (McCullough, 1999). Conclusions from this study are presented by topic in the following paragraphs, followed by associated recommendations in italic text.

Higgins Hole

In the present study of BCC, localized thermal refugia for adult spring-run salmon were not generally observed, even in pools with maximum depths of 3.0 to 4.5 m. However, when considering the entire foothill zone of BCC where adult spring-run holding habitats occurred, Higgins Hole represents a critical thermal refuge.

Onset of lethal stream temperatures in late spring may inhibit migration for spring-run salmon in BCC, as has been demonstrated in other studies (Stabler, 1981; Bumgarner et al., 1997; DFGb, 2004). Migration barriers are known to occur for adult spring-run salmon in Bidwell Park (DWR, 2001). *Correction of fish passage problems presented at*

Bear Hole and Iron Canyon in Bidwell Park is vital for the spring-run salmon population in BCC, as the best thermal holding habitat occurs approximately 14 km upstream at Higgins Hole.

Cumulative Effects

It was observed that changes in mean stream temperature in spring-run salmon holding habitat are magnified when riparian vegetation changes occur upstream as well as within holding habitat reaches. Alteration of hydrologic flow paths in upper watershed reaches would also affect stream temperatures downstream by modifying the natural flow regime (i.e., timing, magnitude, duration, and frequency of streamflow) (Poff et al., 1997; Poole and Berman, 2001). By reducing impacts to natural hydrologic flow processes, groundwater flow during summer above and within the BCC foothill zone may increase, and summer stream temperatures decline as a result. Land-use in the upper watershed includes commercial logging, an activity known to result in degraded stream temperature (Beschta et al., 1987). *Land use activities in the upper watershed (i.e., above the foothill zone) should be conducted so as to protect and/or improve riparian shade characteristics, in recognition of the importance of summer stream temperatures downstream. Design and management of roads in the upper watershed should reflect state-of-the-technology practices in order to reduce winter run-off and transfer water (in non-erosive fashion) from road surfaces to natural receiving areas (i.e., adjacent land). A well-constructed temperature monitoring program should be developed between Sierra Pacific, the State of California, and/or the federal government, including a feed-back* *loop to adjust forest management if stream temperature in the upper watershed (including tributaries) is impaired by logging practices.*

Evaluation of Current Thermal Regime

It is unknown whether the current thermal regime experienced by adult spring-run in Big Chico Creek represents a condition unimpaired by human activities, or if the thermal regime has been modified by land-use activities in the upper watershed (i.e., livestock grazing, logging, road-building). McCullough (1999) suggested that alterations of hydrologic processes in upper watersheds may increase stream temperatures in headwater reaches and tributaries, thus reducing the downstream extent of cooling in the main channel, and effectively causing a headward migration of cold channel reaches (McCullough, 1999; Poole and Berman, 2001). Given that each species of the genus, *Oncorhynchus*, exhibits a characteristic swimming speed and maximum jumping ability, the innate swimming and jumping abilities of adult spring-run salmon may prevent them from accessing cold-water habitats which are migrating headward as summer stream temperatures in former holding reaches warm (McCullough, 1999). *Completion of a watershed analysis in the BCC watershed would allow an effective evaluation as to whether the current thermal regime in BCC is impaired due to cumulative watershed effects.*

Empirically-Derived Mortality Curve

The relationship between water temperature and exposure time leading to mortality of spring-run salmon (e.g., a mortality curve) holding in elevated temperatures is not well documented in empirical studies. *A useful study would present a continuous picture of* *thermal exposure, and indicate a threshold at which mortality occurs, regardless of diel temperature fluctuation.*

Effect of Temperature on Reproductive Success

Adult spring-run salmon in BCC experience temperatures during the holding portion of their life-cycle which significantly exceed temperatures at which reproduction or offspring health is impaired (Berman, 1990). While access to Higgins Hole appears to improve over-summer survival for BCC spring-run salmon, not all individuals of the population should be expected to hold in one pool. *While land managers and agency scientists plan for funding and completing migration barrier improvements below the BCC foothill zone to improve spring-run salmon survival in BCC, they should also investigate the effects of stream temperature on reproduction in the BCC spring-run salmon population. A study which identifies the quality of reproduction at its various stages (e.g., gametes, eggs, and fry) would determine if the current thermal regime affects the BCC spring-run population during these early life-cycle stages.*

Fire Protection

While efforts to increase or protect riparian vegetation along BCC do not appear to result in significant changes in mean stream temperature within spring-run salmon holding habitat, it is reasonable to assume that duration and magnitude of maximum stream temperatures would increase considerably should a major wildfire reduce riparian vegetation density within and above the BCC foothill zone. *Land managers should implement ecologically sensitive projects which reduce opportunity for catastrophic fire to reduce riparian vegetation density along BCC.*

Effect of Disturbance

Spring-run salmon holding in Salmon Hole experience the highest stream temperatures for the longest durations relative to other pools commonly used as holding habitat in BCC. Additionally, spring-run salmon in Salmon Hole are impacted by human use of that pool for recreation in summer. With increased disturbance, the ability of adult salmon to internally cope with stressful stream temperatures is likely reduced. While spring-run salmon holding in Henning Hole also were exposed to temperatures $\geq 21^{o}C$ for significant periods, less mortality was observed in that pool. *Land managers with responsibility for property which includes spring-run salmon holding habitat in BCC should make every effort to eliminate disturbance of adult spring-run salmon during holding and spawning periods.*

Adaptation

Heat shock proteins are involved with repair of other proteins which are distorted upon exposure to stressful temperatures. Individuals chronically exposed to high temperatures incur a relatively large energetic cost due to frequent production of heat shock proteins (Somero and Hofmann, 1996). With sufficient evolutionary time, adaptive changes may occur to allow survival of local populations in environments with differences in maximum temperature of only a few degrees (Somero and Hofman, 1996). Genetic adaptation may even be typical in populations occurring at the extremes of their tolerance, such as spring-run salmon in BCC (Flebbe, 1994). *Examination of variation in heat shock proteins in the regional spring-run salmon populations, as well as comparison* *with populations from other regions, would allow evaluation of adaptation as a significant factor in maintenance of the BCC spring-run population.*

REFERENCES

Anadromous Fish Restoration Program. http://www.delta.dfg.ca.gov/afrp/ws_stats.asp?code=BIGCC, accessed May 2, 2004.

Barnes, H.H. 1967. Roughness characteristics of natural channels. Water-Supply Paper 1849. U.S. Geological Survey.

Bartholow, J.M. 1991. A modeling assessment of the thermal regime for an urban sport fishery. *Environmental Management* 15(6):833-845.

________. 2000. Estimating cumulative effects of clearcutting on stream temperatures. *Rivers* 7(4):284-297.

________. 2002. SSTEMP for Windows: The Stream Segment Temperature Model (Version 2.0). US Geological Survey computer model and documentation. Available on the Internet at http://www.fort.usgs.gov/.

Berman, C.H. 1990. The effect of elevated holding temperatures on adult spring chinook salmon reproductive success. M.S. thesis, University of Washington.

Berman, C.H. and T.P. Quinn. 1991. Behavioural thermoregulation and homing by spring chinook salmon, *Oncorhynchus tshawytscha* (Walbaum), in the Yakima River. *Journal of Fish Biology* 39:301-312.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. Pages 191-232 *in* E.O. Salo and T.W. Cundy, editors. Streamside management: forestry and fishery interactions. University of Washington, Seattle, Washington, USA.

Big Chico Creek Watershed Alliance. 1999. *Big Chico Creek Existing Conditions Report*.

Bilby, R.E. 1984. Characteristics and frequency of cool-water areas in a western Washington stream. *Journal of Freshwater Ecology* 2(6):593-602.

Blann, K., J.F. Nerbonne, and B. Vondracek. 2002. Relationship of riparian buffer type to water temperature in the driftless area ecoregion of Minnesota. *North American Journal of Fisheries Management* 22:441-451.

Boyd, M. 1996. Heat Source: stream, river and open channel temperature prediction. M.S. Thesis, Oregon State University.

Boyd, M., and D. Sturdevant. 1997. The scientific basis for Oregon's stream temperature standard: common questions and straight answers. Oregon Department of Environmental Quality, 29 pp.

Brett, J.R. 1952. Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. *J. Fish. Res. Bd. Can.* 9(6):265-323.

________. 1956. Some principles in the thermal requirements of fishes. *The Quarterly Review of Biology* 31(2):75-87.

Brown, G.W. 1970. Predicting the effects of clearcutting on stream temperature. *Journal of Soil and Water Conservation* 25:11-13.

Brown, G.W. and J.T. Krygier. 1970. Effects of clear cutting on stream temperatures. *Water Resources Research* 6(4):1133-1140.

Brown, G.W., G.W. Swank, and J. Rothacher. 1971. Water temperature in the Steamboat drainage. USDA For. Serv. Res. Pap. PNW-119. Pac. Northwest For. and range Exp. Stn., Portland, Oregon, 17 pp.

Bumgarner, J., G. Mendel, D. Milks, L. Ross, M. Varney, and J. Dedloff. 1997. Tucannon River spring chinook hatchery evaluation. 1996 Annual report. Washington Department of Fish and Wildlife Hatcheries Program Assessment and Development Division. Report #H97-07. Produced for U.S. Fish and Wildlife Service, Cooperative Agreement 14-48-0001-96539.

CH2M Hill. 1993. Assessment of Big Chico Creek salmon and steelhead production.

California Department of Fish and Game (DFG). 1998. A status review of the spring-run chinook salmon (*Oncorhynchus tshawytscha*) in the Sacramento River drainage. Candidate Species Status Report 98-01.

________. 2004a. Sacramento spring-run chinook salmon. 2002-2003 biennial report.

________. 2004b. September 2002 Klamath River fish-kill: final analysis of contributing factors and impacts.

California Department of Water Resources (DWR). 2001. Iron Canyon and Bear Hole Fish Passage Project on Big Chico Creek. Preliminary Engineering Technical Report.

Chow, V.T. 1959. Open-channel hydraulics. McGraw-Hill Book Company, Inc. New York

Claire, E.W. and R.L. Storch. 1977. Streamside management and livestock grazing: an objective look at the situation. In: *Proc. Symp. Livestock and Wildlife-Fisheries Relationships in the Great Basin.* Sparks, Nevada. May 3-5, 1977.

Coutant, C.C. 1976. Thermal effects on fish ecology. pp. 891-896 *in* Encyclopedia of Environmental Engineering, Vol. 2. W&G Baird, Ltd., Northern Ireland.

________. Thermal preference: when does an asset become a liability? *Environmental Biology of Fishes* 18(3):161-172.

Critchfield, Howard J. 1974. General Climatology, Third Edition. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Ebersole, J.L., W.J. Liss, and C.A. Frissell. 2001. Relationship between stream temperature, thermal refugia and rainbow trout, *Oncorhynchus mykiss*, abundance in arid-land streams in the northwestern United States. *Ecology of Freshwater Fish* 10:1-10.

________. 2003. Cold water patches in warm streams: physicochemical characteristics and the influence of shading. *Journal of the American Water Resources Association* 39(2):355-368.

Federal Register, Vol. 64, No. 179, Sept. 16, 1999, p. 50393. Final Rule: Endangered and Threatened Species; Threatened Status for Two Chinook Salmon Evolutionarily Significant Units (ESUs) in California

Fisher, F. 1994. Past and present status of Central Valley chinook salmon. *Conservation Biology* 8(3):870-873.

Flebbe, P.A. 1994. A regional view of the margin: salmonid abundance and distribution in the southern Appalachian Mountains of North Carolina and Virginia. *Transactions of the American Fisheries Society* 123:657-667.

Gaffield, Stephen J. 2000. Evaluation of the controls of summer stream temperature in the Driftless Area of southwestern Wisconsin. Ph.D. thesis, University of Wisconsin-Madison, Madison, WI.

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones. *Bioscience* 41:540-551.

Hallock, R.J., R.F. Elwell, and D.H. Fry. 1970. Migrations of adult king salmon, *Oncorhynchus tshawytscha*, in the San Joaquin Delta as demonstrated by the use of sonic tags. California Department of Fish and Game Bulletin 151. 92 p.

Haro and Wiley. 1992. Secondary consumers and thermal equilibrium hypothesis: Insights from Michigan Spring Brooks. Proceedings of the First International Conference on Ground Water Ecology, Tampa, FL. USEPA. pp. 179-188.

Hostetler, S.W. 1991. Analysis and modeling of long-term stream temperatures on the Steamboat Creek basin, Oregon: implications for land use and fish habitat. *Water Resources Bulletin* 27(4):637-647.

Humboldt State University. Stream Temperature Protocol. Forest Science Project Regional Stream Temperature Assessment. 21 pp. http://www.humboldt.edu/~ifwm/Publications/temp_protocol.pdf. Accessed April 17, 2003.

Johnson, S.L. 2003. Stream temperature: scaling of observations and issues for modelling. *Hydrological Processes* 17:497-499.

Kaya, C.M., L.R. Kaeding, and D.E. Burkhalter. 1977. Use of a cold-water refuge by rainbow and brown trout in a geothermally heated stream. *The Progressive Fish-Culturist* 39(1):37-39.

Li, H.W., G.A. Lamberti, T.N. Pearsons, C.K. Tait, J.L. Li, and J.C. Buckhouse. 1994. Cumulative effects of riparian disturbances along high desert trout streams of the John Day Basin, Oregon. *Transactions of the American Fisheries Society* 123:627-640.

Magnuson, J.J., L.B. Crowder, and P.A. Medvick. 1979. Temperature as an ecological resource. *American Zoologist* 19:331-343.

Marine, K.R. and J.J. Cech, Jr. 1998. Effects of elevated water temperature on some aspects of physiological and ecological performance of juvenile chinook salmon (*Oncorhynchys tshawytscha*): implications for management of California's chinook salmon stocks. Stream temperature monitoring and assessment workshop. January 12-14, 1998. Sacramento, California. Forest Science Project, Humboldt State University, Arcata, California.

Matthews, K.R., N.H. Berg, D.L. Azuma, and T.R. Lambert. 1994. Cool water formation and trout habitat use in a deep pool in the Sierra Nevada, California. *Transactions of the American Fisheries Society* 123:549-564.

McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to chinook salmon. Prepared for the US Environmental Protection Agency, Region 10, Seattle, WA. EPA 910-R-99-010

Moyle, P.B. 1976. Inland fishes of California. University of California Press. Berleley, California. 405 pp.

Myers, J.M., R.G. Kope, G.J. Bryant, D. Teel, L.J. Lierheimer, T.C. Wainwright, W.S. Grand, F.W. Waknitz, K. Neely, S.T. Lindley, and R.S. Waples. 1998. Status review of chinook salmon from Washington, Idaho, Oregon, and California. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-35, 443 p.

Nakamoto, R.J. 1994. Characteristics of pools used by adult summer steelhead oversummering in the New River, California. *Transactions of the American Fisheries Society* 123:757-765.

National Marine Fisheries Service. http://www.nwr.noaa.gov/1salmon/salmesa/pubs/1pgr.pdf, accessed 8/4/04.

Nehlsen, W., J.E. Williams, and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. *Fisheries* 16(2):4-21.

Nielsen, J.L., T.E. Lisle, and V. Ozaki. 1994. Thermally stratified pools and their use by steelhead in northern California streams. *Transactions of the American Fisheries Society* 123:613-626.

Poff, N.L. and J.V. Ward. 1990. Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity. *Environmental Management* 14(5):629-645.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime. *BioScience* 47(11):769-784.

Poole, G.C. and C.H. Berman. 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. *Environmental Management* 27(6):787-802.

Quinn, J.M. and Hickey, C.W. 1990. Characterisation and classification of benthic invertebrate communities in 88 New Zealand rivers in relation to environmental factors. *New Zealand Journal of Marine and Freshwater Research* 24:387-409.

Reynolds, W.W. and M.E. Casterlin. 1979. The role of temperature in the environmental physiology of fishes. In: NATO Advanced Study Institute on Environmental Physiology of Fishes., M.A. Ali (ed.). Plenum Press New York and London

Richards, C., L.B. Johnson, and G.E. Host. 1996. Landscape-scale influences on stream habitats and biota. *Canadian Journal of Fisheries and Aquatic Sciences* 53(Suppl. 1):295-311.

Ricker, W.E. 1972. Heredity and environmental factors affecting certain salmonid populations. Pages 19-169 in R.C. Simon and P.A. Larkin, eds. The Stock Concept in Pacific Salmon. MacMillen Lectures in Fisheries. University of British Columbia, Vancouver, B.C.

Roper, B.B., D.L. Scarnecchia, and T.J. La Marr. 1994. Summer distribution of and habitat use by chinook salmon and steelhead within a major basin of the South Umpqua River, Oregon. *Transactions of the American Fisheries Society* 123:298-308.

Schlosser, I.J. 1991. Stream fish ecology: a landscape perspective. *BioScience* 41(10):704-712.

Sinokrot, B.A. and H.G. Stefan. 1993. Stream temperature dynamics: measurements and modeling. *Water Resources Research* 29(7):2299-2312.

Somero, G.N. and G.E. Hofmann. 1996. Temperature thresholds for protein adaptation: when does temperature change start to 'hurt'? *In* Wood, C.M. and McDonald, D.G., eds. *Global Warming: Implications for freshwater and marine fish.* Society for Experimental Biology Seminar Series 61. Cambridge University Press, 1996, pp. 1-24.

Spence, B.C., G.A. Lomnicky, R.M. Hughes, and R.P. Novitzki. 1996. An ecosystem approach to salmonid conservation. TR-4501-96-6057. ManTech Environmental Research Services Corp., Corvallis, OR. (Available from the National Marine Fisheries Service, Portland, Oregon.)

Stabler, D.F. 1981. Effects of altered flow regimes, temperatures, and river impoundment on adult steelhead trout and chinook salmon. M.S. thesis, University of Idaho, Moscow, Idaho.

Taylor, E.B. 1991. A review of local adaptation in Salmonidae, with particular reference to Pacific and Atlantic salmon. *Aquaculture* 98:185-207.

The Weather Center. www.weatherwatch.com. Accessed on Feb. 18, 2004.

Theurer, F.D., I. Lines, and T. Nelson. 1985. Interaction between riparian vegetation, water temperature, and salmonid habitat in the Tucannon River. *Water Resources Bulletin* 21:53-64.

Torgersen, C.E., D.M. Price, H.W. Li, and B.A. McIntosh. 1999. Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon. *Ecological Applications* 9(1):301-319.

Trihey, E.W., and D.L. Wegner. 1981. Field data collection procedures for use with the Physical Habitat Simulation System of the Instream Flow Group. Cooperative Instream Flow Service Group, Fort Collins, CO.

University of California Cooperative Extension. http://www.cnr.berkeley.edu/departments/espm/extension/PONDEROS.HTM, accessed on April 15, 2004.

USFWS, Anadromous Fisheries Restoration Program. http://www.delta.dfg.ca.gov/afrp/ws_stats.asp?code=BIGCC, Accessed on March 4, 2004.

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.

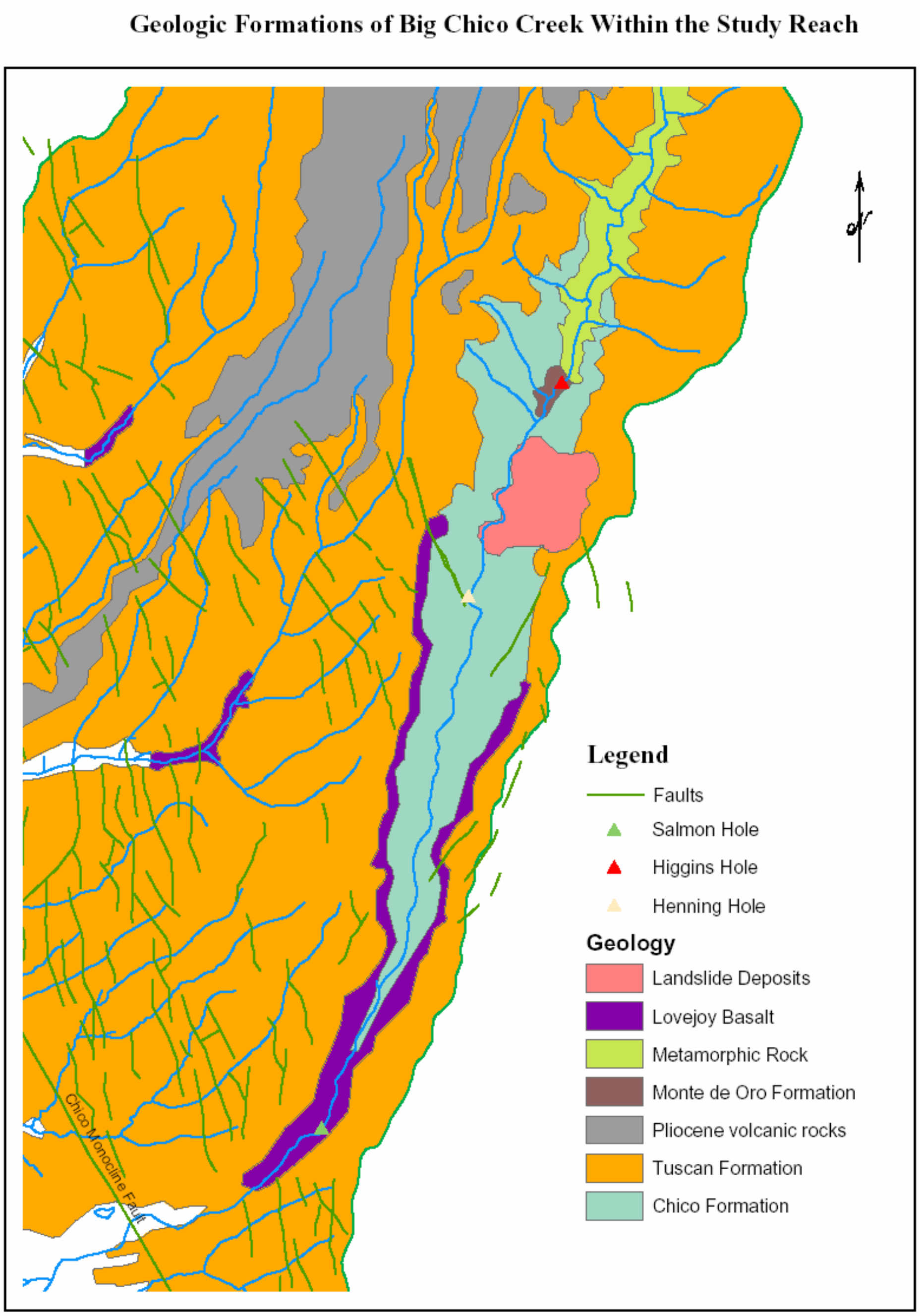
Ward, J.V. 1989. The four-dimensional nature of lotic ecosystems. *Journal of the North American Benthological Society* 8(1):2-8.

Whitledge, G.W. 2001. Quantifying linkages between riparian shading, water temperature, and energetics of smallmouth bass and crayfishes in Ozark streams. Ph.D. Dissertation, University of Missouri-Columbia.

Yoshiyama, R.M., F.W. Fisher, and P.B. Moyle. 1998. Historical abundance and decline of chinook salmon in the Central Valley region of California. North American *Journal of Fisheries Management* 18:487-521.

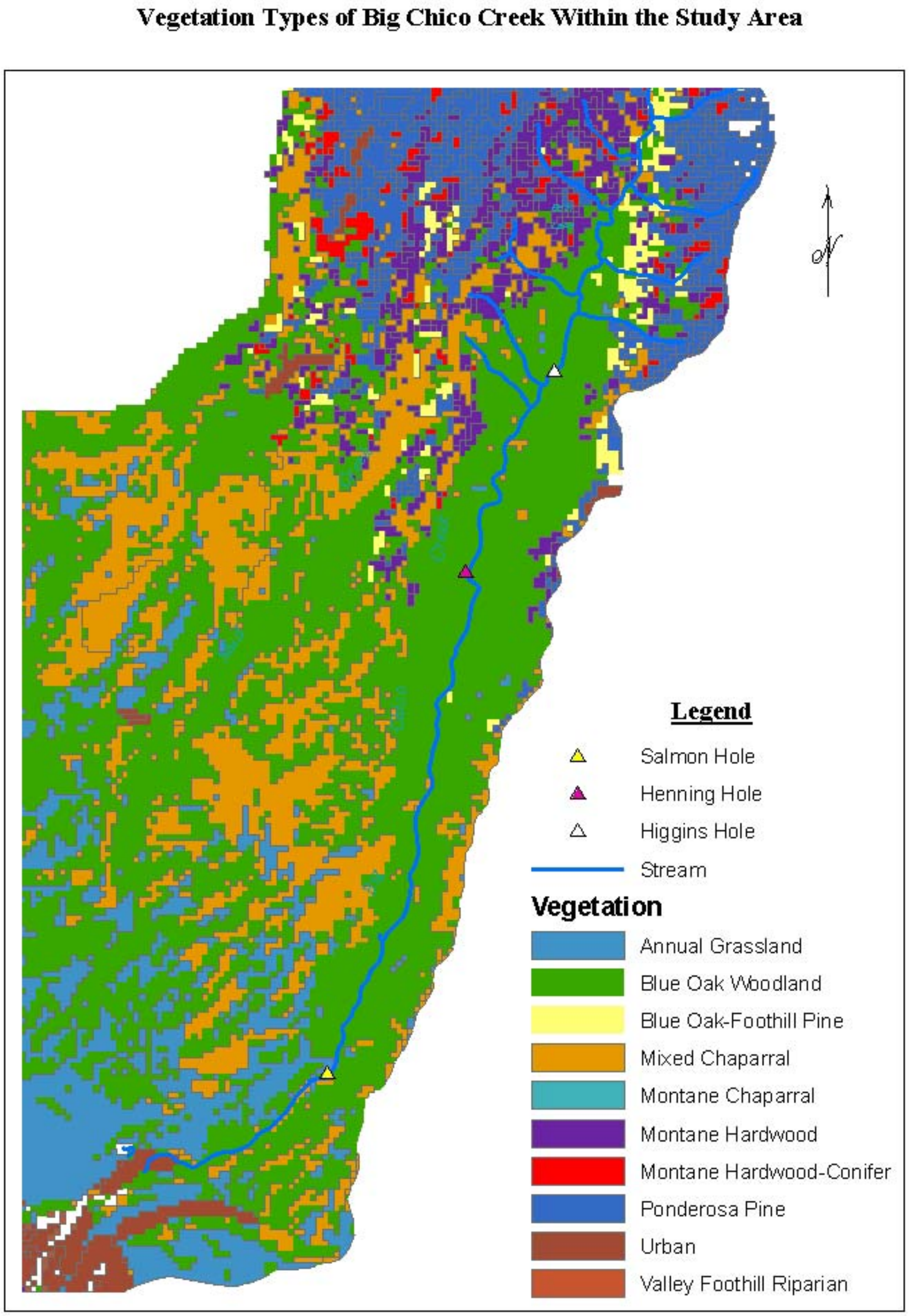
Yoshiyama, R.M., E.R. Gerstung, F.W. Fisher, and P.B. Moyle. 2000. Chinook salmon in the California Central Valley: an assessment. *Fisheries* 25(2):6-20.

Appendix A.



Data Source: California State University, Chico, Geographic Information Center

Appendix B.



Data Source: State of California Vegetation Map (http://casil-mirror1.ceres.ca.gov/casil/gis.ca.gov/teale/vega/)

Appendix C.

Location and Maximum Depth of Potential Holding Habitats

Location of pools identified in BCC as potential holding habitat
(e.g., pools with maximum depth ≥ 1.5 m)

Coordinate System: UTM (Zone 10) Datum: NAD27

Pool Identification	Zone	Easting (m)	Northing (m)	Estimated Max. Depth (m)
Higgins Hole	10S	611925	4416634	9.0-10.0
A	10S	611833	4416448	1.9
B	10S	611809	4416416	1.9
C	10S	611671	4416137	2.2-2.5
D	10S	611091	4415203	1.6-1.9
E	10S	610977	4414862	2.5-2.8
F	10S	610860	4414707	2.5-2.8
G	10S	610885	4414645	2.5
H	10S	611008	4414369	1.6-1.9
I	10S	610961	4414338	1.6-1.9
J	10S	610937	4414307	1.6-1.9
K	10S	610630	4414179	1.9-2.5
L	10S	610663	4413593	1.6-1.9
M	10S	610663	4413563	1.6-1.9
N	10S	610640	4413501	2.5
O	10S	610594	4413407	2.5-2.8
P	10S	610477	4413252	3.1
Henning Hole	10S	610432	4413128	4.4
Q	10S	610433	4413004	1.9-2.2
R	10S	610399	4412109	1.6
S	10S	610306	4411954	1.6-1.9
T	10S	610214	4411706	2.9
U	10S	610144	4411612	2.2-2.8
V	10S	610104	4411118	1.9-2.2
W	10S	609987	4410993	1.9
X	10S	609871	4410776	1.7
Y	10S	609945	4410623	1.7

Z	10S	609901	4410375	1.9
AA	10S	609902	4410314	2.2-2.8
BB	10S	609767	4409757	2.8-3.1
CC	10S	609794	4409510	3.6-3.7
DD	10S	609797	4409356	1.6-1.9
EE	10S	609704	4409201	1.6-1.9
FF	10S	609680	4409170	1.6-1.9
GG	10S	609519	4408797	1.6-1.9
HH	10S	609574	4408305	1.6-1.9
II	10S	609416	4407716	3.3
JJ	10S	609394	4407593	3.1
KK	10S	609306	4407098	1.9
LL	10S	609236	4407005	2.2-2.5
MM	10S	609165	4406942	2.2-2.5
NN	10S	609071	4406879	1.6-1.9
OO	10S	608910	4406476	1.9
PP	10S	608795	4406227	2.2-2.5
QQ	10S	608748	4406165	2.2-2.5
RR	10S	608655	4406010	1.6-1.9
SS	10S	608632	4405948	1.6-1.9
TT	10S	608562	4405854	2.2
Salmon Hole	10S	607988	4404366	3.7

Appendix D.

Mean Stream Temperature at Higgins Hole, Henning Hole, Pool T, and Salmon Hole (07/26/03 – 08/04/03)