State of California
Natural Resources Agency
California Department of Fish and Wildlife

INSTREAM FLOW EVALUATION: Temperature and Passage Assessment for Salmonids in DEER CREEK, Tehama County

STREAM EVALUATION REPORT 17-2

October 2017

Cover photo: Transect at a critical riffle in Deer Creek.

California Department of Fish and Wildlife
Stream Evaluation Report
Report No. 17-2

INSTREAM FLOW EVALUATION: TEMPERATURE AND PASSAGE ASSESSMENT FOR SALMONIDS IN DEER CREEK, TEHAMA COUNTY

October 2017

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California Department of Fish and Wildlife
Water Branch
Instream Flow Program
Report No. 17-2

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Suggested Citation:

CDFW. 2017. Instream Flow Evaluation: Temperature and Passage Assessment for Salmonids in Deer Creek, Tehama County. Report No. 17-2. California Department of Fish and Wildlife Instream Flow Program, Sacramento, CA.

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ABSTRACT

Passage conditions based on water temperature and depth were investigated from 2014 to 2015 for Central Valley spring-run Chinook Salmon (*Oncorhynchus tshawytscha*), fall-run/late fall-run Chinook Salmon, and steelhead (*Oncorhynchus mykiss*), in lower Deer Creek, Tehama County, California. Stream temperature, along with other monitoring data, weather parameters, and amount of riparian shading, were used to develop a predictive Stream Network Temperature Model (SNTEMP). Water temperature data were collected during the two years at monitoring locations throughout lower Deer Creek. Conditions at passage limiting sites were evaluated based on minimum depth and maximum velocity criteria for adult Chinook Salmon and steelhead over a range of flows. The data collected were used to predict the amount of passable channel width meeting the minimum depth criteria for each species. The data and analyses presented here will be used by the California Department of Fish and Wildlife's Instream Flow Program to develop flow criteria for salmonids, to be submitted to the State Water Resources Control Board for their consideration.

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ABBREVIATIONS AND ACRONYMS

°F	degrees Fahrenheit
7DADM	7-day average of the daily maximum temperature
CDEC	California Data Exchange Center
CDFG	California Department of Fish and Game
CDFW	California Department of Fish and Wildlife (previously CDFG)
cfs	cubic feet per second
CR	critical riffle
CRA	critical riffle analysis
DCID	Deer Creek Irrigation District
DWR	California Department of Water Resources
EPA	U.S. Environmental Protection Agency
ESU	Evolutionarily Significant Unit
FDA	Flow Duration Analysis
FRCS	fall-run Chinook Salmon
ft	foot/feet
ft/s	feet per second
GIS	geographic information system
GPS	Global Positioning System
IFG4	Instream Flow Group Model #4
IFIM	Instream Flow Incremental Methodology
in	inch
LFRCS	late fall-run Chinook Salmon
MANSQ	Manning's stage discharge
NAIP	National Agriculture Imagery Program
NMFS	National Marine Fisheries Service
ODFW	Oregon Department of Fish and Wildlife
PHABSIM	Physical Habitat Simulation Model
PRC	Public Resources Code
RM	river mile
SEFA	System for Environmental Flow Analysis
SNTEMP	Stream Network Temperature Model
SOP	standard operating procedure
SRCS	spring-run Chinook Salmon
SVRIC	Stanford Vina Ranch Irrigation Company
SWRCB	State Water Resources Control Board
SZF	stage of zero flow
USBR	United States Bureau of Reclamation
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
XS	cross section
W3T	Water Temperature Transaction Tool
WSEL	water surface elevation
WSP	Water Surface Profile Model

CONVERSIONS

1 cubic foot per second ≈ 2.83×10^{-2} cubic meters per second
1 inch = 2.54 centimeters
1 foot ≈ 30.48 centimeters
1 square mile ≈ 2.59 square kilometers
1 mile ≈ 1.61 kilometers
1 foot ≈ 0.31 meters
°C = (°F - 32) ÷ 1.8

PREFACE

Deer Creek is among the essential streams for recovery and preservation of wild stocks of Central Valley spring-run Chinook Salmon (*Oncorhynchus tshawytscha*), and supports Central Valley anadromous Rainbow Trout (*Oncorhynchus mykiss*), commonly known as steelhead (Armentrout et al. 1998). In addition, Deer Creek is utilized by fall-run Chinook Salmon, late-fall-run Chinook Salmon, and Pacific Lamprey (*Entosphenus tridentatus*). The Recovery Plan for Central Valley Chinook Salmon and Steelhead (NMFS 2014) classified Deer Creek as a high priority Core 1 watershed because of its potential to support independent viable populations. Deer Creek is also identified as a priority stream in the State Water Resources Control Board (SWRCB) Instream Flow Studies for the Protection of the Public Trust Resources: A Prioritized Schedule and Estimate of Cost (SWRCB 2010). As well as the US Fish and Wildlife Service (USFWS) Final Restoration Plan for the Anadromous Fish Restoration Program: A Plan to Increase Natural Production of Anadromous Fish in the Central Valley of California (USFWS 2001).

The California Department of Fish and Wildlife (Department) has interest in ensuring that water flows within streams are maintained at levels that are adequate for long-term protection, maintenance, and proper stewardship of fish and wildlife resources. The Department's Instream Flow Program develops scientific information to determine what flows are needed to maintain healthy conditions for fish and wildlife. For each species of interest, life stage, and stream, relationships between flow and habitat are developed.

The Department recommends using the federal Instream Flow Incremental Methodology (IFIM) to evaluate and develop instream flow criteria for projects that may affect California's aquatic resources. The IFIM process, and instream flow evaluations, in general, should include broad consideration of the structure and function of riverine systems while also providing examination of five core components (i.e., hydrology, biology, geomorphology, water quality, and connectivity) of the riverine system. The Public Resources Code (PRC) §10000-10005 outlines the Department's responsibilities for developing and transmitting flow criteria to the SWRCB for consideration as set forth in §1257.5 of the Water Code. The results from this study are intended to be used, along with other supporting information and data, to identify stream flow requirements necessary for upstream passage of adult Chinook Salmon and steelhead into the Deer Creek watershed pursuant to the Department's PRC mandate. Flow criteria for lower Deer Creek will be developed by the Department in a future document.

1.0 INTRODUCTION

Deer Creek in Tehama County has been identified by the Department as a high priority stream for instream flow assessment. Deer Creek is one of only three Sacramento River tributaries that support a self-sustaining and genetically distinct population of Central Valley spring-run Chinook Salmon (SRCS) in the Sacramento River watershed (NMFS 2014). The Central Valley SRCS Evolutionarily Significant Unit (ESU) is listed as threatened under the state and federal Endangered Species acts. The Deer Creek watershed is considered a conservation stronghold for the SRCS ESU (NMFS 2014). Deer Creek also supports a Distinct Population Segment of Central Valley steelhead, federally listed as threatened, and populations of Central Valley fall and late fall-run ESU Chinook Salmon (FRCS; LFRCS), federally designated as a Species of Concern.

Migrating salmonids require flow levels adequate to provide suitable depths and velocities for successful passage (Bjornn and Reiser 1991). Sustained water depths at essential widths become significant variables for evaluating fish passage opportunities and riverine habitat connectivity in low gradient alluvial river channels (Thompson 1972; Mosley 1982). Naturally occurring low stream flows combined with surface-water withdrawal for anthropogenic uses can interrupt riverine connectivity and limit movement opportunities for anadromous salmonids (Spina et al. 2006), particularly at depth-sensitive critical riffles.

Elevated water temperatures can create a thermal barrier to adult passage, impact juvenile Chinook Salmon and steelhead outmigration, and cause direct or delayed mortality of salmonids (Cramer and Hammack 1952; Harvey-Arrison 2008; DWR 2009). Cramer and Hammack (1952) reported that of the total 10,303 Deer Creek SRCS counted in 1945, 1946, and 1947, nearly 9 percent (864 salmon) died as a result of lethal water temperatures between the Deer Creek Weir, formerly located at River Mile (RM) 6.25, and the downstream confluence with the Sacramento River. Other SRCS mortality incidents below diversions in Deer Creek have been reported and are most likely linked to thermal stress resulting from low flows and delayed passage at diversion structures (M. Johnson, CDFW, pers. comm. 2014). Stream temperature also influences spawning, timing and success of incubation, maturation, growth, and competition, as well as disease and parasite proliferation (Annear et al. 2004).

The upper Deer Creek watershed, upstream of the Deer Creek Irrigation District (DCID) diversion and the canyon mouth, provides ideal cold water holding pools and spawning habitat for SRCS and steelhead. However, agricultural stream diversions in lower Deer Creek, from DCID to the Sacramento River confluence, can result in insufficient stream flows and elevated stream temperatures that can limit the ability of adult SRCS and steelhead to migrate into the upper watershed (Reynolds et al. 1993; McEwan and Jackson 1996; Armentrout et al. 1998; DWR 2005). Inadequate flows also impede adult FRCS and LFRCS from migrating into and accessing their spawning habitat in lower Deer Creek (USFWS 1999), as well as impact outmigration of juvenile salmonids (Johnson and Merrick 2012). Key stressors identified for Central Valley SRCS and steelhead include elevated water temperatures, which affect adult migration and holding and low flows, which affect adult attraction and migratory cues (NMFS 2014).

Stream flow alteration, because of stream diversion, changes water depths and influences water temperatures, which potentially limits the hydrologic connectivity of riverine habitats in lower Deer Creek. Adequate water depths of sufficient width are necessary to enable passage of adult and juvenile salmonids through critically shallow riffle sites. Critically shallow riffles (critical riffles) present in lower Deer Creek are potential barriers to upstream and downstream passage. Critical riffle barriers may be impeding adult SRCS and steelhead movement from the Sacramento River into holding and spawning areas in the upper watershed, as well as hampering adult FRCS and LFRCS migration into the lower watershed, where they spawn and rear.

1.1 Study Goals and Objectives

The goal of this study is to evaluate flow and temperature regimes necessary for successful adult SRCS and steelhead migration to their holding and spawning habitat above the DCID Diversion Dam. This study will quantify stream flows, associated with water temperatures and depths, that are adequate to ensure adult salmonid migration is possible through lower Deer Creek (i.e., the stream reach between the Sacramento River confluence and the DCID Diversion Dam at RM 11.8). Stream flows that are protective for passage of adult salmonids are expected to be adequate for juvenile salmonids, when both life stages are present (CDFG 2012).

The primary objective of this study is to understand the instream flow and temperature regimes needed for long-term protection and maintenance of adult salmonid migration through the natural stream channel in lower Deer Creek. Objectives of this study include: 1) the evaluation of passage impediments in the study reach through use of Critical Riffle Analysis (Thompson 1972; CDFG 2012); and 2) evaluation of the water temperature regimes in the study reach using a predictive stream temperature model. Results of this study will be used to develop flow criteria that support upstream passage of adult SRCS and steelhead through lower Deer Creek into the upper watershed. Results will also be used to determine flows necessary to support migrating adult FRCS and LFRCS into the Deer Creek valley floor, as well as flows necessary to support benthic macroinvertebrate production, which provide a vital food source for salmonids.

1.2 Description of Watershed

Deer Creek originates near the summit of Butt Mountain in the Lassen National Forest at approximately 7,320 feet (2.2 km) in elevation (NMFS 2014; Figure 1). Deer Creek flows for approximately 60 miles (97 km) in a southwesterly direction, passing through meadows and dense forests before descending rapidly through a steep rock canyon into the Sacramento Valley. Upon exiting the canyon, Deer Creek flows across the valley floor and enters the Sacramento River approximately one mile west of the town of Vina, at an elevation of approximately 180 feet (55 m; NMFS 2014).

The upper Deer Creek watershed, referred to in this report as the area upstream of the DCID diversion and canyon mouth (Figure 1), is located primarily on Lassen National Forest lands. Two natural falls are located in the upper Deer Creek watershed: Lower Deer Creek Falls (approx. RM 43) and Upper Deer Creek Falls (approx. RM 48). Lower Deer Creek Falls has a functioning fish ladder; however, the existing structure does not meet Department or National Marine Fisheries Service (NMFS) hydraulic criteria for fish passage. Therefore, a fish passage improvement project is planned for Lower Falls (TEC 2016). Upper Deer Creek Falls represents the natural limit of anadromy for SRCS. Upper Deer Creek Falls has a fish ladder that was operated from late fall to early spring to allow steelhead migration (DCWC 1998), though it is no longer opened (K. Gale, CDFW, pers. comm. 2014). The upper Deer Creek watershed also has private commercial timberlands with large private ranches in the mid- and lower-elevation areas. Irrigated agricultural lands on the valley floor are mainly pastures and orchards (SRWP 2010).

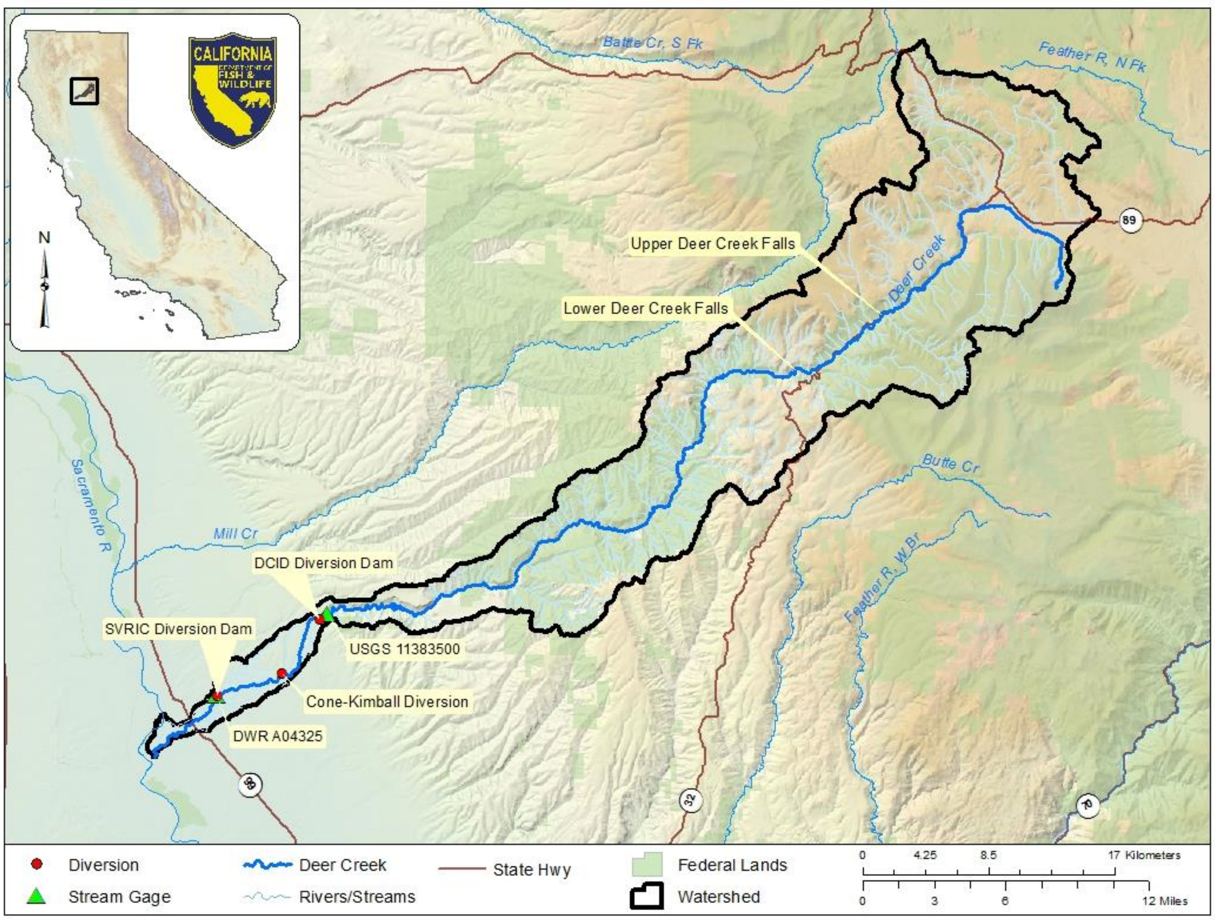

Figure 1. Deer Creek watershed map.

1.3 Deer Creek Hydrology and Water Supply

The Deer Creek watershed drains 208 square miles (539 km^2) and produces on average 233,700 acre-feet of water per year (USGS 2013). High flow events occur December through February, during which peak flows are dominated by rain-on-snow events (NMFS 2014). Deer Creek maintains a perennial flow as it travels from the upper mountains, through the meadows and canyons to the valley floor (McManus 2004).

Between the Deer Creek canyon mouth and the Sacramento River, two irrigation organizations operate three diversion dams and four diversion ditches (NMFS 2014). DCID operates the DCID Diversion Dam near the canyon mouth (RM 11.8). Stanford Vina Ranch Irrigation Company (SVRIC) operates the SVRIC Diversion Dam at RM 5.0, and the Cone-Kimball Diversion located on a side channel adjacent to RM 8.2 (Figure 1). The DCID Diversion Dam does not have a fish ladder; however, temporary fish ladders have been installed in previous years to assist in adult Chinook Salmon migration. During portions of the year, the DCID Diversion Dam can become partially impeded or block fish passage, and a fish passage improvement project is needed (DWR 2014). The SVRIC Diversion Dam diversions are screened, and ladders located on the north and south banks provide fish passage. However, passage at the SVRIC Diversion Dam ladders is deficient based on NMFS and CDFW criteria, and a fish passage improvement project is needed (M. Johnson, CDFW, pers. comm. 2017).

In 1923, the superior court adjudicated 100 percent of the flow in Deer Creek to SVRIC and DCID, with SVRIC receiving 65 percent and DCID receiving 35 percent (Superior Court of the State of California 1923; Court Decree Number 4189 November 27, 1923 SVRIC vs. Charles Dicus). In 1926, the adjudication was amended, granting approximately 66 percent of Deer Creek flow to SVRIC, 33 percent to DCID, and 1 percent to Sheep Camp Ditch for stock watering (McManus 2004). The irrigation companies have a combined maximum diversion rate estimated at 115 cfs, as reported for 2010-2011 to the State Water Resources Control Board Electronic Water Rights Information Management System.

Two gaging stations collect stream flow and water temperature data in Deer Creek, one upstream of all the diversions and one downstream. The U.S. Geological Survey (USGS) operates the upstream gage, USGS 11383500 (California Data Exchange Center [CDEC] station ID: DCV for Deer Creek near Vina), located at the mouth of the canyon at RM 12.3. USGS 11383500 is located above all diversions and represents unimpaired flow for Deer Creek. The California Department of Water Resources (DWR) operates the downstream gaging station, DWR A04325 (CDEC station ID: DVD for Deer Creek below Stanford Vina Dam), located just below the SVRIC Diversion Dam at RM 5.0. DWR A04325 started reporting flow in 1997. The station is rated for low flow only; the highest rated flow for this gage is 428 cfs (D. Ables, DWR, pers. comm. 2015).

Certified flow and water temperature gage data were from the USGS National Water Information System for USGS 11383500 (https://waterdata.usgs.gov/nwis), and the DWR Water Data Library for DWR A04325 (http://www.water.ca.gov/waterdatalibrary/). Gaps in monitoring data represent instances where certified data were not available.

To assess hydrologic regimes of lower Deer Creek, the probability of a particular stream flow occurring was calculated by means of a flow duration analysis, which estimates the likelihood a stream discharge is equaled or exceeded (CDFW 2013b). The likelihood is expressed as a percent of exceedance probability, and is referred to as the exceedance flow. Exceedance flows are typically used as a guideline for describing watershed hydrology and informing decisions regarding water resources management (Bovee et al. 1998). The exceedance probabilities of the daily flow reported at USGS 11383500 (water years 1912 to 2015, excluding water years 1916 through 1920 due to incomplete records) are plotted in Figure 2. The unimpaired flows by month over a standard range of percent probability of exceedance, is given in Table 1.

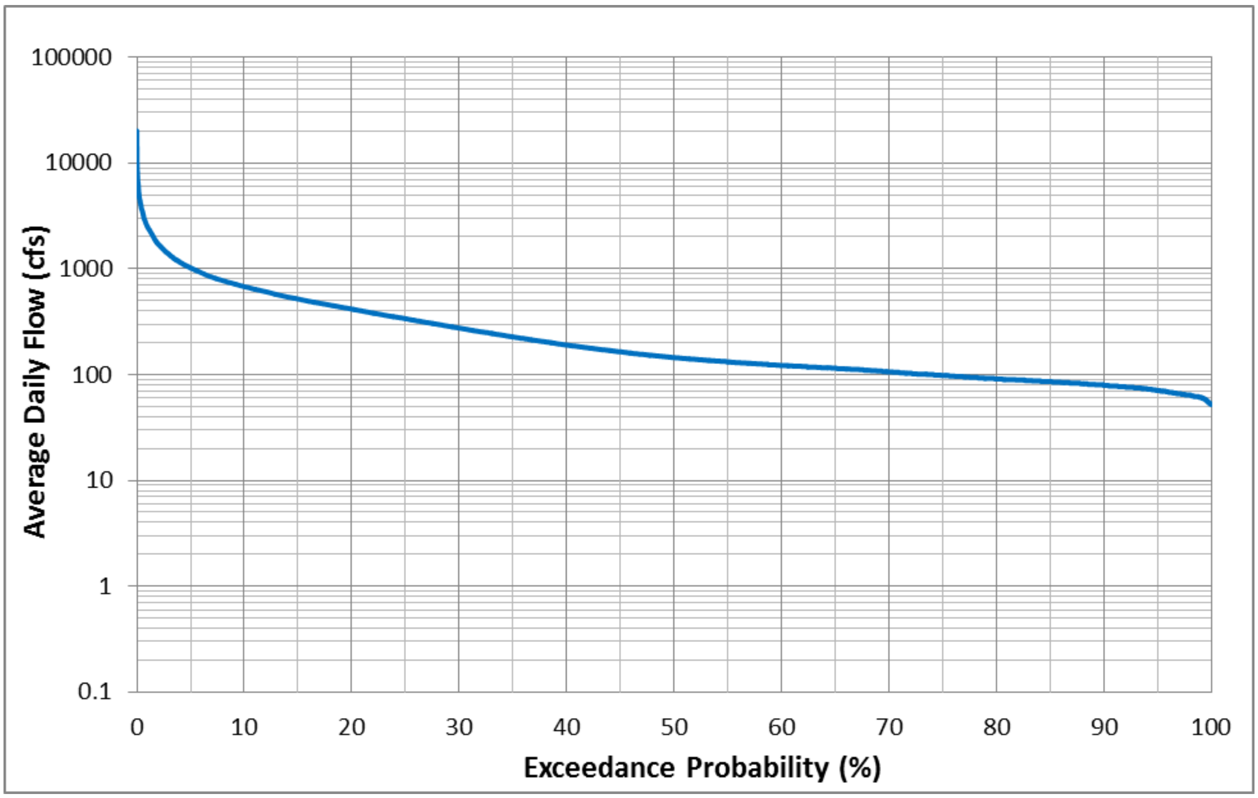

Figure 2. Percent exceedance of unimpaired Deer Creek flows based on average daily flows from USGS 11383500 for water years 1912-2015 (excluding water years 1916-1920).

Table 1. Unimpaired exceedance flows in Deer Creek from USGS 11383500 for water years 1912-2015 (excluding water years 1916-1920).

	Flow (cfs)											
Exceedance	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
90%	72	80	89	105	135	186	178	120	91	72	66	65
80%	79	89	104	122	169	237	245	158	103	82	74	73
70%	85	99	120	142	209	294	304	199	118	89	79	78
60%	90	109	129	172	264	341	363	246	135	95	85	84
50%	96	117	147	220	337	405	432	289	151	104	90	90
40%	104	126	182	293	420	475	504	369	178	116	98	96
30%	113	140	264	426	568	566	597	462	216	133	110	105
20%	121	172	422	645	815	712	727	595	270	152	123	114
10%	135	280	820	1150	1350	1090	952	788	380	182	139	125

Water year types are used to describe interannual variability in watershed water supply. Since Deer Creek is located in the Sacramento Valley, water year designations in this report are based on the Sacramento Valley Eight River Index, reported by the DWR update to Bulletin 120 (DWR 2016). The five-year span from water year 2011 to 2015 is used here to describe recent environmental conditions. These five years represent a variety of water year types, but do lean towards drier conditions with both 2014 and 2015 being classified as critically dry years. 2011 was a wet year, 2012 was a below normal year, and 2013 was a dry year.

The average daily flow is plotted in Figure 3 for gages USGS 11383500 and DWR A04325, in water year 2014. Flow levels between the upstream (USGS) and downstream (DWR) gages are similar between mid-October and early March. Flows recorded at DWR A04325 were lower for the remainder of the year. The maximum difference between the gages is approximately 78 cfs at the end of May. Plots for 2011 through 2013, and 2015 are provided in Appendix A.

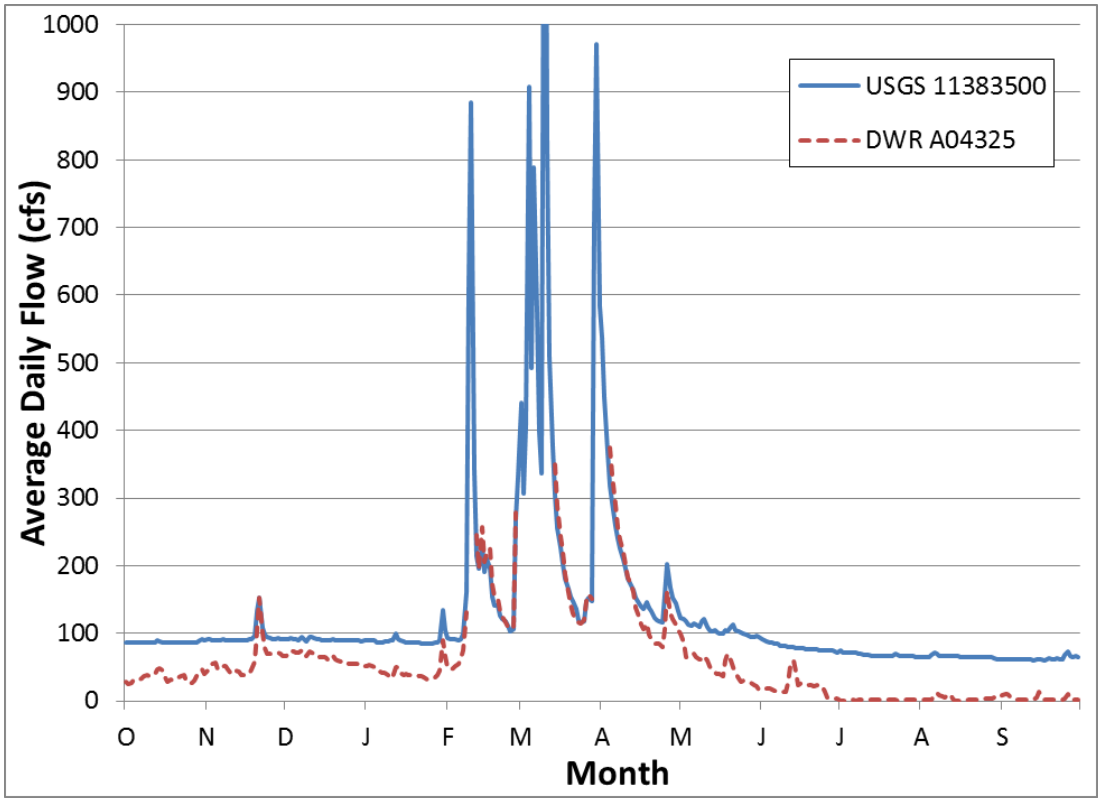

Figure 3. Average daily flow (cfs) at monitoring gages in Deer Creek for water year 2014 (months abbreviated).

1.4 Watershed Temperature Conditions

Water temperatures in upper Deer Creek remain cold year round. However, in lower Deer Creek, warm water temperatures exacerbated by stream diversions potentially impede salmonid migration. Harvey-Arrison (2008) reported that the 2007 SRCS migration in Deer Creek may have been truncated in mid-May as a result of attraction flows dropping below 40 cfs with concurrent water temperatures measuring above 65 degrees Fahrenheit (°F). Ideal water temperatures for upstream migration of adult Chinook Salmon range from 57°F to 67°F in Deer Creek (DCWC 1998). However, Cramer and Hammack (1952) reported that lethal water temperatures of 81°F to 82°F occur every summer in lower Deer Creek, below SVRIC. To understand the relationship between water temperature and fish passage, this study evaluated historical data from the two permanent monitoring gages as well as developed a predictive water temperature model.

Water Temperature

USGS has reported the minimum, maximum, and median water temperature for USGS 11383500 since October 1998. DWR has reported water temperature in 15-minute increments at DWR A04325 since October 1998. The median daily water temperature, reported at the upstream USGS gage and downstream DWR gage, were plotted for five recent water years, 2011 through 2015. The results from 2014 are given in Figure 4. The median daily water temperature for water years 2011 through 2013, and 2015, are presented in Appendix A. Temperature differences between USGS 11383500 and DWR A04325 in water year 2015 could not be evaluated past June 6, 2015, as USGS gage data was unavailable. In water year 2014, a critically dry year, the median daily water temperature between the gages differed throughout the year, by up to 8.8°F. In addition, on July 14, 2014, median water temperature at DWR A04325, the downstream gage, peaked at 83.5°F; median water temperature at USGS 11383500, the upstream gage, was 78.6°F on the same date. By comparison, in the wet year of 2011, median water temperatures between the two gages were similar in winter months, and did not begin to diverge until February. Median water temperature at DWR A04325 peaked at 76.2°F on July 30, 2011; at USGS 11383500 median water temperature reached 73.0°F on the same date.

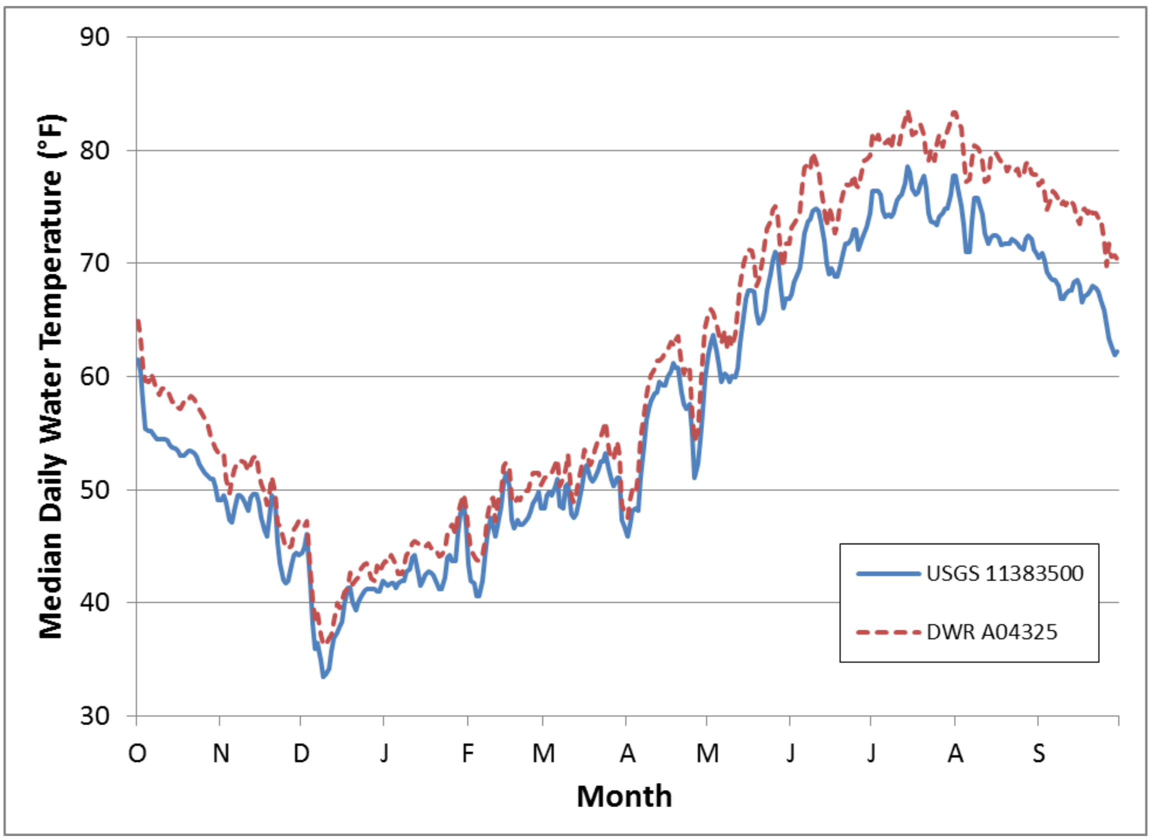

Figure 4. Median daily water temperature (°F) for Deer Creek in 2014 water year (months abbreviated).

Air Temperature

Ambient air temperature is an important parameter that may affect predicted water temperatures in the study reach (Jowett, Payne, and Milhous 2013). Ambient air temperature is estimated for the study reach by averaging daily data from the Chico Municipal Airport and Red Bluff Municipal Airport weather stations. The stations report maximum, mean, and minimum daily air temperature. Similar to water temperature, ambient air temperature was plotted for five recent years, 2011 through 2015. The data for water year 2014 is given in Figure 5. Water years 2011 through 2013 and 2015 are given in Appendix A.

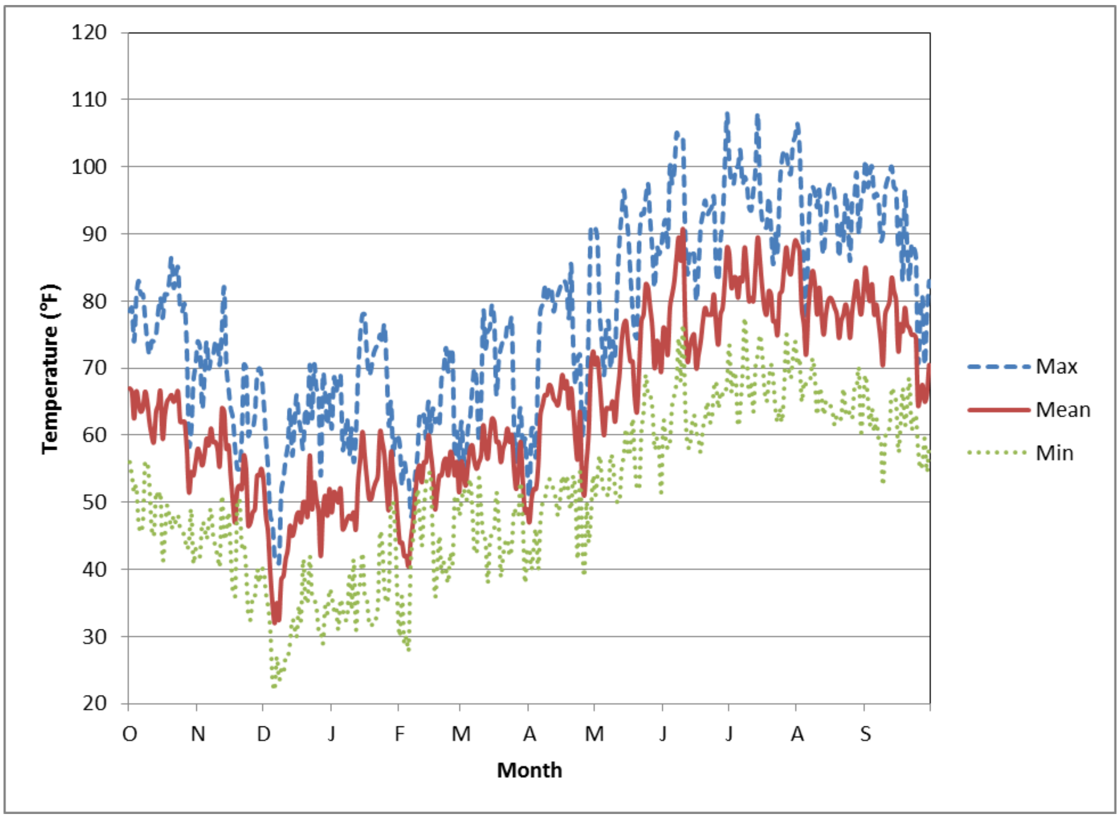

Figure 5. Estimated daily air temperature (°F) for the study reach in 2014 water year (months abbreviated).

EPA Criteria

The U.S. Environmental Protection Agency (EPA) published water temperature criteria in 2003 for salmonids in the Pacific Northwest (EPA 2003). Since that time, those criteria have been applied in California. The EPA criteria use the maximum seven day average of the daily maximum temperature (7DADM). EPA established thresholds of 7DADM for various species and life stages of salmonids including migration of Chinook Salmon (refer to EPA 2003, Table 3, p. 25). The EPA criteria indicate that under summer maximum conditions, for areas where non-core juvenile rearing may occur along with adult migration, the 7DADM is 64°F. In areas where only adult migration occurs, the 7DADM is 68°F.

While the EPA criteria provides important temperature thresholds, use of the 7DADM should take into account: 1) the EPA criteria were developed for salmonids in the Pacific Northwest states of Washington, Oregon, and the northern-most portions of California; and 2) the criteria does not take into account the effects of climate change. This report considers the EPA criteria when evaluating the monitoring data provided from the USGS and DWR gages that reported maximum daily temperatures. The historical monitoring data is used (section 1.5, Fish Passage Conditions) to indicate water temperature conditions, with respect to fish passage data collected by the Department, in the study reach. The Stream Network Temperature (SNTEMP) model employed here was designed to predict average daily temperature, but can be used to predict maximum daily temperatures. Models that can be calibrated and validated to predict maximum daily temperatures necessary for applying the 7DADM metric typically use hourly based time steps and are more complex than the SNTEMP model applied here. Maximum daily temperatures were simulated using the SNTEMP model to identify possible trends in 7DADM between years of varying water type, recognizing the ability of the model to predict maximum daily temperatures is limited.

1.5 Deer Creek Salmonids

The relatively natural physical habitat and unimpaired flow regime in upper Deer Creek supports a high degree of native fish and fauna rarely seen in other Californian streams (DCWC 1998). Deer Creek provides approximately 42 miles (67.6 km) of anadromous salmonid habitat, and is one of three streams supporting a self-sustaining, genetically distinct wild population of Central Valley SRCS (CDFG 1998; NMFS 2014). Deer Creek is especially important because of its consistent and natural production of Central Valley SRCS (DCWC 1998). Deer Creek has also been identified as having a high potential for restoring wild steelhead populations in the Central Valley. In addition, FRCS and LFRCS utilize the lower reaches of Deer Creek and generally spawn in the valley floor (DCWC 1998).

Migration Timing

The annual timing of when salmonid species life stages are expected to occur in Deer Creek is presented in Table 2. Migrating adult SRCS enter Deer Creek from late February through early August (based on Mill Creek timing; Van Woert 1964), quickly travel through lower Deer Creek, and over-summer in cooler water pools in the upper watershed (Johnson and Merrick 2012). SRCS begin spawning in late September, over a distance of approximately 30 miles (48 km) starting downstream of the Ponderosa Bridge, crossing and extending to Upper Deer Creek Falls (Armentrout et al. 1998).

Adult FRCS migrate into Deer Creek starting late September, but more typically in October and November after being prompted by pulses of flow resulting from seasonal rains (DCWC 1998), or following the termination of agricultural diversions (M. Johnson, CDFW, pers. comm. 2016). Adult LFRCS migrate into Deer Creek from December through February (M. Johnson, CDFW, pers. comm. 2016). Adult FRCS and LFRCS spawn primarily in the valley floor of Deer Creek, with most of the adult fish spawning downstream of the DCID Diversion Dam. While field observations have noted that the DCID Diversion Dam sometimes blocks passage of FRCS, field observations have detected FRCS redds to approximately six miles upstream of the DCID Diversion Dam (M. Johnson, CDFW, pers. comm. 2016). FRCS typically spawn from October through December, shortly after migration. LFRCS spawn from January through mid-April (Armentrout et al. 1998).

Steelhead typically enter Deer Creek from late-September through June, with peak runs in the fall (October–November) and late winter/early spring (January–March; Killam, Johnson, and Revnak 2016). A report by the Deer Creek Watershed Conservancy indicates that adult steelhead migrate further upstream in Deer Creek than SRCS, and spawn shortly after migration in late-winter through spring (DCWC 1998).

Table 2. Adult migration timing and juvenile presence for salmonids in lower Deer Creek. Shading indicates timing span, with darker shading indicating months of peak movement.

Species/Life Stage	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Spring-run Chinook Salmon												
Adult SRCS[3,4,5]												
Juvenile SRCS[6,7]												
Fall-run Chinook Salmon												
Adult FRCS[3,4,5]												
Juvenile FRCS[6,7]												
Late Fall-run Chinook Salmon												
Adult LFRCS[3,4]												
Juvenile LFRCS[6,7]												
Steelhead												
Adult steelhead[3,4]												
Juvenile steelhead[6,7]												

[3] Van Woert. May 25, 1964. Department of Fish and Game Memorandum: Mill Creek Fish Counting Station. Adult spring-run Chinook salmon counted upstream through the Fishway at Clough Dam during the ten-year period 1954-63.
[4] California Department of Fish and Wildlife Mill Creek Video Station. Adult spring-run Chinook salmon counts, Upper Sacramento River Basin Salmonid Monitoring Annual Reports 2011 through 2014, and Office Files 2009-2010 and 2015 through 2016.
[5] Needlam, Hanson, and Parker. June 30, 1943. Supplementary Report on Investigations of Fish-Salvage Problems in Relation to Shasta Dam. United States Department of the Interior. Fish and Wildlife Service.
[6] Johnson and Merrick. 2012. Juvenile Salmonid Monitoring Using Rotary Screw Traps in Deer Creek and Mill Creek, Tehama County, California Summary Report: 1994-2010. California Department of Fish and Wildlife.
[7] California Department of Fish and Wildlife Red Bluff Fisheries Office, Office Files. Lower Mill Creek snorkel juvenile salmonid snorkel investigation field notes 2012 through 2016.

Fish Passage Conditions – Video Monitoring Station

A video monitoring station located at SVRIC Diversion Dam began recording the upstream movement of SRCS in 2014 (Killam, Johnson, and Revnak 2015, 2016). This data was used to detect trends between passage, flow, and water temperature. Both 2014 and 2015 fish passage data are summarized in Figure 6 as cumulative percent of total. In both critically dry water years, SRCS adults primarily moved through the study reach from early March through mid-May.

Daily fish counts at the video station were plotted for 2014 and 2015 and are provided in Figures 7 and 8, respectively. In 2014, a total of 830 adult SRCS were estimated to have passed the video station; in 2015, a total of 268 adult SRCS were counted (Killam, Johnson, and Revnak 2015, 2016). Overall passage dates were similar for the two critically dry years, with fish passing SVRIC Diversion Dam from February 27 to June 4 in 2014, and from February 21 to June 4 in 2015. By April 12, 50 and 52 percent of adult SRCS had passed the SVRIC Diversion Dam in 2014 and 2015, respectively.

Included in Figures 7 and 8 are the average daily flows recorded at the upstream USGS 11383500 gage and downstream DWR A04325 gage. Also included in the figures are estimates of the first day when the 7DADM water temperature was exceeded each year, estimated from 15-minute data recorded at DWR A04325. The longer segmented, orange line refers to the 64°F 7DADM and the dotted orange line refers to the 68°F 7DADM.

Several observations stood out while assessing the 2014-2015 passage data. 1) The approximate difference in the flows between the upstream and downstream gage at the end of the SRCS passage season was roughly 70 cfs both years. 2) More than half of all fish passed by the time the 68°F 7DADM threshold was exceeded in each year. 3) Pulse flow events coordinated by the Department with DCID in 2014[8] and 2015[9] can be seen by the peaks in the DWR A04325 gage flows, below the steady USGS 11383500 gage flows. 4) Fish movement upstream was evident in response to the pulse flow events.

The ability to draw conclusions on SRCS passage from the video monitoring data is limited. While both 2014 and 2015 were classified as critically dry years, the spring flow events that likely influenced passage opportunities in 2014 were nonexistent in 2015. Additionally, the effects of water temperature on fish passage are difficult to assess,

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[8] Memorandum of Understanding by and between Deer Creek Irrigation District and California Department of Fish and Wildlife. 2014. Available at: https://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/docs/mill_deer_antelope_creeks/deer_mou_cdfw_dcid.pdf

[9] Memorandum of Understanding by and between Deer Creek Irrigation District and California Department of Fish and Wildlife. Deer Creek. 2015. Available at: https://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/docs/mill_deer_antelope_creeks/mou_dcid_cdfw20150316.pdf

given that 75 and 69 percent of the SRCS had already passed before the 7DADM had exceeded 68°F in 2014 and 2015, respectively. However, the video passage data does suggest that flows supporting upstream passage are needed from late February through at least early June, with peak migration occurring in March and April. In general, higher flows and lower water temperatures in the later months could allow for broader run timing and life history expression.

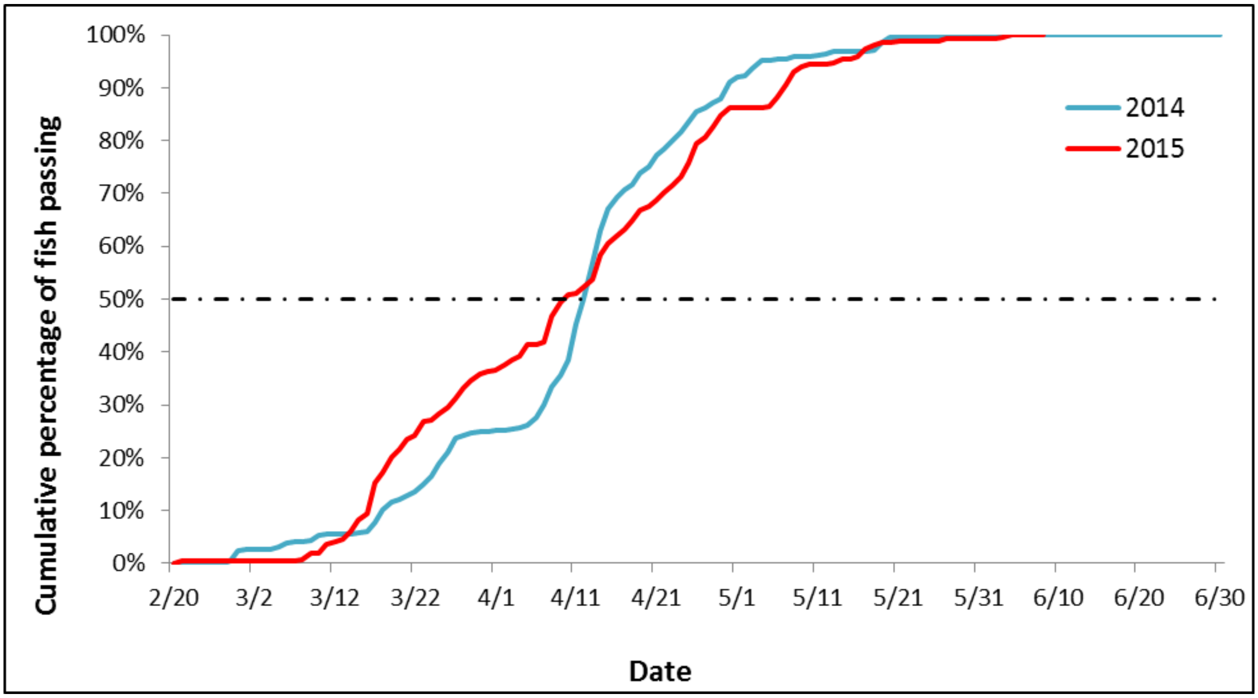


Figure 6. Cumulative percent of total adult SRCS passage from the Deer Creek video station, 2014-2015.

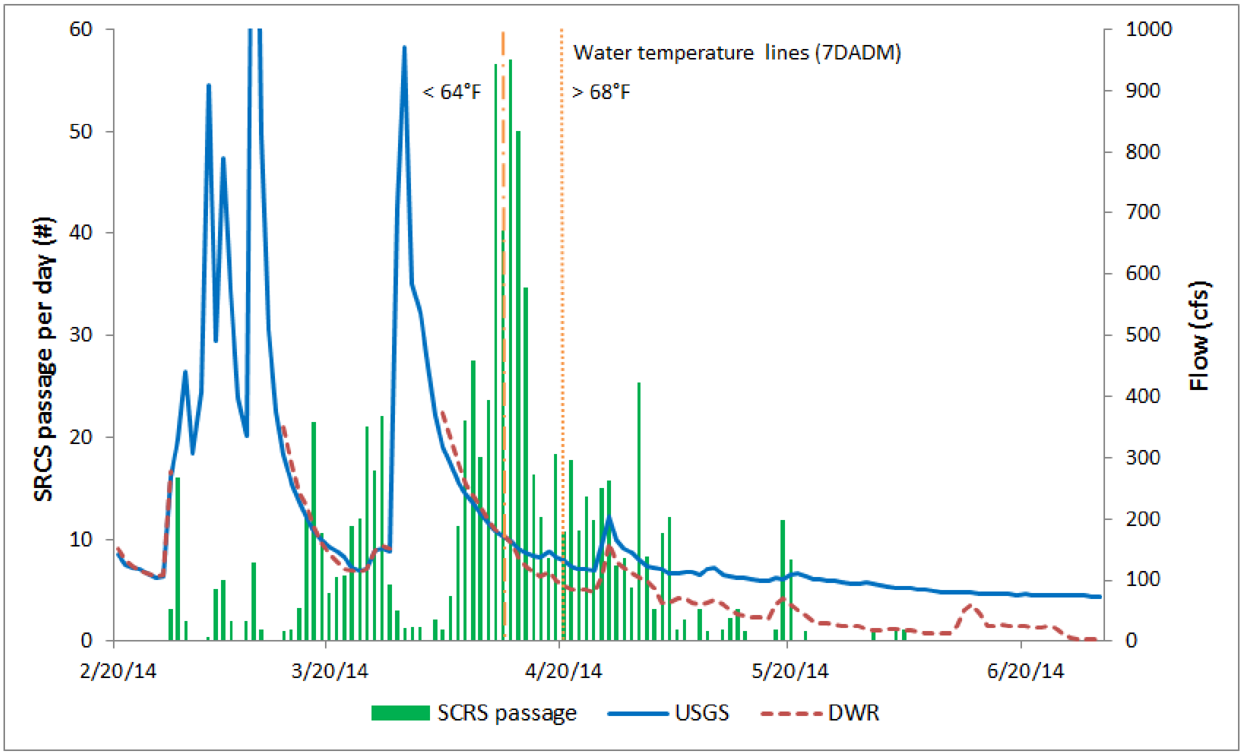


Figure 7. Video station data, average daily flows, and EPA criteria for 2014.

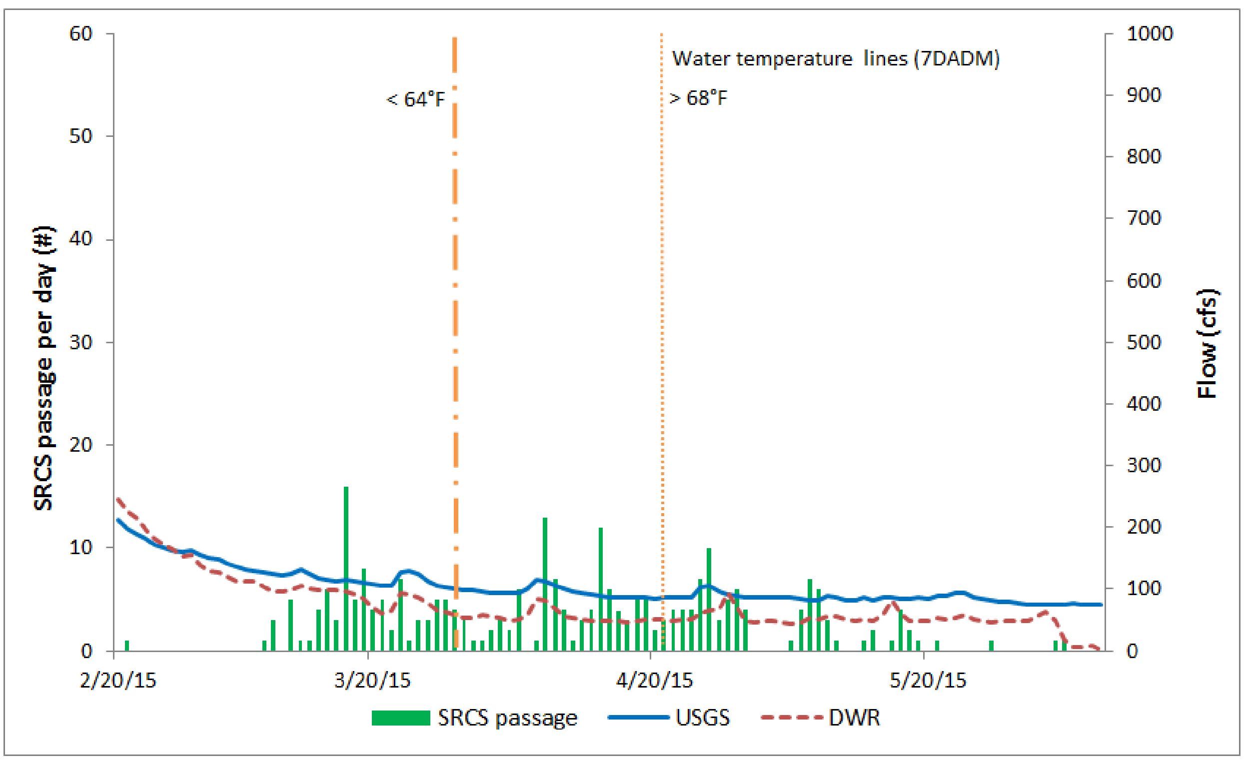


Figure 8. Video station data, average daily flows, and EPA criteria for 2015.

Historically steelhead have not been well studied in Deer Creek. However, monitoring increased following the installation of the video monitoring station at SVRIC in February of 2014. Observations from the video monitoring station indicate that current Deer Creek steelhead run-timing and population sizes are similar to those observed in nearby Mill Creek (M. Johnson, CDFW, pers. comm. 2017). A total of 201 steelhead were counted during the 2014-2015 run (Killam, Johnson, and Revnak 2016).

2.0 METHODS

Selection of appropriate methods for an instream flow assessment is a fundamental step of the Instream Flow Incremental Methodology (IFIM; Bovee et al. 1998). While the most commonly applied components of the IFIM process are hydrology and biology (Dunbar et al. 1998), aquatic habitat connectivity is an equally important and often overlooked element (Fullerton et al. 2010). Aquatic habitat connectivity between Deer Creek's confluence with the Sacramento River and upper Deer Creek, above the DCID diversion and canyon mouth, is essential if adult SRCS and steelhead are to reach cool-water summer holding pools. Methods were chosen to assess Deer Creek's connectivity, focusing on passage requirements necessary for adult salmonids to migrate through the lower Deer Creek watershed. Passage requirements include physical parameters (i.e., depth and velocity though shallow critical riffles), as well as temporal conditions (i.e., temperature regimes), required for passage through the lower watershed.

Critical riffles (i.e., depth sensitive riffles with less than 4 percent gradient, and substrate dominated by gravel and cobble) are features that potentially limit fish passage if stream flows do not allow for sufficient passage depths to be maintained during migration periods. Critical Riffle Analysis (CRA) involves identifying the most critical riffles through a riffle inventory in the study reach (see section 3.0 Site Selection), and measuring water depth along the shallowest course across each riffle, over a wide range of flows. Suitability of water velocity across the riffle is also assessed. The association between riffle depth and flow can then be used to create empirical relationships based on the percent total and contiguous width meeting specified depth and velocity criteria available to migrating fish.

In addition to assessing salmonid passage over critical riffles, the Wetted Perimeter method was conducted to evaluate if a summer low flow, necessary to maintain critical habitat conditions for ecological function and benthic macroinvertebrate production, could be determined (CDFW 2013d). Unless outside energy sources are greater than food resources instream, effective fisheries management should account for macroinvertebrate resources and habitat (Wallace and Webster 1996). A visual survey of potential Wetted Perimeter sites was conducted between the Sacramento River confluence (RM 0.0) and the SVRIC Diversion Dam (RM 5.0). Representative riffles having rectangular streambed profiles with typical geomorphic structure were identified and selected for further analysis (see section 3.0 Site Selection). The Wetted Perimeter method uses a plot of the wetted perimeter versus discharge as a surrogate for physical habitat to determine a minimum instream flow for the low flow period. It assumes that the minimum flow will protect the food producing riffle habitats at a level sufficient to maintain resident fish populations (Annear et al. 2004).

Water temperatures elevated above natural levels in salmonid streams is a growing concern of the Department and stakeholders because elevated water temperatures in the study reach may act as a thermal barrier to upstream salmonid migration. To address this, a predictive water temperature model was developed to evaluate the impact of reduced flows in the study reach. Stream temperatures in the study reach were monitored and modeled using a Stream Network Temperature model (SNTEMP; Theurer, Voos, and Miller 1984). The SNTEMP model is a standard method for water temperature modeling used in instream flow studies (Annear et al. 2004). The SNTEMP model was designed to predict the average daily water temperature and can be used to predict maximum daily water temperatures throughout a stream system network.

2.1 Critical Riffle Analysis

CRA is an empirical method used to determine flow rates necessary for passage of a specified fish species and life stage. The Department developed a Standard Operating Procedure (SOP) for Critical Riffle Analysis for Fish Passage in California (CDFG 2012) based upon Thompson (1972). The Oregon Department of Fish and Wildlife (ODFW) developed the Thompson procedure (1972) specifically for identifying stream flows necessary for passage of migrating salmonids through depth-sensitive critical riffles (Bjornn and Reiser 1991; Reiser et al. 2006). The Department's CRA SOP was developed to evaluate and identify stream flows necessary to protect anadromous salmonid migratory needs, and overall riverine habitat connectivity, in California streams and rivers. Critical riffles are defined as the shallowest riffles in a stream channel and are considered particularly sensitive to changes in stream flow level. As flows diminish in a stream channel, the critical riffles will contain the shallowest water depths, potentially reducing the channel's overall hydraulic connectivity and/or restricting the movement of aquatic species such as adult Chinook Salmon.

CRA requires that the riffles in each stream reach are inventoried and ranked to identify passage-limiting locations. One or more critical riffles from each reach are subsequently evaluated. A transect is established across each critical riffle, following the shallowest course from bank to bank (Figure 9). Water depth and velocity data are collected along a given transect over a minimum of three flow events, containing at least one measurement per flow event where the depth criteria is met, and across a range of representative flows. Stream discharge rates and correlating feet of transect meeting the depth and velocity criteria are then plotted to determine the flows necessary for salmonid passage.

Figure 9. Critical riffle analysis transect along the shallowest course from bank to bank at riffle CR31 in lower Deer Creek. Photo looking downstream.

In accordance with the Department CRA SOP (CDFG 2012) and Thompson (1972), depth and velocity criteria were used to assess critical riffles; criteria are presented below in Table 3. A site is deemed passable when a combination of minimum stream flow depths and wetted widths are greater than the percentage of the maximum transect length meeting the life stage-specific depth criteria and the contiguous percentage of the maximum transect length meeting the life stage-specific depth criteria (Thompson 1972).

Suitability of stream velocities that support passage were assessed at each riffle (Thompson 1972). Passage velocities have been established based on the perceived swimming abilities of salmon and trout to pass over barriers. A maximum passage velocity of 8.0 feet per second (ft/s) is considered appropriate for adult Chinook Salmon and steelhead (Thompson 1972; Table 3).

The minimum depth criteria used in CRA is based on the water depth needed for a salmonid to adequately navigate over a critical riffle with sufficient clearance underneath it, so that contact with the streambed and abrasion are minimized (R2 Resource Consultants 2008). The minimum depth passage criteria for adult Chinook Salmon, adult steelhead, and juvenile salmonids is 0.9 ft, 0.7 ft, and 0.3 ft, respectively (CDFG 2012; Table 3). Where migration timing overlaps (see Table 2), the deeper body depth criteria must take precedence to protect all species and life stages present. Since adult salmonid timing coincides with juvenile timing, results will only be presented for adult Chinook Salmon and adult steelhead due to their deeper body depth criteria.

Table 3. Depth and velocity criteria for adult and juvenile salmonid passage.

Species (life stage)	Minimum Depth (ft)	Maximum Velocity (ft/s)
Chinook Salmon (adult)	0.9	8.0
Steelhead (adult)	0.7	8.0
Salmonid (young-of-year/juvenile)	0.3	---

Source: Thompson 1972; R2 Resource Consultants 2008; CDFG 2012.

2.2 Wetted Perimeter

There are two main approaches to conducting Wetted Perimeter analysis; a field-based approach and a model-based approach. The field based approach requires a minimum of ten site visits at prescribed flow events to generate a relationship between flow and wetted perimeter. A modeling approach uses a single flow field measurement and computer program based on Manning's equation to develop a relationship between streamflow and wetted perimeter. This study utilizes the modeling approach. To derive a Manning's n value representative of the low flow period, data collection targeted a flow no greater than the 80 percent annual exceedance flow (i.e., 91 cfs).

The Wetted Perimeter method requires a graphical plot to be generated showing the relationship between wetted perimeter and discharge. This plot has a maximum visual breakpoint which represents the lower ecosystem threshold flow. Flow below this level is indicative of rapidly declining aquatic invertebrate food production. Often, an upper point of curvature will also be visible on the wetted perimeter versus discharge graph (the incipient asymptote); this represents the upper ecosystem threshold flow, which provides for optimum or near optimum food production at the riffle (Figure 10; Annear et al. 2004; CDFW 2013d).

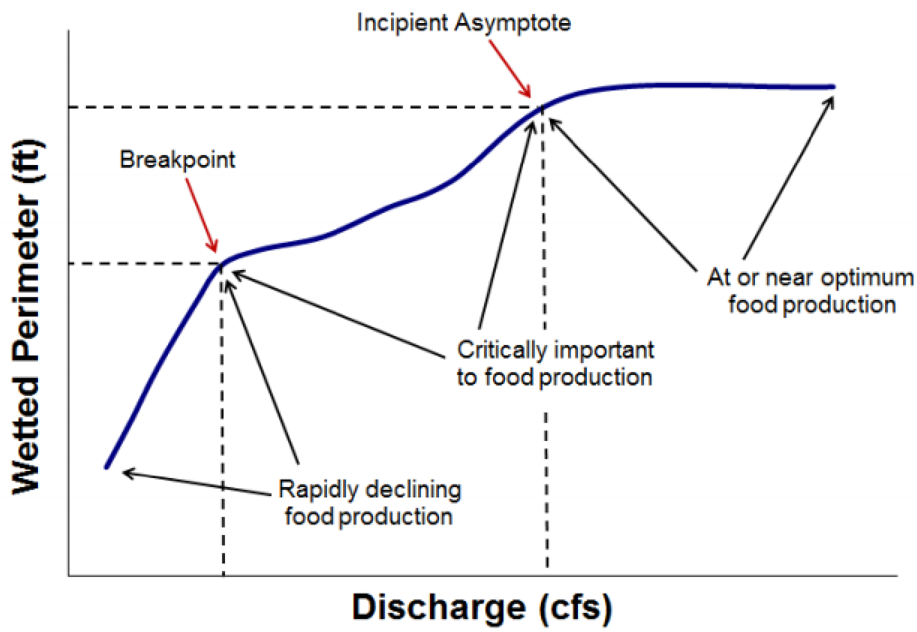


Figure 10. An example of a wetted perimeter-discharge curve (CDFW 2013d).

The commercially available software program NHC Hydraulic Calculator (HydroCalc; Molls 2000) is based on Manning's equation and can be used to develop stage-discharge relationships for cross sections. Bed elevation measurements and stream width (i.e., wetted width) are used to calculate flow area and wetted perimeter. The slope of the water surface of each riffle site is calculated using water surface elevation (WSEL) measurements at the hydraulic control and downstream of the control at the transition between the riffle and subsequent habitat type. The Manning's equation is described below.

$$\text{Manning's n} = \frac{1.4859 \times \text{depth}^{5/3} \times \text{width} \times \text{slope}^{1/2}}{\text{flow}}$$

Determination of the breakpoint can be subjective (Gippel and Stewardson 1998; Annear et al. 2004). To decrease bias, the flow providing at least 50 percent of the wetted perimeter is used as the lower threshold for identifying the breakpoint, and the incipient asymptote is used as the upper threshold. Calculations of change in slope between each point of curvature on the wetted perimeter-discharge curve are then used to identify possible breakpoint flows.

2.3 Temperature Models

Stream network temperature (SNTEMP) models are mechanistic one-dimensional heat transport models that can be applied to streams of any size or order (Annear et al. 2004). A SNTEMP water temperature model was prepared for Deer Creek to predict the difference in average daily water temperature between unimpaired and impaired flows within the study reach. Deer Creek was divided into six sub-reaches based on the locations of the major diversions and returns: SVRIC Diversion Dam, DCID Diversion Dam, and Cone-Kimball Diversion. An SNTEMP model was selected because the model can predict temperature within sub-reaches allowing the end-user to estimate water temperature changes caused by reductions or cut-offs in diversions. Conceptually, results from the SNTEMP model could be used in the future to optimize water operations when fish are migrating through the study reach.

The solver in SNTEMP predicts mean daily temperatures (Bartholow 2000). The program estimates maximum daily temperatures by applying empirically based regression coefficients to the mean daily values, as opposed to calculating the values based on a proven mechanistic approach. Bartholow (2000) suggested, “that one should always treat the maximum daily water temperature predictions from SNTEMP with care and should subject the predictions to validations” (p.74). This approach was followed when using the SNTEMP model to predict maximum daily temperatures for this report.

SNTEMP is a model type that can be run on different commercially available software programs. The Department uses the software program StreamTemp (Payne and Associates 2005) to run SNTEMP simulations. The SNTEMP model used to estimate water temperature changes within the Deer Creek study reach will be referred to as StreamTemp. When solving the water temperature change within each sub-reach, StreamTemp executes four submodels: (1) heat transport model, (2) heat flux model, (3) solar model, and (4) shade model. The heat transport model predicts average mean daily and diurnal water temperatures as a function of stream distance, with the change in temperature calculated as a function of net heat flux. The heat flux model predicts the energy balance between the water and its surrounding environment. The solar model, which quantifies one of the primary heat fluxes, predicts solar radiation penetrating the water as a function of latitude, time of year, and meteorological conditions. The shade model predicts the extent to which heat flux from the solar model is decreased by the interception of solar radiation by topography and riparian vegetation. Inputs required by the model include measured water temperatures, meteorological data, solar radiation, shading, flow data and stream geometry data. StreamTemp requires that the stream network sub-reaches have uniform flow[10], stream azimuth, crown diameter, shade density and slope. StreamTemp does not use wind direction as an input.

The StreamTemp model was used to predict average daily water temperatures at the model subreach nodes for water years 2008 through 2013 for both unimpaired and impaired flow conditions. Although StreamTemp is intended to predict average daily water temperatures, the model can predict maximum daily water temperatures. Recognizing the limitations of a network model like StreamTemp, maximum daily water temperatures were simulated for the same water years to help identify possible trends in 7DADM temperatures with in the study reach.

[10] Uniform flow means that the flow is the same throughout each sub-reach (i.e. no inflows or outflows within the sub-reach.

A second predictive water temperature model was applied to Deer Creek. The Water Temperature Transaction Tool (W3T) is a spreadsheet model developed by Watercourse Engineering, Inc. (2013) which can be run without any special software. W3T has benefits and limitations when compared to StreamTemp. The main advantages of W3T are that the model is spreadsheet based; W3T uses the same basic mechanisms as StreamTemp to predict water temperature, and can operate on an hourly time step while StreamTemp is limited to daily increments. W3T does have several limitations; inflow and outflow are static, and changes in the amount of flow entering the model and operational scenarios cannot be simulated in a single model run. Also, the model simulation is limited to one week, but without the ability to change flows during the week. As a result, W3T could only be run for one day at a time. W3T is a simplified model meant to inform water operations that can be run quickly and without excessive computer software or hardware. However, W3T may be an option for real time water operations management as it relates to water temperature.

3.0 SITE SELECTION

Sites were selected for each method (i.e., Critical Riffle Analysis, Wetted Perimeter, and StreamTemp) following the California Salmonid Stream Habitat Restoration Manual (Flosi et al. 2010) and the California Department of Fish and Game Guidelines for Instream Flow Assessment and Resource Protection (CDFG 2006). Site selection for each method follows the same general steps and protocols: perform a walking survey of the entire study reach; inventory habitat units, hydraulic controls, and passage limiting sites; measure key parameters like unit length, width, and/or thalweg depth along passage limiting path; choose habitat units based upon inventory results or measurement for limiting sites; and use random transect selection where appropriate to minimize bias.

3.1 Critical Riffle Survey and Site Selection

The study reach, defined as lower Deer Creek, extends from the confluence with the Sacramento River (RM 0.0) upstream to the DCID Diversion Dam (RM 11.8; Figure 6). Reconnaissance surveys were conducted in 2012 and 2013. Throughout the study reach, riffles were identified, numbered, photographed, and the location was recorded with a hand held GPS unit. The greatest depth (i.e., the thalweg) along the shallowest path from bank to bank was measured at each riffle to 0.1 ft (3 cm). A total of 21 critical riffle sample sites were identified. The three most depth-sensitive riffles identified during the reconnaissance survey were selected for CRA. All three riffle sites (CR24, CR31, and CR32) were located in the lower half of the reach below the known diversion points, downstream of the SVRIC Diversion Dam. All riffles observed upstream of the SVRIC Diversion Dam were less depth-sensitive.

Once field data collection began in 2014, the selected sites were reviewed by field staff to confirm winter flows had not altered their riffle bed structure nor changed the ranking of the depth sensitive riffles. The two most depth limiting sites, CR31 and CR32, were found to still be the most limiting to passage (Figure 11). The third site, CR24, experienced bed form change over the winter and was no longer depth limited. Field crews used survey data to identify the next most limiting riffle site, which was CR26, also located downstream of the SVRIC Diversion Dam. CR26 was selected for analysis and sampled along with sites CR31 and CR32. Over the course of field data collection and as flow levels receded, CR26 maintained thalweg depths that were appreciably deeper than those measured at CR31 and CR32. When compared to the other two critical riffle sites, the critical riffle pathway (shallowest course from bank to bank) of CR26 was much shorter than those of CR31 and CR32. Depth by percentage was not limited at CR26 at the same flow levels as CR31 and CR32, and as a result, CR26 was excluded from further data analysis and is excluded from this report.

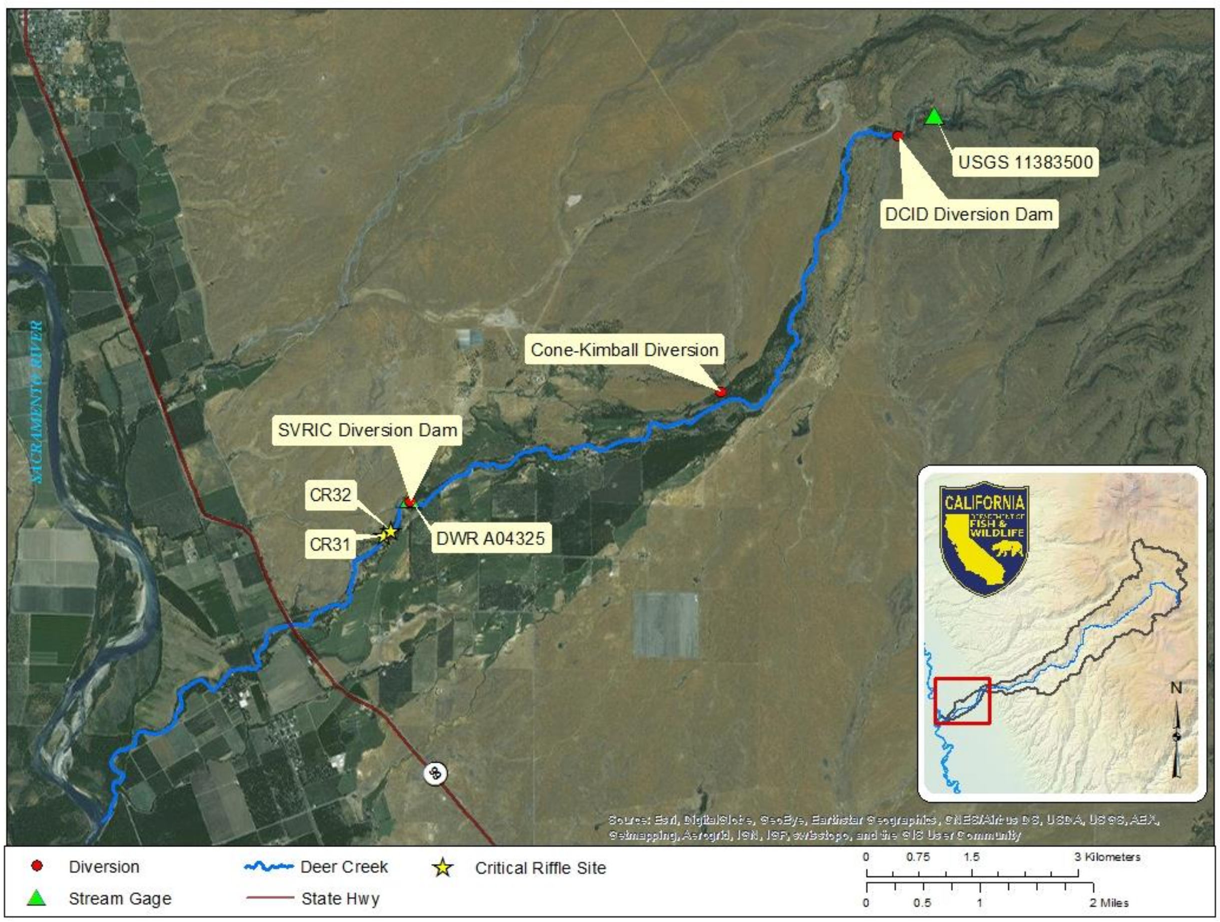


Figure 11. Map of selected critical riffle sites on lower Deer Creek.

The selected critical riffles are described below.

- CR31 was a wide, broad crested transverse riffle approximately 4.6 miles upstream of the mouth, and 0.4 miles downstream of the SVRIC Diversion Dam (Figure 12). This riffle had a maximum wetted width of 171.2 ft. It represents the shallowest critical riffle, having a minimum thalweg depth of 0.5 ft during the riffle survey. This riffle was interspersed with occasional vegetation.

- CR32 was a broad U-shaped riffle approximately 4.7 miles upstream of the mouth, and 0.3 miles downstream of the SVRIC Diversion Dam (Figure 13). This was the longest critical riffle, having a maximum wetted width of 211.7 ft.

Figure 12. CR31 at approximately 49 cfs, looking upstream.

Figure 13. CR32 at approximately 49 cfs, looking upstream.

3.2 Wetted Perimeter Site Selection

Sites were selected in lower Deer Creek for Wetted Perimeter analysis between the Sacramento River confluence (RM 0.0) and the SVRIC Diversion Dam (RM 5.0). The Wetted Perimeter method is limited to use in riffles with rectangular streambed profiles. Sites were selected based on their geomorphic structure as well as the shape of the river channel (CDFW 2013d). Three representative riffles were identified and selected for analysis (Figure 14).

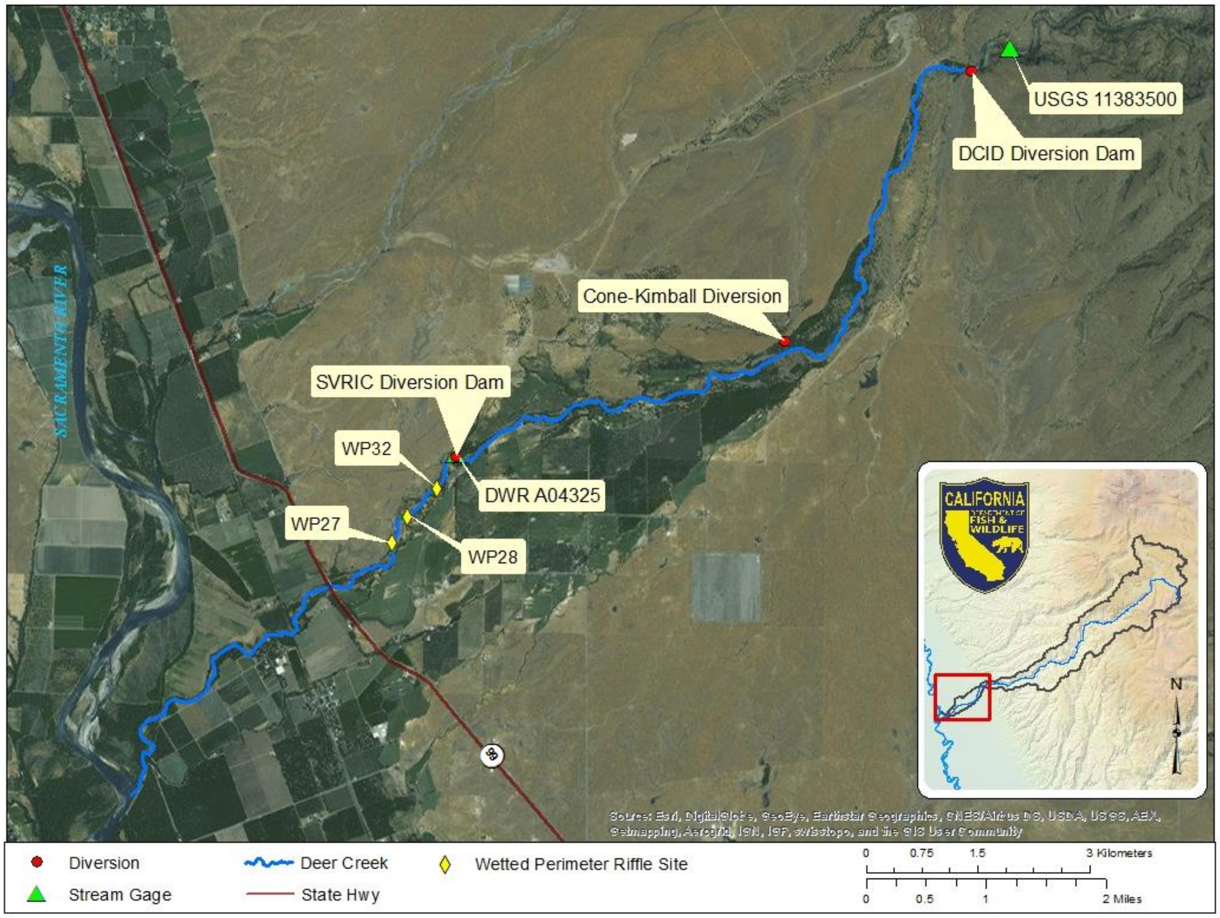


Figure 14. Wetted Perimeter riffle site locations on lower Deer Creek.

3.3 Mesohabitat Mapping and Temperature Model Site Selection

Six stream study reaches were established for the Stream Temp model based on the locations of stream water diversions and returns, stream hydrology, and gradient (Table 4; Figure 15). W3T was run on the same reaches of Deer Creek as the StreamTemp model. Reach 1 is downstream of the DCID diversion, but upstream of the Cone-Kimball side channel. Reach 2 is the main channel of Deer Creek adjacent to the Cone-Kimball side channel. Reach 3 is downstream of the Cone-Kimball side channel but upstream of the SVRIC diversion. Reach 4 extends from the SVRIC diversion to the Sacramento River. Reach 5 is the portion of the Cone-Kimball side channel upstream of the Cone-Kimball diversion, while Reach 6 is the portion of the Cone-Kimball side channel downstream of the Cone-Kimball diversion. Stream gage USGS 11383500 is located approximately 0.5 miles upstream of the DCID Diversion Dam at RM 12.3. Above the DCID Diversion Dam, Deer Creek is assumed to be unimpaired, and upstream of any influence of the diversion dam.

Table 4. Lower Deer Creek temperature model study reaches from DCID Diversion Dam downstream to Sacramento River confluence.

Reach #	Begin	End
1	DCID Diversion Dam	Cone-Kimball Side Channel Entrance
2	Cone-Kimball Side Channel Entrance	Cone-Kimball Side Channel Exit
3	Cone-Kimball Side Channel Exit	SVRIC Diversion Dam
4	SVRIC Diversion Dam	Sacramento River Confluence
5	Cone-Kimball Side Channel Entrance	Cone-Kimball Diversion
6	Cone-Kimball Diversion	Cone-Kimball Side Channel Exit

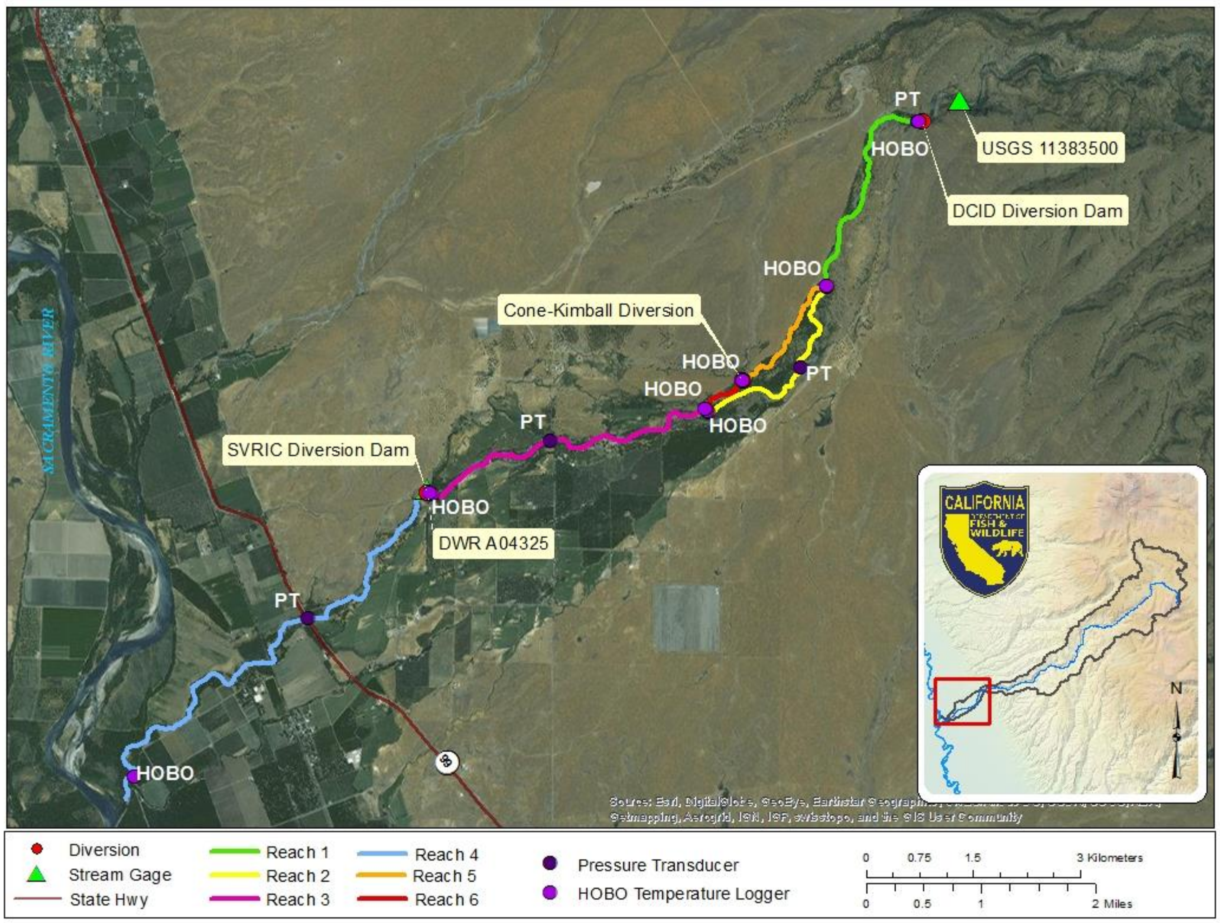


Figure 15. Temperature model study reaches on lower Deer Creek.

Mesohabitat mapping was conducted to select transect locations and to weight transects based on the percentage of each mesohabitat type in each reach. Mesohabitat mapping of the entire length of all six reaches was conducted during March 24-27, 2014 by walking downstream, and marking the downstream end of each mesohabitat unit with a GPS unit. Mapping was based on the mesohabitat definitions in Table 5 (adapted from Snider et al. 1992). Polyline shapefiles of the mesohabitat units were generated in GIS using the GPS data and NAIP imagery, and the lengths of the shapefiles were used to calculate the mesohabitat composition of each reach. An example of the mesohabitat type composition for Reach 1 is shown in Figure 16. The mesohabitat composition of each reach was used to extrapolate the flow-width and flow-depth relationships for the transects in each reach to the entire length of each reach.

Table 5. Mesohabitat type definitions, adapted from Snider et al. (1992).

Habitat Type	Definition
Pool	Fine and uniform substrate, below average water velocity, above average depth, tranquil water surface. Primary determinant is downstream control - thalweg gets deeper moving upstream from tail of pool. Depth is not used to determine whether a mesohabitat unit is a pool.
Glide	Low gradient, uniform substrate across channel width with channel composed of small gravel and/or sand/silt, depth below average and similar across channel width, below average water velocities, generally associated with tails of pools or heads of riffles, width of channel tends to spread out, thalweg has relatively uniform slope going downstream. Primary determinants are no turbulence (surface smooth, slow, and laminar) and no downstream control.
Run	Moderate gradient, mixed substrate particle sizes composed of small cobble and gravel, with some large cobble and boulders, above average water velocities, usually slight gradient change from top to bottom, generally associated with downstream extent of riffles, thalweg has relatively uniform slope going downstream. Primary determinants are moderate turbulence and average depth.
Riffle	Below average depth, above average velocity, thalweg has relatively uniform slope going downstream, substrate of uniform size and composed of large gravel and/or cobble, change in gradient noticeable. Primary determinants are relatively high gradient and turbulence.

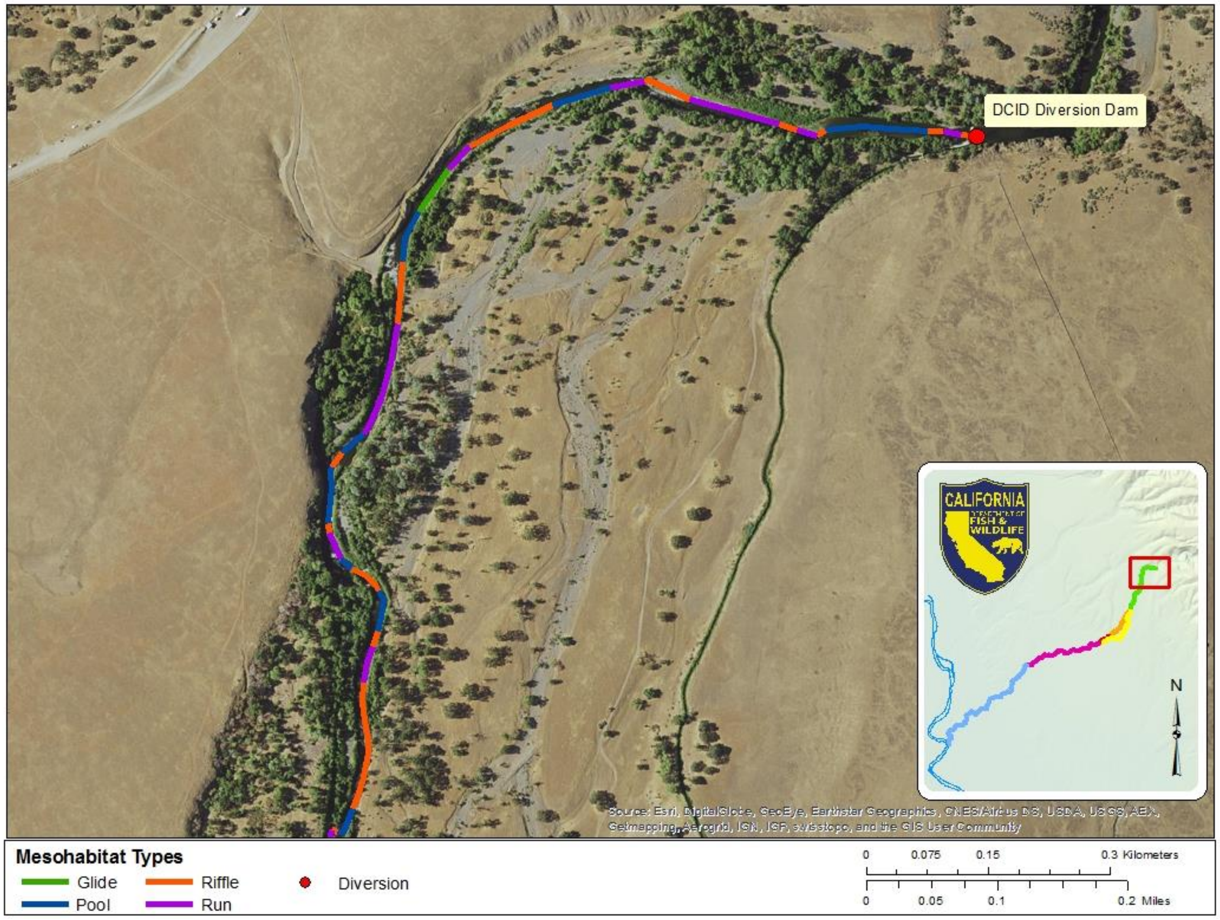


Figure 16. Mesohabitat type composition of upper Reach 1.

Results of mesohabitat mapping were used to randomly select locations for seven transects in Reach 1, eight transects each in Reaches 2 and 3, and four transects each in Reaches 4, 5 and 6. For Reach 4, width and depth data collected on the critical riffles and critical riffle discharge measurement transects were also used to empirically develop flow-width and flow-depth relationships. Transects were established during April 14-17, 2014 by navigating to the GPS points marked at the downstream end of the selected mesohabitat units and proceeding upstream for a randomly-selected distance from the GPS point; the transect was installed at this location.

The percent of mesohabitat type in each reach is shown in Table 6, while the number of transects in each mesohabitat type is shown in Table 7. The number of transects for each mesohabitat was selected to roughly correspond to the mesohabitat characterization of each reach. The pool transects in Reaches 5 and 6 were also used to represent glide mesohabitat units in these reaches. Transects were not placed in glides in these reaches because they comprised less than 5 percent of the habitat present.

Table 6. Mesohabitat composition by percentage (%).

Habitat Type	Glide	Pool	Riffle	Run
Reach 1	6.9%	34.2%	29.4%	29.6%
Reach 2	20.0%	24.9%	32.0%	23.2%
Reach 3	13.5%	43.2%	24.2%	19.1%
Reach 4	31.4%	25.6%	23.3%	19.7%
Reach 5	1.8%	41.8%	31.9%	24.5%
Reach 6	4.8%	55.8%	24.4%	15.0%

Table 7. Number of transects of each mesohabitat type.

Habitat Type	Glide	Pool	Riffle	Run
Reach 1	1	2	2	2
Reach 2	2	2	2	2
Reach 3	1	3	2	2
Reach 4*	0	2	0	2
Reach 5	0	2	1	1
Reach 6	0	2	1	1

*In addition to the transects in this table, there were three critical riffle transects, and two critical riffle discharge measurement transects located in glides, that were used to develop flow-width and flow-depth relationships for Reach 4.

4.0 DATA COLLECTION

Data collection on the Deer Creek study was consistent with the pre-existing standards and protocols for each method. The method specific standards and protocols are described in further detail in each sub-section.

4.1 Critical Riffle Data Collection

CRA data collection was completed consistent with the Department CRA SOP (CDFG 2012). Sampling took place from March to June 2014 on the receding limb of the hydrograph. The timing of sampling events was intended to capture the range of discharges needed to adequately bracket and identify passage flows for Chinook Salmon and steelhead (CDFG 2012). Measurements were taken at six distinct flows, in the range of the 40^{th} to 100^{th} percentile exceedance flows (193-12 cfs). A precipitation event provided the opportunity to survey the riffles at the highest sampled flows on April 9, 2014. Sample dates and corresponding flows are summarized in Table 8. Drought conditions precluded sampling of exceedance level flows lower than the ~40^{th} percentile (i.e., greater than 193 cfs). Desktop methods were used to estimate depths and widths for passage at higher flow levels. These desktop methods are described in further detail in the Results section.

Table 8. Sample dates and associated flows (cfs) for critical riffle surveys.

Site	Date	Flow (cfs)
CR31	3/17/14	167.8
	4/9/14	193.3
	4/29/14	98.3
	5/6/14	64.9
	5/14/14	45.5
	6/11/14	12.4
CR32	3/18/14	153.8
	4/9/14	193.3
	4/29/14	98.3
	5/6/14	64.9
	5/14/14	45.5
	6/11/14	12.4

At each sampling event, a passage transect was established through each critical riffle using flagging and rebar. Facing upstream, the headpin for each critical riffle transect was located on the left bank and the tailpin on the right bank. The passage transects were non-linear, following the contours of the riffle along its shallowest course from headpin to tailpin (Figures 17 to 19). The course was marked by driving sections of rebar at regularly spaced intervals along the shallowest course. Each transect was recorded with digital images, and the approximate locations of the rebar were recorded with handheld GPS.

Water depths were measured along each passage transect to the nearest 0.01 ft with a stadia rod at two foot intervals. Water velocities measured to the nearest 0.01 ft/s were collected at the same intervals. A temporary staff gage was used to record the stage at the beginning and end of each data collection event to determine whether flow levels had changed during data collection. Flow levels did not change by more than 0.01 ft during the CRA data collection events, and therefore did not have any effect on method performance or data quality. Discharge measurements were taken consistent with the Department SOP (CDFW 2013a) at sites adjacent to the riffles.

Headpins and tailpins were placed at the wetted edge of each bank. The exact position of the headpins and tailpins fluctuated between flow events because the pathways tended to shorten as the flows receded. The maximum wetted width used in CRA was defined as the maximum wetted width recorded during the survey following the shallowest course from bank to bank.

Transect depth profiles were reviewed for inconsistencies after data collection. The CR31 passage transect sampled on 3/17/15 at 167.8 cfs was found to be taken along a pathway with a substantially different depth profile when compared with the other shallowest courses selected for CR31. The depth profile of the CR32 transect sampled on 5/6/14 at 64.9 cfs was also markedly inconsistent with the other pathways at CR32. These transects were omitted from further CRA analysis.

Velocity was recorded at all sites except for the first sampling events on 3/17/14 and 3/18/14. Velocities within the surveyed areas sampled on these dates were assumed to have been below the maximum criteria for adult Chinook Salmon and steelhead. The maximum velocity criteria were not exceeded during the second sampling event when flows were higher, 193.3 cfs on 4/9/14, as compared to the flows during the first sampling events, 167.8 cfs and 153.8 cfs, respectively. The maximum velocity criteria were not exceeded for any of the life stages considered, at any of the sampling events.

The CRA data were transferred into Excel workbooks for calculations and analysis. Water depths measured along each critical riffle transect were evaluated to calculate the total width and longest contiguous portion of the transect meeting minimum depth and maximum velocity criteria.

Figure 17. Transect along CR31 at high flow (193.3 cfs, 4/9/14, top photo) and low flow (12.4 cfs, 6/11/14, bottom photo). View facing downstream.

Figure 18. Transect along CR32 at high flow (193.3 cfs, 4/9/14, top photo) and low flow (12.4 cfs, 6/11/14, bottom photo). View facing downstream.

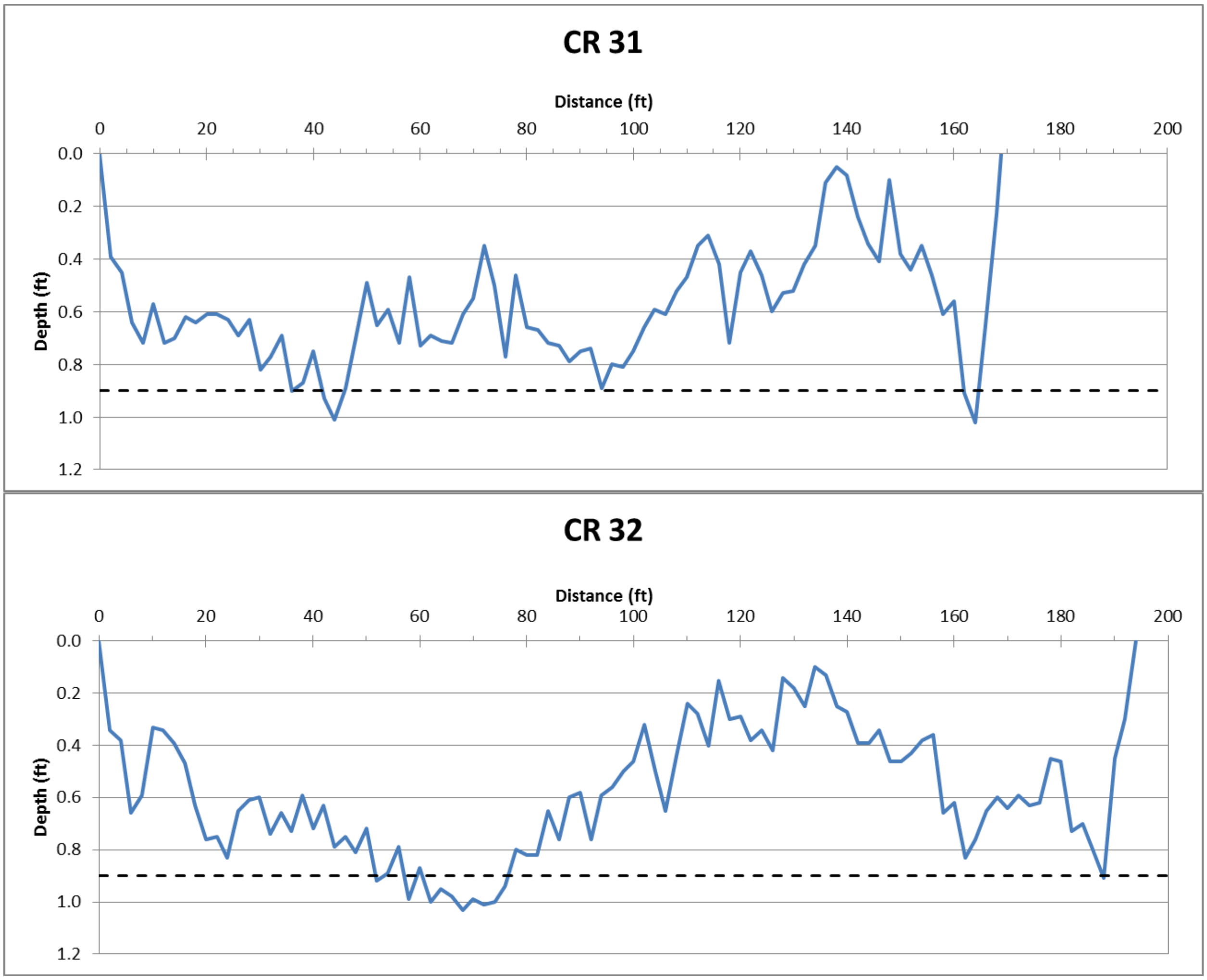


Figure 19. Depth profiles for CR31 (top) and CR32 (bottom), surveyed at 193.3 cfs. Dotted line indicates 0.9 ft depth.

4.2 Wetted Perimeter Data Collection

Wetted Perimeter transects were established on each riffle site on June 11, 2014 and June 12, 2014 at flows of 12.4 cfs and 52.0 cfs, respectively (Table 9). Linear transects were installed from the top of each riffle bank to bank, perpendicular to flow, and across the hydraulic control located at the crest of the riffle. Bed elevations were surveyed using an autolevel and stadia rod at one-foot intervals following the Department's SOP for Streambed and Water Surface Elevation Data Collection (CDFW 2013c). Water surface elevations were also measured near the left and right banks to correlate measured flow to the profile. A stream discharge was collected near each transect using a Marsh-McBirney Model 2000 Flo-Mate (Model 2000) velocity meter in accordance with the Department's SOP for Discharge Measurements in Wadeable Streams (CDFW 2013a).

WSEL measurements were used as a surrogate for the energy slope in Manning's equation. WSELs were measured on July 9, 2014 at each riffle site along the left and right water's edge as well as in the middle of the channel. WSELs were also measured in each riffle 10 to 20 feet downstream of the associated wetted perimeter transect, at the location of transition between the riffle and the subsequent habitat type. A corresponding discharge measurement was taken in accordance with the Department's SOP (CDFW 2013a).

Table 9. Wetted perimeter flow parameters.

Riffle Site	Date	Flow (cfs)	Riffle Slope (ft/ft)	Manning's n
WP27	6/12/2014	52.0	0.007243	0.064574
WP28	6/12/2014	52.0	0.011890	0.085894
WP32	6/11/2014	12.4	0.007911	0.164895

4.3 Temperature Model Data Collection

StreamTemp data collection had three nested levels: stream reach, mesohabitat unit (riffle, run, pool, or glide), and transect. Meteorological parameters (air temperature, relative humidity, daily wind speed, and cloud cover during daylight hours) apply to the entire stream network, and were obtained from internet sources. Stream reach parameters include stream flow (from pressure transducers and flow measurements), water temperature (measured with water temperature data loggers), and the elevation and upstream distance at the end of each reach (which were obtained from GIS databases). The same input data used for StreamTemp was also used to run W3T. W3T required the same types of data as the StreamTemp input data, with the only difference being the use of hourly data for the W3T model, versus daily average data for the StreamTemp model.

Transect data (bed elevation profiles and stage-discharge measurements) were used to develop relationships between stream flow and hydraulic parameters. Water temperature is the only dependent variable; all other parameters identified above are independent variables. Bed elevation profiles and stage measurements were made using standard differential leveling techniques (see CDFW 2013c).

Transect locations were selected though mesohabitat mapping (Figure 20; see Section 3.3). Transect pins (headpins and tailpins) were marked on each creek bank using rebar driven into the ground and/or lag bolts placed in tree trunks. The transect pins were placed at bed elevations above the highest predicted WSELs in each reach. Survey flagging was used to mark the locations of each pin. Vertical benchmarks, which consisted of lag bolts driven into the base of trees, were established for each transect to serve as the vertical elevations to which all elevations (streambed and water surface) were referenced.

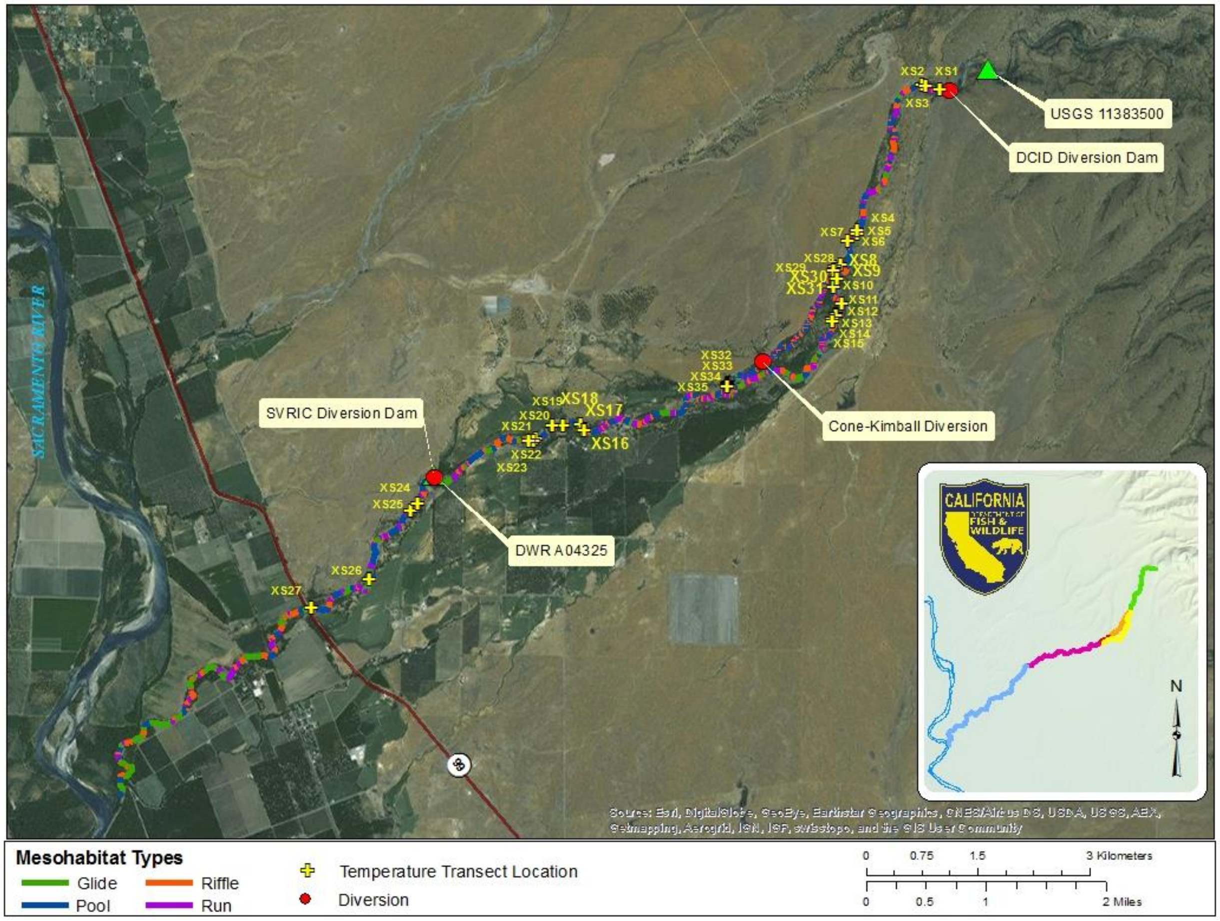


Figure 20. Temperature transects selected through mesohabitat mapping.

Hydraulic data were collected for the transects in April through June 2014. Flows for calibrating the transects were measured in each reach using a fiberglass measuring tape and a wading rod equipped with a Model 2000 velocity meter. The data collected on each transect included: 1) WSEL measured to the nearest 0.01 foot at a minimum of three significantly different stream discharges, using standard surveying techniques (differential leveling); and 2) measurements of both wetted and dry streambed elevations to points above bank-full discharge, surveyed to the nearest 0.1 foot. WSELs were measured along both banks and in the middle of each transect. The WSELs at each transect were then derived by averaging the values, except when the difference in elevation exceeded 0.1 foot, in which case the WSEL for the side of the river that was considered most representative was used. The stations for the wetted and dry streambed elevation measurements were measured using a fiberglass measuring tape.

The stage of zero flow (SZF) is the WSEL that would be present at a flow of zero. For sites where there was a gradual gradient change in the vicinity of the downstream transect, there could be a point in the thalweg a short way downstream of the transect that was higher than that measured at the downstream transect thalweg simply due to natural variation in topography (Figure 21). The SZF downstream of the site acts as a control on the WSELs at the downstream transect. Transects that had higher downstream controls were surveyed using standard differential leveling techniques in order to accurately calibrate the WSELs. If the true SZF was not measured as described above, the thalweg elevation at the transect was used as the default SZF.

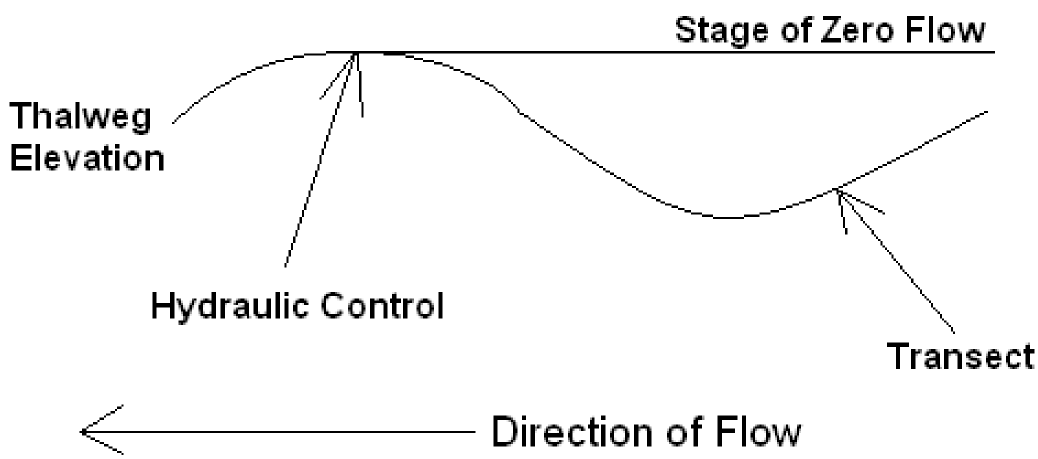


Figure 21. Stage of zero flow diagram.

WSELs at the transects were collected at low, medium, and high flow sample events (Table 10). Discharge measurements for the transects were measured in each reach (Table 10; Appendix B), so that stage-discharge relationships could be developed.

Table 10. Summary of sample dates and corresponding flows when water surface elevations were measured for calibration of transects used to develop flow-width and flow-depth relationships.

Reach	High Flow (cfs)	High Flow Date	Mid Flow (cfs)	Mid Flow Date	Low Flow (cfs)	Low Flow Date
1	150.3	4/14/14	92.2	5/12/14	56.1	6/9/14 6/10/14
2	153.1	4/15/14	85.7	5/13/14	46.2, 54.9	6/10/14 6/12/14
3	145.0	4/16/14	73.3, 87.5	5/14/14 5/15/14	44.4	6/11/14
4	97.8	4/17/14	35.1	5/15/14	12.1, 22.9, 24.0	6/11/14 6/23/14
5	19.4	4/15/14	10.3	6/4/14	8.7	5/14/14
6	10.0	4/17/14	3.2	6/4/14	2.8	5/14/14

Shade data were collected in June and September 2014. In June, a SUUNTO clinometer was used to measure the vertical angle to the top of trees on the left and right banks, with the person operating the clinometer standing mid-channel. Measurements were made every 500 feet going downstream through the entire length of all six reaches. In September, ocular estimates were made every 500 feet of vegetation density on the left and right banks, going downstream through the entire length of all six reaches. Vegetation density is the average screening factor (0 to 100 percent) of the shade producing vegetation. It is composed of two parts: the continuity of the vegetative coverage along the stream (quantity), and the percent of light filtered by the vegetation's leaves and trunks (quality). For example, if there is vegetation along 25 percent of the stream and the average density of that coverage is 50 percent, the total vegetative density is 0.25 times 0.50, which equals 0.125, or 12.5 percent.

Solinst Model 3001 Levelogger Edge pressure transducers were installed in Reaches 1, 2, 3 and 4 between March 26 and April 14, 2014. Flows for Reach 5 were calculated as the difference between Reach 1 and 2 flows. The Cone-Kimball diversion was calculated as the difference between Reach 1 and 3 flows. Reach 6 flows were calculated by subtracting the Cone-Kimball diversion from Reach 5 flows. A Solinst Barologger Edge was also installed on high ground next to nearby Mill Creek to compensate for the atmospheric pressure (see CDFW 2017). The instream pressure transducers were placed in stilling wells consisting of a 1 ½ inch diameter PVC pipe with ¼ inch holes drilled in the lower foot of the pipe to allow water to equilibrate in the pipe.

The pipe was mounted on an angle and attached to two metal T fence posts to ensure the pressure transducer elevation would not change during data collection. The pressure transducers were attached to one end of a stainless steel cable with loops at each end; the loop at the other end of the cable went through a padlock inserted through a hole drilled through the pipe. The length of cable used resulted in the pressure transducers being located an inch from the lower end of the pipe. WSELs measured at the pressure transducer locations were used to calculate the elevation of the pressure transducers and, together with measured discharges and SZF, to develop rating curves for the gages.

Two Hobo U22 Water Temp Pro v2 loggers were installed at the downstream end of each reach, along with two loggers installed at the upstream end of Reach 1, between March 26 and April 8, 2014. The water temperature loggers were attached to one end of a stainless steel cable with loops at each end; the loop at the other end of the cable went around the base of a tree or bush near the water's edge. The length of cable used was expected to be sufficient for the temperature loggers to be installed where they would remain submerged at the lowest expected flows. All loggers were removed on July 9, 2015.

Additional pressure transducer, barometer and water temperature data were collected in 2015 to validate the water temperature model. Flow, stage, and SZF measurements were made in 2015 to develop new rating curves for all of the pressure transducers as a result of channel changes due to high flows in December 2014 and February 2015. In 2015, a Davis Instruments Vantage Vue weather station was installed near the USGS 11381500 gage on Mill Creek. Data collected at this station was used to develop regression equations to correct weather data from internet sources for local conditions. Data was collected for this weather station from March 13 to April 26 and June 14 to July 5, 2015.

Temperature model construction, calibration, and validation procedures are detailed in Appendix B. Data collected for transect stage-discharge calibration are presented in Appendix C.

5.0 RESULTS

The results for the three different instream flow assessment methods (i.e., CRA, Wetted Perimeter, and StreamTemp) are presented below. The results of the CRA used to evaluate passage conditions for salmonids based on depth and velocity are presented first. The Wetted Perimeter method used to determine a low flow threshold is presented next, followed by results of the StreamTemp model used to simulate impaired and unimpaired water temperature conditions in Deer Creek.

5.1 Critical Riffle Analysis Results

Stream discharge rates and the percent of each critical riffle transect meeting the minimum depth criteria for adult Chinook Salmon (0.9 feet) and steelhead (0.7 feet), were compiled. The CRA method recommends three to six empirical data points be used to generate a best-fit regression, with at least one measurement meeting the depth criteria per sampling event (CDFG 2012). Even though 2014 was a critically dry year, staff were able to sample sites CR31 and CR32 at enough distinct flows to meet the field sampling requirements. However, at CR31 only four of the five events sampled resulted in a depth profile where at least one point along the shallowest course met the minimum depth criteria for adult steelhead. At CR32, only three of the five events sampled comprised flows high enough to evaluate conditions for adult steelhead. Points collected at flow levels where the minimum depth criteria were not met could not be used to generate the best-fit regression. The issue of measuring flows with usable depth profiles was exacerbated for Chinook Salmon, which requires deeper water depths (i.e., 0.9 ft); only two of the five flow events sampled at CR31 and CR32 contained depths meeting the minimum criteria. The CRA data are summarized in Table 11.

Best-fit regressions of flow versus width were developed for CR31 and CR32 by developing stage-discharge relationships (rating curves) from field measurements combined with the depth profile measured at the highest flow level sampled. Development of rating curves is detailed in Appendix D.

Table 11. Field data, with total and contiguous wetted widths meeting adult steelhead and adult Chinook Salmon depth criteria at CR31 and CR32 from highest to lowest flow.

			Adult Steelhead (0.7 ft criteria)				Adult Chinook (0.9 ft criteria)			
	Date	Flow (cfs)	Total width (ft)	Total width (%)	Cont. width (ft)	Cont. width (%)	Total width (ft)	Total width (%)	Cont. width (ft)	Cont. width (%)
CR31	4/9/14	193.3	58	33.9%	18	10.5%	10	5.8%	4	2.3%
	4/29/14	98.3	18	10.5%	8	4.7%	2	1.2%	2	1.2%
	5/6/14	64.9	6	3.5%	4	2.3%	0	0.0%	0	0.0%
	5/14/14	45.5	2	1.2%	2	1.2%	0	0.0%	0	0.0%
	6/11/14	12.4	0	0.0%	0	0.0%	0	0.0%	0	0.0%
CR32	4/9/14	193.3	68	32.1%	40	18.9%	22	10.4%	16	7.6%
	3/18/14	153.8	46	21.7%	14	6.6%	10	4.7%	6	2.8%
	4/29/14	98.3	4	1.9%	2	0.9%	0	0.0%	0	0.0%
	5/14/14	45.5	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	6/11/14	12.4	0	0.0%	0	0.0%	0	0.0%	0	0.0%

Adult Chinook Salmon and adult steelhead depth criteria were applied to the rating curve developed for each site to facilitate comparison with results of the CRA field sampling, and to expand the critical riffle data by simulating widths and depths over a broader range of flows. The rating curve was used to estimate the total and maximum contiguous width at each flow in 5 cfs intervals (Tables 12 to 15). The tables are abbreviated to include only the flow levels which increase the amount of width meeting the depth criteria. The lowest flow presented in each table is the highest estimated flow level where total or contiguous width was equal to zero. Tables with the complete list of flows simulated are provided in Appendix D (Tables D-1 to D-8).

Depths were measured at two foot increments along the critical path at CR31 and CR32. Stage-discharge relationships in Appendix D (Figures D-1 to D-3) were used to expand the critical riffle data, simulating flows over a broader range, to estimate available wetted width and depth at each riffle. The results of the stage-discharge regressions versus percent of maximum wetted width based on adult Chinook Salmon and adult steelhead depth criteria are plotted with the total and contiguous wetted widths measured in the field (Figures D-4 to D-15).

Table 12. Abbreviated CR31 rating curve results for adult Chinook Salmon. Total width versus flow (top), and contiguous width versus flow (bottom).

Adult Spring-run Chinook Salmon (minimum depth criteria = 0.9 ft)					
Maximum Wetted Width = 171.2 ft					
Flow (cfs)	**Total Width (ft)**	**Percent Total Width**	**Flow (cfs)**	**Total Width (ft)**	**Percent Total Width**
475	100	58%	310	34	20%
465	96	56%	290	28	16%
450	94	55%	275	24	14%
440	84	49%	265	22	13%
430	82	48%	260	20	12%
415	78	46%	250	18	11%
405	74	43%	215	16	9%
395	70	41%	200	14	8%
385	66	39%	195	10	6%
365	64	37%	185	8	5%
355	58	34%	175	6	4%
345	54	32%	130	4	2%
335	52	30%	125	2	1%
325	40	23%	120	0	0%
315	36	21%	-	-	-
Flow (cfs)	**Contiguous Width (ft)**	**Percent Contiguous Width**	**Flow (cfs)**	**Contiguous Width (ft)**	**Percent Contiguous Width**
450	38	22%	320	14	8%
430	26	15%	310	12	7%
400	24	14%	200	6	4%
365	20	12%	175	4	2%
335	18	11%	125	2	1%
330	16	9%	120	0	0%

Table 13. Abbreviated CR32 rating curve results for adult Chinook Salmon. Total width versus flow (top), and contiguous width versus flow (bottom).

Adult Spring-run Chinook Salmon (minimum depth criteria = 0.9 ft)					
Maximum Wetted Width = 211.7 ft					
Flow (cfs)	**Total Width (ft)**	**Percent Total Width**	**Flow (cfs)**	**Total Width (ft)**	**Percent Total Width**
440	114	54%	270	44	21%
425	112	53%	265	40	19%
415	110	52%	255	36	17%
405	102	48%	250	34	16%
400	96	45%	245	30	14%
390	94	44%	220	26	12%
385	90	43%	210	24	11%
375	84	40%	200	22	10%
365	82	39%	195	20	9%
360	74	35%	185	18	9%
330	68	32%	180	16	8%
315	66	31%	165	14	7%
310	62	29%	160	12	6%
305	58	27%	155	8	4%
300	58	27%	150	4	2%
295	56	26%	145	2	1%
290	52	25%	140	0	0%
Flow (cfs)	**Contiguous Width (ft)**	**Percent Contiguous Width**	**Flow (cfs)**	**Contiguous Width (ft)**	**Percent Contiguous Width**
440	80	38%	220	20	9%
425	78	37%	185	16	8%
415	72	34%	180	14	7%
405	50	24%	165	10	5%
385	48	23%	160	8	4%
365	44	21%	155	4	2%
315	40	19%	145	2	1%
270	32	15%	140	0	0%
265	26	12%	-	-	-

Table 14. Abbreviated CR31 rating curve results for adult steelhead. Total width versus flow (top), and contiguous width versus flow (bottom).

Adult Steelhead (minimum depth criteria = 0.7 ft)					
Maximum Wetted Width = 171.2 ft					
Flow (cfs)	Total Width (ft)	Percent Total Width	Flow (cfs)	Total Width (ft)	Percent Total Width
475	140	82%	220	70	41%
450	138	81%	215	66	39%
440	136	79%	200	64	37%
415	132	77%	195	58	34%
405	130	76%	185	54	32%
395	126	74%	180	52	30%
385	120	70%	175	40	23%
365	116	68%	170	36	21%
355	114	67%	165	34	20%
335	112	65%	155	28	16%
325	108	63%	140	24	14%
310	106	62%	135	22	13%
300	104	61%	130	20	12%
290	102	60%	125	18	11%
275	100	58%	105	16	9%
265	96	56%	95	14	8%
260	94	55%	90	8	5%
250	84	49%	85	6	4%
240	82	48%	60	4	2%
235	78	46%	55	2	1%
230	74	43%	50	0	0%
Flow (cfs)	Contiguous Width (ft)	Percent Contiguous Width	Flow (cfs)	Contiguous Width (ft)	Percent Contiguous Width
480	70	41%	180	18	11%
410	68	40%	175	16	9%
390	66	39%	170	14	8%
365	52	30%	165	12	7%
290	44	26%	95	6	4%
260	38	22%	85	4	2%
245	26	15%	55	2	1%
220	24	14%	50	0	0%
200	20	12%	-	-	-

Table 15. Abbreviated CR32 rating curve results for adult steelhead. Total width versus flow (top), and contiguous width versus flow (bottom).

Adult Steelhead (minimum depth criteria = 0.7 ft)					
Maximum Wetted Width = 211.7 ft					
Flow (cfs)	Total Width (ft)	Percent Total Width	Flow (cfs)	Total Width (ft)	Percent Total Width
475	166	78%	235	82	39%
465	164	77%	230	74	35%
460	162	77%	205	68	32%
440	154	73%	195	66	31%
425	152	72%	190	62	29%
415	146	69%	185	58	27%
405	140	66%	180	56	26%
390	138	65%	175	52	25%
385	136	64%	160	44	21%
375	134	63%	155	40	19%
365	132	62%	150	36	17%
360	128	60%	145	30	14%
350	120	57%	125	26	12%
330	118	56%	120	24	11%
290	114	54%	110	22	10%
275	112	53%	100	18	9%
270	110	52%	90	14	7%
265	102	48%	85	12	6%
255	96	45%	80	4	2%
250	94	44%	75	2	1%
245	90	43%	70	0	0%
240	84	40%	-	-	-
Flow (cfs)	**Contiguous Width (ft)**	**Percent Contiguous Width**	**Flow (cfs)**	**Contiguous Width (ft)**	**Percent Contiguous Width**
475	108	51%	245	48	23%
465	100	47%	235	44	21%
460	90	43%	195	40	19%
415	88	42%	160	32	15%
360	86	41%	155	26	12%
350	84	40%	125	20	9%
330	82	39%	100	16	8%
290	80	38%	90	10	5%
275	78	37%	85	8	4%
270	72	34%	75	2	1%
265	50	24%	70	0	0%

5.2 Wetted Perimeter Results

The Wetted Perimeter method can be used to determine an instream flow for the low flow period, sufficient to protect food producing riffle habitats (Annear et al. 2004). Three riffles were selected in lower Deer Creek for Wetted Perimeter analysis. The computer program HydroCalc, based on Manning's equation, was used to develop the stage-discharge relation for each surveyed cross section and subsequent wetted perimeter versus discharge graphical plots (Appendix E). Breakpoint flows (cfs) were identified where the discharge covered at least 50 percent of the wetted perimeter and where a marked change in the slope of the curve occurred (Table 16).

Table 16. Wetted perimeter breakpoint and incipient asymptote flows (cfs).

Name	Breakpoint (cfs)	Incipient Asymptote (cfs)
WP27	15	106
WP28	38	119
WP32	17	66

5.3 Temperature Model Results

Input data from several sources including weather data from two local airports, monitoring data from the two stream gages in the study reach, and monitoring data collected in 2014 and 2015 from an array of temporary locations in the study reach were combined to run water temperature simulations using StreamTemp and W3T. The focus of the study was to determine the difference in water temperature between impaired and unimpaired water supply at locations within the study reach. The StreamTemp model was used to simulate impaired and unimpaired water temperature conditions in Deer Creek during the spring for water years 2008 through 2013. Those results are presented below. The results of the W3T model are given in Appendix B, and include comparisons with the StreamTemp outputs and historical monitoring data. The performance of both models to simulate maximum daily water temperature was tested against the monitoring data. Those results are also given in Appendix B, along with a comparison of the modeled simulated flow runs to 7DADM values at the downstream end of Reach 4.

Pressure Transducer and Temperature Logger Data

Flows generated from the pressure transducer data are shown in Figures 22 and 23, while measured water temperatures are shown in Figures 24 and 25. The measured 7DADM at the downstream end of Reach 4 (i.e., nearest the Sacramento River confluence) first reached 64°F on April 10, 2014 and March 29, 2015, and reached 68°F on May 1, 2014 and April 21, 2015. Peaks in the flows that are not expressed at the USGS gage are indicative of the pulse flow events coordinated by the Department. In

2014, these peaks are visible on May 19 and June 13 (Figure 22). Peaks in 2015 are visible on April 28, May 16, and June 2 (Figure 23).

Each reach was equipped with two loggers at the downstream end. One of the temperature loggers at the downstream end of Reach 4, located 1,080 feet upstream of the confluence of Deer Creek with the Sacramento River, started to show decreased water temperatures due to effects of Sacramento River flows on May 21, 2014. The other temperature logger at the downstream end of Reach 4, located 1,130 feet upstream of the confluence of Deer Creek with the Sacramento River, started to show decreased water temperatures due to effects of Sacramento River flows on June 26, 2014. As a result, the calibration water temperatures used for the downstream end of Reach 4 were the water temperatures recorded by the upstream temperature logger for the period of May 21 to June 25, 2014. The water temperature model was not calibrated for the downstream end of Reach 4 after June 25, 2014. Reach 4 was split into two subreaches (upstream and downstream of Highway 99), so the water temperature model was calibrated at the downstream end of the upper subreach after June 25, 2014 using water temperatures from the pressure transducer in Reach 4.

Water temperatures used for calibrating Reach 3 were taken entirely from one temperature logger because the other logger launched incorrectly, and did not record any data. The data from one of the temperature loggers at the downstream end of Reach 6 was more than 3°F cooler than the data from the other temperature logger after July 4, 2014. As a result, the water temperatures used in calibration for Reach 6 were the average of both temperature loggers through July 4, 2014, and were from the second temperature logger at the downstream end of Reach 6 after July 4, 2014. The spatial distribution of water temperatures was as expected, with water temperatures increasing going downstream, except that water temperatures decreased going through Reach 6, indicating there may be seepage of cooler groundwater into Reach 6[11].

[11] We suspect that this may be why the data from the one thermologger at the downstream end of Reach 6 were more than 3°F cooler than the data from the other temperature logger after July 4, 2014.

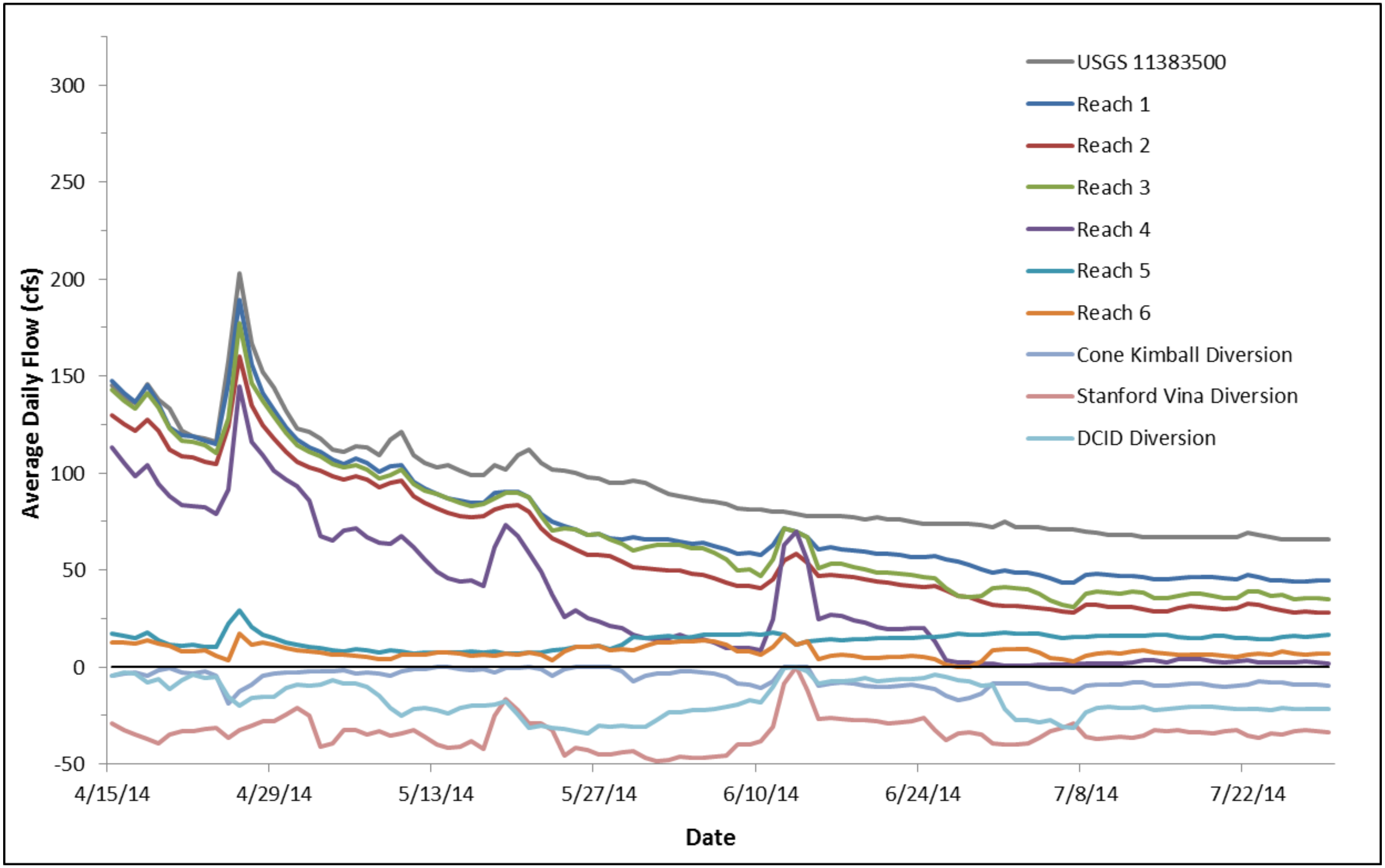


Figure 22. Deer Creek 2014 flow data from pressure transducers, USGS 11383500, and diversions. Flows are plotted as positive values, while diversions are plotted as negative values.

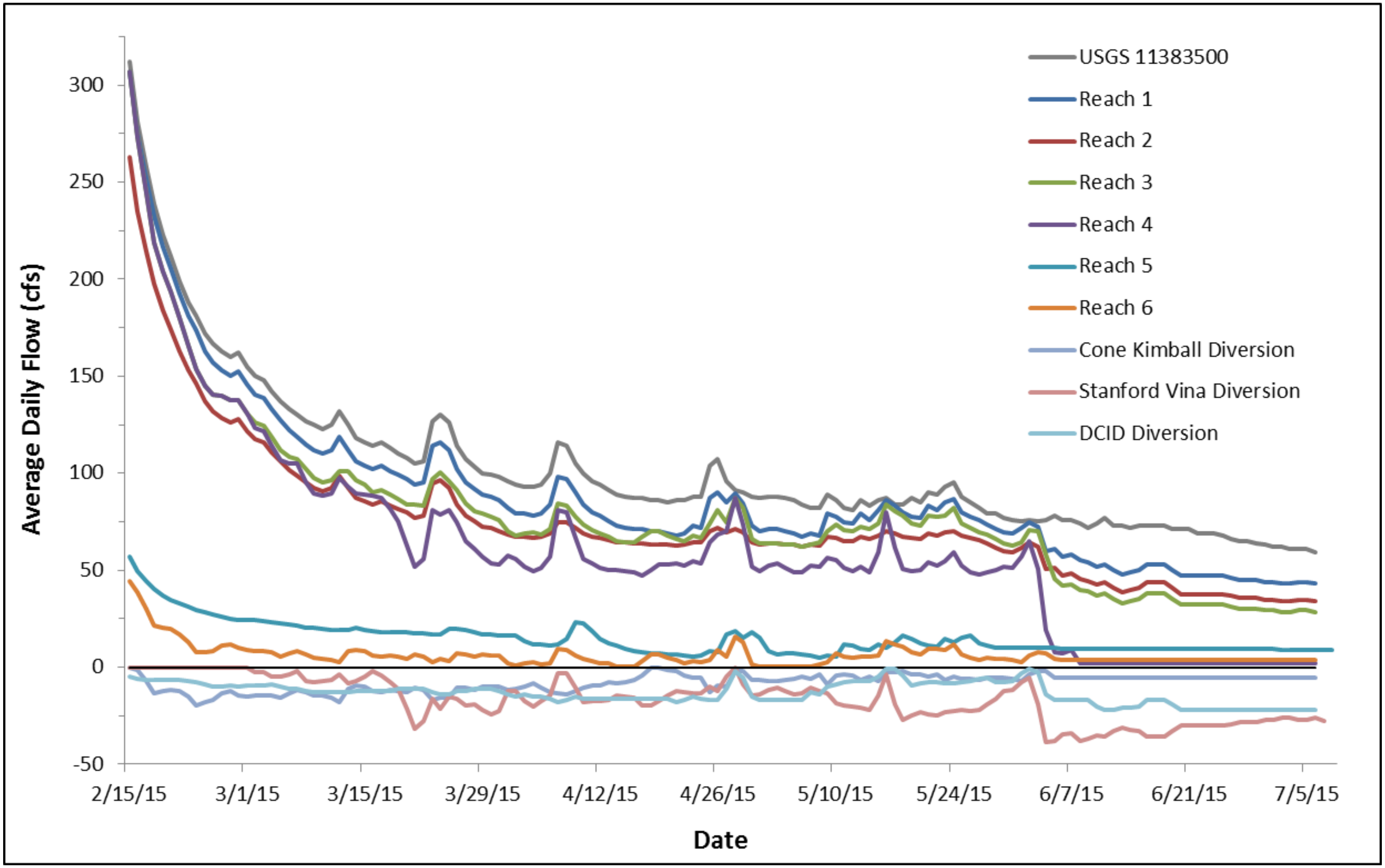


Figure 23. Deer Creek 2015 flow data from pressure transducers, USGS 11383500, and diversions. Flows are plotted as positive values, while diversions are plotted as negative values.

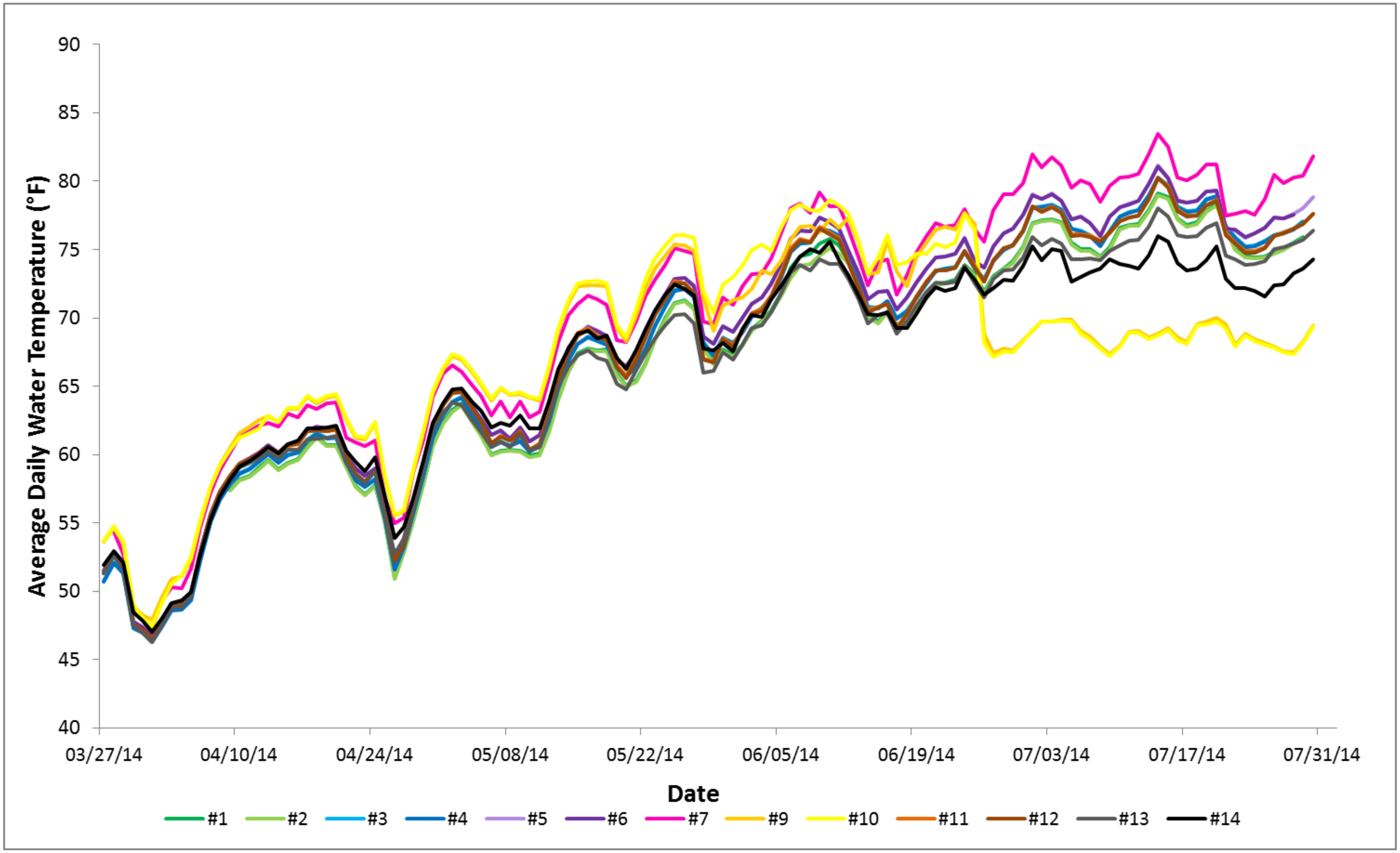


Figure 24. Deer Creek 2014 measured water temperatures. Temperature loggers 1 and 2 were at the upstream end of Reach 1, loggers 3 and 4 were at the downstream end of Reach 1, loggers 5 and 6 at the downstream end of Reach 2, logger 7 at the downstream end of Reach 3, loggers 9 and 10 at the downstream end of Reach 4, loggers 11 and 12 at the downstream end of Reach 5, and loggers 13 and 14 at the downstream end of Reach 6.

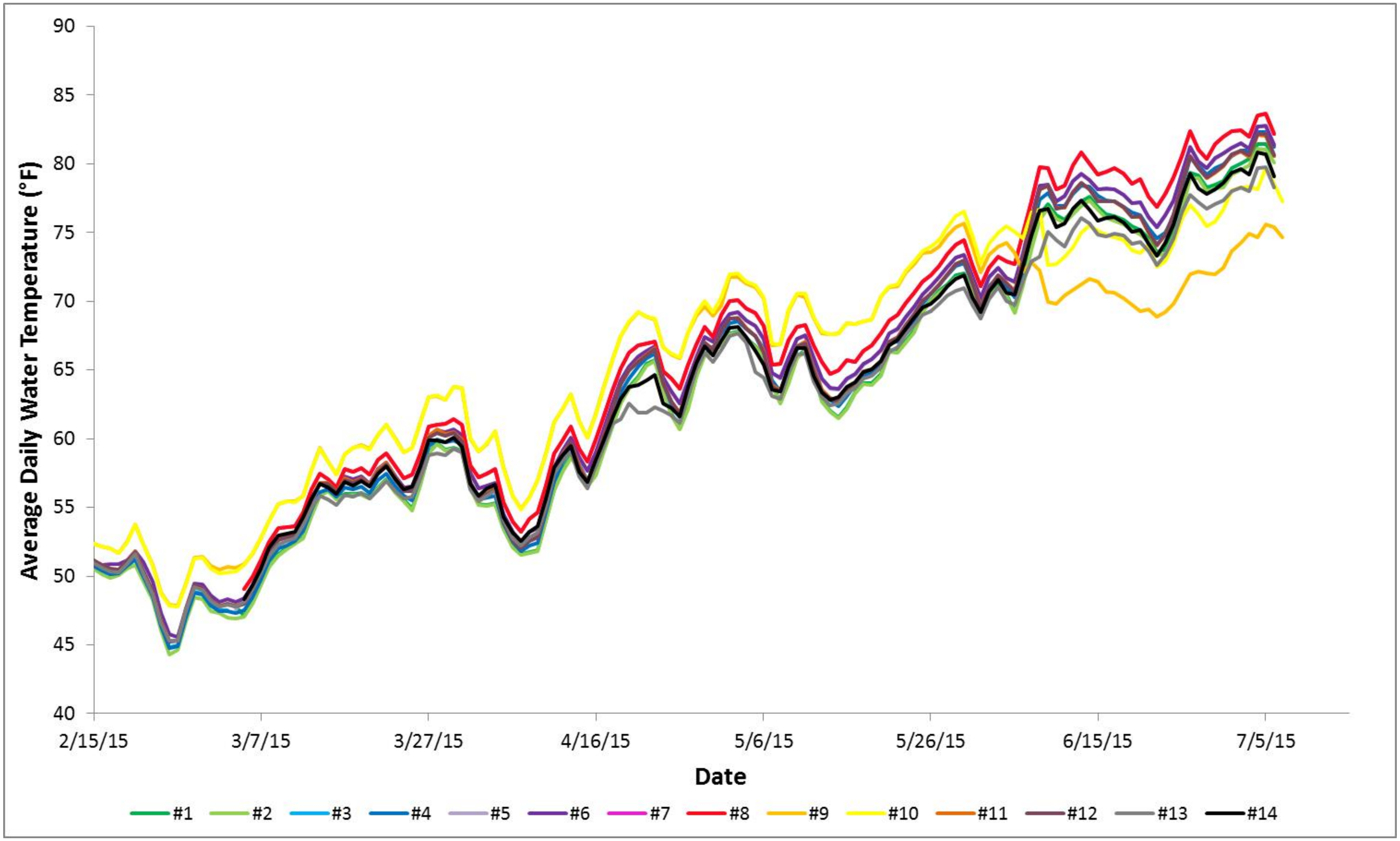


Figure 25. Deer Creek 2015 measured water temperatures. Temperature loggers 1 and 2 were at the upstream end of Reach 1, loggers 3 and 4 were at the downstream end of Reach 1, loggers 5 and 6 at the downstream end of Reach 2, loggers 7 and 8 at the downstream end of Reach 3, loggers 9 and 10 at the downstream end of Reach 4, loggers 11 and 12 at the downstream end of Reach 5, and loggers 13 and 14 at the downstream end of Reach 6.

One of the temperature loggers at the downstream end of Reach 1 was missing after March 3, 2015. As a result, water temperatures to validate the water temperature model after that date were based on the water temperatures measured by the one remaining temperature logger. Similarly, one of the temperature loggers at the upstream end of Reach 1, the downstream end of Reach 2, and at the downstream end of Reach 5 were missing when temperature loggers were downloaded in early March 2015. These three missing temperature loggers were replaced at that time. Accordingly, validation data for those reaches from February 15 to early March 2015 were based on the one remaining temperature logger at the upstream end of Reach 1 and downstream end of Reaches 2 and 5. In 2015, the temperature loggers at the downstream end of Reach 4 were moved a significant distance upstream of the Sacramento River to avoid the issues encountered in 2014 with temperature logger data reflecting Sacramento River water temperatures, rather than Deer Creek water temperatures. However, temperatures from these loggers started to decline on June 5, 2015, relative to water temperatures at the downstream end of Reach 3. It appeared that at very low flows in Reach 4, groundwater inputs start to have an increasingly larger effect on water temperatures in the creek. As a result, the StreamTemp predictions of water temperatures in Reach 4 could not be validated after June 4, 2015.

StreamTemp Model Results

Unimpaired mean daily water temperature values were generated for the SRCS migration season (i.e., mid-February through mid-August). As shown in Figures 26 through 28, mean daily water temperature values were generally lower for unimpaired flows versus impaired flows in the latter half of the SRCS migration season. The difference between impaired and unimpaired water temperatures was exacerbated in dry years versus wet. In 2008, a critically dry year, the mean daily water temperature began to diverge sometime in early April. The median difference in mean daily water temperature was 1.5°F, while the peak difference was 5.5°F. In comparison, in the wet year of 2011, mean daily water temperatures were similar through mid-June, with a median difference of 0.2°F and a peak difference of 2.6°F.

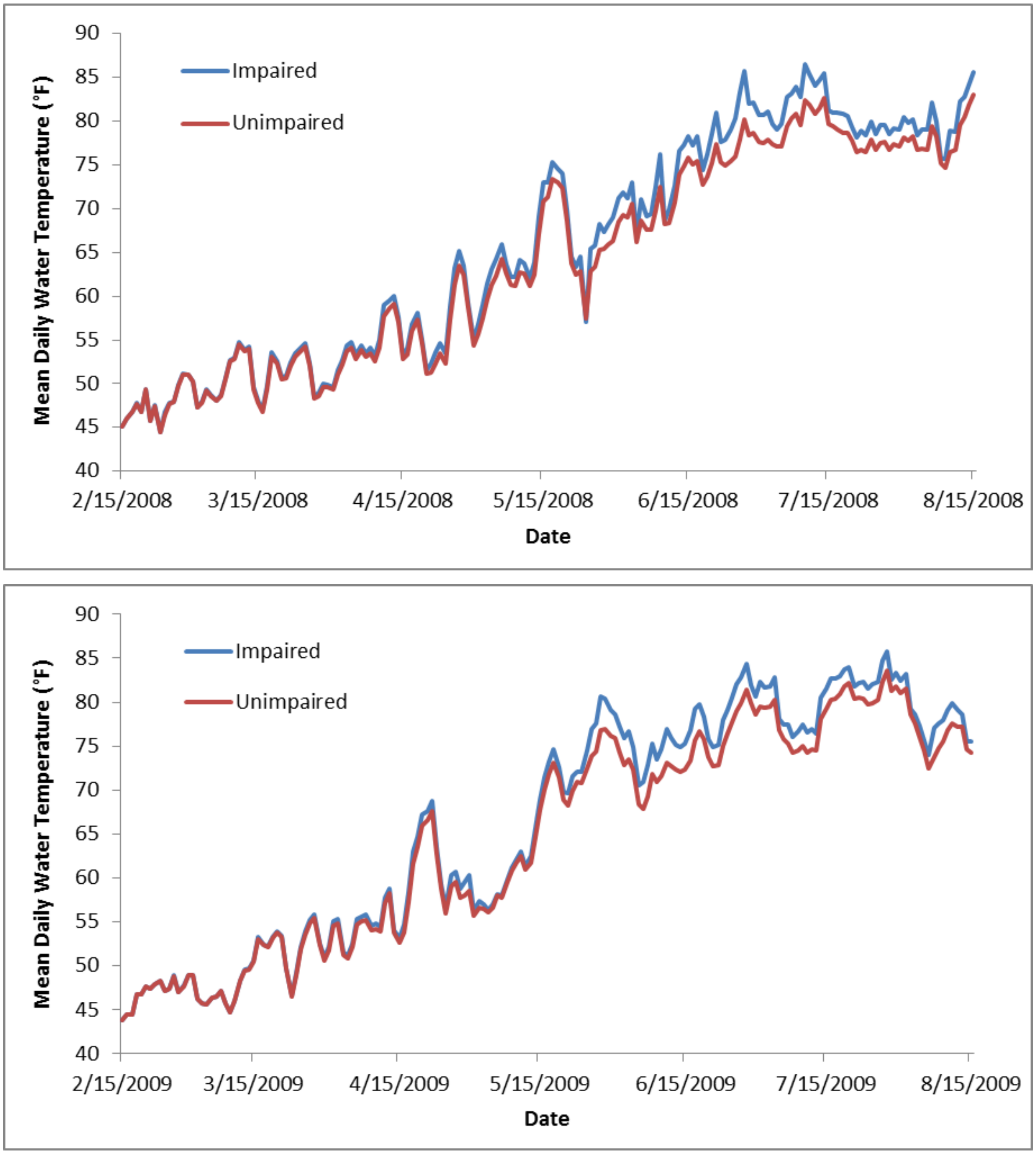
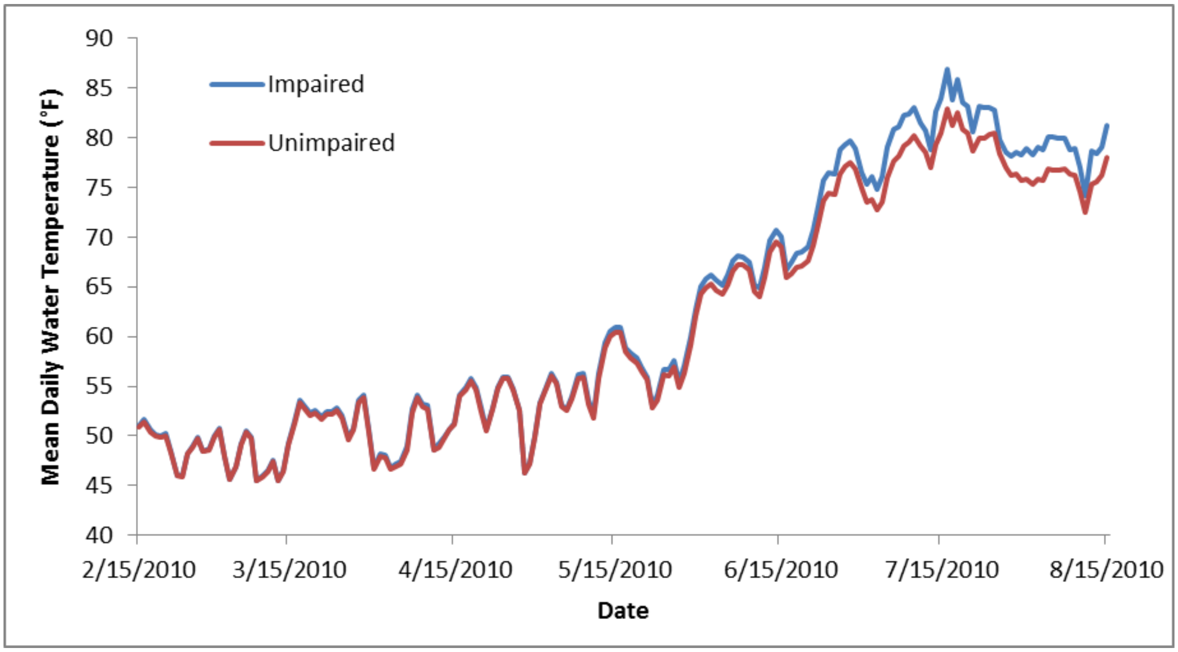


Figure 26. Predicted mean daily water temperature (°F) at the downstream end of Reach 4 for impaired and unimpaired flows during season of migration in 2008-2009.



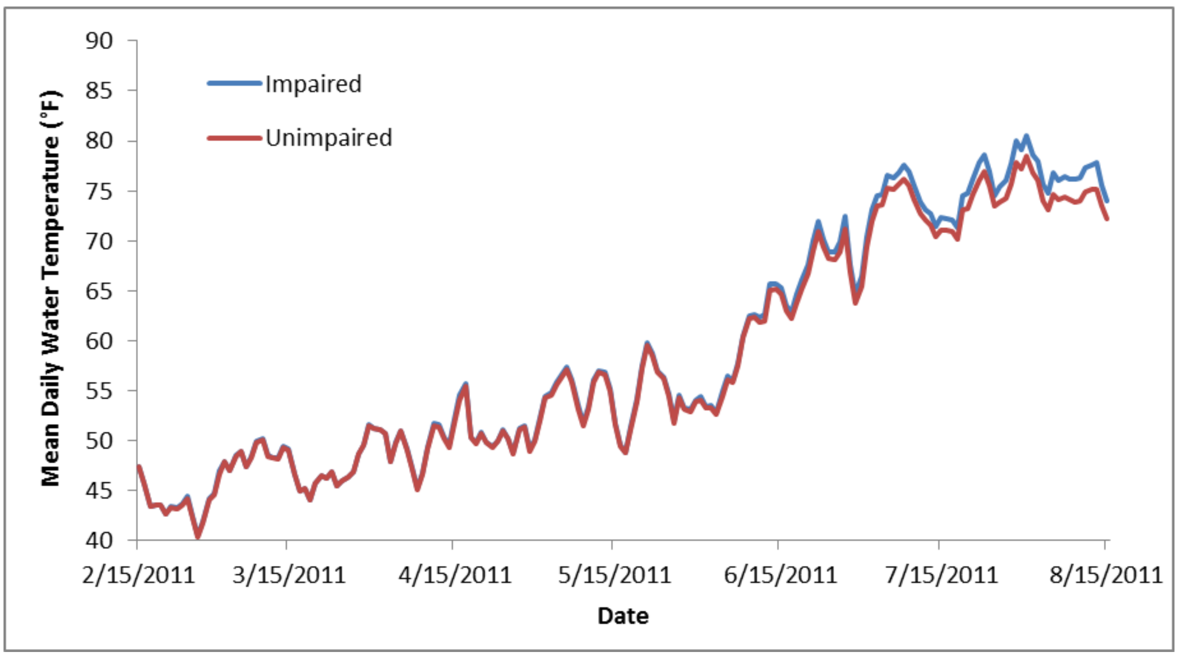


Figure 27. Predicted mean daily water temperature (°F) at the downstream end of Reach 4 for impaired and unimpaired flows during season of migration in 2010-2011.

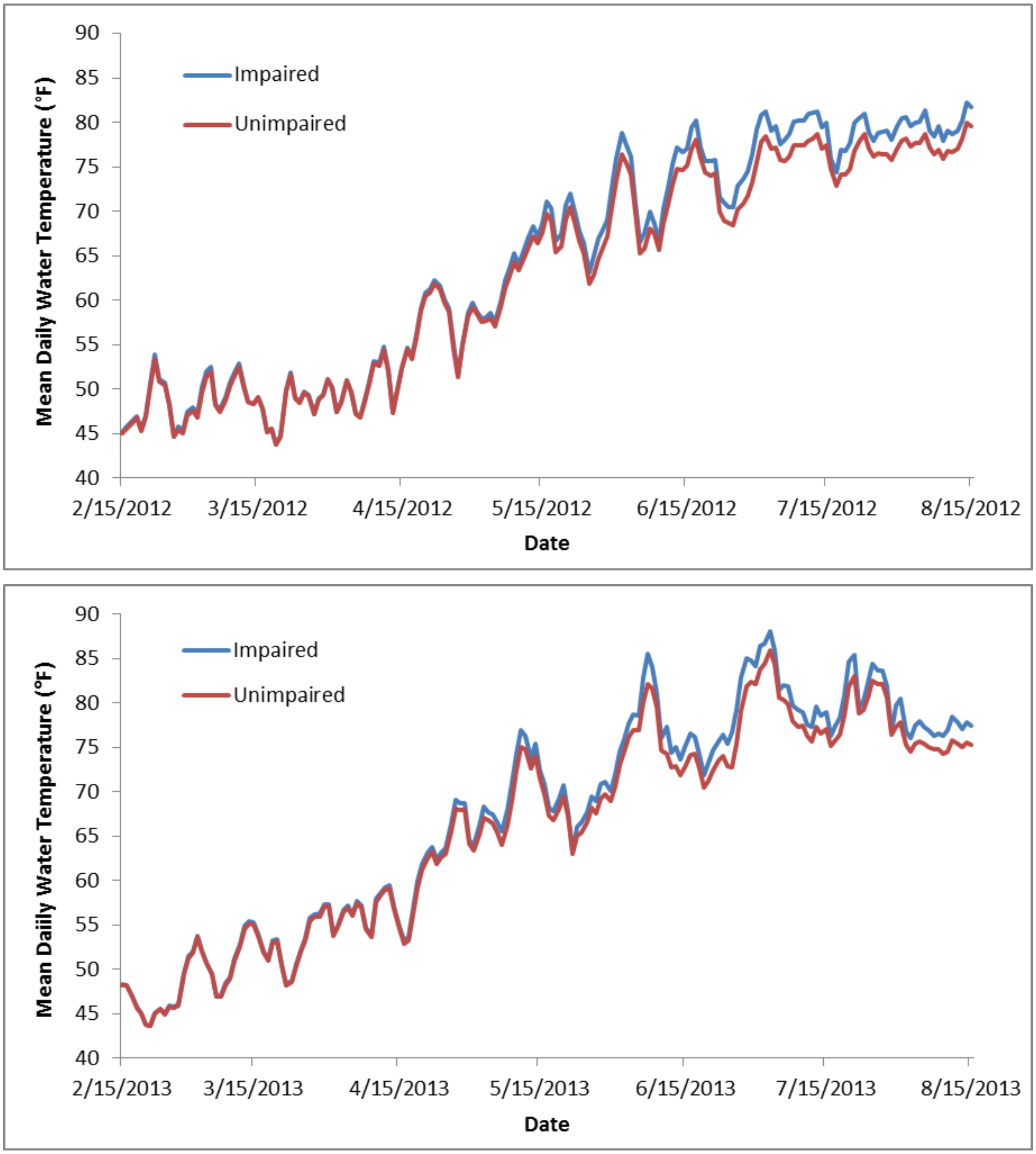


Figure 28. Predicted mean daily water temperature (°F) at the downstream end of Reach 1 for impaired and unimpaired flows during season of migration in 2012-2013.

6.0 DISCUSSION

This technical report focuses on documenting the methods used to assess both physical and temporal passage-limiting conditions that affect salmonid migration through the study reach. It presents the results of models used to predict stream conditions including depth, width, velocity, and temperature over a range of flows. Flow criteria necessary to maintain healthy conditions for fish and wildlife in lower Deer Creek will be presented in a separate report.

6.1 Critical Riffle Passage Assessment

Assessment of salmonid passage through critical riffles was based on the Thompson (1972) methodology, an empirical method commonly used to evaluate flows necessary for salmonid passage (Bjornn and Reiser 1991; Reiser et al. 2006; Holmes et al. 2015). The purpose of the CRA methodology and associated transect width metrics is to determine flow conditions which allow for the physical movement of salmonids through critical riffle locations. The Thompson (1972) methodology is based on more than a decade of extensive field observations by ODFW spanning all 18 drainages and including several hundred of the most important salmonid streams in Oregon. This method has also been used to identify steelhead passage flows in a coastal California river, with results validated by hydraulic modeling (Holmes et al. 2015). The width metrics are therefore assumed to identify flows for passage and habitat connectivity that protect against partial or complete blockages in salmonid migration, particularly as flows recede in shallow depth sensitive cobble-dominated riffle habitats (Holmes et al. 2014).

The CRA method considers maximum velocity as well as depth and width (Thompson 1972). The maximum allowable velocity for adult Chinook through low gradients riffles is 8.0 ft/s (Thompson 1972). No limiting velocities were encountered during any of the CRA sampling events at CR31 or CR32 for any of the life stages considered.

To build a robust relationship between habitat passage metrics and flow, CRA depends on data being collected over a sufficient number of flow sample events at a wide enough range, to bracket flows necessary for salmonid passage. Generally, CRA targets three to six sampling events with flows between the 20th to 80th percentile of exceedance (Figure 2; CDFG 2012). Each riffle site was surveyed at five distinct flow events, meeting the SOP guidance (CDFG 2012). However, some of these flows were limited in capturing sufficient stream depths needed to meet Thompson depth criteria. Sampled events captured a range of flows from 12.4 to 193.3 cfs, approximating the 40th to 100th percentile of exceedance. Unfortunately, flows above 200 cfs (approximately the 35th percentile of exceedance) at Deer Creek riffle sites were hazardous and un-wadeable for field crews.

6.2 Wetted Perimeter

A Wetted Perimeter breakpoint defines the threshold below which aquatic habitat conditions for benthic macroinvertebrates rapidly declines (CDFW 2013d). The Wetted Perimeter method only addresses low flows and is restricted to stream segments where the stage at the transect area is flow-sensitive (i.e., the hydraulic control), and representative of the geomorphic structure and shape of the river channel (Annear et al. 2004). Breakpoint flows were identified for each wetted perimeter site as the flow which correlated to at least 50 percent of the wetted perimeter being covered, and where a large change in the slope of the wetted perimeter versus discharge curve occurred.

Annear et al. (2004) recommends that if the Wetted Perimeter method is used to determine a low flow threshold, that either the breakpoint on the wetted perimeter discharge relation or the flow corresponding to a proportion of the wetted perimeter be used. In the latter case, in streams less than 50 feet wide, use the flow corresponding to at least 50 percent of the wetted perimeter being covered; in larger streams, use the flow corresponding to between 60 to 70 percent of the wetted perimeter being covered. All three sites were wider than 50 feet and had a breakpoint flow identified higher than the 60 percent wetted perimeter flow.

The three wetted perimeter sites evaluated varied in geomorphic shape (Appendix E). Since sites were selected based on their structure and their representativeness of riffle habitat types in lower Deer Creek, no one site was considered to be more or less limiting than the other. Therefore, the average low flow, or breakpoint flow, may better represent the overall characteristics of the entire reach; this equates to 23 cfs.

6.3 Temperature Models

StreamTemp outputs for impaired versus unimpaired water supply showed the magnitude of change to be slight until the latter half of the SRCS migration season (Figures 26 through 28). The simulations of impaired and unimpaired flows indicated that water temperatures are most sensitive to air temperatures, but that increased flows can result in a reduction in water temperatures. In general, wet water year types maintained similar water temperatures when comparing impaired and unimpaired flow. In contrast, water temperature diverged several months earlier in dry water year types. This indicates that in wetter years, temperatures favorable to salmonid migration are maintained for a longer period of time than in drier years.

The EPA-established thresholds of 7DADM for Chinook Salmon (EPA 2003) remain the only temperature criteria currently available for evaluation of passage conditions relating to stream temperature. A 7DADM of 64°F represents areas where non-core juvenile rearing may occur along with adult migration. In areas where only adult migration occurs, the 7DADM is 68°F. Review of the simulations of maximum daily water temperature used to calculate 7DADM in lower Deer Creek (presented in Appendix B), indicate that 7DADM values will be exceeded earlier in drier water year types compared to wetter water year types.

7.0 CONCLUSIONS

Conditions that could potentially limit upstream migration of salmonids were evaluated for lower Deer Creek. Two passage limiting riffle sites were identified in the creek below the most downstream diversion. CRA data was collected at the sites in 2014 to evaluate passage limiting conditions based on flow depth, width, and velocity. Passage conditions at the riffles were assessed by identifying the shallowest course from bank to bank, and using the field data to develop stage/discharge regression rating relationships at each site. Depths meeting the minimum criteria for migrating steelhead and Chinook Salmon were derived from regression relationships, validated with field measurements, and used to estimate the amount of passable width available over a range of simulated flow levels. The results are presented in Tables 12 through 15 for CR31 and CR32, respectively. The Wetted Perimeter method was also used to determine a minimum instream flow for the summer low flow period.

A predictive SNTEMP model, StreamTemp, was developed for the lower, migratory reach of Deer Creek to assess unimpaired and impaired flow conditions. A second model, W3T, was developed using the same basic mechanisms as a SNTEMP model. Both model outputs were compared against measured temperatures to see how they performed. Although W3T operates on an hourly time step, the more robust StreamTemp model was better at predicting average daily water temperatures. The difference in impaired and unimpaired water temperature was found to be significant in the simulations for the later part of the spring-run migration in drier water year types.

The information presented in this report will be used by the Department to help develop flow criteria necessary to protect adult salmonids migrating through lower Deer Creek. Subsequent recommendations will be developed separately from the scientific process presented above, and are not incorporated into this technical report.

ACKNOWLEDGEMENTS

We would like to thank the following Department staff for their assistance with this report: Todd Carlin (Water Branch); Brad Henderson and Matt Johnson (Region 1); Marjorie Caisley (Conservation Engineering); and Kelly Souza (Fisheries Branch). The data in this report were collected with assistance by the following California Department of Fish and Wildlife staff: Krystal Acierto, Don Baldwin, Michael Eakin, Mike Hancock, Candice Heinz, and David Strunk (Water Branch); Daniel Rankin (Data and Technology Division); Patricia Bratcher, Kristin Hubbard, Matt Johnson, and Sam Reece (Region 1). The following U.S. Fish and Wildlife Service staff also assisted with data collection: John Henderson and Rick Williams. We also thank the following staff for their field assistance: Will Anderson, Carl Beckham, Emily Mortazavi, and Jeff Sanchez (State Water Resources Control Board); Lance Downing, Patrick Jarrett, Byron Mache, Darin Olsen, Ryan Revnak, and Carly Wickhem (Pacific States Marine Fisheries Commission).

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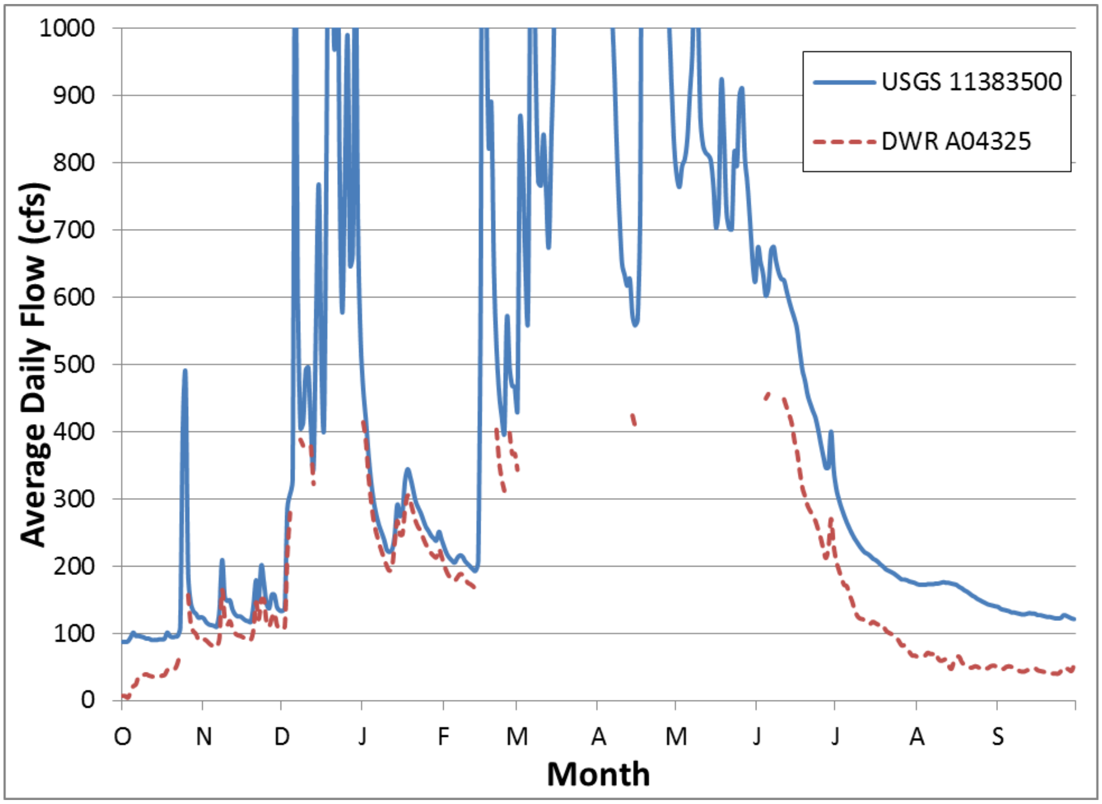
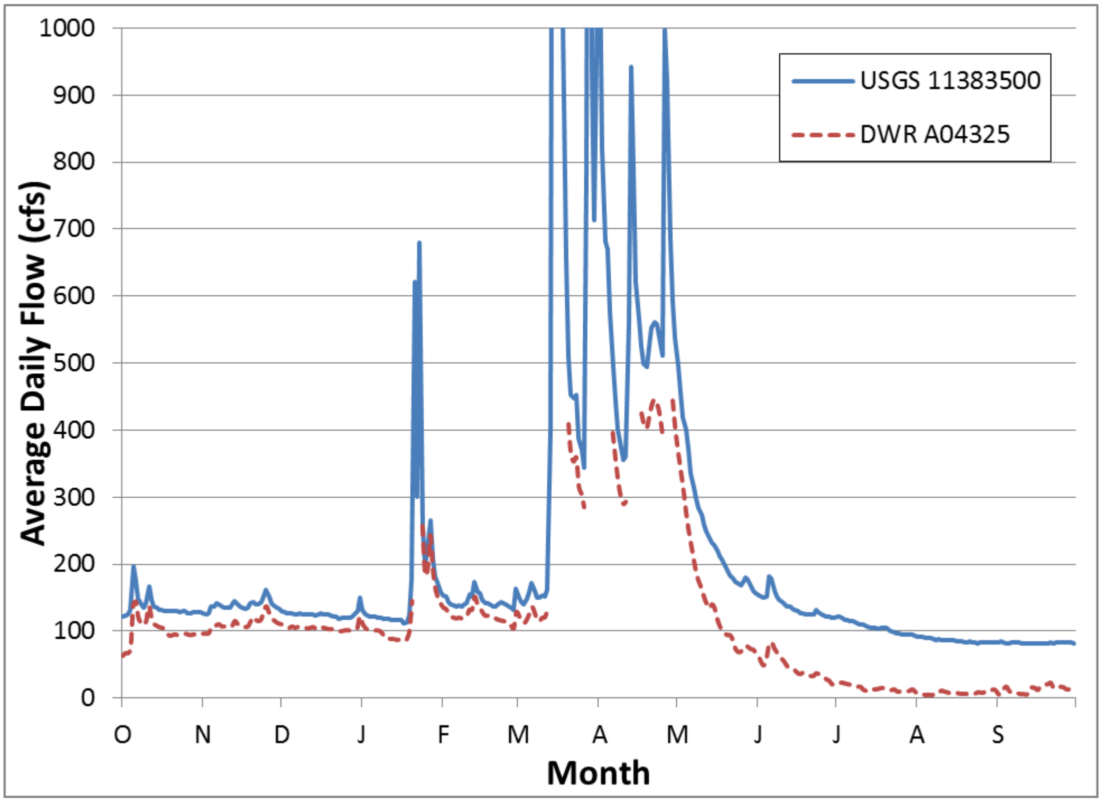
APPENDICES

Appendix A. Monitoring Data

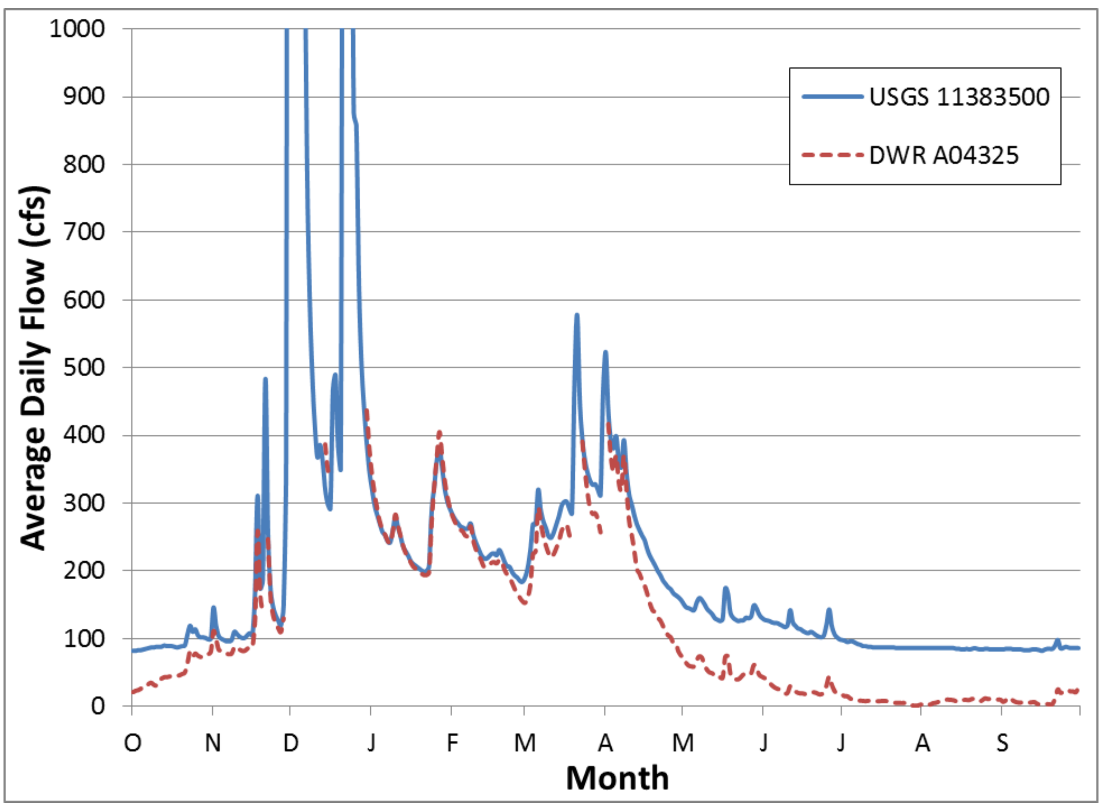
Average Daily Flow



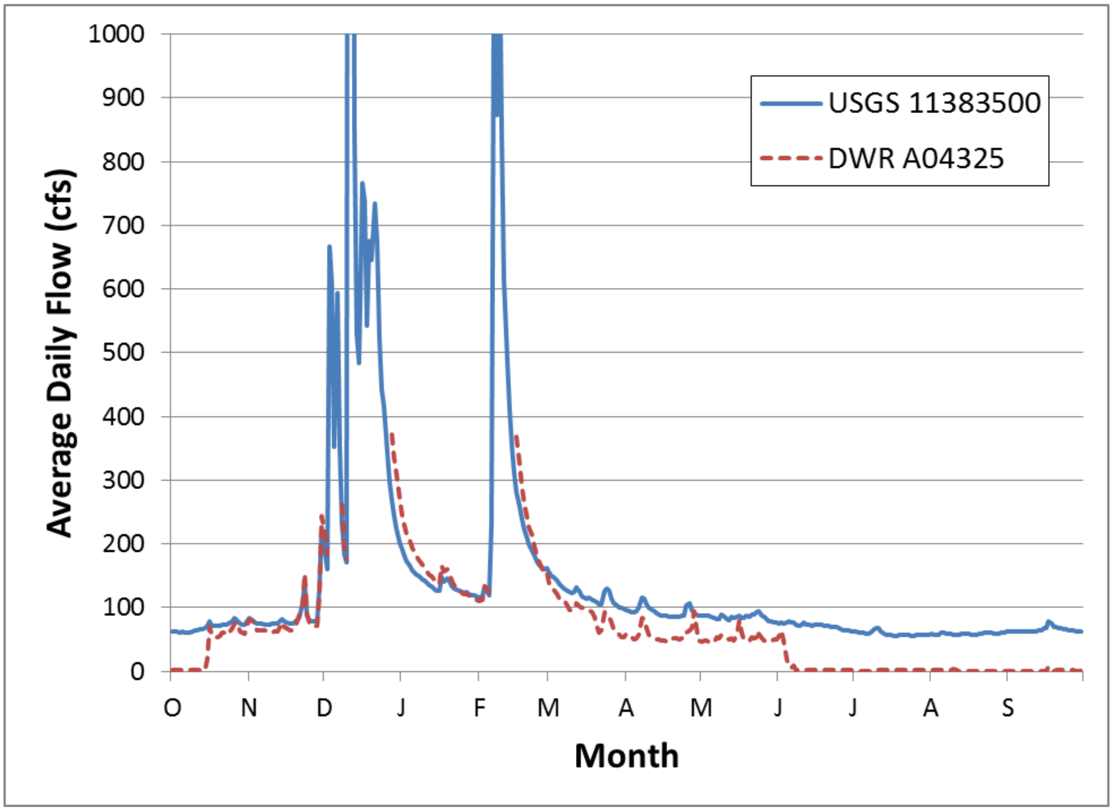
Average daily flow at monitoring gages in Deer Creek for water year 2011.



Average daily flow at monitoring gages in Deer Creek for water year 2012.

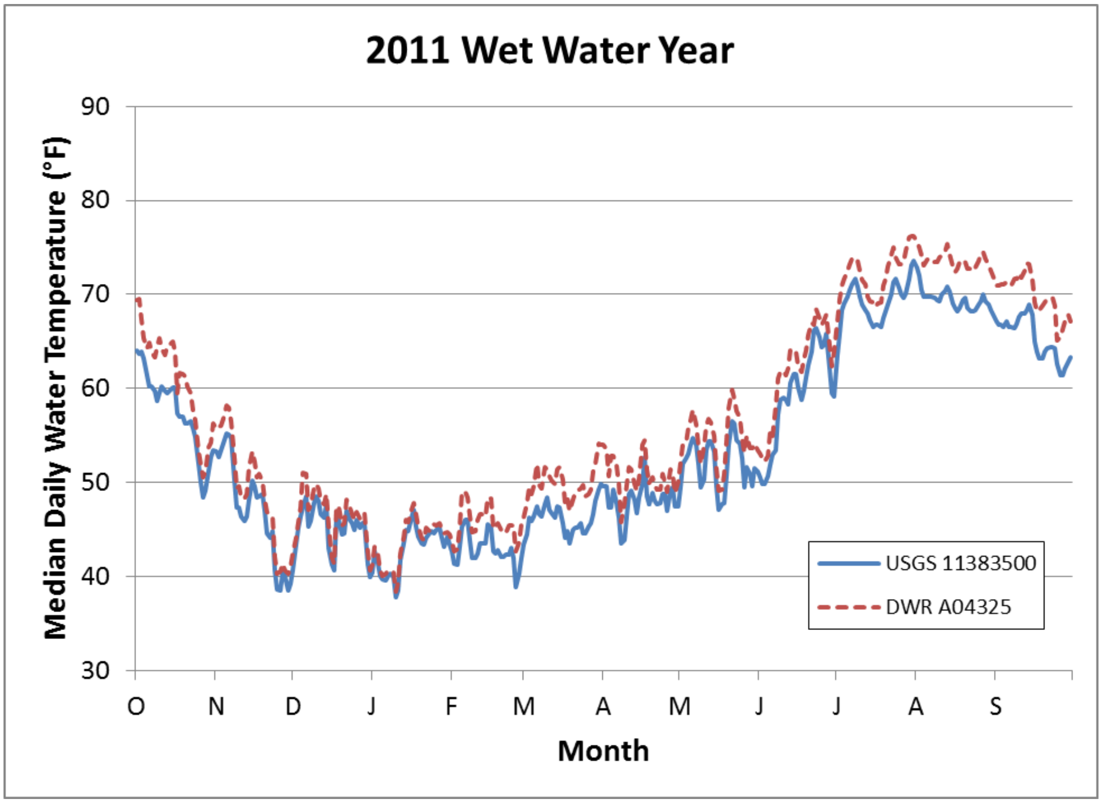


Average daily flow at monitoring gages in Deer Creek for water year 2013.

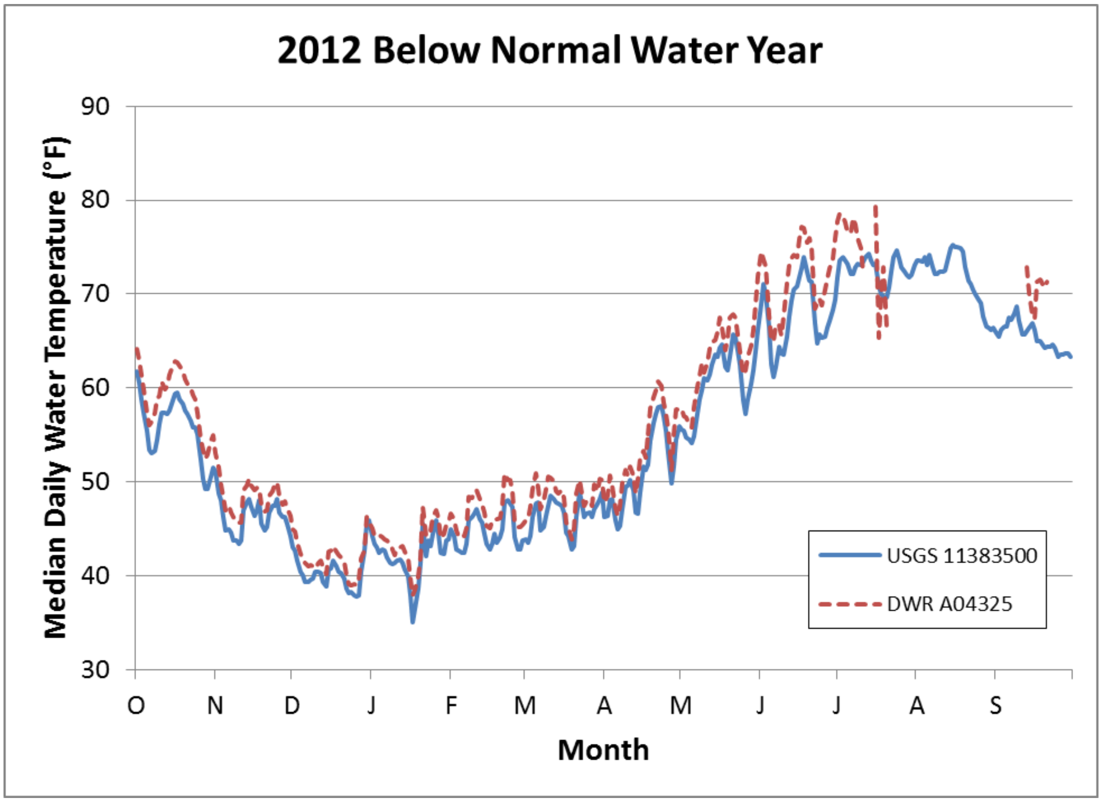


Average daily flow at monitoring gages in Deer Creek for water year 2015.

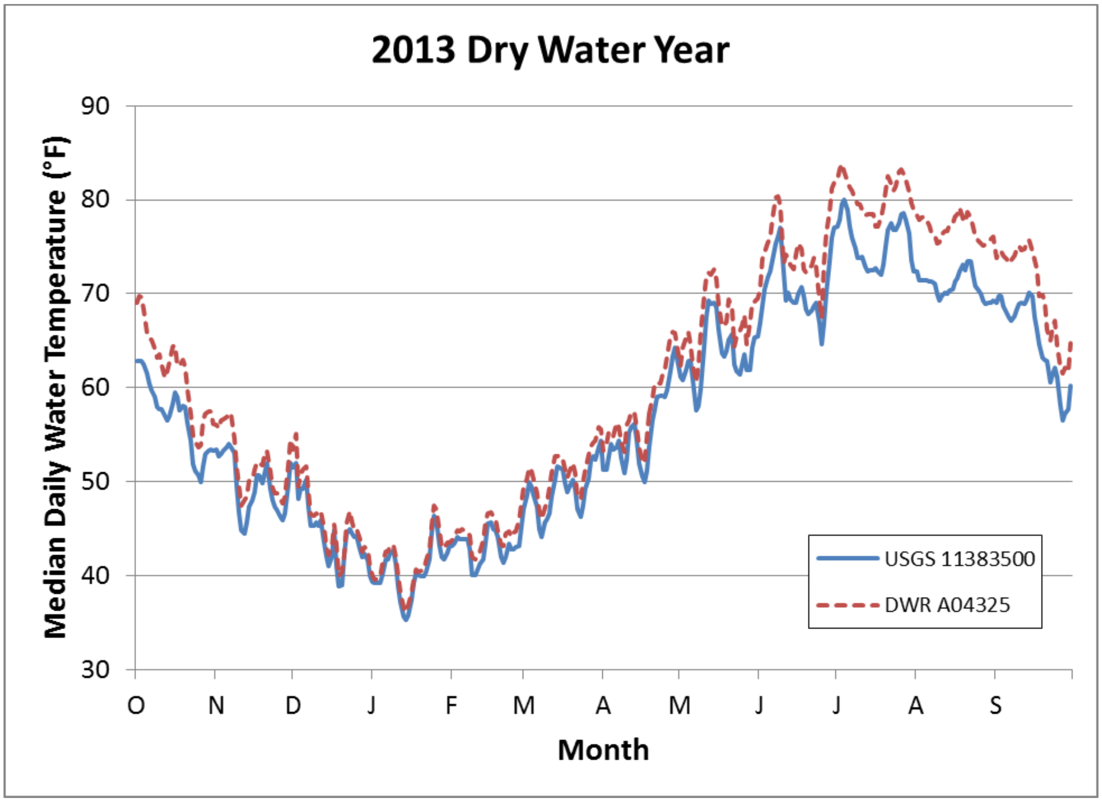
Mean Daily Water Temperature



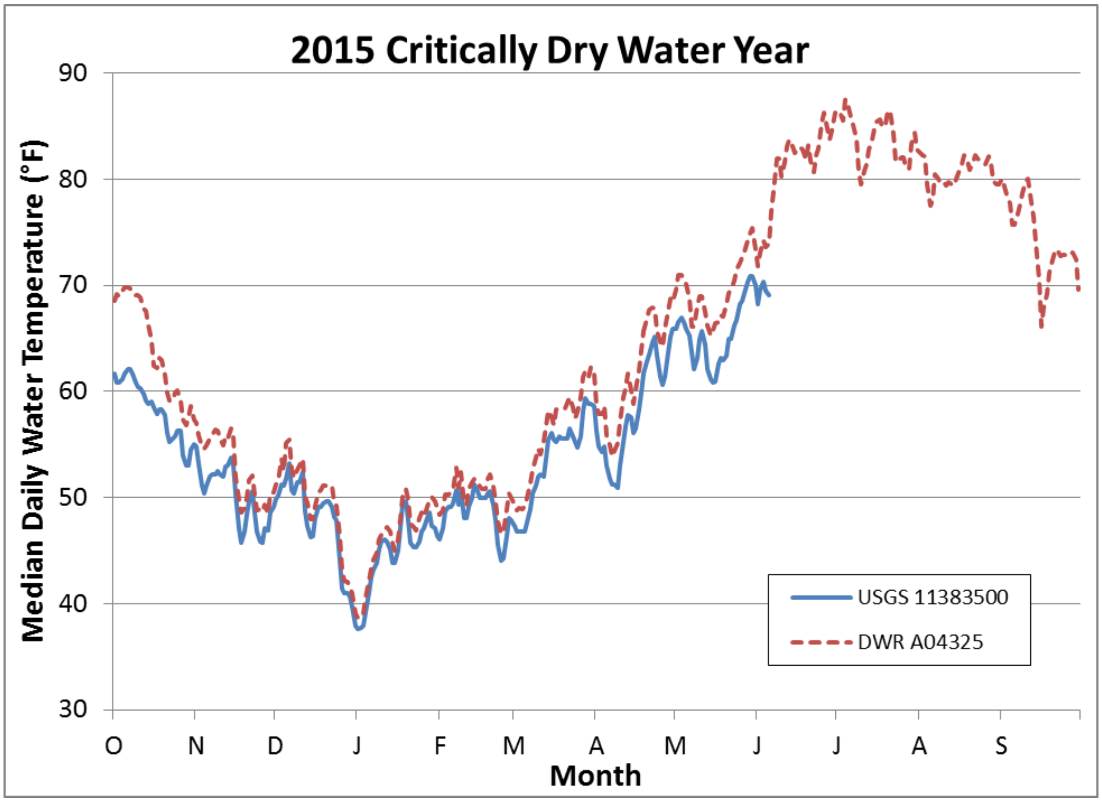
Median daily water temperature for Deer Creek in 2011 water year.



Median daily water temperature for Deer Creek in 2012 water year.

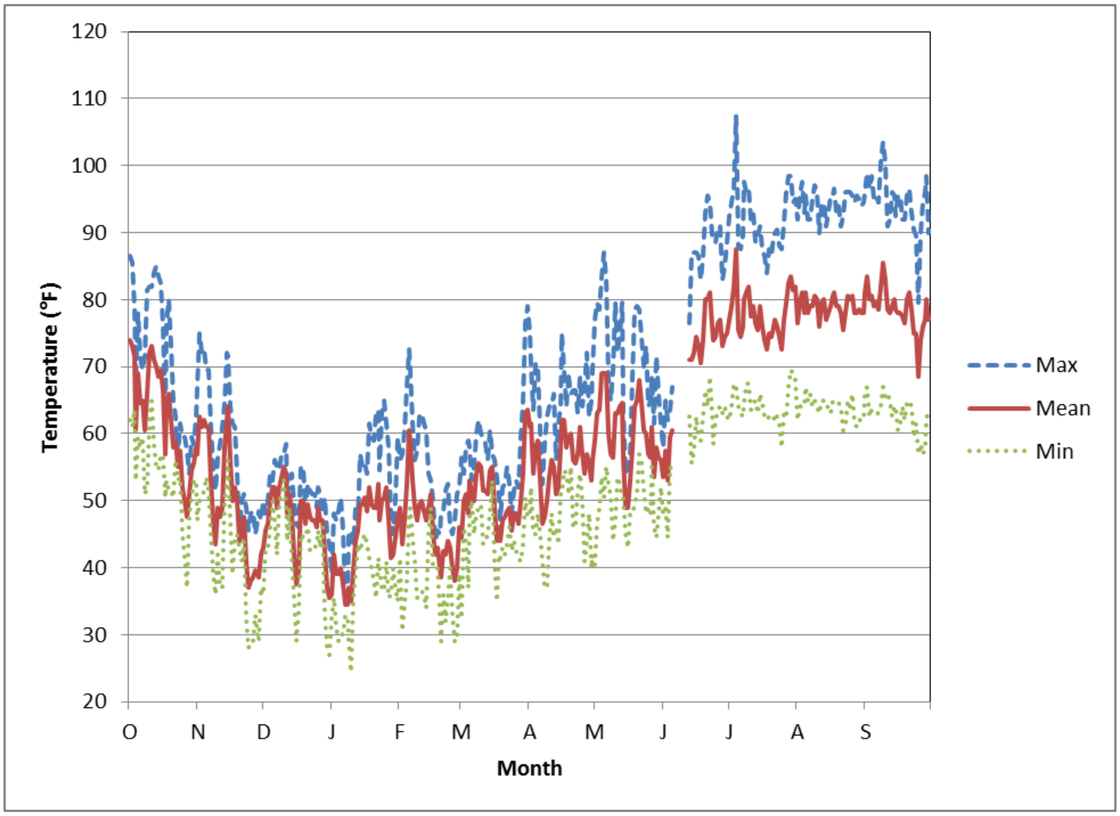


Median daily water temperature for Deer Creek in 2013 water year.

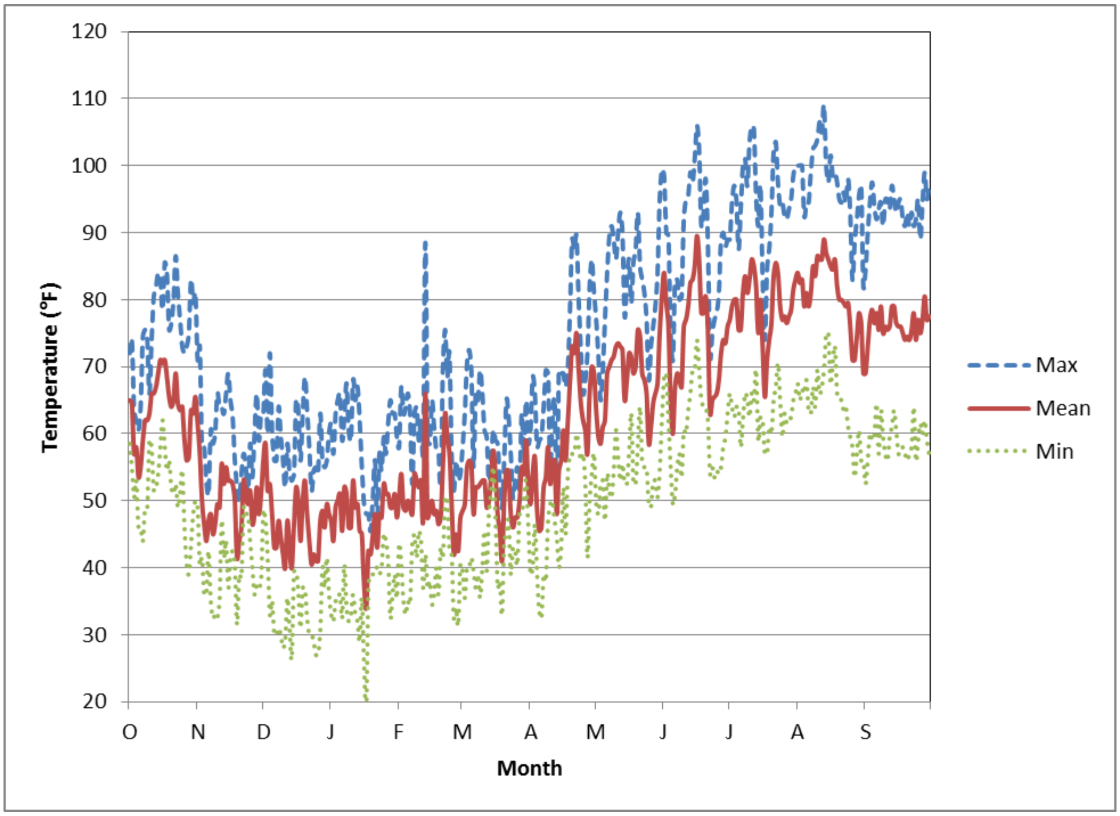


Median daily water temperature for Deer Creek in 2015 water year.

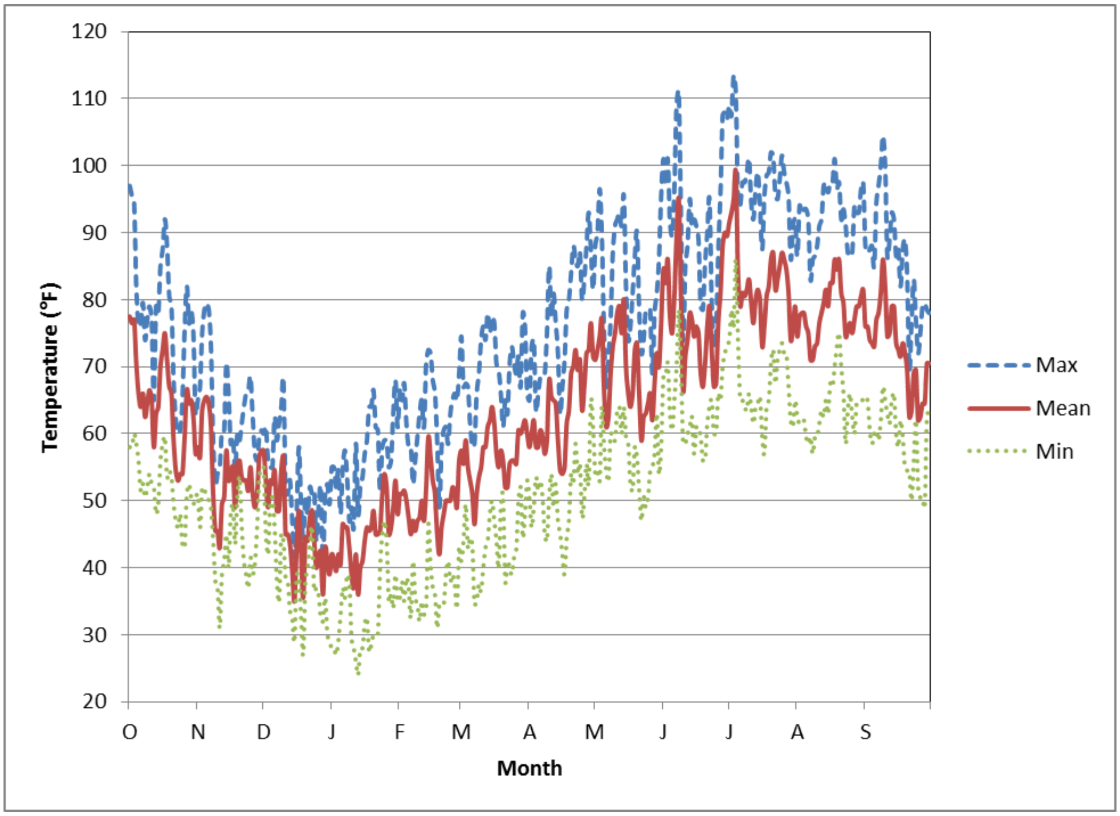
Daily Air Temperature



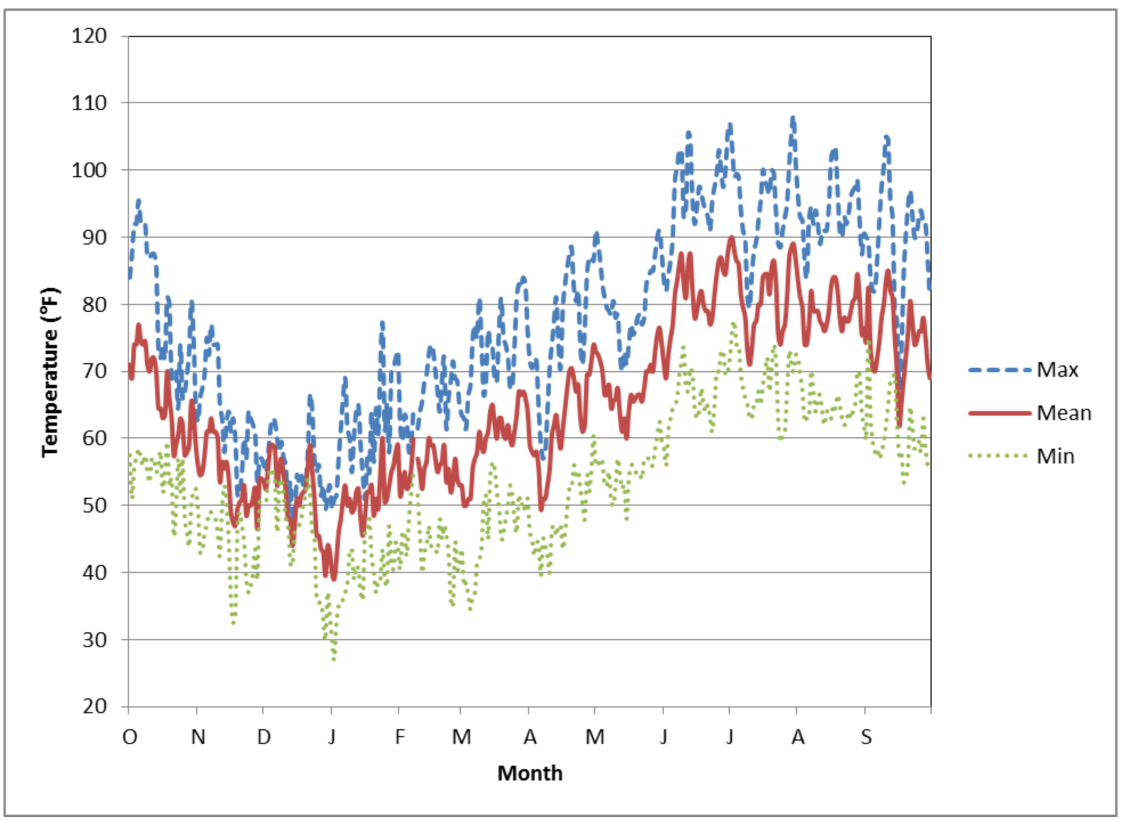
Estimated daily air temperature for the study reach in water year 2011.



Estimated daily air temperature for the study reach in water year 2012.



Estimated daily air temperature for the study reach in water year 2013.



Estimated daily air temperature for the study reach in water year 2015.

Appendix B. StreamTemp Model Construction, Calibration, and Validation

Water Temperature Model Construction

The PHABSIM utility in the commercially available instream flow software package SEFA (Jowett, Payne, and Milhous 2013), short for System for Environmental Flow Analysis, was used to execute WSEL predictions. All data were compiled and checked before entry into SEFA data files. A separate SEFA file was constructed for each reach. All of the measured WSELs were checked to make sure that water did not appear to be flowing uphill due to measurement errors or other factors. The slope for each transect was computed at each measured flow as the difference in WSELs between the two transects divided by the distance between the two. The slope used for each transect was calculated by averaging the slopes computed for each flow. A total of three WSEL sets at low, medium, and high flows were used. Calibration flows in the data files were the flows measured in each reach. The SZF (see section 4.3), an important parameter used in calibrating the stage-discharge relationship, was determined for each transect and entered. In habitat types without backwater effects (e.g., riffles and runs), this value generally represents the lowest point in the streambed across a transect. However, if a transect directly upstream contains a lower bed elevation than the adjacent downstream transect, the SZF for the downstream transect applies to both.

Transects having a higher downstream control were surveyed using standard differential leveling to accurately calibrate WSELs on the transect. If the true SZF was not measured as described above, the thalweg elevation at the transect was used as the default SZF.

The first step in the calibration procedure was to determine the best approach for WSEL simulation. Initially, the *IFG4* hydraulic model (Milhous et al. 1989) was run on each dataset to compare predicted and measured WSELs. This model produces a stage-discharge relationship using a log-log linear rating curve calculated from at least three sets of measurements taken at different flows. Besides *IFG4*, two other hydraulic models are available in PHABSIM to predict stage-discharge relationships. These models are: 1) *MANSQ*, which operates under the assumption that the condition of the channel and the nature of the streambed control WSELs; and 2) *WSP*, the water surface profile model, which calculates the energy loss between transects to determine WSELs. *MANSQ*, like *IFG4*, evaluates each transect independently. *WSP* must, by nature, link at least two adjacent transects.

IFG4, the most versatile of these models, is considered to have worked well if the following criteria are met: 1) the beta value (a measure of the change in channel roughness with changes in stream flow) is between 2.0 and 4.5; 2) the mean error in calculated versus given discharges is less than 10%; 3) there is no more than a 25% difference for any calculated versus given discharge; and 4) there is no more than a 0.1

foot difference between measured and simulated WSELs[12]. *MANSQ* is considered to have worked well if the second through fourth of the above criteria are met, and if the beta value parameter used by *MANSQ* is within the range of 0 to 0.5. The first *IFG4* criterion is not applicable to *MANSQ*. *WSP* is considered to have worked well if the following criteria are met: 1) the Manning's n value used falls within the range of 0.04 - 0.07; 2) there is a negative log-log relationship between the reach multiplier[13] and flow; and 3) there is no more than a 0.1 foot difference between measured and simulated WSELs. The first three *IFG4* criteria are not applicable to *WSP*.

After the transect stage-discharge relationships were calibrated, the SEFA files were used to generate wetted width and average depth for flows from 25 to 375 cfs for Reach 1, 25 to 380 cfs for Reach 2, 20 to 360 cfs for Reach 3, 10 to 240 cfs for Reach 4, 3.5 to 45 cfs for Reach 5, and 1.2 to 25 cfs for Reach 6 (Appendix C). The flow ranges were selected to go from 40% of the flow for the lowest measured WSEL to 2.5 times the flow for the highest measured WSEL. Overall, flow-width and flow-depth relationships for each reach were generated from the individual transects by weighting the transects based on the mesohabitat composition of each reach. Log-log regression of wetted width versus flow was then used to compute the width parameters (width A constant, width B coefficient and maximum width[14]) used in StreamTemp[15], while a plot of depth versus flow was used to extrapolate the residual depth parameter in StreamTemp (the average depth present at a flow of zero). The value of Manning's n for each reach used in StreamTemp was computed from the discharge, slope, depth, and width values using Manning's equation (see section 2.2).

Average vegetation shade angle and vegetation density values for left and right banks of each reach were calculated in Excel from the field data. The shade angle data were converted to vegetation heights using the following formula:

Vegetation height = ½ x maximum width x tan (vegetation shade angle)

Vegetation crown widths were calculated by multiplying the vegetation height by 0.57[16]. Data to compute topographic shade angles were developed from a digital terrain model in GIS as follows. Elevations of the stream channel and the topographic horizon (such as ridge tops) were recorded from the digital terrain model, while the horizontal distance from the stream channel to the topographic horizon was measured in GIS. The topographic shade angles for left and right banks of each reach were then computed from the following formula:

---

[12] The first three criteria are from U.S. Fish and Wildlife Service (1994), while the fourth criterion is our own criterion.
[13] The reach multiplier is used to vary Manning's n as a function of discharge.
[14] The maximum width used in SNTEMP was calculated from the log-log regression equation using the highest simulated flow.
[15] StreamTemp is a commercially produced software (Payne and Associates 2005) that incorporates the modeling procedures used in SNTEMP.
[16] The value of 0.57 was derived from the average height (50 to 90 feet) and width (40 feet) of white alders, which were the predominant tree species along Deer Creek.

Topographic shade angle = Atan ([horizon elevation – stream channel elevation]/distance)

The azimuth for each reach was measured and the latitude of each reach was determined in Google Earth. The length of each reach was computed from the mesohabitat polyline shapefiles, while the elevation at the downstream end of each reach and at the upstream end of Reach 1 was interpolated from USGS quad map elevation contour lines in GIS. Daily average air temperatures, percent humidity, wind speed and cloud cover data for Red Bluff Municipal Airport (KRBL) and Chico Municipal Airport (KCIC) were downloaded from the Weather Underground website (www.wunderground.com). Cloud cover data, which have values ranging from zero to eight, were converted to percent possible sun (the input variable for StreamTemp), using the equation:

Percent possible sun = 100 x (1 – 0.125 x cloud cover)

The values for the meteorological variables used in the StreamTemp model were the average of the Red Bluff and Chico data, since Deer Creek is located half-way between Red Bluff and Chico. The air temperature data from the barologger was used with the average of the Red Bluff and Chico air temperature to develop a linear regression equation to correct air temperatures for local variations. Similarly, the wind speed and percent humidity data from the weather station at the USGS gage on Mill Creek were used with the average of the Red Bluff and Chico wind speed and percent humidity to develop linear regression equations to correct wind speed and percent humidity for local variations.

The first step in entering data into the StreamTemp data files was to define network streams, nodes and reaches. The Deer Creek model had two streams: Deer Creek and Cone-Kimball Side Channel. Nodes were defined at the upstream and downstream end of each reach. Deer Creek had four reaches (Reaches 1-4); while the Cone-Kimball Side Channel had two reaches (Reaches 5 and 6). The Cone-Kimball Side Channel was defined as a tributary of Deer Creek, with a diversion flow from the upstream end of Reach 2 corresponding to a return flow to the upstream end of Reach 5. The reach channel geometry parameters are then entered into StreamTemp for each reach followed by a time series of hydrology data, including diversion flows at the Cone-Kimball and SVRIC diversions, computed, respectively, as the difference between Reach 1 and 3, and Reach 3 and 4 flow data from the pressure transducers. The time series of hydrology data also included the average daily water temperature from the temperature logger at the upstream end of Reach 1 (an input to the model), and average and maximum daily water temperatures at the downstream end of each from the temperature loggers (used to calibrate the model). Finally, shade data for each reach and a time series of weather data were entered into StreamTemp.

Water Temperature Model Calibration and Validation

Model calibration and validation followed these basic steps: 1) calibrate model using the data from the monitoring network collected in 2014; 2) validate the model for years 2008 through 2013 using the more limited monitoring data set from the stream gaging stations; and 3) validate the model with the data from the monitoring network collected in 2015.

The first step in model calibration was to run StreamTemp and compare the model output to the measured water temperature data at the downstream end of each reach for the period of April 15 to July 29, 2014. The calibration of the model was evaluated based on the following criteria: 1) average error for each reach less than 1.8°F (1°C); and 2) maximum error for each reach less than 2.7°F (1.5°C) from Kimmerer and Carpenter (1989). Model performance was also evaluated using the following recommendations from Payne and Associates (2005): 1) Correlation Coefficient (R-Squared) as close to 1.0 as possible; 2) Mean Error as close to zero as possible; 3) Probable Error equal to or less than 0.5; 4) Maximum Error equal to or less than 1.5 degrees; 5) Number of Predicted Errors greater than 1.0 degrees less than 10%; and 6) Bias minimal. Parameters were then varied to improve the agreement between simulated and measured water temperatures.

The calibration process had three steps: 1) the solar radiation parameter was varied to globally minimize the mean error and percent greater than 1 degree values of mean daily water temperature; 2) vegetation density and crown width were varied for each reach, going from upstream to downstream, to minimize the mean error and percent greater than 1 degree values of mean daily water temperature for each reach; and 3) Manning's n values were varied to minimize the mean error in 7DADMs for each reach.

The Deer Creek StreamTemp model was validated by comparing measured and simulated water temperatures at the downstream end of each reach for the period of February 15 to July 6, 2015, and by comparing simulated water temperatures at the downstream end of Reach 3 to the measured water temperatures at the DWR gage, located just downstream of the SVRIC diversion, for the period of January 14, 2008 to September 30, 2013[17]. Reach 2 flows were computed as the difference between Reach 1 and 5 flows. Reach 3 flows were computed by subtracting the Cone-Kimball diversion from Reach 1 flows. As for the calibration, Reach 6 flows were computed by subtracting the Cone-Kimball diversion from Reach 5 flows. Validation was assessed using the same water temperature parameters that were used in calibration.

For the 2008 to 2013 validation, water temperatures from the USGS gage were used for the water temperatures at the upstream end of the model. Flows for Reach 1 were computed by subtracting the DCID diversions (downloaded from www.water.ca.gov/waterdatalibrary/index.cfm) from the USGS gage flows. For Reach 1

[17] This was the time period for which there was a complete dataset available for both meteorological and flow data.

flows of less than 130 cfs, a fixed Reach 5 flow of 14.1 cfs,[18] was used, which was the average Reach 5 flow for the period of May 12 to July 29, 2014. For Reach 1 flows of 130 cfs and higher, flows for Reach 5 were computed from the following regression equation, derived from the Reach 1 and 5 flows for the period of April 15 to May 11, 2014:

Reach 5 flow = -17.2 + 0.242 x Reach 1 flow

Constant Cone-Kimball diversions of 3 cfs for October 1 to June 7 and 9.2 cfs for June 8 to September 30 were used for Reach 6. The above diversions were the average Cone-Kimball diversions for April 15 to June 7, 2014 and June 8 to July 29, 2014. The DWR gage flows were used for the flows for Reach 4, and SVRIC diversions were computed as the difference between Reach 3 and 4 flows. Since the DWR gage is only rated to 428 cfs, the combined maximum diversion rate of 115 cfs was used as a quality assurance check on DWR gage flows; when DWR gage flows indicated a total diversion rate exceeding 115 cfs, the DWR flows were calculated by subtracting 115 cfs from the USGS gage flows.

To further evaluate model performance, Deer Creek water temperatures were also simulated using the Water Temperature Transaction Tool (W3T) spreadsheet model (Watercourse Engineering, Inc. 2013). The W3T model uses the same basic mechanisms as StreamTemp, but operates on an hourly time step; StreamTemp operates on a daily time step. The same input data was used for W3T as for StreamTemp, except that hourly meteorological data were downloaded from the Remote Automatic Weather Stations website (RAWS 2015). Meteorological data used in the model were the average of values for Corning and Chico.

Water Temperature Model Results

Included is this section are the results of the StreamTemp model construction, calibration, validation, and model simulations including comparisons of the StreamTemp results with the W3T model.

Water Temperature Model Construction

No problems were found with water appearing to flow uphill due to measurement error or inaccuracies for any of the transects. A total of three WSEL sets at low, medium, and high flows were used for all transects. For 27 of the 35 transects, *IFG4* met the criteria described in the methods for *IFG4* (Appendix C). All *IFG4* construction and calibration parameter results were within acceptable ranges for beta values, mean error in calculated and given discharges, percent difference in calculated and given discharge, and difference in measured and simulated WSELs (Appendix C), with the exception of

[18] This takes into account human-made channel changes at the upper end of the Cone-Kimball side channel to keep the Cone-Kimball side channel flowing at lower Deer Creek flows. The above regression equation indicates that, without these changes, Reach 5 would have stopped flowing for Reach 1 flows lower than 71 cfs. With the changes, the Reach 5 flow was still 15 cfs at a Reach 1 flow of 43.4 cfs.

the beta value for Transects 5, 6, 22, 29 and 35, which were greater than 4.5, the mean error values for Transects 32-35, and the difference in calculated versus measured discharge for the mid flow for Transects 32-34.

The 2014 rating curve for the pressure transducer in Reach 1 (Figure B-1) was developed from three flow measurements made in Reach 1, ranging from 56.1 to 150.3 cfs, along with the pressure transducer data at the corresponding times to when the flow measurements were made. The resulting regression equation was as follows:

$$\log(\text{flow}) = 1.511 + 2.574 \times \log(\text{stage} - 94.47)$$

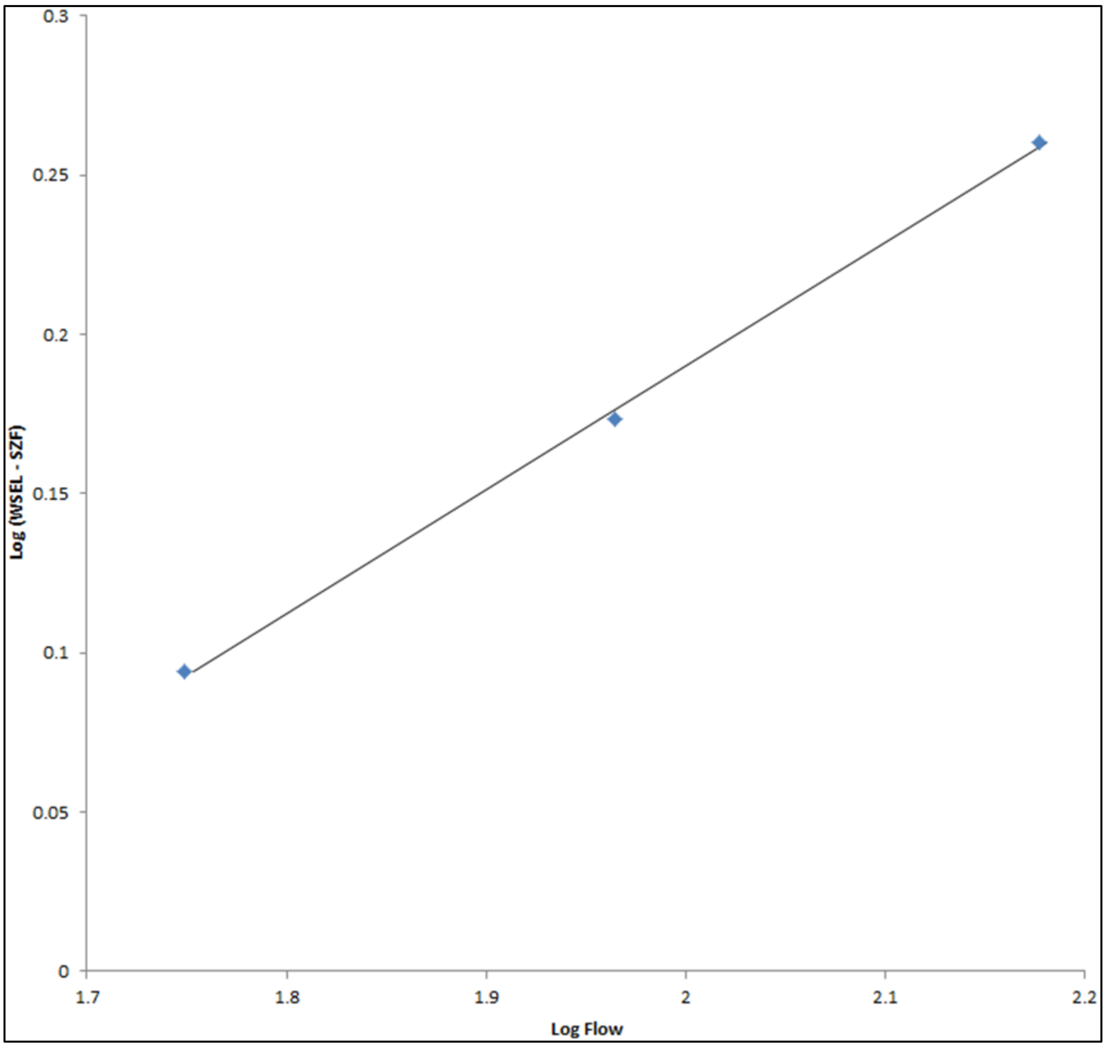


Figure B-1. 2014 Reach 1 rating curve.

The 2014 rating curve for the pressure transducer in Reach 2 (Figure B-2) was developed from four flow measurements made in Reach 2, ranging from 41.1 to 129 cfs, along with the pressure transducer data at the times that the flow measurements were made. The resulting regression equation was as follows:

$$\log(\text{flow}) = 0.900 + 3.347 \times \log(\text{stage} - 98.21)$$

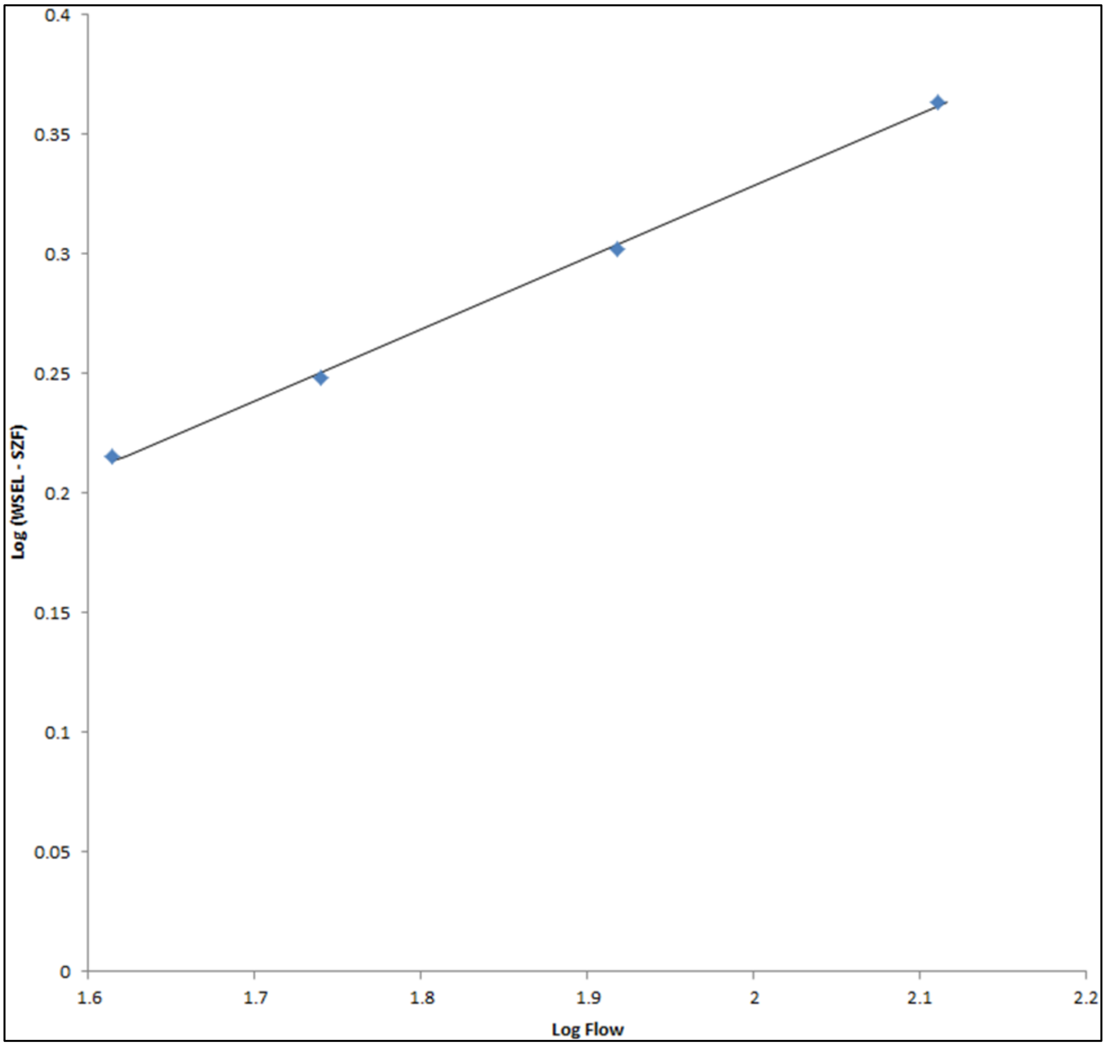


Figure B-2. 2014 Reach 2 rating curve.

The 2014 rating curve for the pressure transducer in Reach 3 (Figure B-3) was developed from six flow measurements made in Reach 3, ranging from 44.4 to 145 cfs, along with the pressure transducer data at the times that the flow measurements were made. The data indicated that there were two distinct log-log linear portions of the rating curve: up to 87.5 cfs, and greater than 87.5 cfs. Accordingly, the rating curve was developed by performing regressions of the log of flow versus the log of (stage – SZF) for the data in each of the above two flow ranges. The resulting regression equations were as follows:

Flows < 87.5 cfs: log (flow) = 0.654 + 4.559 x log (stage – 95.12)

Flows > 87.5 cfs: log (flow) = 1.112 + 2.892 x log (stage – 95.12)

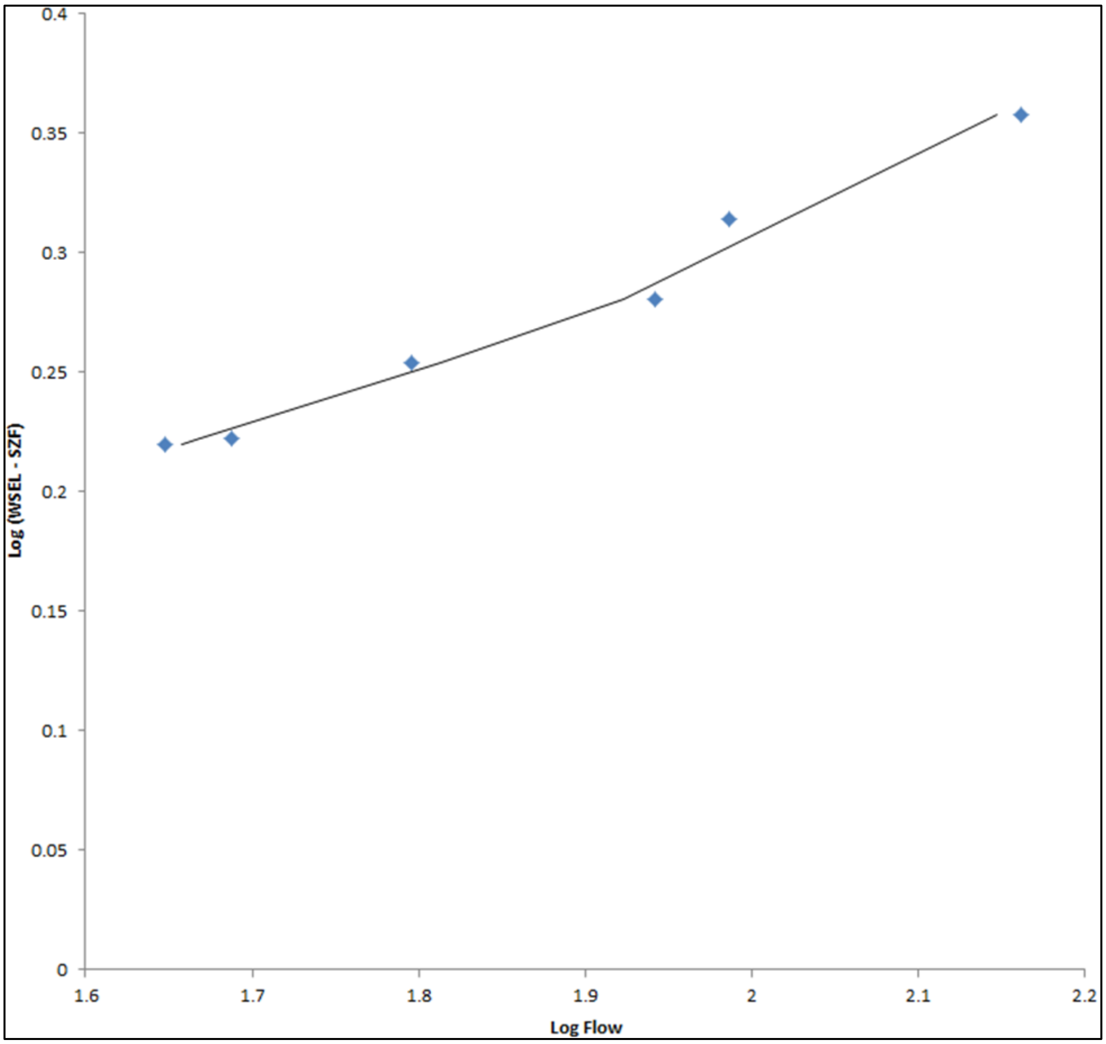


Figure B-3. 2014 Reach 3 rating curve.

The 2014 rating curve for the pressure transducer in Reach 4 (Figure B-4) was developed from ten flow measurements made in Reach 4, ranging from 1.5 to 193.3 cfs, along with the pressure transducer data at the times that the flow measurements were made. The data indicated that there were three distinct log-log linear portions of the rating curve: up to 12 cfs, from 12 to 45 cfs, and greater than 45 cfs. Accordingly, the rating curve was developed by performing regressions of the log of flow versus the log of (stage – SZF) for the data in each of the above three flow ranges. The resulting regression equations were as follows:

Flows < 12 cfs: log (flow) = 1.082 + 9.065 x log (stage – 97.27)

Flows 12-45 cfs: log (flow) = 1.066 + 6.591 x log (stage – 97.27)

Flows > 45 cfs: log (flow) = 1.396 + 3.009 x log (stage – 97.27)

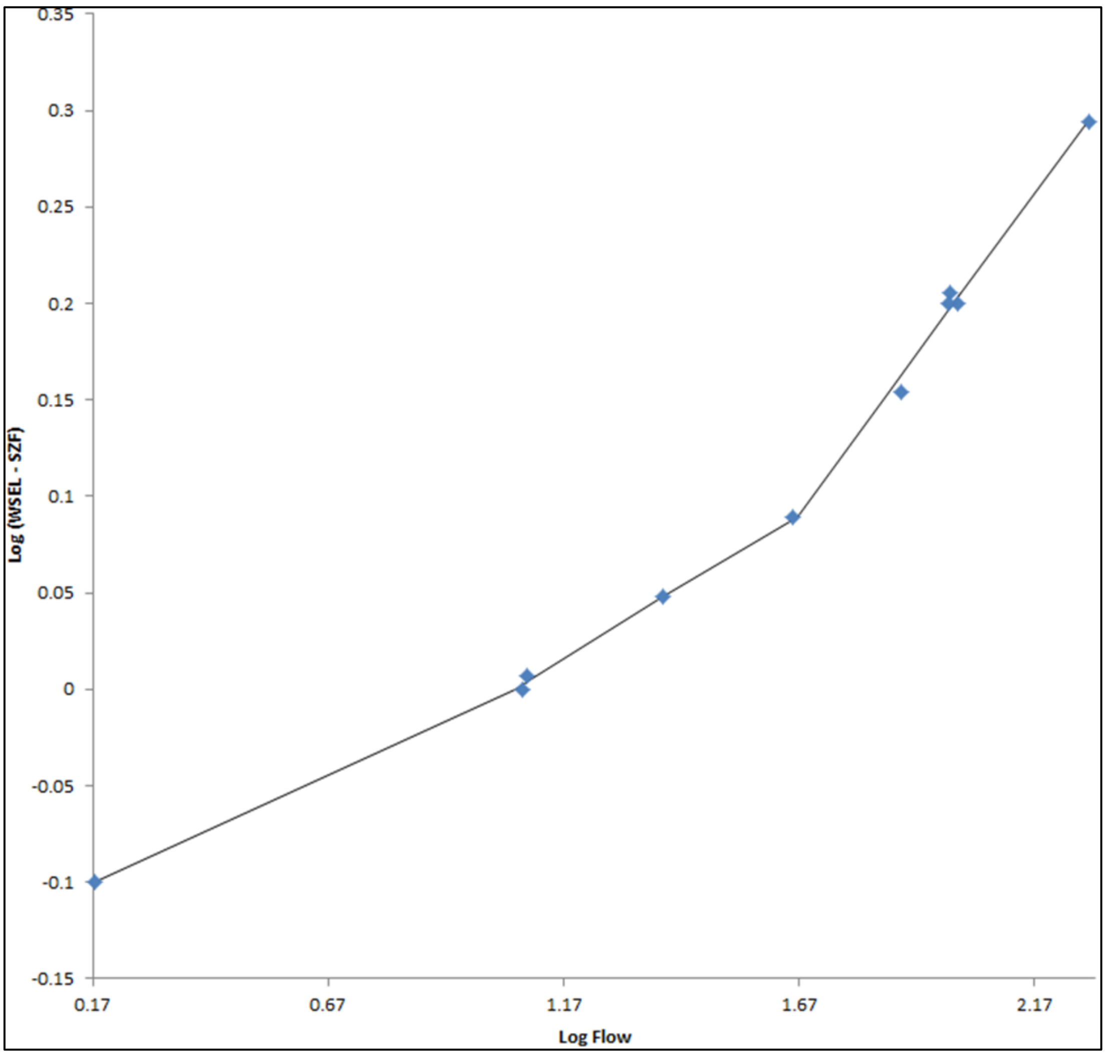


Figure B-4. 2014 Reach 4 rating curve.

In developing the 2015 rating curves, it was discovered that there had been several shifts in the rating curves as a result of a small flow peak on April 26 and from algae growth. In addition, the pressure transducers stopped recording data on June 5, 2015 (for Reaches 1 to 3) and on May 17, 2015 (for Reach 4). For Reach 1, the timing and magnitude of the rating curve shifts were quantified by comparing the flows for Reach 1 (calculated by subtracting the preliminary daily DCID diversions[19] from the USGS gage flows) with the daily average stage data recorded from our pressure transducer in Reach 1. This analysis indicated that the rating curve for the Reach 1 pressure transducer shifted down 0.04 feet on April 26 and shifted back up 0.07 feet on May 6. However, because there was still variation in the daily flow-stage plot, even after applying the above rating curve shifts (Figure B-5), it appeared more accurate to use the daily flows calculated as discussed above for the Reach 1 flows in validating the SNTEMP model.

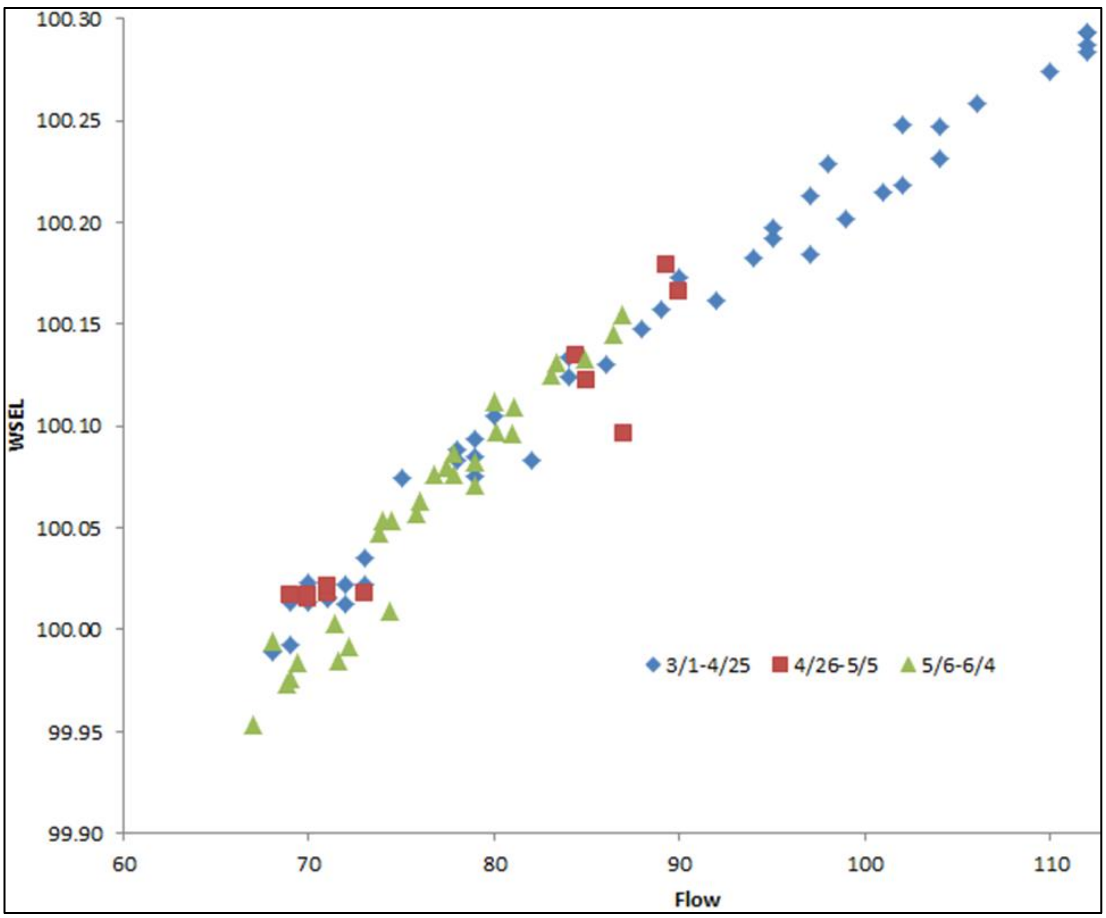


Figure B-5. 2015 Reach 1 flows and water surface elevations.

For Reach 2, we were unable to determine the timing and magnitude of the rating curve shifts. As a result, the 2015 flows for Reach 2 were calculated by subtracting the Reach

[19] This data was supplied by the California Department of Water Resources.

5 flows from the Reach 1 flows. The following regression equations were developed (from measured Reach 5 flows versus the calculated Reach 1 flows) to predict Reach 5 flows:

2/15 – 3/31: Reach 5 flow = 5 + 0.13 x Reach 1 flow
4/1 – 5/27: Reach 5 flow = -34.7 + 0.59 x Reach 1 flow
5/28 – 7/6: Reach 5 flow = 8 + 0.03 x Reach 1 flow

The changes in the regression equations over time (Figure B-6) represent both non-linearities in the flow-flow relationship and human-made channel changes at the upper end of the Cone-Kimball side channel to keep the Cone-Kimball side channel flowing at lower Deer Creek flows.

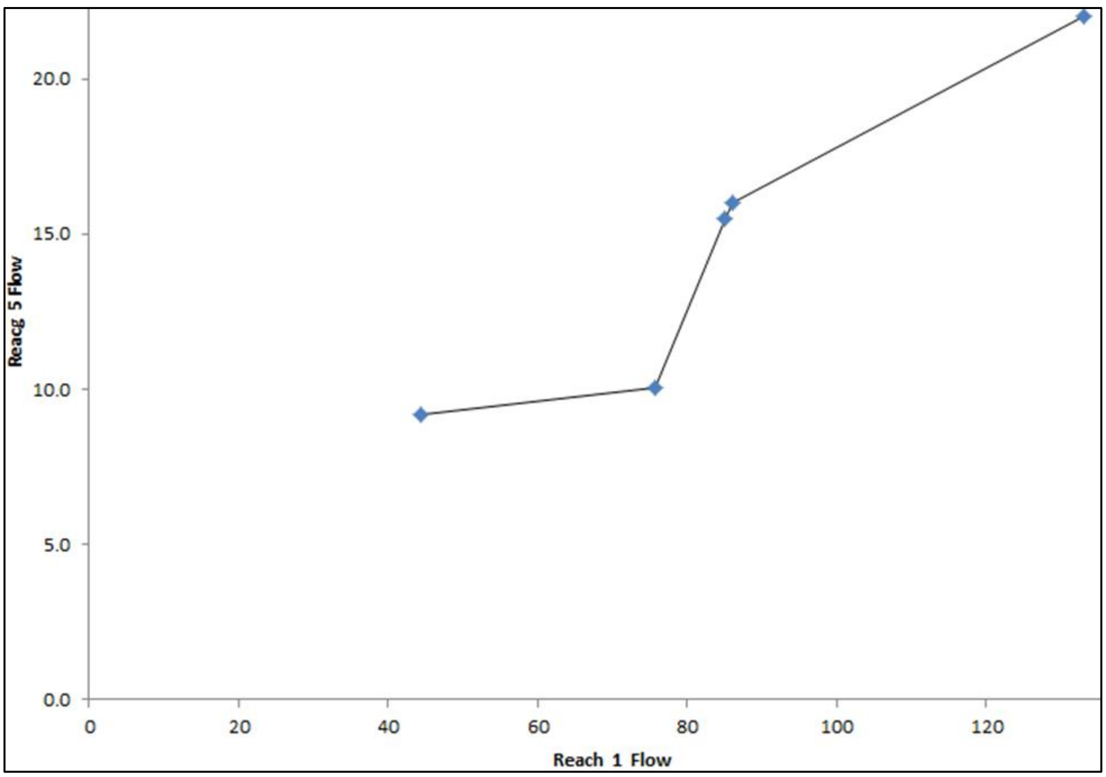


Figure B-6. Reach 1 versus Reach 5 flows.

For Reach 3, two rating curve shifts were identified by discontinuities in the stage data: a 0.07 foot shift on March 4 associated with downloading and reinstalling the pressure transducer, and a 0.08 foot shift on May 11 that may have been caused by human created channel changes (rocks piled up at the pool tail near the Reach 3 pressure transducer location). Despite these rating curve shifts, the accuracy of the resulting rating curve was suboptimal, with errors in the predicted flows of up to 7.2 percent. We were unable to simply subtract the Cone-Kimball diversion from the Reach 1 flows to calculate the Reach 3 flows, since the measured Cone-Kimball diversions ranged from

3.8 to 12.4 cfs, and were independent of Reach 1 flows. The regression equation for the Reach 3 pressure transducer stage-discharge relationship (Figure B-7) was:

log (flow) = 1.709 + 2.260 x log (stage – 98.87)

For Reach 4, we were unable to determine the timing and magnitude of the rating curve shifts. As a result, flows from the DWR gage were used for Reach 4 in validating the StreamTemp model in 2015.

The flow-width and flow-depth relationships for each reach are below in the next section, Flow-width and Flow-depth Relationships. The initial values of universal parameters and reach-specific parameters are shown in Tables B-1 and B-2.

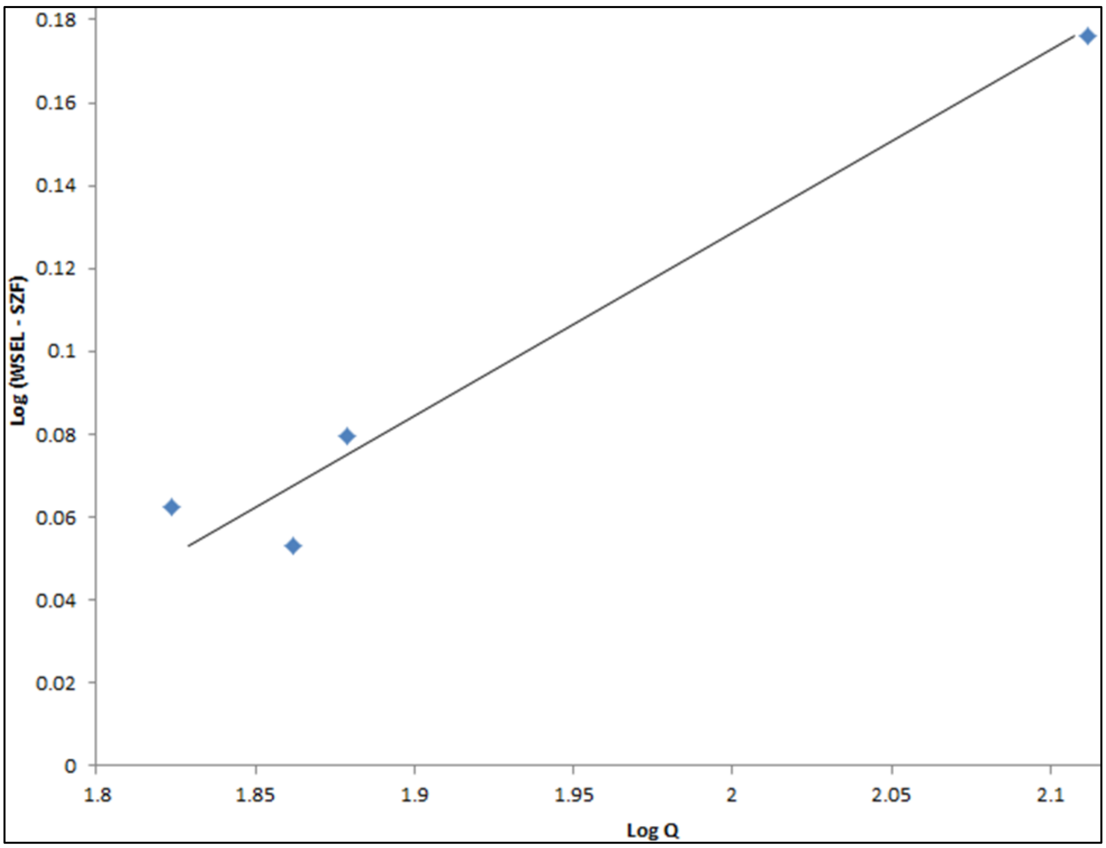


Figure B-7. 2015 Reach 3 rating curve.

Table B-1. Initial values of global SNTEMP parameters.

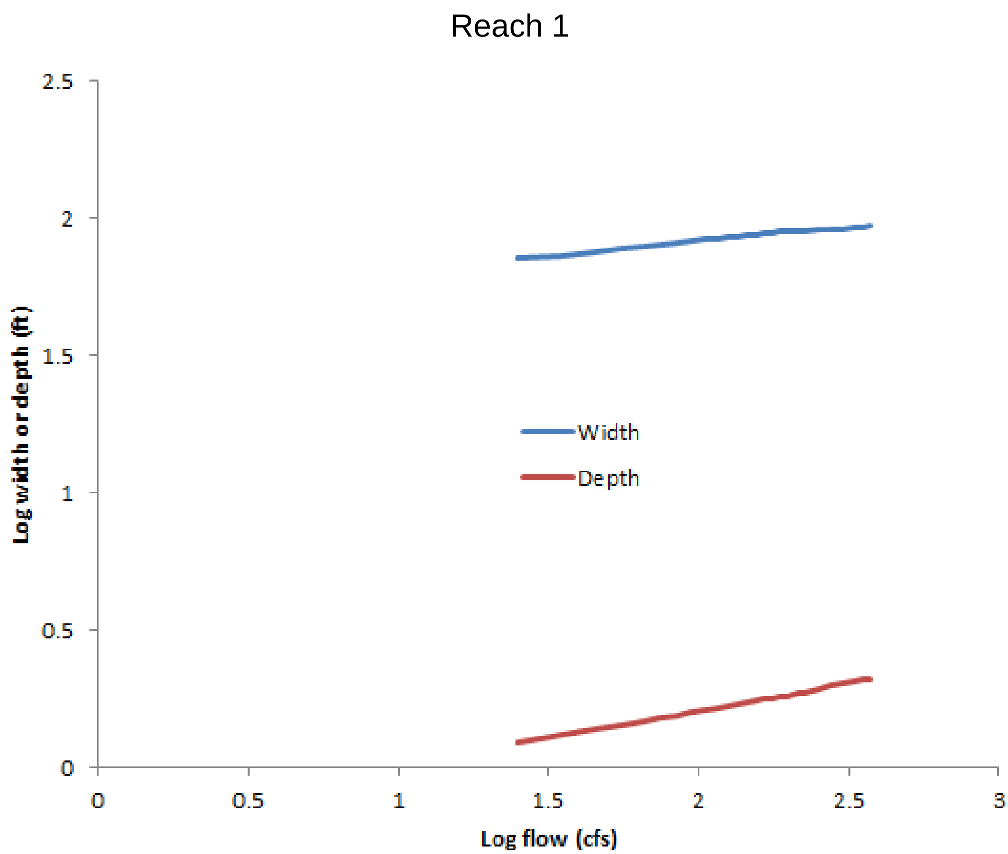
Parameter/Variable	Value	Constant	Coefficient
Average Annual Air Temperature (°F)	62.3	-	-
Bowen Ratio	0.00062	-	-
Evaporation Factor A	40	-	-
Evaporation Factor B	15	-	-
Evaporation Factor C	0	-	-
Dust	4	-	-
Ground Reflection	17	-	-
Air Temperature	-	0.3109	1.011
Wind Speed	-	0.3699	0.1779
Relative Humidity	-	0	1.0377
Percent Sunshine	-	0	1
Solar Radiation	-	0	1

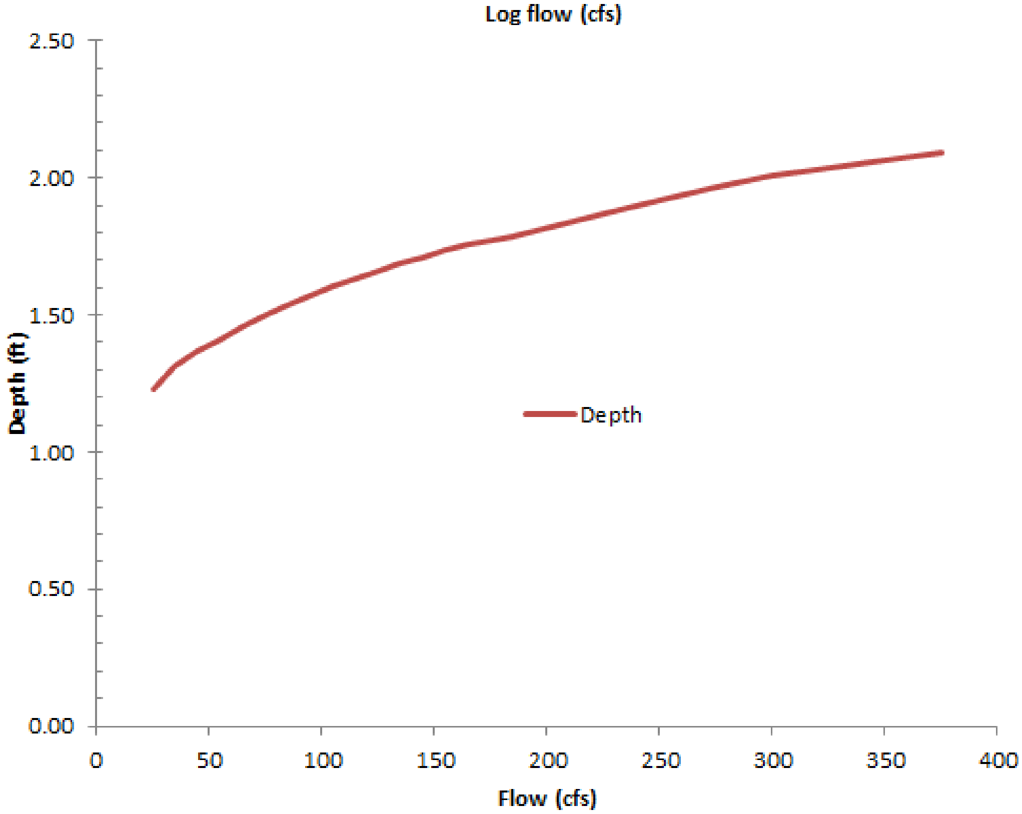
Table B-2. Initial values of reach-specific SNTEMP parameters.

Parameter	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6
Thermal Gradient	1.65	1.65	1.65	1.65	1.65	1.65
Left Bank Vegetation Height	37	27	29	33	44	16
Right Bank Vegetation Height	46	23	28	28	25	19
Left Bank Vegetation Crown Width	21	16	17	19	25	9
Right Bank Vegetation Crown Width	26	13	16	16	14	11
Left Bank Vegetation Density	15	35	21	19	65	48
Right Bank Vegetation Density	19	27	28	18	56	58
Left Bank Topographic Shade	8	2	2	5/4[20]	9	4
Right Bank Topographic Shade	3	1	1	4/1	2	0
Width A Constant	51.10	26.29	34.45	44.23	22.13	15.02
Width B Coefficient	0.105	0.151	0.111	0.147	0.045	0.117
Maximum Width	95	65	67	99	26.3	21.9
Residual Depth	1.0	1.2	1.92	0.75	0.63	0.48
Slope	0.007	0.004	0.004	0.005	0.007	0.005
Manning's n	0.21	0.1	0.22	0.17	0.22	0.15

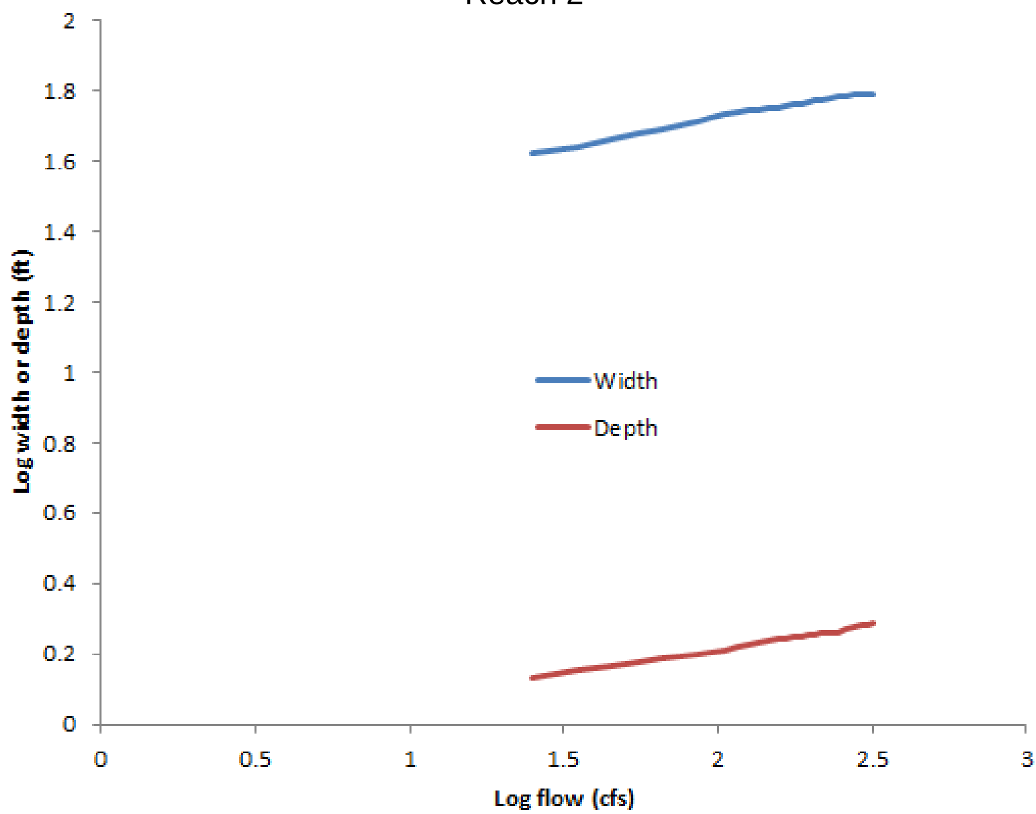
[20] The first value is for the upper subreach of Reach 4, while the lower value is for the lower subreach of Reach 4.

Flow-Width and Flow-Depth Relationships

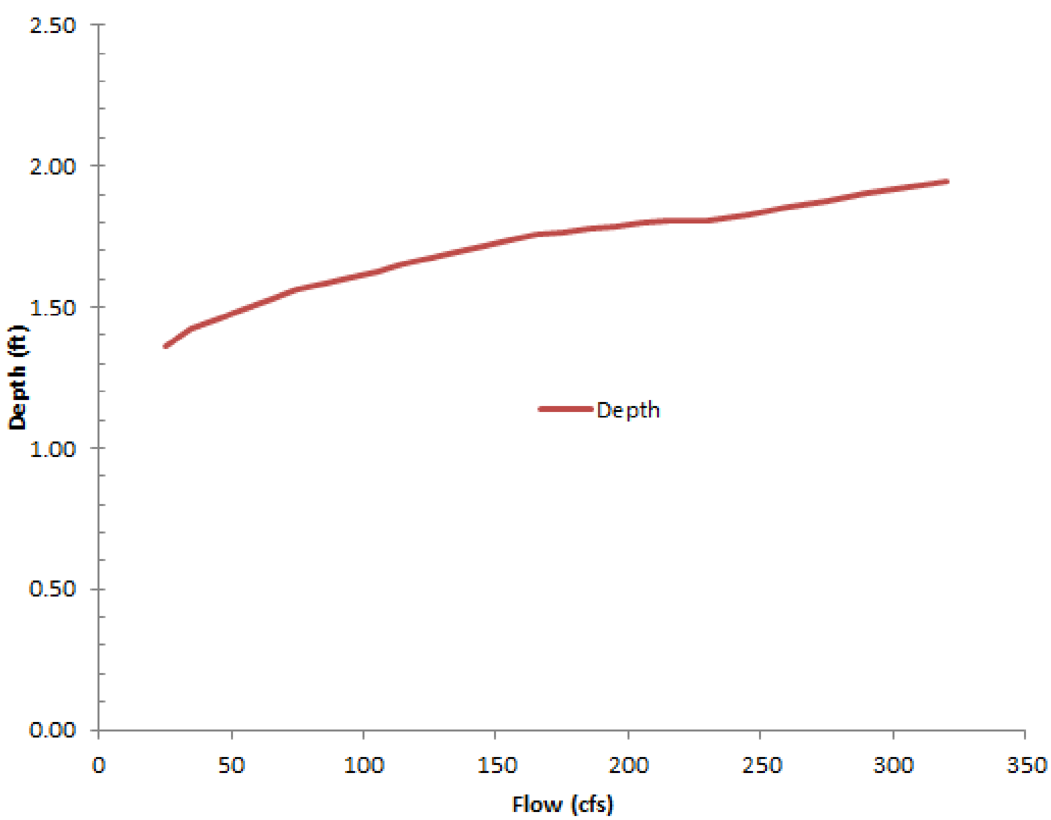




Reach 2

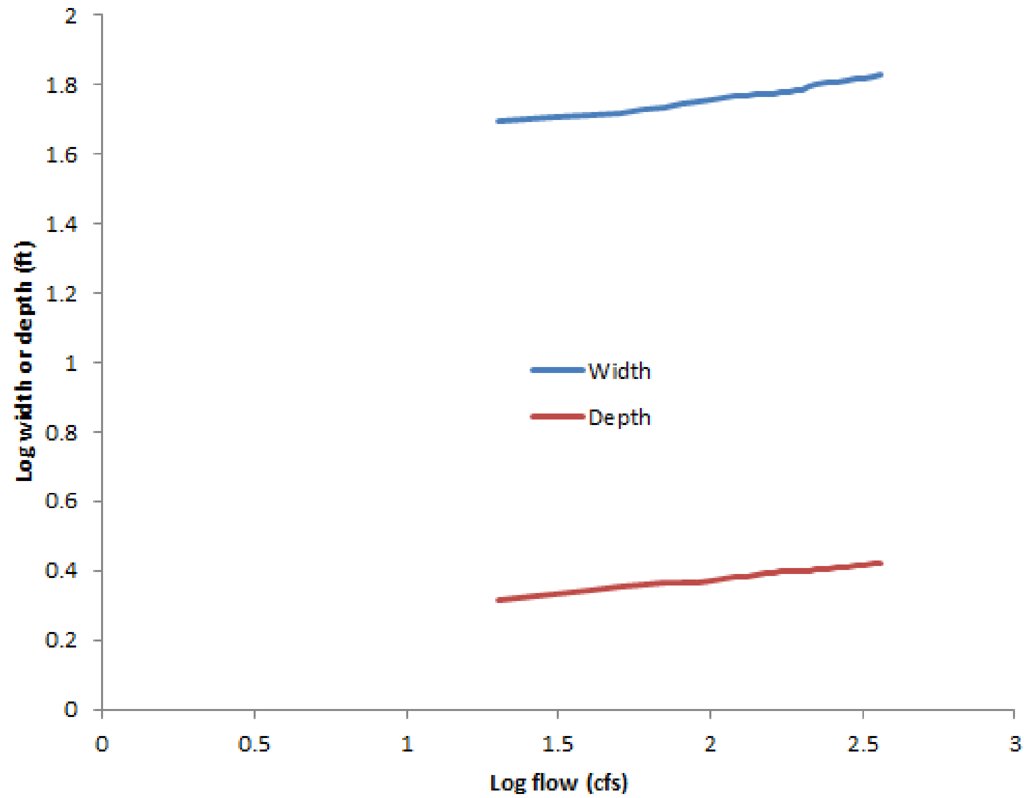


2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Log width or depth (ft)
Width
Depth
0
0.5
1
1.5
2
2.5
3
Log flow (cfs)

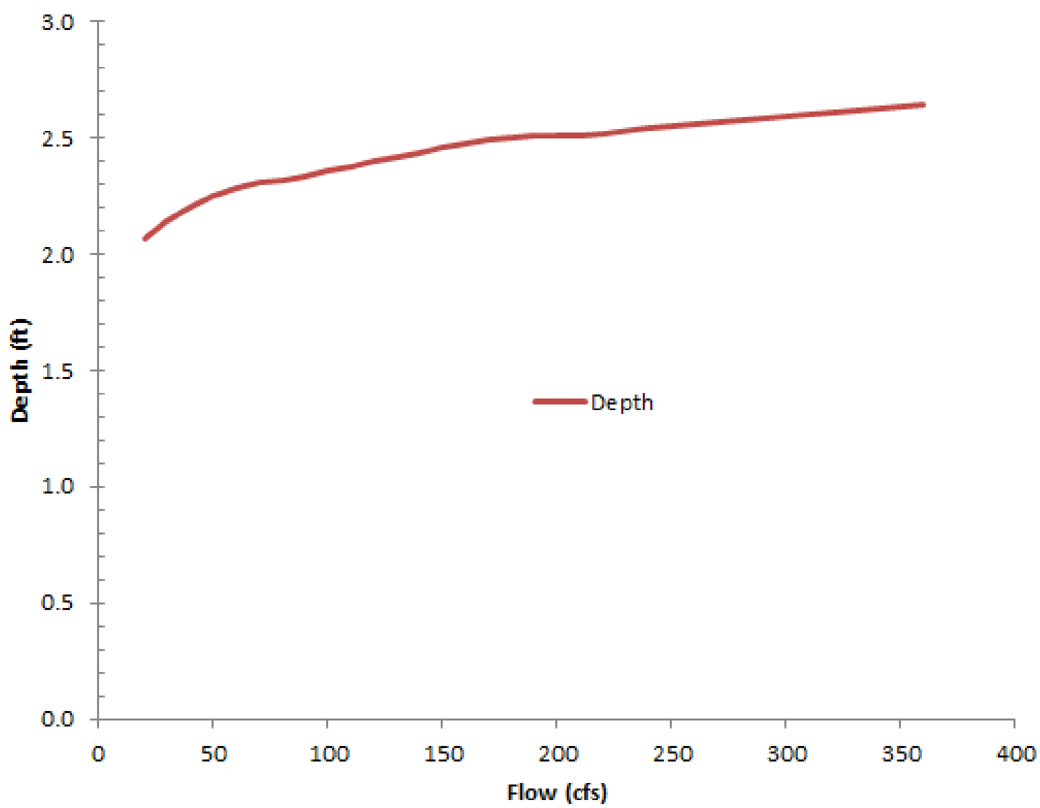


2.50
2.00
1.50
1.00
0.50
0.00
Depth (ft)
Depth
0
50
100
150
200
250
300
350
Flow (cfs)

Reach 3

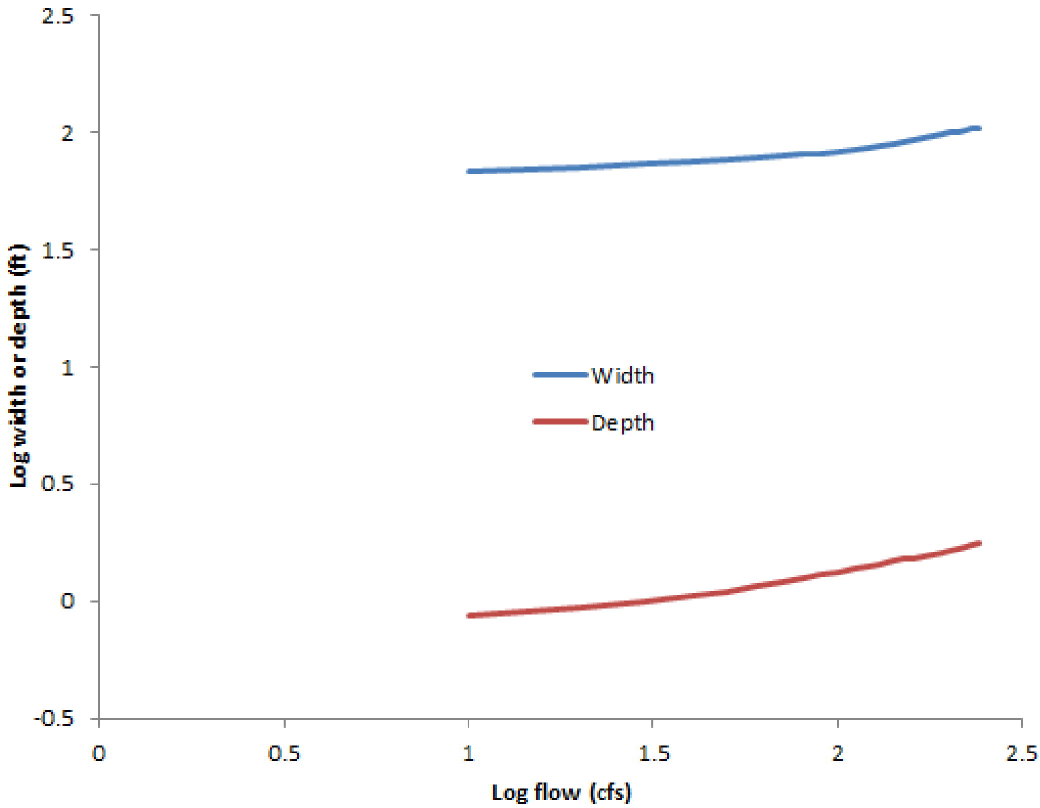


2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
Log width or depth (ft)
Log flow (cfs)
Width
Depth

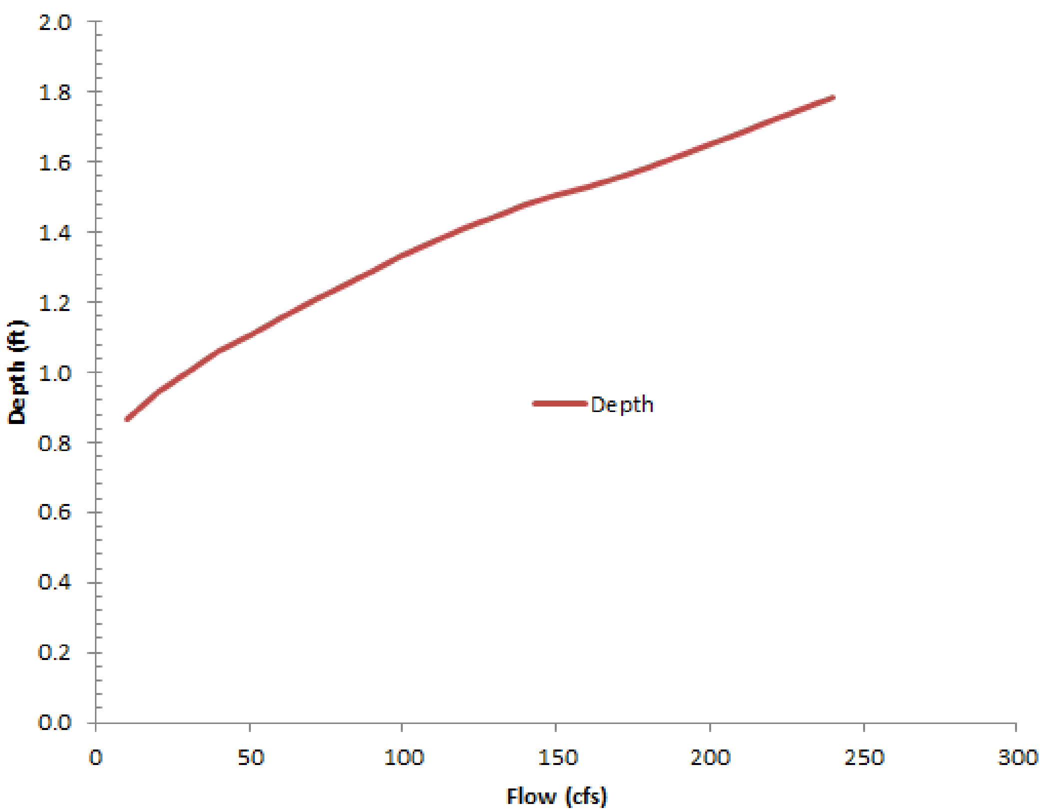


3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
350
400
Depth (ft)
Flow (cfs)
Depth

Reach 4

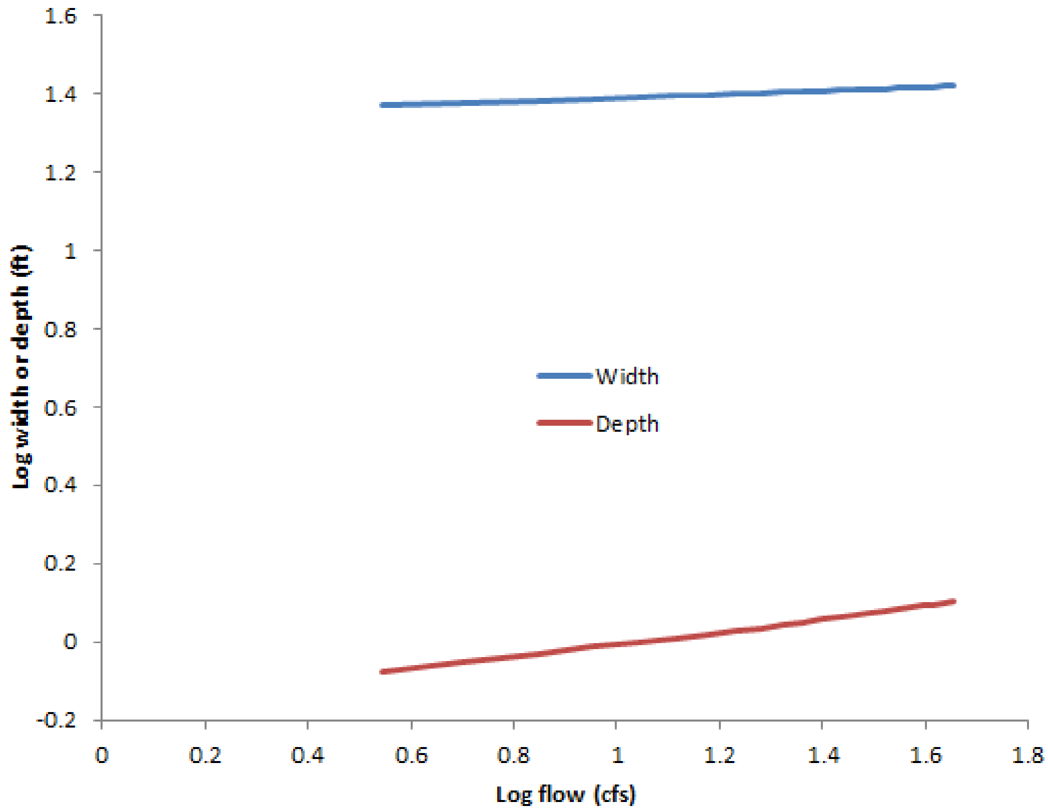


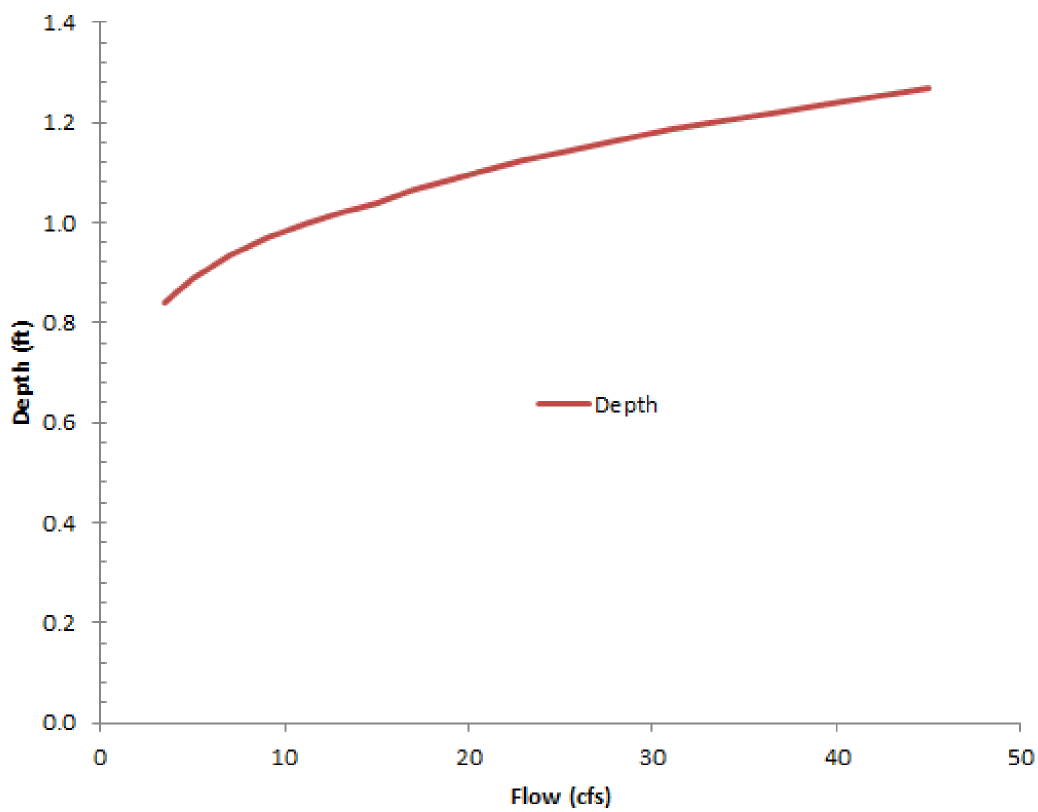
2.5
2
1.5
1
0.5
0
-0.5
Log width or depth (ft)
Width
Depth
0
0.5
1
1.5
2
2.5
Log flow (cfs)



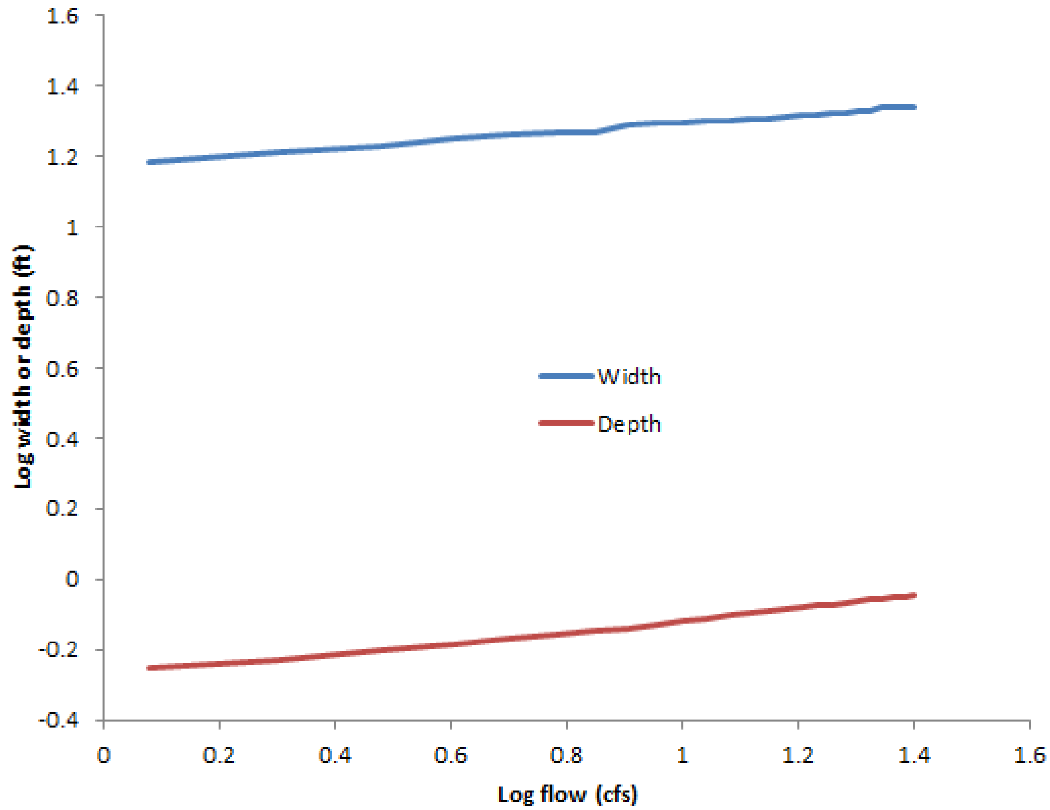
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Depth (ft)
Depth
0
50
100
150
200
250
300
Flow (cfs)

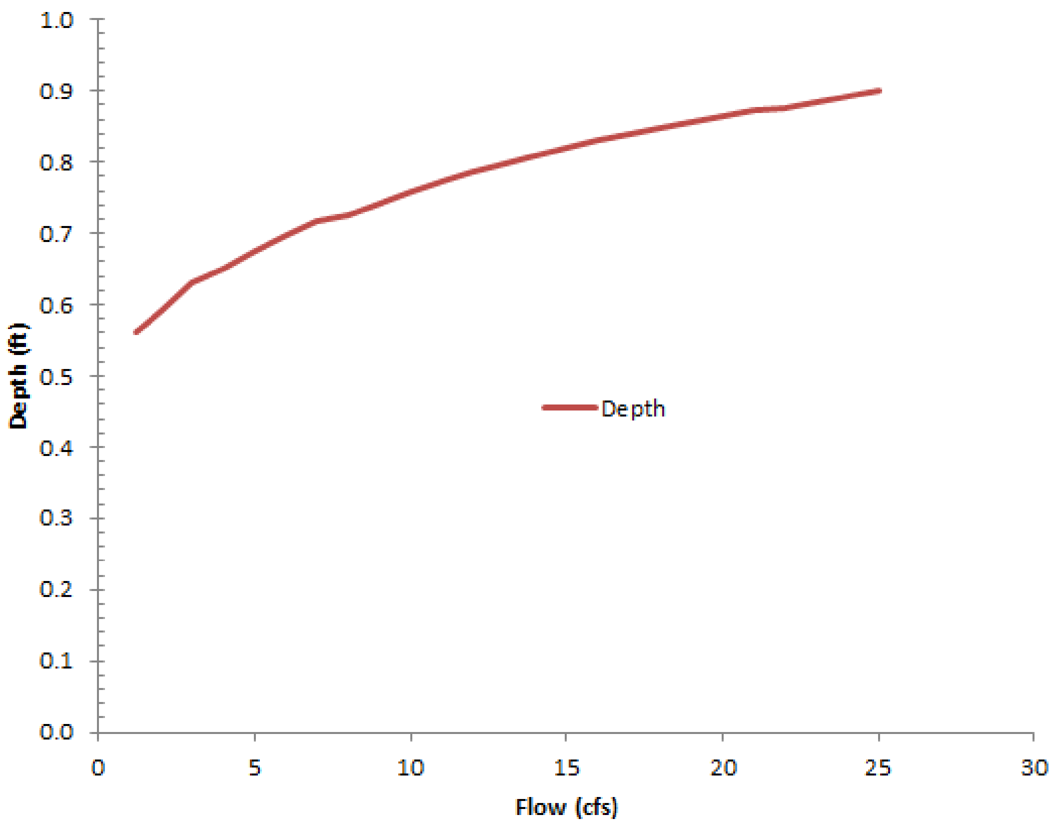
Reach 5


1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Log width or depth (ft)
Width
Depth
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Log flow (cfs)


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Depth (ft)
Depth
0
10
20
30
40
50
Flow (cfs)

Reach 6


1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Log width or depth (ft)
Width
Depth
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Log flow (cfs)


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Depth (ft)
Depth
0
5
10
15
20
25
30
Flow (cfs)

Water Temperature Model Calibration, Validation, and Additional Criteria

To account for the cooling of water in Reach 6, a constant lateral flow of 0.38 cfs at 53°F (11.6°C) was added to that reach. The calibrated values of universal parameters and reach-specific parameters are shown in Tables B-3 and B-4. The calibrated model generally met the criteria from Kimmerer and Carpenter (1989) for mean daily average water temperature but generally did not meet these criteria for 7DADM (Table B-5). The calibrated model had a correlation coefficient of 0.9839, a mean error of 0.1341, a probable error of 0.80, a maximum error of 5.42, and a bias of 0.031, as well as 32.9% of the predicted errors less than 1.0. As shown in Figures B-8 to B-14, the calibrated StreamTemp model generally tracks measured mean daily temperatures through the end of June, but deviates from measured mean daily temperatures in July.

Table B-3. Calibrated values of universal StreamTemp parameters.

Parameter/Variable	Value	Constant	Coefficient
Average Annual Air Temperature (°F)	62.3	-	-
Bowen Ratio	0.00062	-	-
Evaporation Factor A	40	-	-
Evaporation Factor B	15	-	-
Evaporation Factor C	0	-	-
Dust	4	-	-
Ground Reflection	17	-	-
Air Temperature	-	0.3109	1.011
Wind Speed	-	0.3699	0.1779
Relative Humidity	-	0	1.0377
Percent Sunshine	-	0	1
Solar Radiation	-	-48	0.8

Table B-4. Calibrated values of reach-specific StreamTemp parameters.

Parameter	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6
Thermal Gradient	1.65	1.65	1.65	1.65	1.65	1.65
Left Bank Vegetation Height	37	27	29	33	44	16
Right Bank Vegetation Height	46	23	28	28	25	19
Left Bank Vegetation Crown Width	30	16	13	26	25	9
Right Bank Vegetation Crown Width	37	13	12	23	14	11
Left Bank Vegetation Density	30	35	11	38	65	48
Right Bank Vegetation Density	38	27	14	36	56	58
Left Bank Topographic Shade	8	2	2	5/4[21]	9	4
Right Bank Topographic Shade	3	1	1	4/1	2	0
Width A Constant	51.10	26.29	34.45	44.23	22.13	15.02
Width B Coefficient	0.105	0.151	0.111	0.147	0.045	0.117
Maximum Width	95	65	67	99	26.3	21.9
Residual Depth	1.0	1.2	1.92	0.75	0.63	0.48
Slope	0.007	0.004	0.004	0.005	0.007	0.005
Manning's n	0.03	0.03	0.03	0.03	0.22	0.03

[21] The first value is for the upper subreach of Reach 4, while the lower value is for the lower subreach of Reach 4.

Table B-5. Calibrated StreamTemp model performance.

Parameter (°F)	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6
Mean Error for Daily Mean Temp	0.2	0.2	-0.9	0.6	0.0	0.1
Error Range for Daily Mean Temp	-0.09 to 1.3	-1.3 to 2.1	-3.1 to 1.5	-4.6 to 3.8	-1.2 to 1.7	-4.2 to 2.1
Mean Error for 7DADM	-3.2	-4.1	-6.6	-0.6	1.3	-1.8
Error Range for 7DADM	-0.5 to -3.2	-1.4 to -6.0	-4.1 to -9.2	-2.5 to 1.2	0.7 to 2.3	-0.2 to -4.5

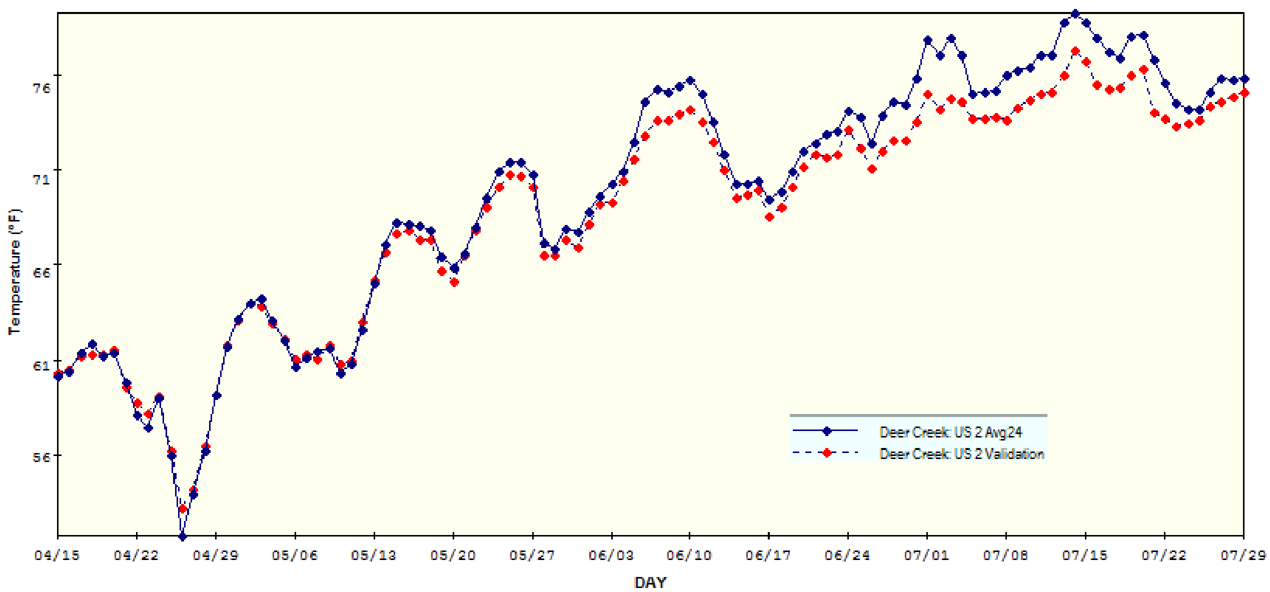


Figure B-8. StreamTemp model calibration result for Reach 2.

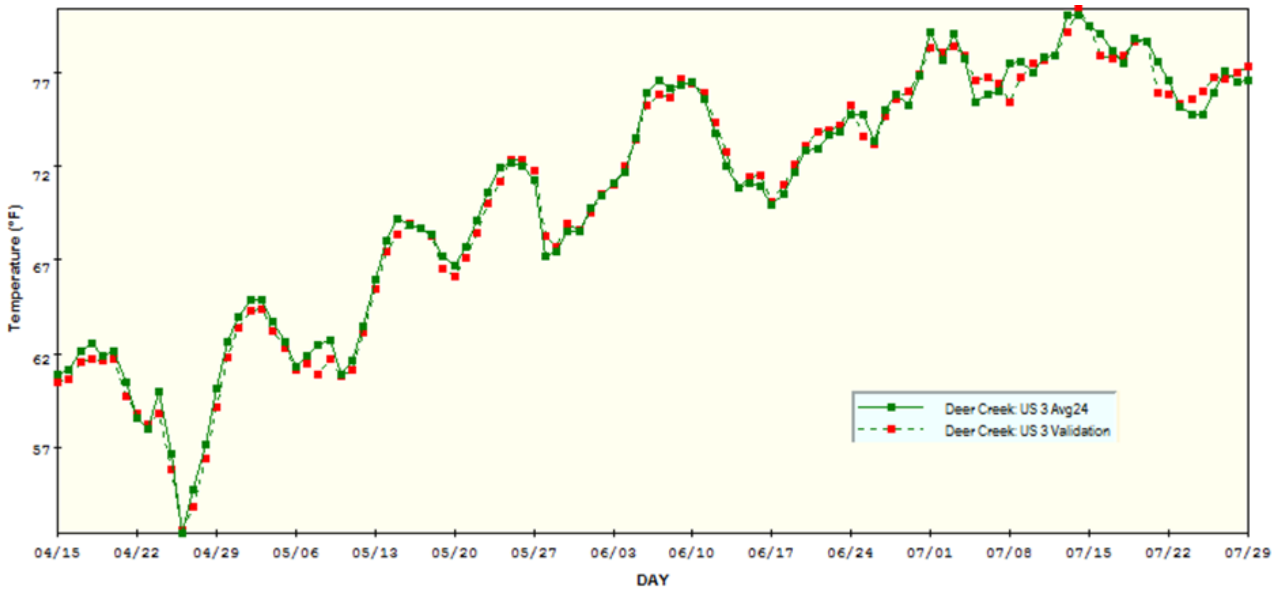


Figure B-9. StreamTemp model calibration result for Reach 3.

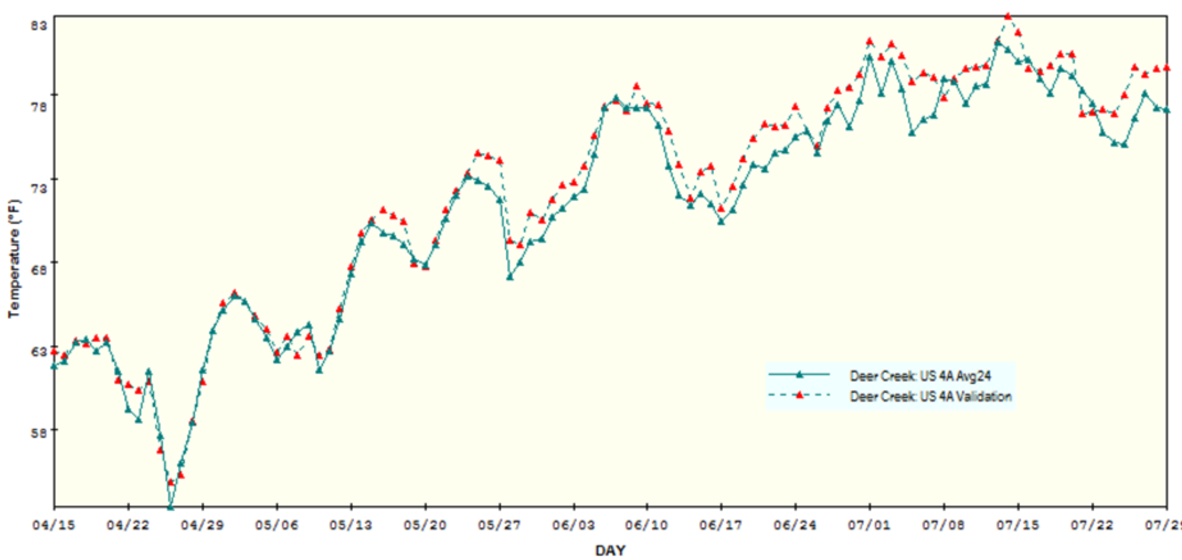


Figure B-10. StreamTemp model calibration result for upstream end of Reach 4.

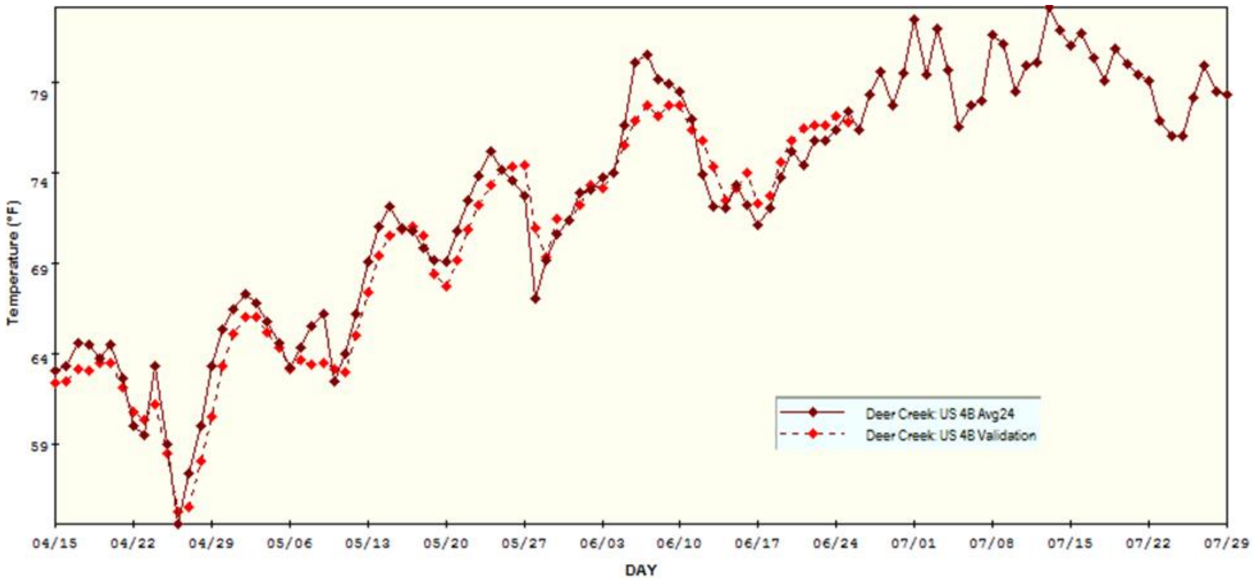


Figure B-11. StreamTemp model calibration result for downstream end Reach 4, comparison to pressure transducer data.

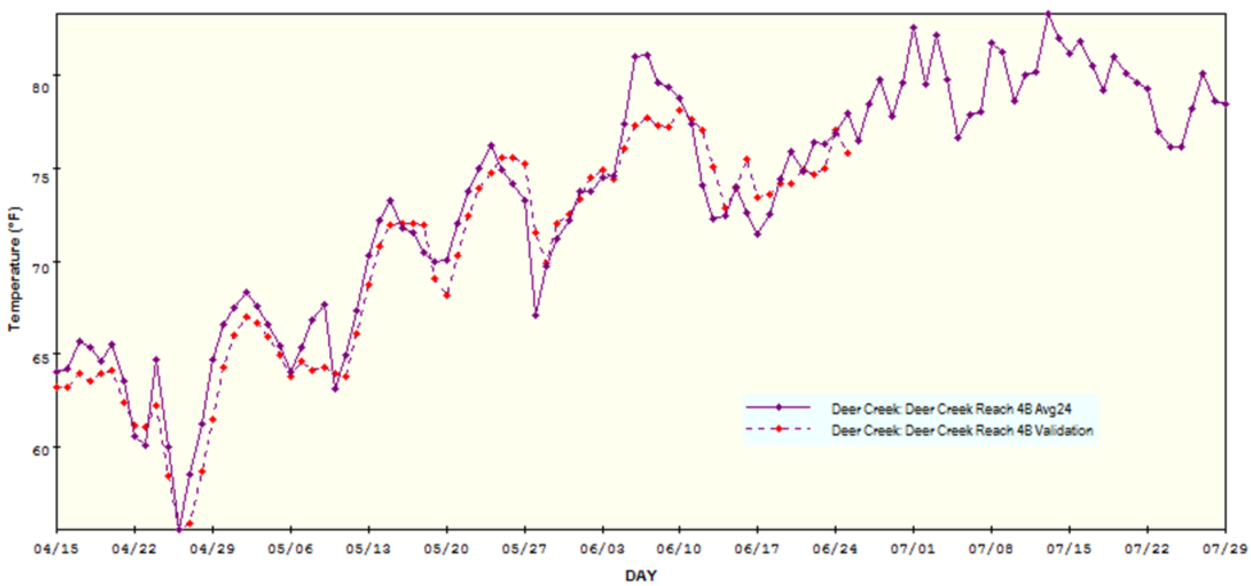


Figure B-12. StreamTemp model calibration result for downstream end of Reach 4, comparison to temperature logger data.

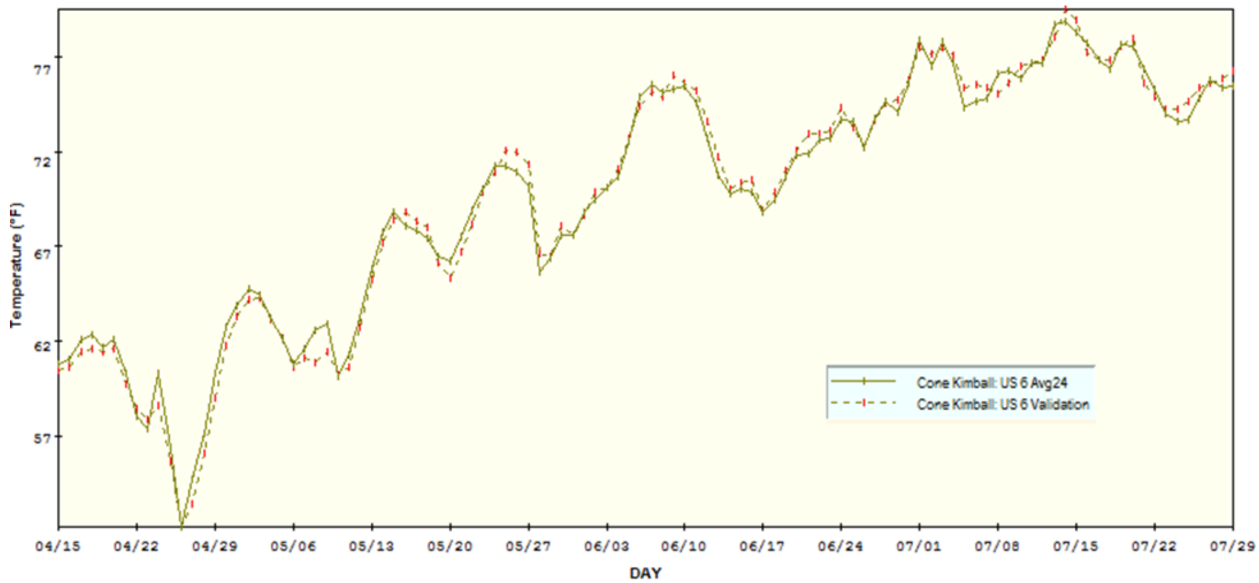


Figure B-13. StreamTemp model calibration result for Reach 5.

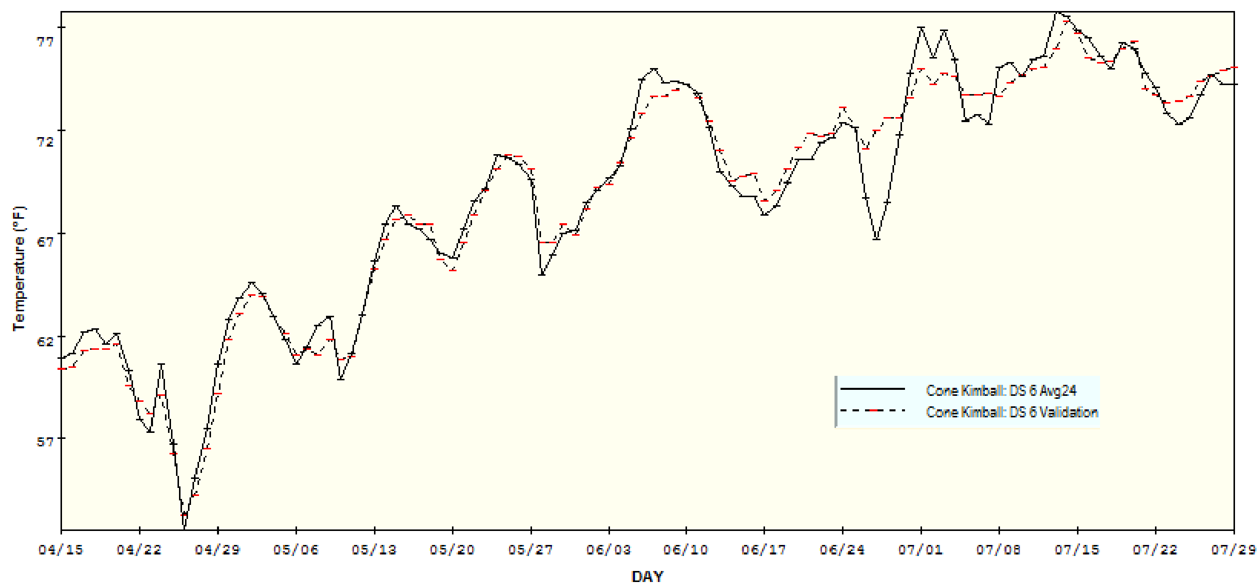


Figure B-14. StreamTemp model calibration result for Reach 6.

For the 2008 to 2013 validation, the error in mean daily water temperature ranged from -8.2 to 3.8°F (average of -1.4°F) and the error in 7DADM ranged from -0.8 to -12.6°F (average of -4.3°F). The StreamTemp model had a correlation coefficient of 0.9939, a mean error of -1.46, a probable error of 1.01, a maximum error of -8.25, 54.6% of the predicted errors less than 1.0, and a bias of 0.02. When only April through June water temperatures were examined (corresponding to the period of time in which calibration data were collected), the error in mean daily water temperature ranged from -4.1 to 3.0°F (average of -1.1°F) and the error in 7DADM ranged from -1.1 to -7.4°F (average of -4.5°F). As shown in Figure B-15, the StreamTemp model generally tracked the 2008 to 2013 mean daily measured water temperatures, with the biggest deviation seen in the summer of 2012, where the StreamTemp model consistently underestimated the measured water temperatures.

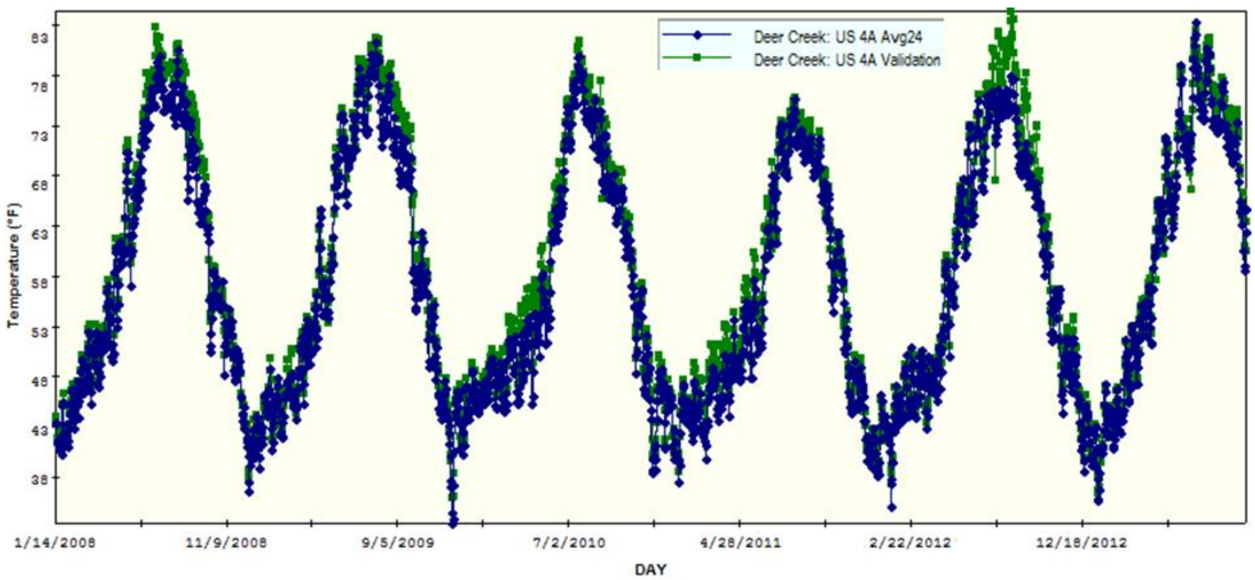


Figure B-15. StreamTemp model validation result for 2008 through 2013.

For the 2015 validation, as shown in Table B-6, the StreamTemp model generally met the criteria from Kimmerer and Carpenter (1989) for mean daily average water temperature but generally did not meet these criteria for 7DADM. The StreamTemp model had a correlation coefficient of 0.9827, a mean error of 1.012, a probable error of 1.297, a maximum error of 12.30, 42.02% of the predicted errors less than 1.0, and a bias of 0.0444. As shown in Figures B-16 to B-20, the StreamTemp model generally tracks 2015 measured mean daily temperatures through the end of May, but then deviates from measured mean daily temperatures in June and July at the downstream end of Reach 4.

Table B-6. 2015 StreamTemp model validation performance.

Parameter (°F)	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6
Mean Error for Daily Mean Temp	0.5	0.7	0.6	1.4	0.4	0.9
Error Range for Daily Mean Temp	-0.9 to 2.1	-1.0 to 2.9	-2.4 to 3.8	-3.0 to 7.8	-2.1 to 2.9	-3.7 to 3.9
Mean Error for 7DADM	-2.2	-2.7	-2.7	3.6	1.7	0.0
Error Range for 7DADM	-5.0 to 0.6	-4.9 to 0.4	-5.4 to 2.7	1.2 to 5.3	0.5 to 2.9	-3.7 to 2.5

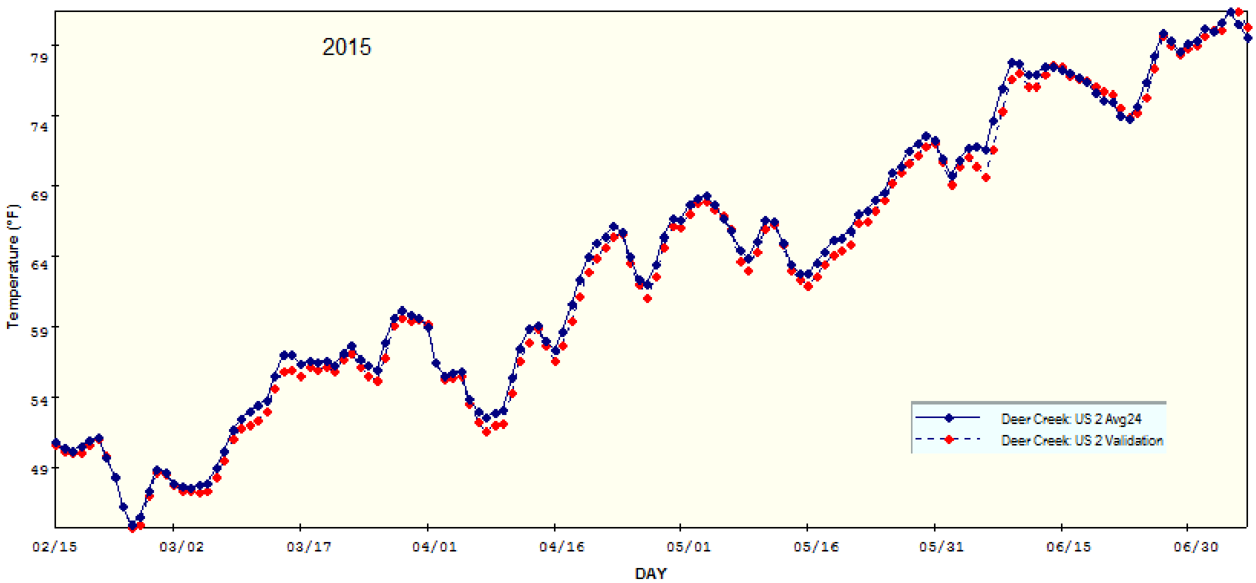


Figure B-16. StreamTemp model validation result for Reach 2 in 2015.

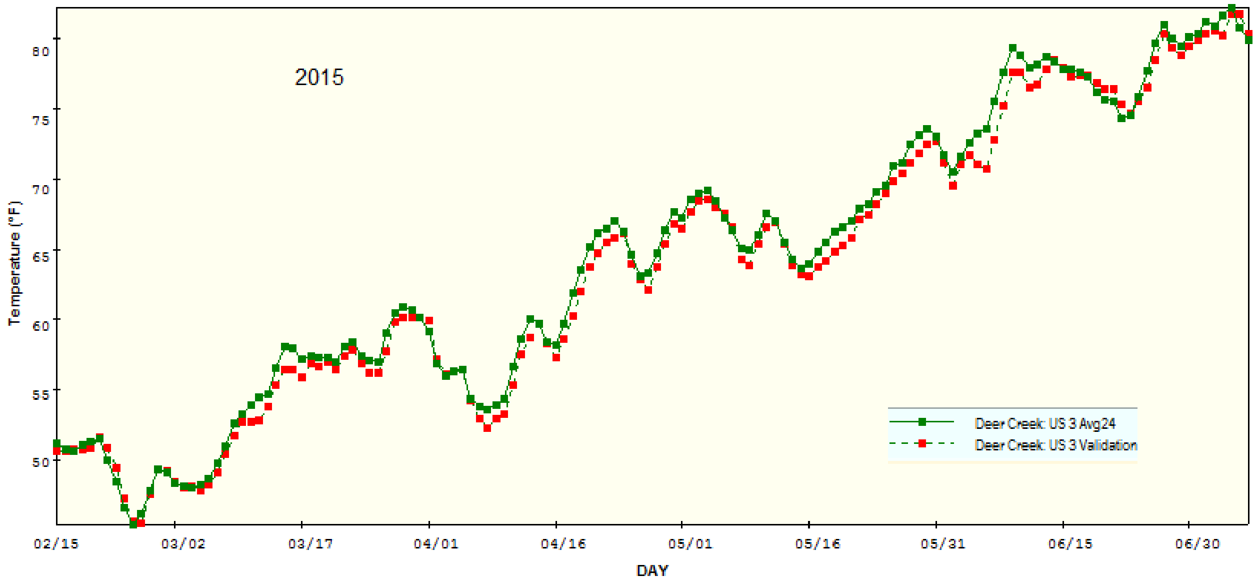


Figure B-17. StreamTemp model validation result for Reach 3 in 2015.

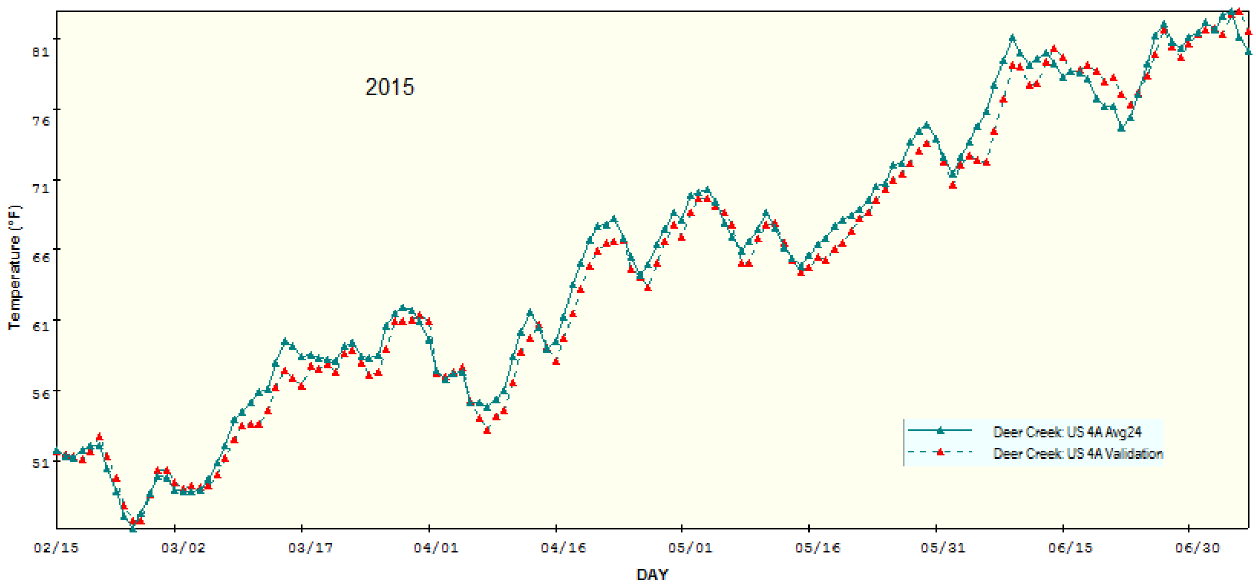


Figure B-18. StreamTemp model validation result at the upstream end of Reach 4 in 2015.

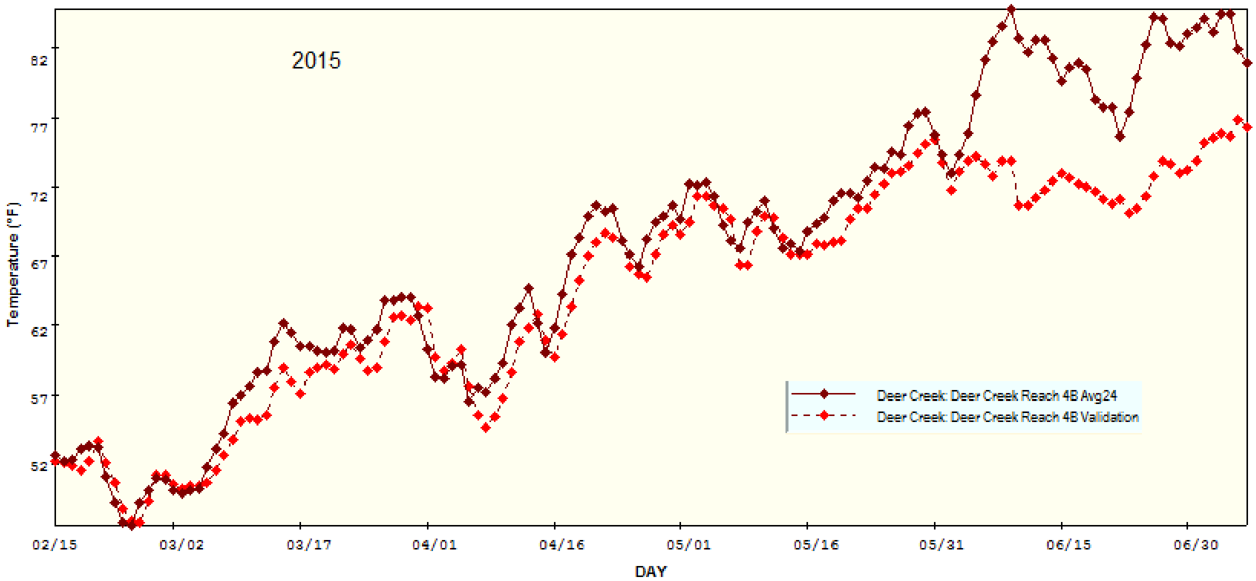


Figure B-19. StreamTemp model validation result at the downstream end of Reach 4 in 2015.

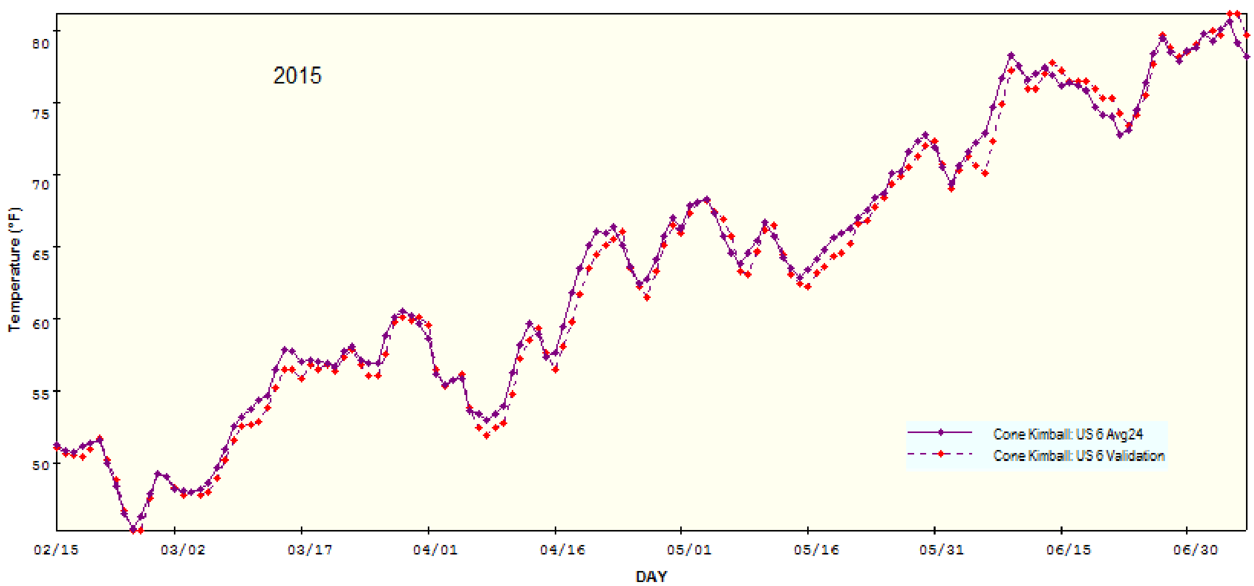


Figure B-20. StreamTemp model validation result for Reach 6 in 2015.

As shown in Figure B-21 and B-22, the W3T model generally did not perform as well as the StreamTemp model in predicting average daily water temperatures or 7DADM, despite having an hourly time step.

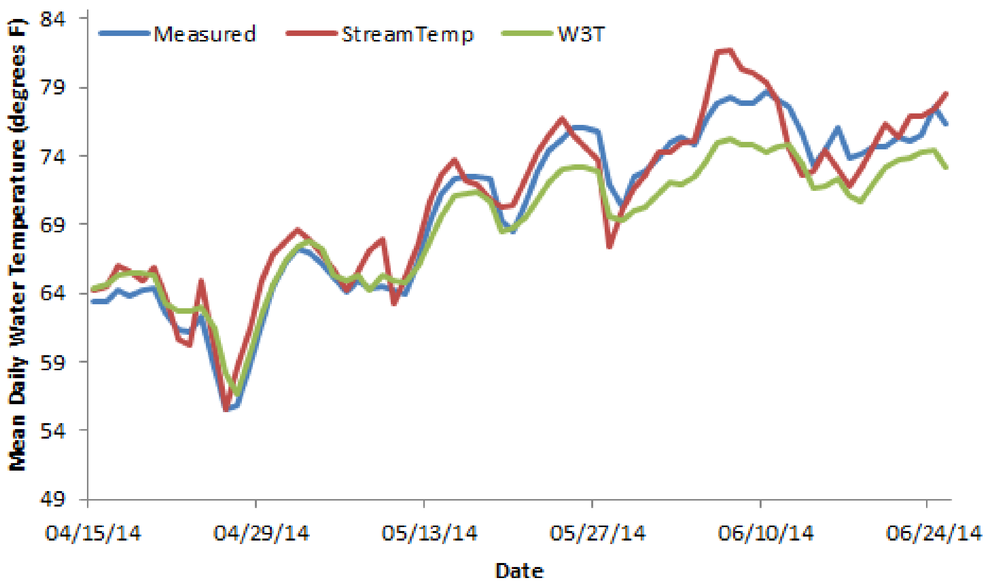


Figure B-21. Comparison of predicted mean daily water temperatures from the StreamTemp and W3T models at the downstream end of Reach 4 in 2014.

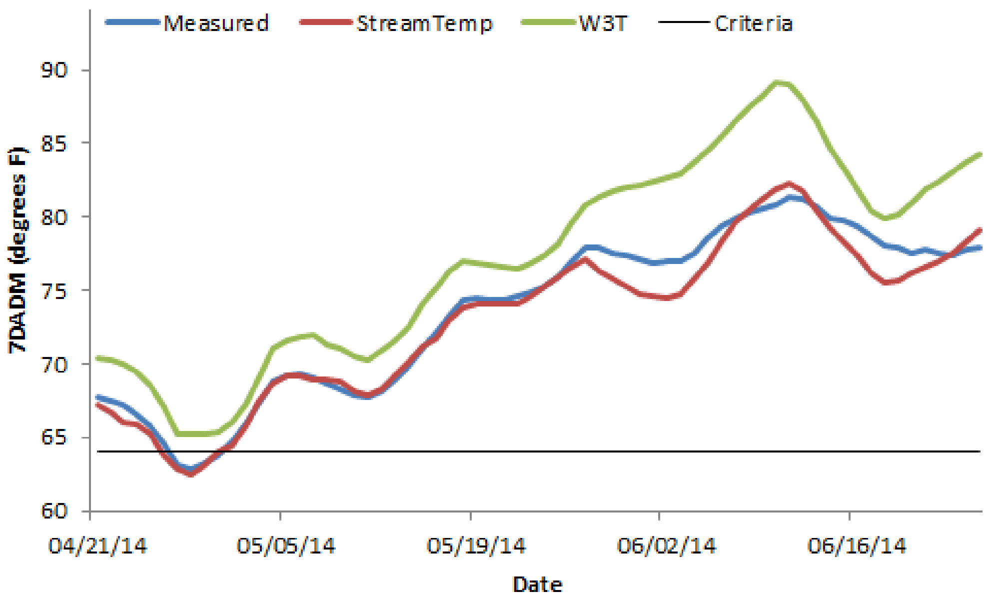


Figure B-22. Comparison of predicted 7DADM water temperatures from the StreamTemp and W3T models at the downstream end of Reach 4 in 2014.

Model Simulated Flow Runs

Water temperatures were simulated for unimpaired conditions for the period of January 14, 2008 to September 30, 2013 by setting all diversions equal to zero. As shown in Figures B-23 to B-25, 7DADM values at the downstream end of Reach 4 first exceeded 64°F between April 22 and June 14 in years 2008-2013 for both impaired and unimpaired flows. 7DADM values reached 68°F generally four to eight days later, exceeding 68°F between April 29 and June 22 for both impaired and unimpaired flows.

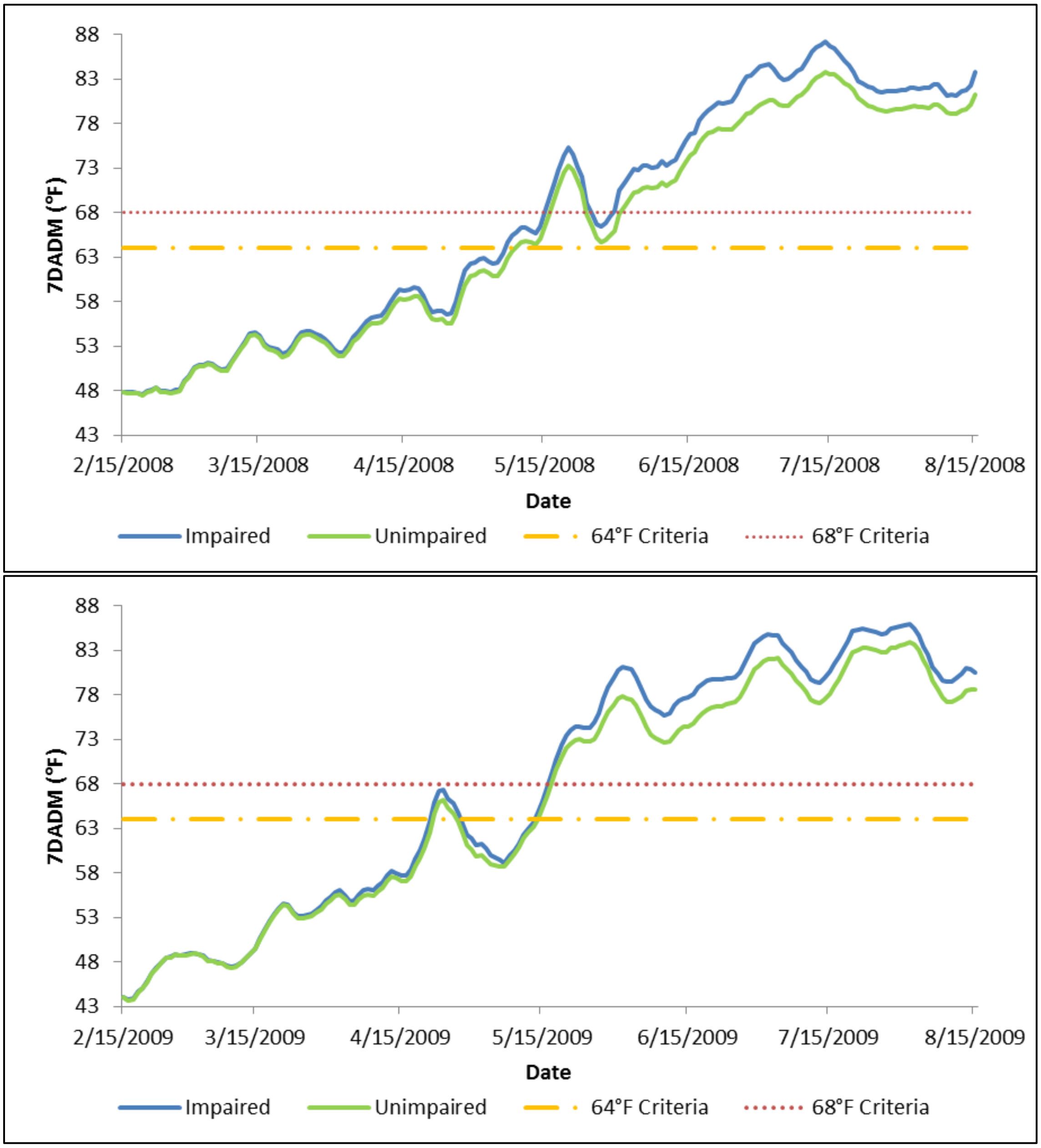
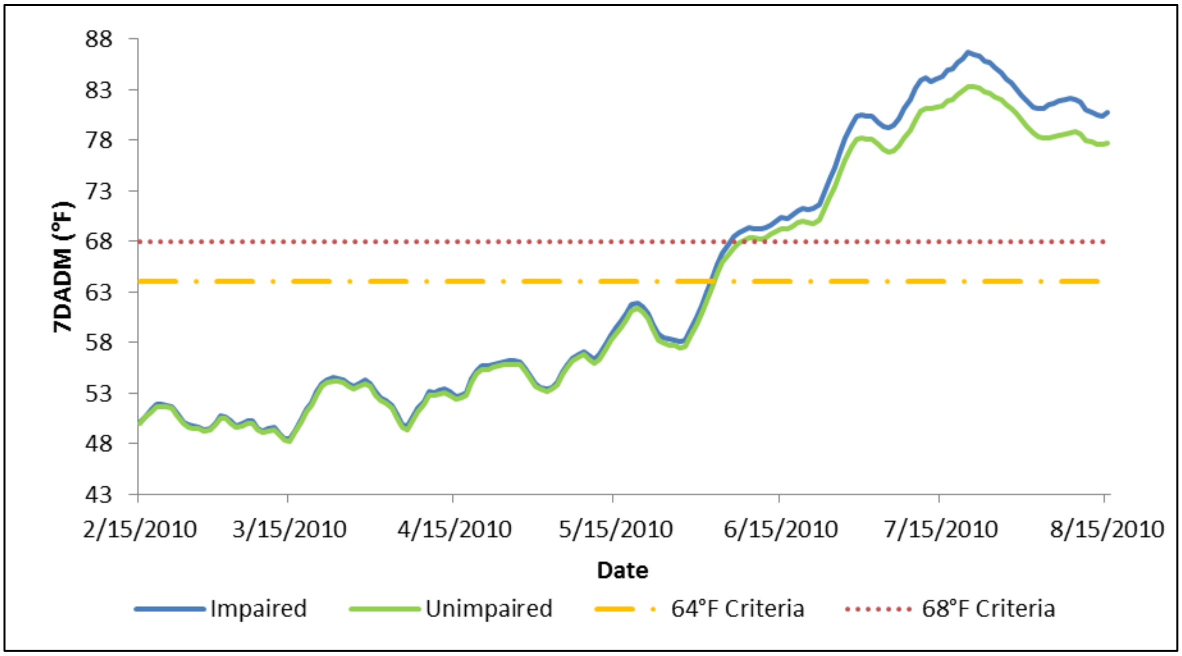


Figure B-23. Predicted 7DADM at the downstream end of Reach 4 for impaired and unimpaired flows during season of migration in 2008-2009.



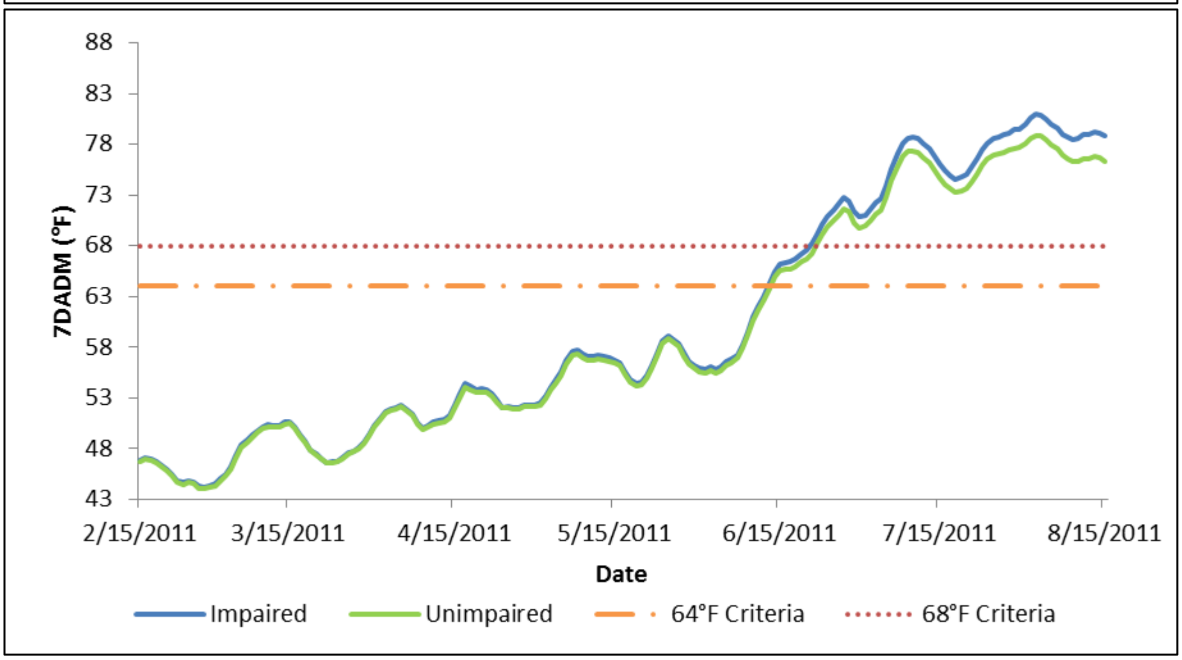


Figure B-24. Predicted 7DADM at the downstream end of Reach 4 for impaired and unimpaired flows during season of migration in 2010-2011.

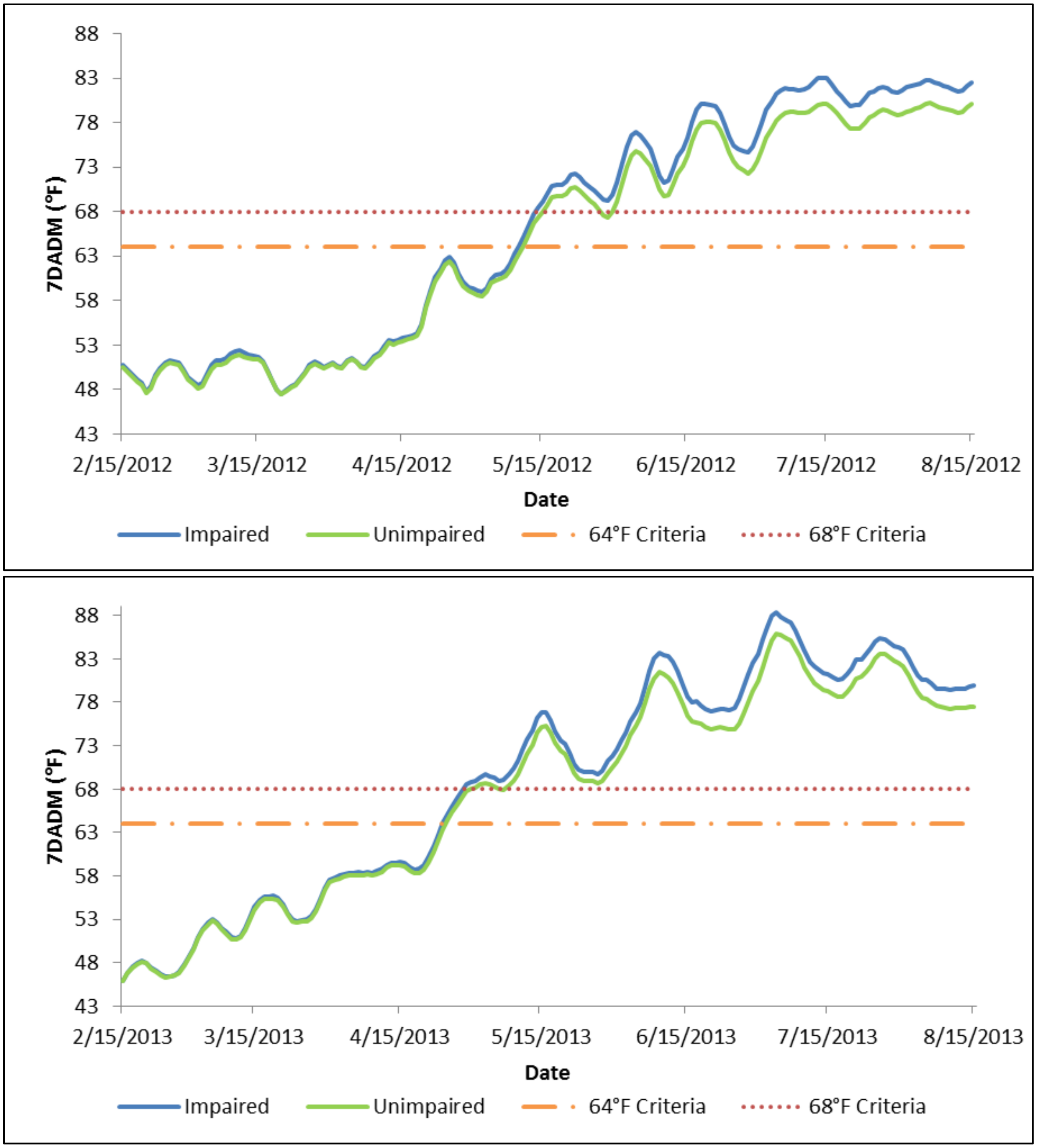


Figure B-25. Predicted 7DADM at the downstream end of Reach 4 for impaired and unimpaired flows during season of migration in 2012-2013.

Water Temperature Model Discussion

The StreamTemp model uses transect data to determine overall flow-width and flow-depth relationships for each reach. Transects were weighted based on the mesohabitat composition of each reach. Glides were represented by pools in Reaches 5 and 6, since glides constituted less than 5 percent of the length of both of these reaches.

In general, beta values greater than 4.5 for *IFG4* occur when a hydraulic control has not been correctly identified. For transects 5 and 6, we concluded that the beta values greater than 4.5 were due to the complex nature of the downstream hydraulic control (a transverse bar), and thus concluded that the hydraulic calibration was acceptable for these transects. Similarly, the calibration of transect 22 was accepted because transects 22 and 23 have the same hydraulic control, and the beta value for transect 23 was less than 4.5. The hydraulic calibration for transects 29 and 35 were accepted because the SZF values would only need to be raised by 0.02 feet to get beta values less than 4.5; thus, the accuracy of our SZF value relative to the WSELs fell within the range of accuracy of the measurements. The high mean errors and difference in calibration versus given flows for transects 32 to 35 likely is a result of the inherent difficulty in measuring very low flows. A change in the lower two calibration flows for these transects of 0.5 cfs would have reduced the mean error to less than 10 percent. Accordingly, we accepted the hydraulic calibration for these transects.

In calibrating the StreamTemp model, the adjustment of parameters was restricted to ranges deemed reasonable given the underlying data and level of accuracy of this data. For example, the values of vegetation crown widths were restricted to 44 to 80 percent of vegetation crown heights, reflecting the range of heights of white alders from the literature. In addition, calibrated values of vegetation density were restricted to half to twice the measured values, reflecting what we feel to be the possible range of true values of this parameter, given the large sampling errors possible for vegetation density. Manning's n values, which are the only parameter that affects maximum daily water temperature values in StreamTemp, were restricted to values no less than 0.03, since natural channels generally do not have Manning's n values less than 0.03. While additional adjustment of parameters could have improved the performance of the water temperature models, it would have come with a cost in terms of how well the model can predict water temperatures at conditions different from those during the calibration period.

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Appendix C. SEFA WSEL Calibration

Transect Stage-Discharge Calibration Parameters Used

Reach	Transect	Flow Range	Calibration Flows	SZF
1	1	25 - 375	56.1, 92.2, 150.3	94.47
1	2	25 - 375	56.1, 92.2, 150.3	94.56
1	3	25 - 375	56.1, 92.2, 150.3	94.14
1	4	25 - 375	56.1, 92.2, 150.3	92.81
1	5	25 - 375	56.1, 92.2, 150.3	97.50
1	6	25 - 375	56.1, 92.2, 150.3	96.25
1	7	25 - 375	56.1, 92.2, 150.3	94.61
2	8	25 - 380	46.2, 85.7, 153.1	97.70
2	9	25 - 380	46.2, 85.7, 153.1	97.70
2	10	25 - 380	46.2, 85.7, 153.1	96.73
2	11	25 - 380	46.2, 85.7, 153.1	96.41
2	12	25 - 380	54.9, 85.7, 153.1	94.38
2	13	25 - 380	54.9, 85.7, 153.1	94.38
2	14	25 - 380	54.9, 85.7, 153.1	97.26
2	15	25 - 380	54.9, 85.7, 153.1	96.40
3	16	20 - 360	44.4, 87.5, 145	96.64
3	17	20 - 360	44.4, 87.5, 145	96.10
3	18	20 - 360	44.4, 87.5, 145	96.45
3	19	20 - 360	44.4, 87.5, 145	95.12
3	20	20 - 360	44.4, 73.3, 145	93.86
3	21	20 - 360	44.4, 73.3, 145	96.00
3	22	20 - 360	44.4, 73.3, 145	95.98
3	23	20 - 360	44.4, 73.3, 145	96.63
4	24	10 - 240	12.1, 35.1, 97.8	96.74
4	25	10 - 240	24, 35.1, 97.8	95.86
4	26	10 - 240	12.1, 35.1, 97.8	96.66
4	27	10 - 240	22.9, 35.1, 97.8	97.27
5	28	3.5 - 45	8.7, 10.3, 19.4	95.06
5	29	3.5 - 45	8.7, 10.3, 19.4	98.60
5	30	3.5 - 45	8.7, 10.3, 19.4	97.15
5	31	3.5 - 45	8.7, 10.3, 19.4	95.51
6	32	1.2 - 25	2.8, 3.2, 10	96.34
6	33	1.2 - 25	2.8, 3.2, 10	96.20
6	34	1.2 - 25	2.8, 3.2, 10	95.95
6	35	1.2 - 25	2.8, 3.2, 10	95.27

	BETA	%MEAN	Calculated vs Given[22] Discharge (%)			Difference[23] (measured vs. pred. WSELs)		
XS	**COEFF.**	**ERROR**	56.1	92.2	150.3	56.1	92.2	150.3
1	2.77	2.3	1.9	3.4	1.6	0.02	0.02	0.01
2	3.56	0.2	0.1	0.3	0.1	0.00	0.00	0.00
3	3.31	4.0	2.4	6.1	3.5	0.01	0.03	0.02
4	3.08	7.0	3.4	10.9	6.7	0.01	0.03	0.03
5	4.79	0.9	0.7	1.4	0.8	0.00	0.00	0.00
6	4.68	1.7	1.2	2.6	1.4	0.00	0.01	0.01
7	3.57	2.5	2.1	3.7	1.7	0.01	0.01	0.01
	BETA	**%MEAN**	**Calculated vs Given Discharge (%)**			**Difference (measured vs. pred. WSELs)**		
XS	**COEFF.**	**ERROR**	46.2	85.7	153.1	46.2	85.7	153.1
8	4.00	3.4	2.1	5.2	2.9	0.01	0.01	0.01
9	3.69	3.5	2.2	5.4	3.0	0.01	0.02	0.01
10	3.97	8.4	3.9	13.2	8.1	0.01	0.03	0.03
11	4.13	1.8	1.2	2.7	1.4	0.00	0.01	0.01
	BETA	**%MEAN**	**Calculated vs Given Discharge (%)**			**Difference (measured vs. pred. WSELs)**		
XS	**COEFF.**	**ERROR**	54.9	85.7	153.1	54.9	85.7	153.1
12	3.61	3.2	2.4	4.9	2.4	0.01	0.02	0.01
13	3.31	0.4	0.3	0.6	0.2	0.00	0.00	0.00
14	3.76	0.8	0.7	1.2	0.6	0.00	0.00	0.00
15	2.61	1.7	1.3	2.5	1.2	0.01	0.01	0.00

[22] Given refers to measured flows.
[23] Units of Difference are feet.

	BETA	%MEAN	Calculated vs Given Discharge (%)			Difference (measured vs. pred. WSELs)		
XS	**COEFF.**	**ERROR**	44.4	87.5	145	44.4	87.5	145
16	3.29	1.5	0.9	2.2	1.4	0.00	0.00	0.00
17	2.88	1.0	0.6	1.5	0.9	0.00	0.00	0.00
18	3.47	3.7	2.8	5.4	2.8	0.01	0.02	0.01
19	3.78	---	---	---	---	---	---	---
	BETA	**%MEAN**	**Calculated vs Given Discharge (%)**			**Difference (measured vs. pred. WSELs)**		
XS	**COEFF.**	**ERROR**	44.4	73.3	145	44.4	73.3	145
20	3.78	4.8	3.4	7.4	3.6	0.01	0.02	0.02
21	3.79	1.4	1.3	2.1	0.9	0.00	0.01	0.00
22	4.65	4.5	3.3	7.0	3.4	0.01	0.02	0.02
23	3.71	1.5	1.2	2.3	1.0	0.00	0.01	0.01
	BETA	**%MEAN**	**Calculated vs Given Discharge (%)**			**Difference (measured vs. pred. WSELs)**		
XS	**COEFF.**	**ERROR**	12.1	35.1	97.8	12.1	35.1	97.8
24	3.47	1.7	1.2	2.6	1.3	0.00	0.01	0.01
26	4.40	3.4	2.7	4.9	2.4	0.01	0.02	0.01
	BETA	**%MEAN**	**Calculated vs Given Discharge (%)**			**Difference (measured vs. pred. WSELs)**		
XS	**COEFF.**	**ERROR**	24	35.1	97.8	24	35.1	97.8
25	4.24	1.5	1.8	2.3	0.6	0.00	0.00	0.00
	BETA	**%MEAN**	**Calculated vs Given Discharge (%)**			**Difference (measured vs. pred. WSELs)**		
XS	**COEFF.**	**ERROR**	22.9	35.1	97.8	22.9	35.1	97.8
27	2.81	2.1	2.4	3.1	0.8	0.01	0.01	0.00

	BETA	%MEAN	Calculated vs Given Discharge (%)			Difference (measured vs. pred. WSELs)		
XS	**COEFF.**	**ERROR**	8.7	10.3	19.4	8.7	10.3	19.4
28	4.39	8.1	6.5	12.6	5.0	0.01	0.02	0.01
29	4.60	0.6	0.7	0.9	0.2	0.00	0.00	0.00
30	3.98	7.0	6.0	10.6	4.1	0.01	0.01	0.01
31	3.74	3.1	3.2	4.8	1.4	0.01	0.01	0.01
	BETA	**%MEAN**	**Calculated vs Given Discharge (%)**			**Difference (measured vs. pred. WSELs)**		
XS	**COEFF.**	**ERROR**	2.8	3.2	10	2.8	3.2	10
32	4.01	16.3	13.5	26.7	8.8	0.02	0.02	0.02
33	3.13	18	14.1	29.7	10.2	0.02	0.04	0.02
34	3.37	23	15.4	38.8	14.9	0.02	0.04	0.03
35	4.64	10.1	10.0	16.0	4.2	0.02	0.02	0.01

Appendix D. Critical Riffle Rating Curve Analysis

Best-fit regressions of flow versus width were developed for critical riffles CR31 and CR32 by developing stage-discharge rating curves from field measurements combined with the depth profile measured at the highest flow level sampled. The rating curves were used to calculate simulated water surface elevations (WSELs) at incremental flows for each critical riffle transect. Development of the rating curves is analogous to an empirical version of two-dimensional hydraulic habitat modeling, and similar to the methodology employed in Physical Habitat Simulation (PHABSIM) systems (Waddle 2012). To develop a rating curve for a critical riffle, each transect for which data were collected in the field (i.e., flow event) was compared. A WSEL of 100 was assigned to the highest measured flow. WSELs for the remaining measured flows were calculated using the following equation:

$$WSEL_{\text{Flow } i} = 100 + \text{Average Depth}_{\text{Flow } i} - \text{Average Depth}_{\text{Highest Flow}}$$

The average depth at each flow event was calculated using the locations along a transect that remained inundated by water, at all of the sampled flows. The stage of zero flow (SZF) for each critical riffle was calculated by subtracting the maximum depth from the WSEL at the highest measured flow. A rating curve was then developed for each critical riffle using the above calculated WSELs and measured flows.

A log-log linear rating curve was calculated from at least three sets of measurements taken at different flows for each critical riffle. Regressions were developed consistent with the equation entry method for developing rating curves in Sauer (2002). The resulting regression equation was used to estimate WSELs up to 2.5 times the highest measured flow. Bed elevations were calculated by subtracting the measured depths taken along the shallowest pathway at the highest flow from 100. Depths at each simulation flow were calculated as the difference between the WSEL at that flow and the bed elevations going across the critical riffle. The contiguous and total widths with depths greater than or equal to the species-specific passage criteria were then computed from the simulated depths using the same methods described above for the measured depths. The results indicate the widths meeting depth criteria at a range of flows for each riffle.

Stage-discharge relationships were used to expand the transect data to a greater range of representative flows. The rating curve for CR31 was developed from the three highest measured flows. The lowest two flows were excluded because the slope of the rating curve shifted from the low flows to the high flows. Only the high flow rating curve was found to apply. The resulting regression equation was as follows:

$$\log(\text{stage}-98.98) = -0.667 + 0.295 \times \log(\text{flow})$$

The rating curve for CR32 was calculated from the four highest measured flows. The lowest flow was excluded because the slope of the rating curve shifted from the low flow to the higher flows. The resulting regression equation was as follows:

log (stage-98.97) = -0.849 + 0.373 x log (flow)

The slope of rating curves often shift with flows; in PHABSIM, it is common to have to break rating curves into several components, with the lower portion of the rating curve developed from lower flows and the upper portion of the rating curve developed from higher flows. Because the slope of the rating curves for CR31 and CR32 shifted at flows near or lower than flows required to provide minimal passable widths and results would not be affected, the rating curve was developed without these flows.

The rating curves for CR31 and CR32 are shown in below (Figures D-1 and D-2). The rating curves were used to compute the total and contiguous width at simulated flows generated to 2.5 times the highest measured flow and to 40% of the lowest measured flow used in each rating curve.

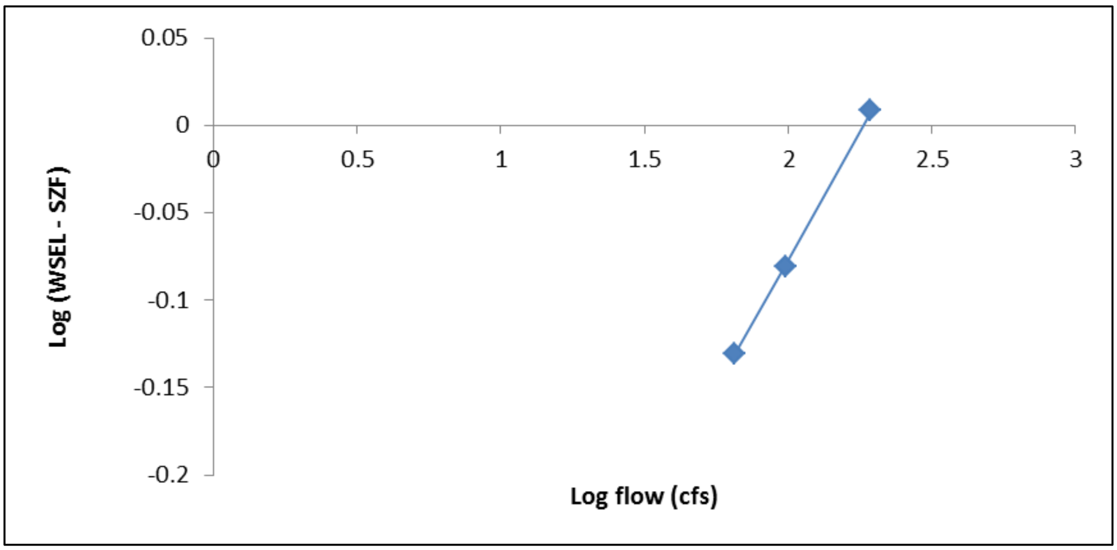


Figure D-1. Rating curve for CR31.

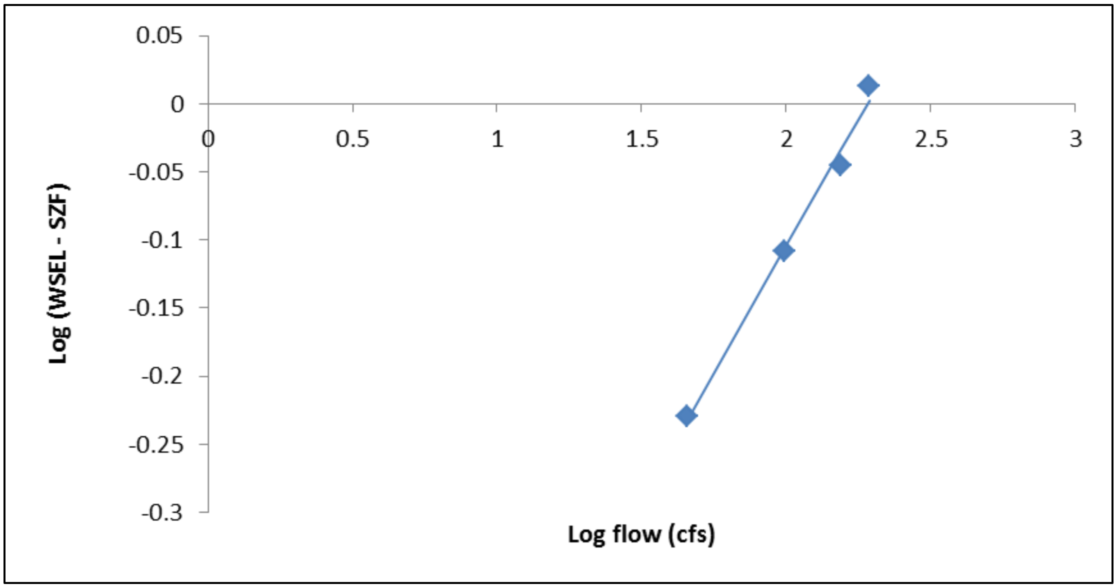


Figure D-2. Rating curve for CR32.

The results of the stage-discharge regressions versus wetted width (ft) based on adult Chinook Salmon depth criteria are plotted with the total and contiguous CRA wetted widths measured in the field (Figures D-3 to D-6). Results of the stage-discharge regressions versus wetted width (ft) based on adult steelhead depth criteria are plotted with the total and contiguous CRA wetted widths measured in the field (Figures D-7 to D-10). The rating curve was used to estimate the total and maximum contiguous width at each flow in 5 cfs intervals (Tables D-1 to D-8). The bottom of each table begins with 40% of the lowest measured flow used in each rating curve.

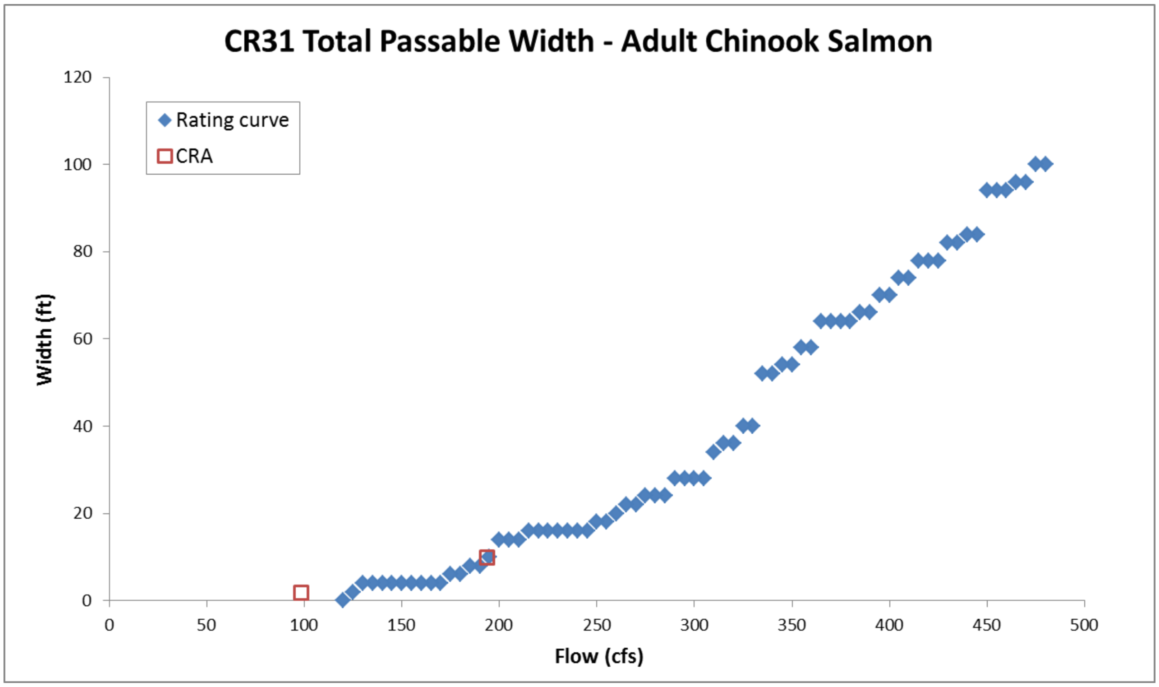


Figure D-3. Rating curve results of total passable width as a function of flow for the 0.9 ft minimum body depth criteria for adult Chinook Salmon at CR31. The red symbols indicate field-collected data.

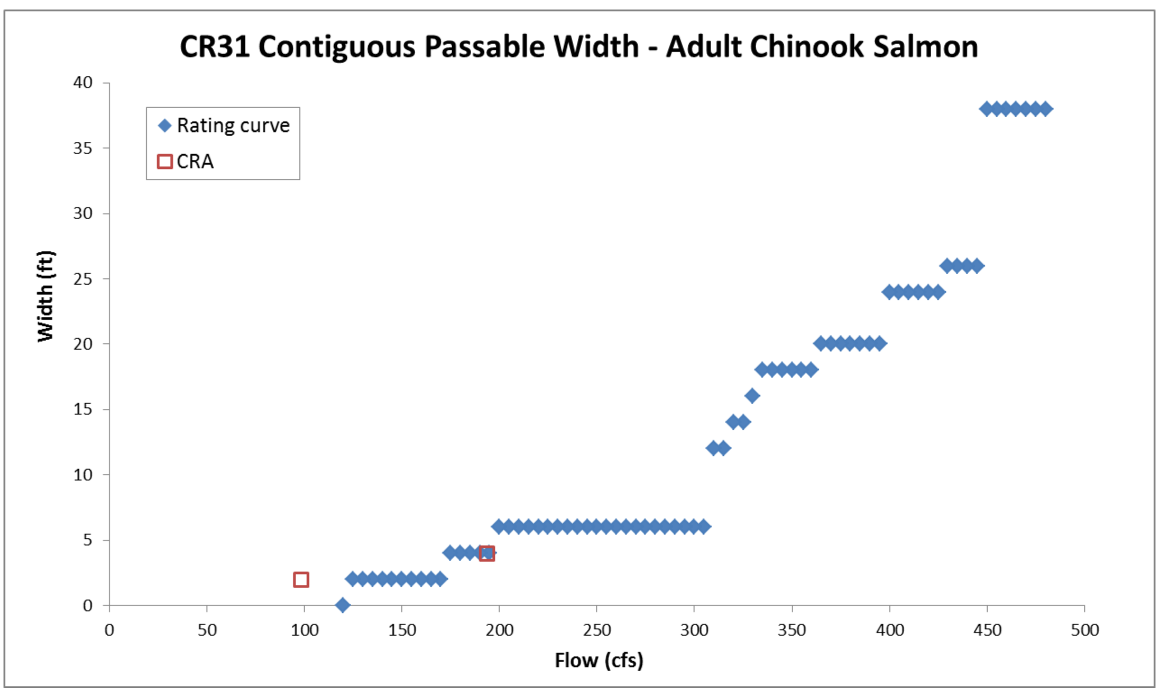


Figure D-4. Rating curve results of contiguous passable width as a function of flow for the 0.9 ft minimum body depth criteria for adult Chinook Salmon at CR31. The red symbols indicate field-collected data.

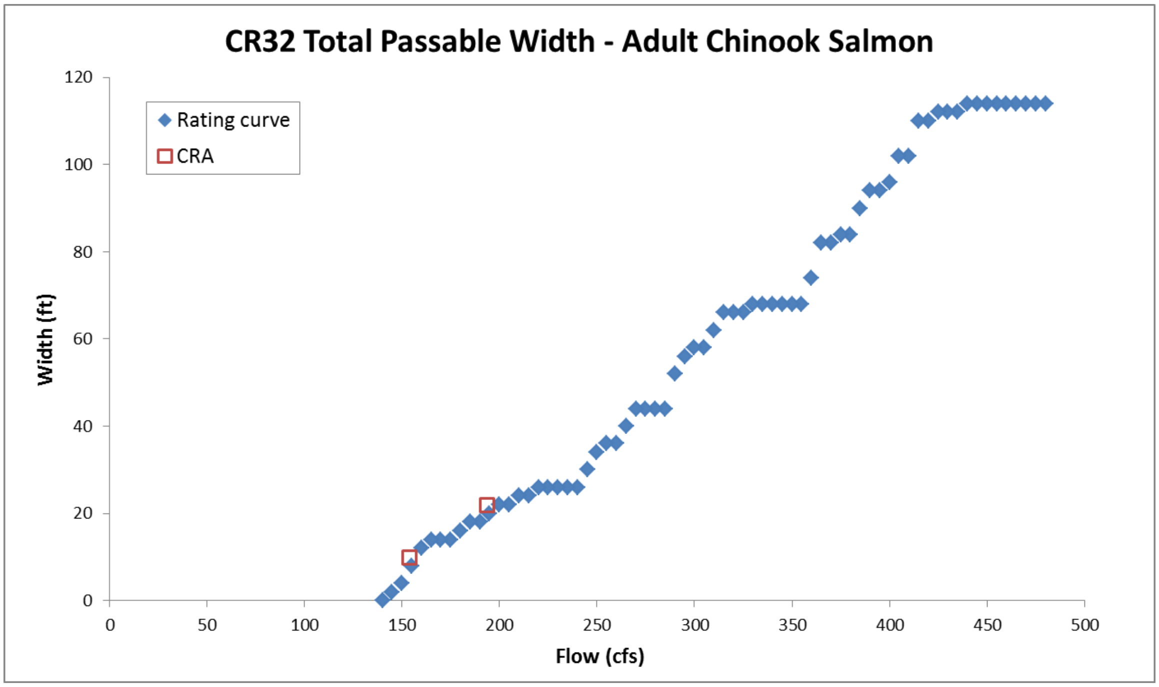


Figure D-5. Rating curve results of total passable width as a function of flow for the 0.9 ft minimum body depth criteria for adult Chinook Salmon at CR32. The red symbols indicate field-collected data.

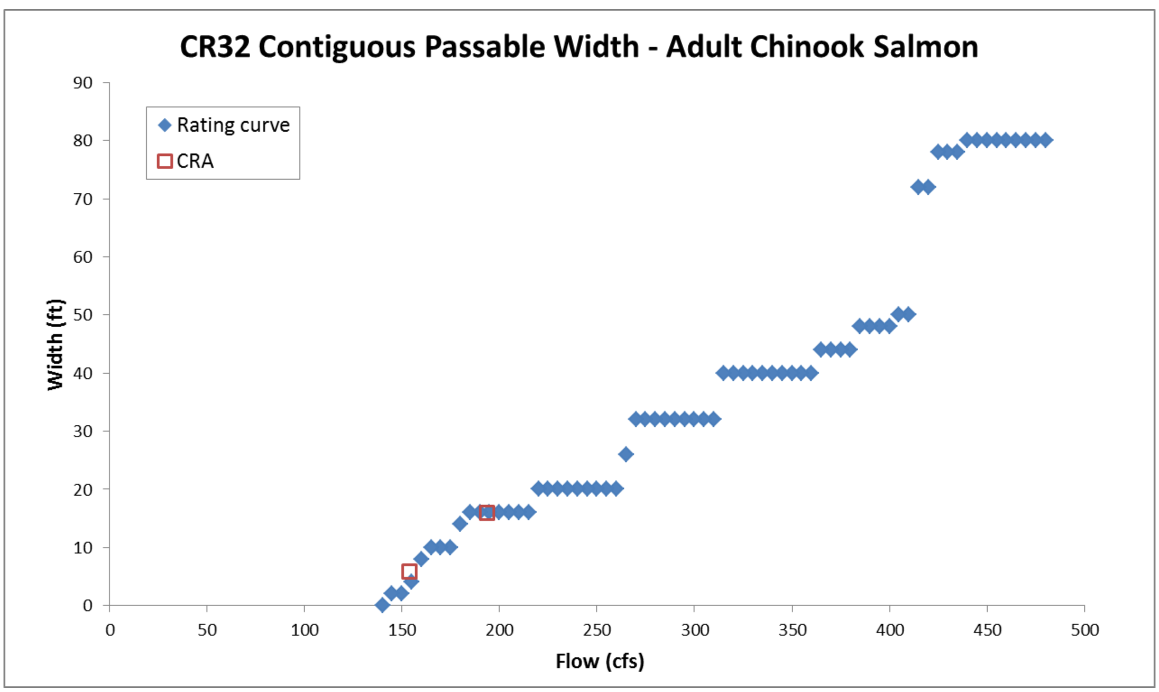


Figure D-6. Rating curve results of contiguous passable width as a function of flow for the 0.9 ft minimum body depth criteria for adult Chinook Salmon at CR32. The red symbols indicate field-collected data.

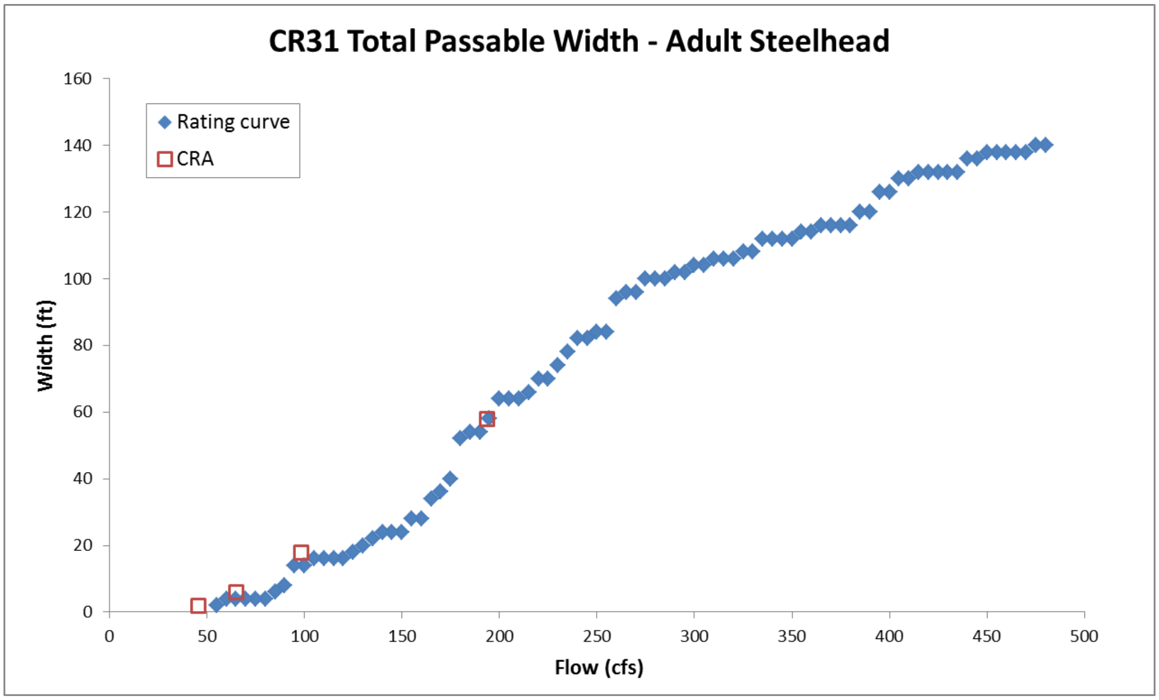


Figure D-7. Rating curve results of total passable width as a function of flow for the 0.7 ft minimum body depth criteria for adult steelhead at CR31. The red symbols indicate field-collected data.

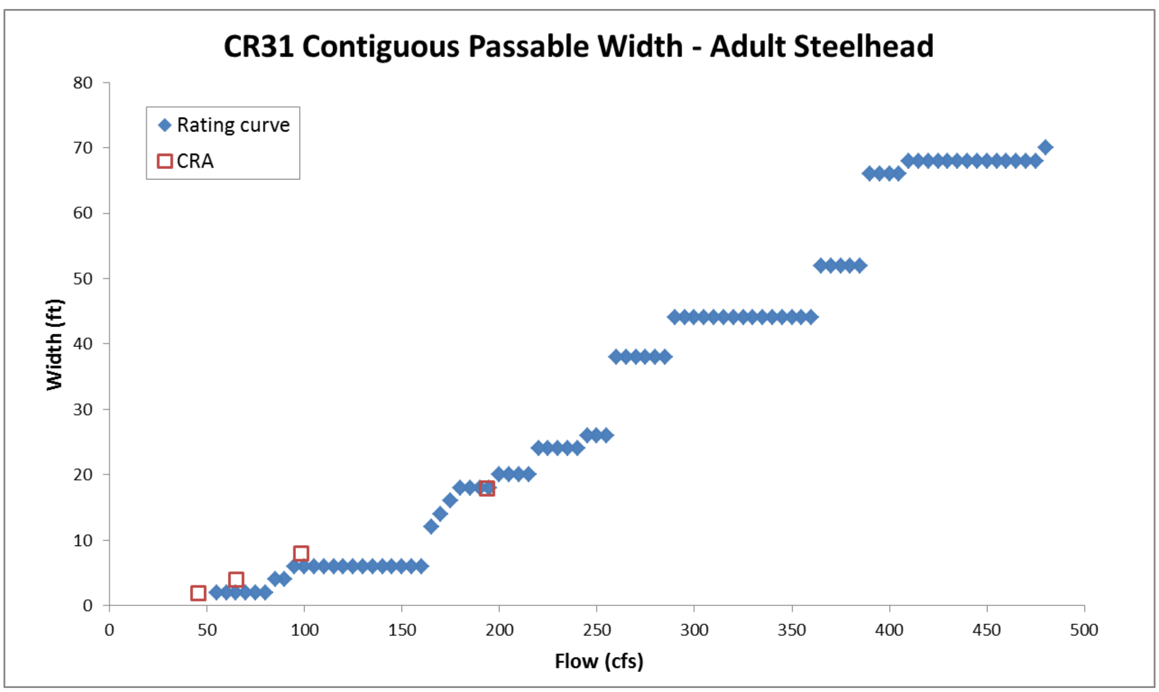


Figure D-8. Rating curve results of contiguous passable width as a function of flow for the 0.7 ft minimum body depth criteria for adult steelhead at CR31. The red symbols indicate field-collected data.

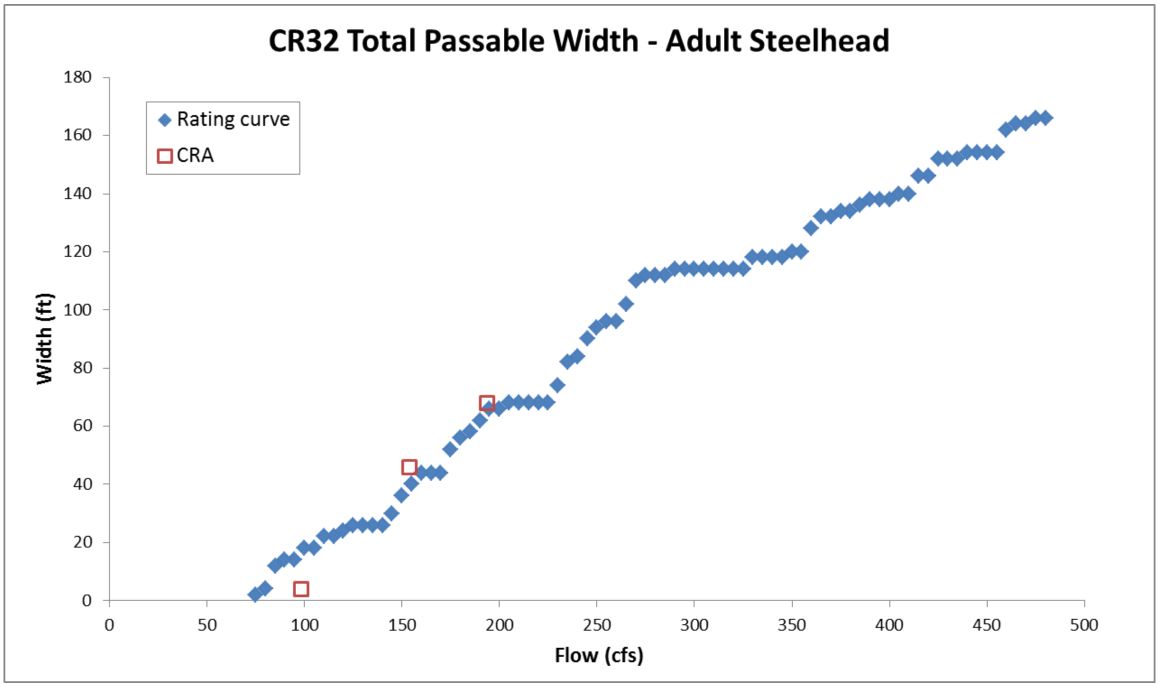


Figure D-9. Rating curve results of total passable width as a function of flow for the 0.7 ft minimum body depth criteria for adult steelhead at CR32. The red symbols indicate field-collected data.

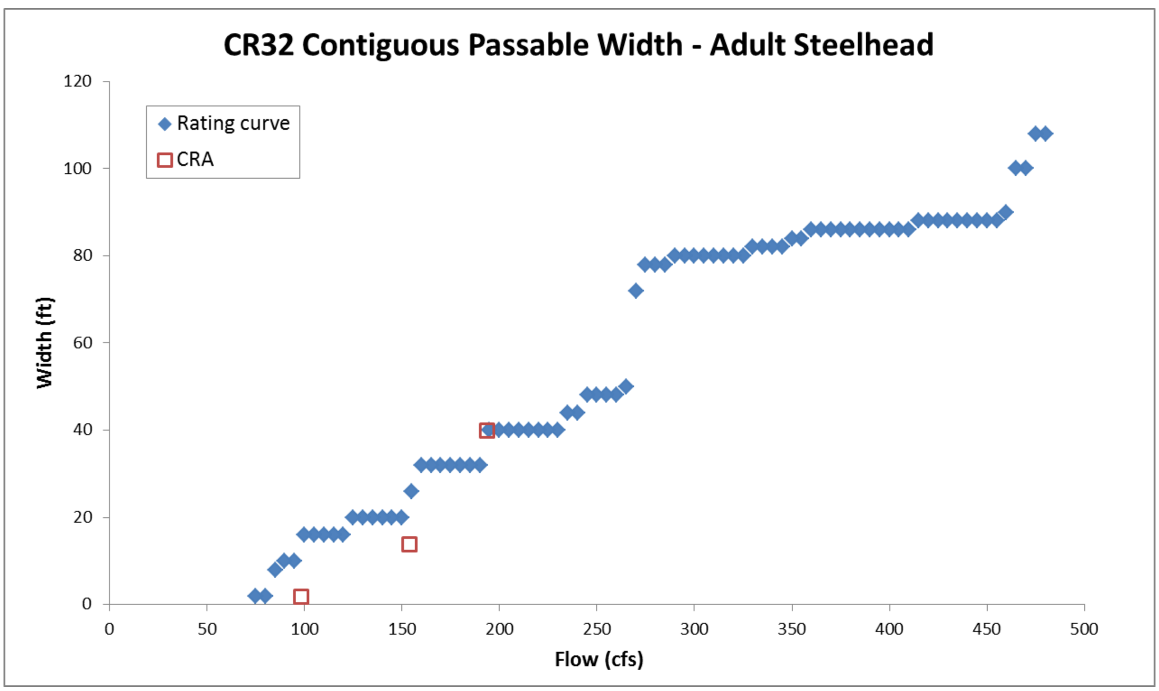


Figure D-10. Rating curve results of contiguous passable width as a function of flow for the 0.7 ft minimum body depth criteria for adult steelhead at CR32. The red symbols indicate field-collected data.

Table D-1. CR31 rating curve results for adult Chinook, total width (ft).

Adult Spring-run Chinook Salmon (minimum depth 0.9 ft)					
Maximum Wetted Width = 171.2 ft					
Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)
480	100	325	40	170	4
475	100	320	36	165	4
470	96	315	36	160	4
465	96	310	34	155	4
460	94	305	28	150	4
455	94	300	28	145	4
450	94	295	28	140	4
445	84	290	28	135	4
440	84	285	24	130	4
435	82	280	24	125	2
430	82	275	24	120	0
425	78	270	22	115	0
420	78	265	22	110	0
415	78	260	20	105	0
410	74	255	18	100	0
405	74	250	18	95	0
400	70	245	16	90	0
395	70	240	16	85	0
390	66	235	16	80	0
385	66	230	16	75	0
380	64	225	16	70	0
375	64	220	16	65	0
370	64	215	16	60	0
365	64	210	14	55	0
360	58	205	14	50	0
355	58	200	14	45	0
350	54	195	10	40	0
345	54	190	8	35	0
340	52	185	8	30	0
335	52	180	6	-	-
330	40	175	6	-	-

Table D-2. CR31 rating curve results for adult Chinook, contiguous width (ft).

Adult Spring-run Chinook Salmon (minimum depth 0.9 ft)					
Maximum Wetted Width = 171.2 ft					
Flow (cfs)	**Contiguous Width (ft)**	**Flow (cfs)**	**Contiguous Width (ft)**	**Flow (cfs)**	**Contiguous Width (ft)**
480	38	325	14	170	2
475	38	320	14	165	2
470	38	315	12	160	2
465	38	310	12	155	2
460	38	305	6	150	2
455	38	300	6	145	2
450	38	295	6	140	2
445	26	290	6	135	2
440	26	285	6	130	2
435	26	280	6	125	2
430	26	275	6	120	0
425	24	270	6	115	0
420	24	265	6	110	0
415	24	260	6	105	0
410	24	255	6	100	0
405	24	250	6	95	0
400	24	245	6	90	0
395	20	240	6	85	0
390	20	235	6	80	0
385	20	230	6	75	0
380	20	225	6	70	0
375	20	220	6	65	0
370	20	215	6	60	0
365	20	210	6	55	0
360	18	205	6	50	0
355	18	200	6	45	0
350	18	195	4	40	0
345	18	190	4	35	0
340	18	185	4	30	0
335	18	180	4	-	-
330	16	175	4	-	-

Table D-3. CR32 rating curve results for adult Chinook Salmon, total width (ft).

Adult Spring-run Chinook Salmon (minimum depth 0.9 ft)					
Maximum Wetted Width = 211.7 ft					
Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)
480	114	325	66	170	14
475	114	320	66	165	14
470	114	315	66	160	12
465	114	310	62	155	8
460	114	305	58	150	4
455	114	300	58	145	2
450	114	295	56	140	0
445	114	290	52	135	0
440	114	285	44	130	0
435	112	280	44	125	0
430	112	275	44	120	0
425	112	270	44	115	0
420	110	265	40	110	0
415	110	260	36	105	0
410	102	255	36	100	0
405	102	250	34	95	0
400	96	245	30	90	0
395	94	240	26	85	0
390	94	235	26	80	0
385	90	230	26	75	0
380	84	225	26	70	0
375	84	220	26	65	0
370	82	215	24	60	0
365	82	210	24	55	0
360	74	205	22	50	0
355	68	200	22	45	0
350	68	195	20	40	0
345	68	190	18	35	0
340	68	185	18	30	0
335	68	180	16	25	0
330	68	175	14	20	0

Table D-4. CR32 rating curve results for adult Chinook, contiguous width (ft).

Adult Spring-run Chinook Salmon (minimum depth 0.9 ft)					
Maximum Wetted Width = 211.7 ft					
Flow (cfs)	Contiguous Width (ft)	Flow (cfs)	Contiguous Width (ft)	Flow (cfs)	Contiguous Width (ft)
480	80	325	40	170	10
475	80	320	40	165	10
470	80	315	40	160	8
465	80	310	32	155	4
460	80	305	32	150	2
455	80	300	32	145	2
450	80	295	32	140	0
445	80	290	32	135	0
440	80	285	32	130	0
435	78	280	32	125	0
430	78	275	32	120	0
425	78	270	32	115	0
420	72	265	26	110	0
415	72	260	20	105	0
410	50	255	20	100	0
405	50	250	20	95	0
400	48	245	20	90	0
395	48	240	20	85	0
390	48	235	20	80	0
385	48	230	20	75	0
380	44	225	20	70	0
375	44	220	20	65	0
370	44	215	16	60	0
365	44	210	16	55	0
360	40	205	16	50	0
355	40	200	16	45	0
350	40	195	16	40	0
345	40	190	16	35	0
340	40	185	16	30	0
335	40	180	14	25	0
330	40	175	10	20	0

Table D-5. CR31 rating curve results for adult steelhead, total width (ft).

Adult Steelhead (minimum depth 0.7 ft)					
Maximum Wetted Width = 171.2 ft					
Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)
480	140	325	108	170	36
475	140	320	106	165	34
470	138	315	106	160	28
465	138	310	106	155	28
460	138	305	104	150	24
455	138	300	104	145	24
450	138	295	102	140	24
445	136	290	102	135	22
440	136	285	100	130	20
435	132	280	100	125	18
430	132	275	100	120	16
425	132	270	96	115	16
420	132	265	96	110	16
415	132	260	94	105	16
410	130	255	84	100	14
405	130	250	84	95	14
400	126	245	82	90	8
395	126	240	82	85	6
390	120	235	78	80	4
385	120	230	74	75	4
380	116	225	70	70	4
375	116	220	70	65	4
370	116	215	66	60	4
365	116	210	64	55	2
360	114	205	64	50	0
355	114	200	64	45	0
350	112	195	58	40	0
345	112	190	54	35	0
340	112	185	54	30	0
335	112	180	52	-	-
330	108	175	40	-	-

Table D-6. CR31 rating curve results for adult steelhead, contiguous width (ft).

Adult Steelhead (minimum depth 0.7 ft)					
Maximum Wetted Width = 171.2 ft					
Flow (cfs)	**Contiguous Width (ft)**	**Flow (cfs)**	**Contiguous Width (ft)**	**Flow (cfs)**	**Contiguous Width (ft)**
480	70	325	44	170	14
475	68	320	44	165	12
470	68	315	44	160	6
465	68	310	44	155	6
460	68	305	44	150	6
455	68	300	44	145	6
450	68	295	44	140	6
445	68	290	44	135	6
440	68	285	38	130	6
435	68	280	38	125	6
430	68	275	38	120	6
425	68	270	38	115	6
420	68	265	38	110	6
415	68	260	38	105	6
410	68	255	26	100	6
405	66	250	26	95	6
400	66	245	26	90	4
395	66	240	24	85	4
390	66	235	24	80	2
385	52	230	24	75	2
380	52	225	24	70	2
375	52	220	24	65	2
370	52	215	20	60	2
365	52	210	20	55	2
360	44	205	20	50	0
355	44	200	20	45	0
350	44	195	18	40	0
345	44	190	18	35	0
340	44	185	18	30	0
335	44	180	18	-	-
330	44	175	16	-	-

Table D-7. CR32 rating curve results for adult steelhead, total width (ft).

Adult Steelhead (minimum depth 0.7 ft)					
Maximum Wetted Width = 211.7 ft					
Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)
480	166	325	114	170	44
475	166	320	114	165	44
470	164	315	114	160	44
465	164	310	114	155	40
460	162	305	114	150	36
455	154	300	114	145	30
450	154	295	114	140	26
445	154	290	114	135	26
440	154	285	112	130	26
435	152	280	112	125	26
430	152	275	112	120	24
425	152	270	110	115	22
420	146	265	102	110	22
415	146	260	96	105	18
410	140	255	96	100	18
405	140	250	94	95	14
400	138	245	90	90	14
395	138	240	84	85	12
390	138	235	82	80	4
385	136	230	74	75	2
380	134	225	68	70	0
375	134	220	68	65	0
370	132	215	68	60	0
365	132	210	68	55	0
360	128	205	68	50	0
355	120	200	66	45	0
350	120	195	66	40	0
345	118	190	62	35	0
340	118	185	58	30	0
335	118	180	56	25	0
330	118	175	52	20	0

Table D-8. CR32 rating curve results for adult steelhead, contiguous width (ft).

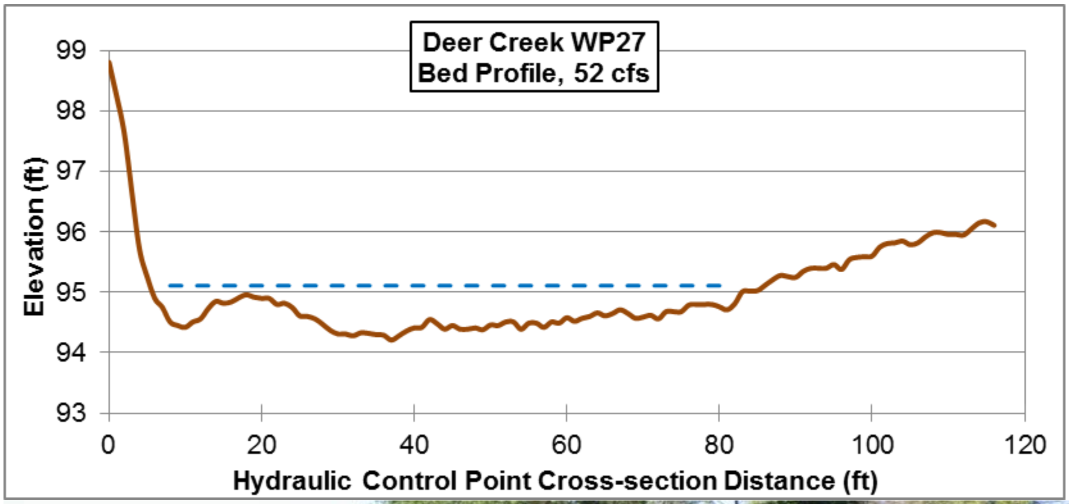
Adult Steelhead (minimum depth 0.7 ft)					
Maximum Wetted Width = 211.7 ft					
Flow (cfs)	Contiguous Width (ft)	Flow (cfs)	Contiguous Width (ft)	Flow (cfs)	Contiguous Width (ft)
480	108	325	80	170	32
475	108	320	80	165	32
470	100	315	80	160	32
465	100	310	80	155	26
460	90	305	80	150	20
455	88	300	80	145	20
450	88	295	80	140	20
445	88	290	80	135	20
440	88	285	78	130	20
435	88	280	78	125	20
430	88	275	78	120	16
425	88	270	72	115	16
420	88	265	50	110	16
415	88	260	48	105	16
410	86	255	48	100	16
405	86	250	48	95	10
400	86	245	48	90	10
395	86	240	44	85	8
390	86	235	44	80	2
385	86	230	40	75	2
380	86	225	40	70	0
375	86	220	40	65	0
370	86	215	40	60	0
365	86	210	40	55	0
360	86	205	40	50	0
355	84	200	40	45	0
350	84	195	40	40	0
345	82	190	32	35	0
340	82	185	32	30	0
335	82	180	32	25	0
330	82	175	32	20	0

References

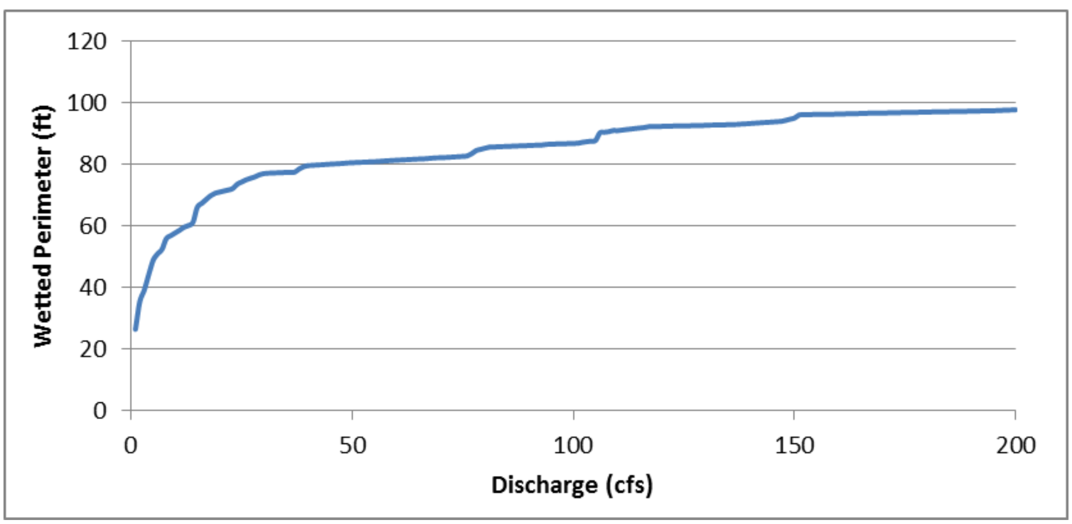
Sauer, V.B. 2002. Standards for the analysis and processing of surface-water data and information using electronic methods: U.S. Geological Survey Water-Resources Investigations Report 01-4044, 91 p.

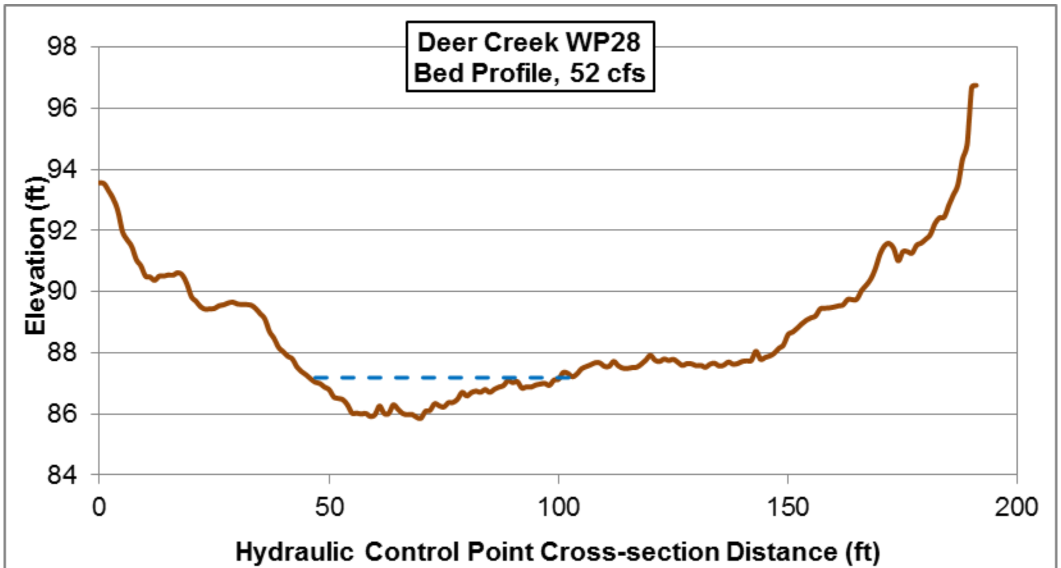
Waddle, T.J. (ed.). 2012. PHABSIM for Windows user's manual and exercises. Open-File Report 2001-340. Fort Collins, CO: U.S. Geological Survey. 288 p.

Appendix E. Wetted Perimeter Profiles

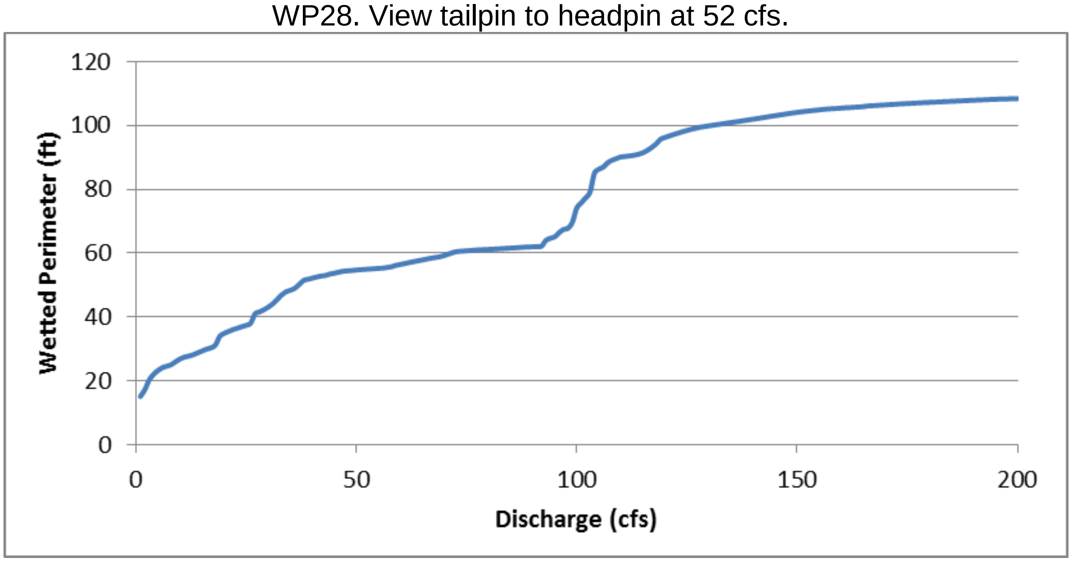


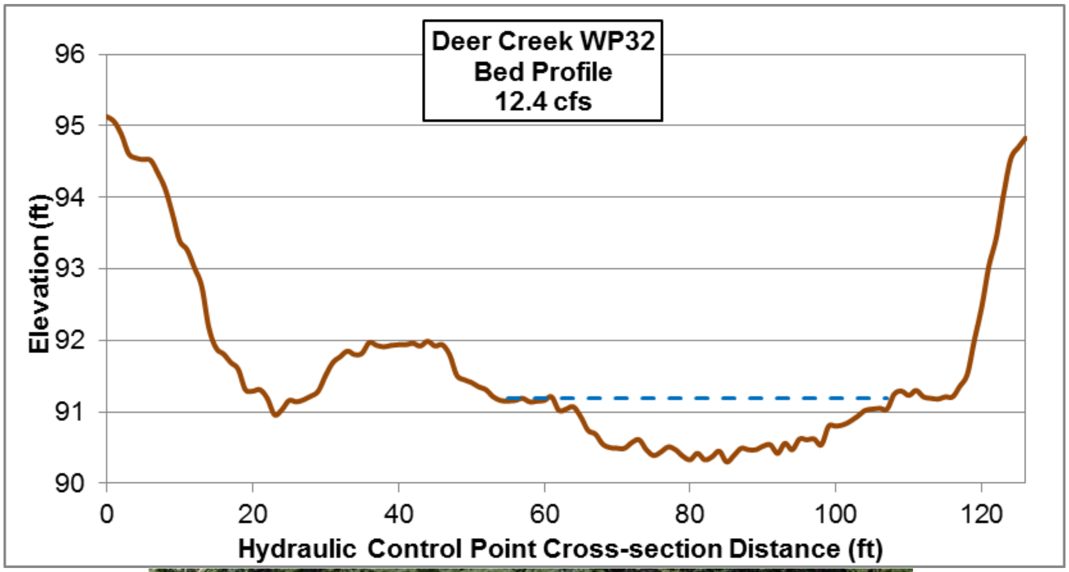
WP27. View downstream at 52 cfs.



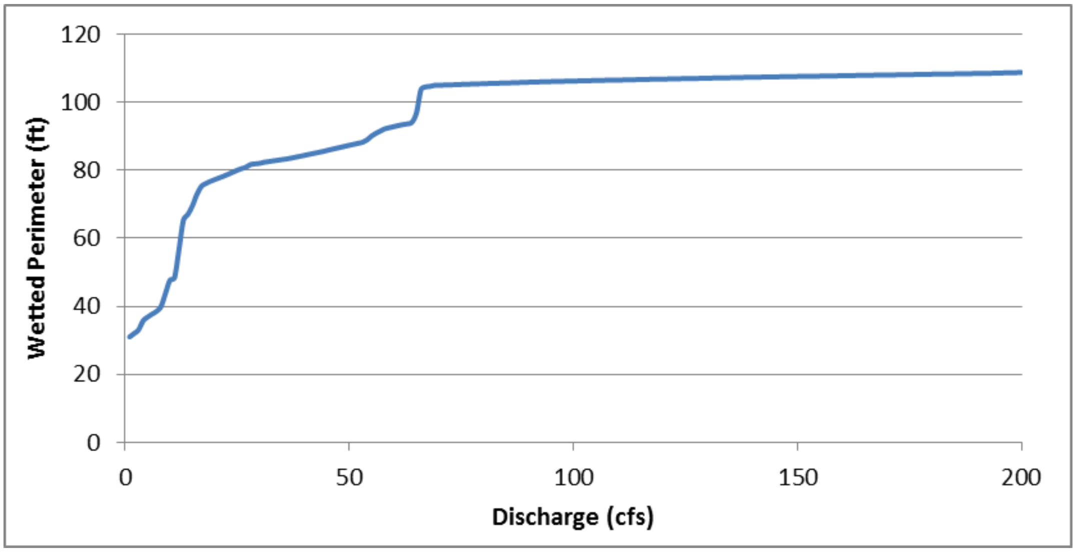


WP28. View tailpin to headpin at 52 cfs.





WP32. View tailpin to headpin at 12.4 cfs.



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Department of Fish and Wildlife
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