California Department of Fish and Wildlife
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INSTREAM FLOW EVALUATION: TEMPERATURE AND PASSAGE ASSESSMENT FOR SALMONIDS IN MILL CREEK, TEHAMA COUNTY

STREAM EVALUATION REPORT 17-1

January 2017

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

California Department of Fish and Wildlife
Stream Evaluation Report
Report No. 17-1

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January 2017

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California Department of Fish and Wildlife
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ABSTRACT

Passage conditions based on water temperature, depth, and velocity were investigated for anadromous salmonids, including Central Valley spring-run Chinook salmon (*Oncorhynchus tshawytscha*), fall-run Chinook salmon, and steelhead (*Oncorhynchus mykiss*) in lower Mill Creek, Tehama County, California from 2014 to 2015. Stream temperature, along with other monitoring data including river stage, climate 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 Mill Creek. Conditions at passage limiting sites were evaluated based on minimum depth and maximum velocity criteria for adult salmon and steelhead over a range of flows. Passage conditions at a hydraulically complex, depth sensitive, low gradient critical riffle were evaluated using a two-dimensional hydraulic habitat model. Additional depth sensitive riffles were evaluated using empirical field measurements of depth and velocity. 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 produced by this study, and presented here, will be used by the California Department of Fish and Wildlife's Instream Flow Program to develop flow criteria for salmonids.

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ABBREVIATIONS AND ACRONYMS

°F	degrees Fahrenheit
1D	one-dimensional (physical habitat simulation model)
2D	two-dimensional (physical habitat simulation model)
7DADM	7-day average of the daily maximum temperature
BR Mult	bed roughness multiplier
CDEC	California Data Exchange Center
CDFG	California Department of Fish and Game
CDFW	California Department of Fish and Wildlife (previously CDFG)
cdg	characteristic dissipative galerkin
cfs	cubic feet per second
CR	critical riffle
CRA	critical riffle analysis
CSV	comma-separated value
DWR	California Department of Water Resources
EPA	Environmental Protection Agency
ESU	Evolutionarily Significant Unit
FDA	Flow Duration Analysis
FN	Froude number
FRCS	fall-run Chinook salmon
ft	foot/feet
ft/s	feet per second
GIS	geographic information system
GPS	Global Positioning System
HWY	highway
IFG4	Instream Flow Group Model #4
IFIM	Instream Flow Incremental Methodology
in	inch
LFRCS	late fall-run Chinook salmon
MANSQ	Manning's stage discharge
MAX F	maximum Froude number
Model 2000	Marsh-McBirney Model 2000 Flo-Mate velocity meter
NAIP	National Agriculture Imagery Program
Net Q	net flow
NMFS	National Marine Fisheries Service
ODFW	Oregon Department of Fish and Wildlife
PHABSIM	Physical Habitat Simulation Model
PRC	Public Resources Code
QI	quality index
r^2	coefficient of determination
RIVER2D	River2D Model
RM	river mile
RTK	real time kinematic
SEFA	System for Environmental Flow Analysis
SNTEMP	Stream Network Temperature (model)

Sol Δ	solution change
SOP	standard operating procedure
SRCS	spring-run Chinook salmon
SWRCB	State Water Resources Control Board
SWRP	Sacramento River Watershed Program
SZF	stage of zero flow
TIN	triangulated irregular network
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
VAF	velocity adjustment factor
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

Mill Creek is among the essential streams for recovery and perpetuation of wild stocks of Central Valley spring-run Chinook salmon (*Oncorhynchus tshawytscha*), and supports Central Valley steelhead trout (*Oncorhynchus mykiss*; Armentrout et al. 1998). In addition, Mill 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 Mill Creek as a high priority Core 1 watershed because of its potential to support independent viable populations. Mill 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), and 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 which 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 which 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 upper Mill Creek watershed pursuant to the Department's PRC mandate. Flow criteria for lower Mill Creek will be developed by the Department in a future document.

1.0 INTRODUCTION

Mill Creek in Tehama County was identified by the California Department of Fish and Wildlife (Department) as a high priority stream for instream flow assessment. Mill Creek is one of only three Sacramento River tributaries that support a self-sustaining and genetically distinct population of spring-run Chinook salmon (SRCS; CDFG 1998; Johnson and Merrick 2012). The Central Valley SRCS Evolutionarily Significant Unit (ESU) is state and federally listed as threatened; Mill Creek has been identified as one of the essential streams for recovery and perpetuation of the wild stocks (Armentrout et al. 1998; NMFS 2014). Mill 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 listed as a Species of Special 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 as well as impact juvenile Chinook salmon and steelhead outmigration (Harvey-Arrison 2009; DWR 2009). Stream temperature also influences spawning, timing and success of incubation, maturation and growth, competition, in addition to disease and parasite proliferation (Annear et al. 2004).

Upper Mill Creek, upstream of the Upper Diversion Dam, provides ideal cold water holding pools and spawning habitat for SRCS and steelhead. However, agricultural stream diversions in lower Mill Creek can result in insufficient stream flows and elevated stream temperatures which 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 from migrating into and accessing their spawning habitat in lower Mill Creek, as well as impact outmigration of juvenile Chinook salmon and steelhead (USFWS 2000; 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, as a result of stream diversion, changes water depths and temperatures, which potentially limits the hydrologic connectivity of riverine habitats in lower Mill 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 Mill 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 located in the upper watershed; as well as, hampering adult FRCS migration into the lower watershed, where they spawn and rear.

Two site specific instream flow studies have previously been conducted in the lower 5.25 miles of Mill Creek. Alley (1996) conducted a study using a Physical Habitat Simulation Systems (PHABSIM) model on lower Mill Creek, while Harvey-Arrison (2009) conducted a study that documented visual observation of fish passage under flow, water temperature, and riffle depth conditions recorded during prescribed flow conditions. Both studies recommended annual riffle modification for fish passage. While ongoing riffle modification might improve salmonid passage into the upper watershed, this approach has not been evaluated, and has the potential to generate significant adverse environmental impacts. Kondolf (2001) advises that mechanical modification of the active stream channel, including excavation for channel 'maintenance' or 'cleaning', especially with heavy equipment should be avoided whenever possible because it reduces channel complexity by simplifying the complex bed morphology necessary for continuous flow, connection of pools, and connection to side channels. In addition, annual channel modification would not address thermal conditions impacting Mill Creek salmonids.

1.1 Study Goals and Objectives

The goal of this study is to evaluate flow and water temperature regimes necessary for unimpeded adult SRCS, FRCS, and steelhead migration through lower Mill Creek. This study will quantify the stream flows associated with water temperatures and depths that are adequate to ensure adult salmonid migration is possible through lower Mill Creek (i.e., the stream reach between the Sacramento River confluence and the Upper Diversion Dam at River Mile (RM) 5.4). Stream flows that are protective for passage of adult salmonids are expected to be adequate for juvenile salmonids, when both life-stages are present.

The primary objective of this study is to understand the instream flow and temperature regimes needed for long-term protection and maintenance of salmonid migration through the natural stream channel in lower Mill Creek. Objectives of this study include: 1) the evaluation of depth-limiting passage impediments in the study reach through use of a two-dimensional (2D) hydraulic habitat model and Critical Riffle Analysis (CDFG 2012); and 2) evaluation of water temperature regimes in the study reach through the use of the 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 Mill Creek into the upper watershed. They may also be used to determine flows necessary to support migrating adult FRCS into the lower watershed as well as flows necessary to support the development of benthic macroinvertebrates, which provide a food source for salmonids.

1.2 Description of Watershed

The Mill Creek watershed comprises approximately 134 square miles. The creek originates on the slopes of Lassen Peak and flows approximately 60 miles west until it joins the Sacramento River near the town of Los Molinos, Tehama County (Figure 1). Elevations in the watershed range from 8,000 feet in Lassen Volcanic National Park to 200 feet at the Sacramento River confluence. Mill Creek is mostly confined within a narrow canyon, except for some alluvial meadows around the 5,000 foot elevation; below the canyon in the valley floor, the stream flows for 8 miles through irrigated agricultural lands (SRWP 2010).

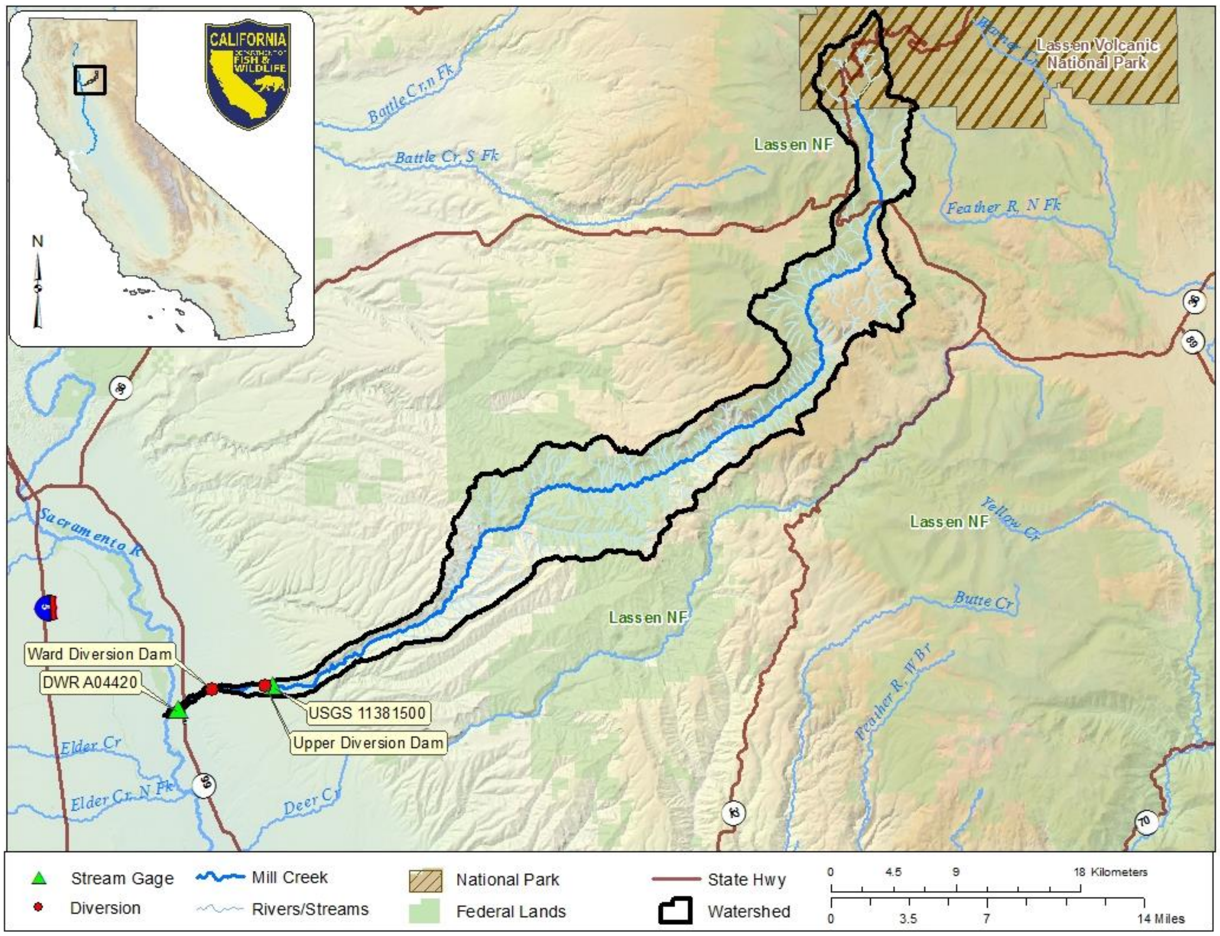

Figure 1. Mill Creek watershed map.

1.3 Mill Creek Hydrology and Water Supply

Mill Creek's hydrology is extremely variable as a result of the large influence that rainfall and snowmelt both have on the timing and amount of runoff in the watershed. Annual average precipitation is 60 inches in the upper watershed, decreasing to 20 inches in the lower watershed (SRWP 2010). Average daily flows, monthly mean flows, and average annual peak flows are all variable with the lowest flows and variability in September (Kondolf 2001). Kondolf (2001) analyzed the distribution of peak flows in Mill Creek from 1929-1997 and concluded that there is approximately a 90% chance that a flow event equal to 2,000 cfs or more will occur at least once a winter. Stream flows in Mill Creek usually peak during heavy, winter rains between December and February, and again as a result of spring snowmelt between April and May (USDA 1992; USFWS 2000). However, flows in April and May are highly variable due to their reliance on snowpack conditions. Most of the flow in Mill Creek is dominated by glaciated snow melt from Mount Lassen, sometimes giving it a milky appearance in spring and summer (SRWP 2010).

There are two major water diversion dams on Mill Creek: Upper Diversion Dam (RM 5.4) and Ward Diversion Dam (RM 2.8) both operated by Los Molinos Mutual Water Company (LMMWC). In 1920, the Tehama County superior court adjudicated rights to all flows below 203 cfs in Mill Creek, based on riparian and appropriated water rights at the time, with LMMWC appointed to serve as watermaster (USBR 2002; Superior Court of the State of California 1920, Court Decree Number 3811, August 16, 1920, Los Molinos Land Company and Coneland Water Company vs. Clarence V. Clough et al). The Upper and Ward diversions are authorized a maximum rate of 123 cfs and 60 cfs, respectively (USFWS 2000). The combined maximum diversion rate (183 cfs) from the two active diversion dams can exceed natural flows, especially during summer and early fall (USFWS 2000). A third diversion, Clough Diversion Dam (RM 4.75), historically diverted from Mill Creek. Clough Diversion Dam was damaged in a 1997 flood, and was removed in 2002 and replaced with an inverted siphon, which transfers diverted water from LMMWC's Main Canal on the north side of the stream through a pipe under Mill Creek to fill a canal on the south side of the stream (USBR 2002). Additionally, there is a siphon located downstream of Ward Diversion Dam which does not divert water directly from Mill Creek but moves water diverted at Ward Dam from the south side of Mill Creek to the north side, downstream of Ward Dam.

Two stream gages currently collect flow and water temperature data on Mill Creek. The downstream gage is operated by the Department of Water Resources (DWR), DWR A04420 (CDEC Station ID: MCH for Mill Creek below HWY 99), and is located below both major diversions at RM 0.8. The station is rated for low flow only; the highest rated flow for this gage is 462 cfs (D. Ables, DWR, pers. comm. 2015), and records above this rating are unreliable. The U.S. Geological Survey (USGS) operates the upstream gage, USGS 11381500 (CDEC Station ID: MLM for Mill Creek near Los Molinos), which is located above both of the major diversions at RM 5.8 (see Figure 1).

Certified flow and water temperature gage data were retrieved for use in this report from the USGS National Water Information System for USGS 11381500 (https://waterdata.usgs.gov/nwis), and from the DWR Water Data Library for DWR A04420 (http://www.water.ca.gov/waterdatalibrary/). Gaps in monitoring data represent instances where certified data were not available.

To assess hydrologic regimes of lower Mill 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 2013a). The likelihood is expressed as a percent of exceedance probability and 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 probability of the daily flows reported at USGS 11381500 (water years 1929-2015) are plotted in Figure 2. The monthly recurrence flows over a standard range of probability exceedance thresholds is given in Table 1.

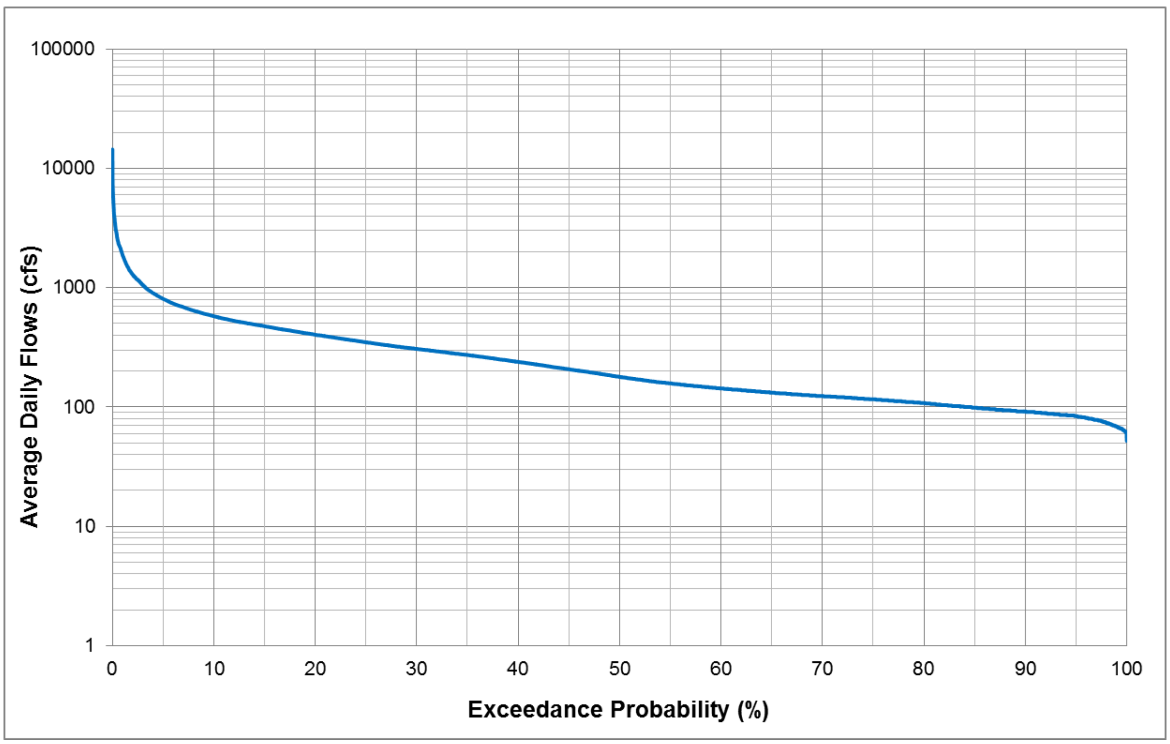

Figure 2. Percent exceedance of unimpaired Mill Creek flows based on average daily flows from USGS 11381500 for water years 1929-2015.

Table 1. Unimpaired monthly exceedance flows in lower Mill Creek from USGS 11381500 for water years 1929- 2015.

	Flow (cfs)											
Exceedance	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
90%	82	88	97	114	136	188	223	207	130	92	78	76
80%	88	97	114	134	162	224	261	261	170	105	88	85
70%	93	108	126	147	198	258	290	308	206	116	94	90
60%	99	118	139	175	237	291	321	354	245	129	100	95
50%	106	125	154	212	280	326	365	401	288	147	110	102
40%	115	136	188	274	328	370	412	455	330	166	119	110
30%	122	152	260	351	426	432	470	510	388	198	132	119
20%	128	181	394	518	589	532	542	577	463	246	146	126
10%	148	286	751	924	965	804	685	715	587	314	164	136

Water year types are used to describe interannual variability in watershed water supply. Since Mill 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 wet year, 2012 was a below normal year, and 2013 was a dry year.

The average daily flow is plotted in Figure 3 for the two gages, USGS 11381500 and DWR A04420, in water year 2015. USGS 11381500 is located above all diversions and represents unimpaired flow for Mill Creek. Flow levels between the upper and lower gage in the watershed are similar between mid-October and mid-March. Flows recorded at DWR A04420 were lower for the remainder of the year. The maximum difference between the gages is approximately 96 cfs in June. Plots for the four previous years, 2011 through 2014, are provided in Appendix A.

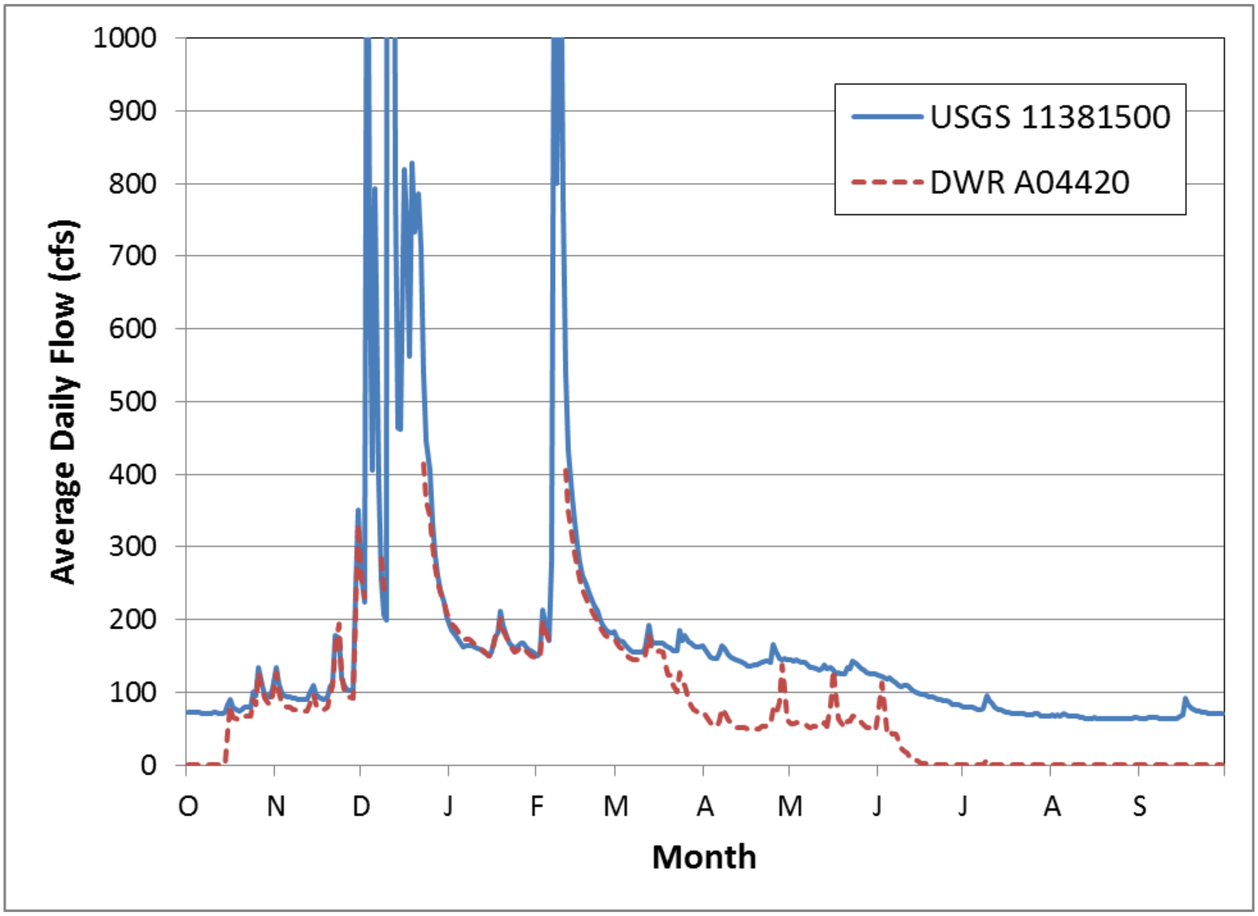

Figure 3. Average daily flow levels (cfs) at monitoring gages in Mill Creek for water year 2015 (months abbreviated).

1.4 Watershed Temperature Conditions

Water temperatures in the upper Mill Creek watershed remain cold year round. However, warm water temperatures exacerbated by stream diversions in lower Mill Creek potentially impede salmonid passage. The Harvey-Arrison (2009) report found in their monitoring of Mill Creek adult salmon passage in 2006 through 2008, that a potential thermal barrier to migration occurred when water temperatures reach between 65°F and 67°F, and that SRCS migration possibly ceased when minimum daily water temperatures were sustained above 67°F. Data from the impaired stream flow gage (DWR A04420) verify the annual occurrence of elevated temperatures in summer months. However, salmonids have been observed passing at temperatures in excess of 67°F in Mill Creek. Therefore, monitoring and modeling water temperature helps to evaluate the relationships between flow magnitude, water temperature, and climatic factors like ambient air temperature, wind speed, and solar heat gain; factors potentially affecting conditions for salmonids migrating through the valley floor. To understand the relationship between water temperature and fish passage, the report evaluated historical data from the two permanent monitoring gages and developed a predictive water temperature model.

Water Temperature

USGS has reported the minimum, maximum, and median water temperature for USGS 11381500 since October 1998. DWR has reported water temperature in 15-minute increments at DWR A04420 since October 1998. The median daily water temperature, reported at the upstream USGS gage and computed for the downstream DWR gage, were plotted for five recent water years, 2011 through 2015. The results from 2015, a critically dry year, are given in Figure 4. The previous four water years, 2011 through 2014, are presented in Appendix A. In 2015, the median daily water temperature began to diverge sometime in late March. The difference in degrees began to consistently be greater than one degree Fahrenheit (F) by March 19, 2015. At the peak of the summer on July 31, 2015 the difference in median water temperature peaks at 6.7°F. By comparison, in the wet year of 2011, the difference in median temperature did not consistently exceed one degree F until August 4. In 2011, the peak difference in median water temperature between the gages was 5.6°F on September 20, 2011.

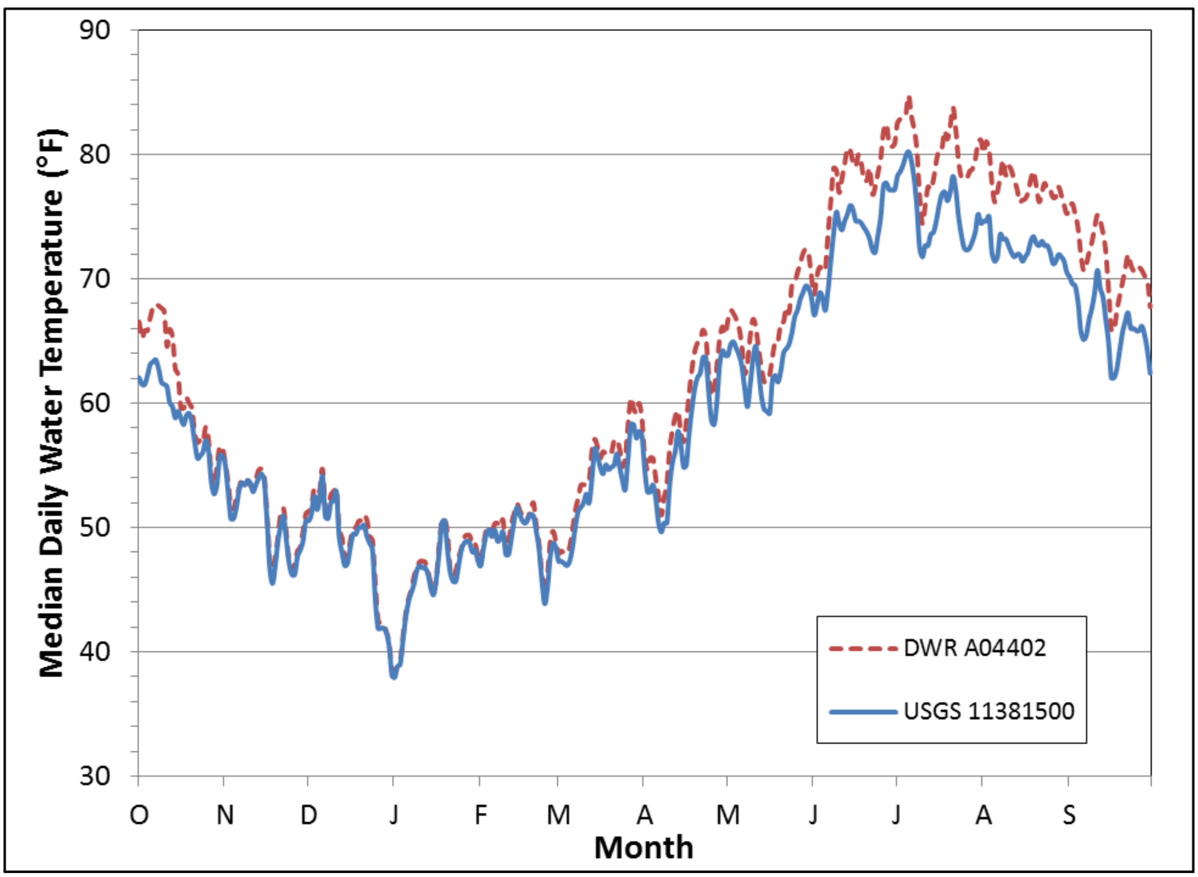

Figure 4. Median daily water temperature (°F) in Mill Creek for water year 2015 (months abbreviated).

Air Temperature

Ambient air temperature is an important parameter that may affect predicted water temperatures in the study reach. Ambient air temperature is estimated for the study area by averaging daily data from the Chico Municipal Airport (KCIC) and Red Bluff Municipal Airport (KRBL) 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 2015 is given in Figure 5. The four previous years, 2011 through 2014, are given in Appendix A.

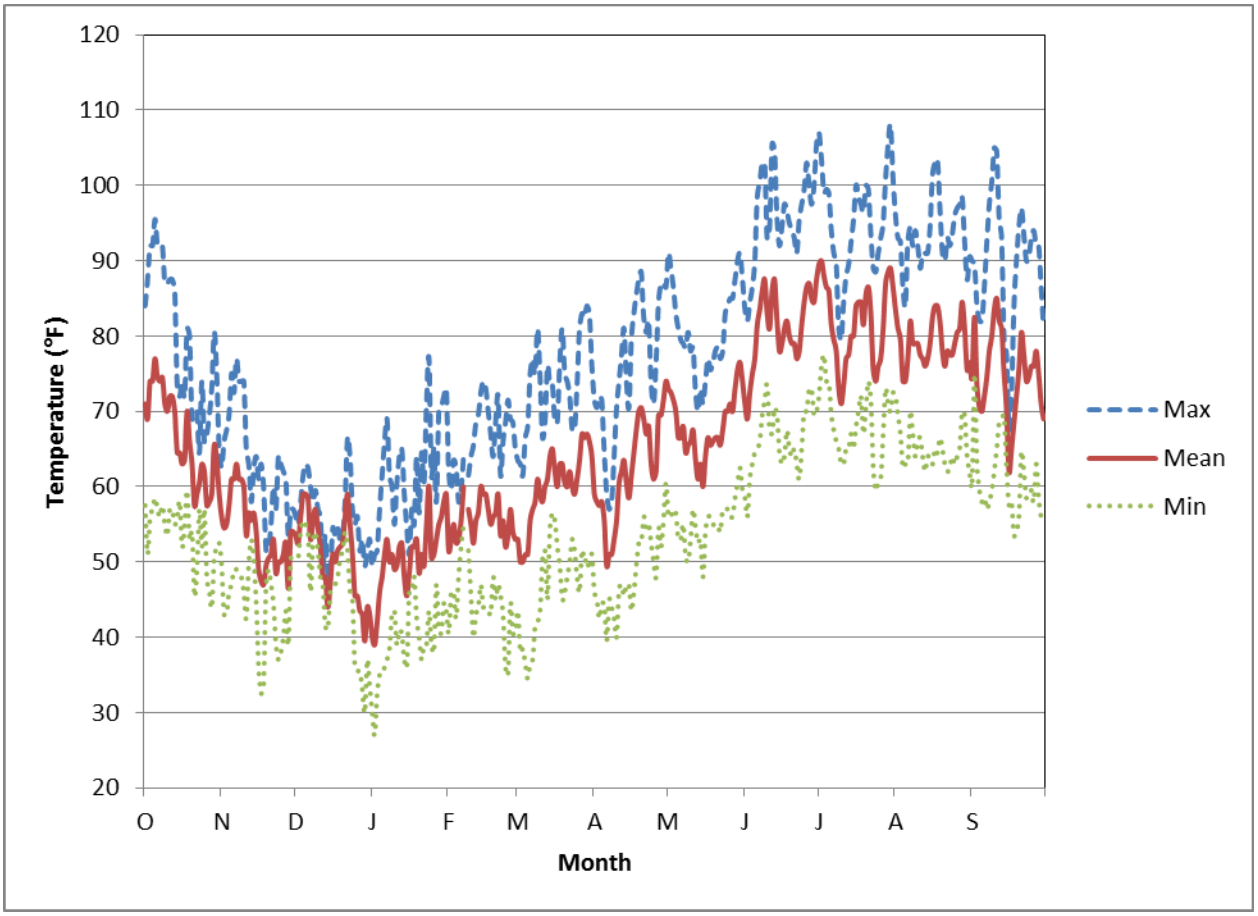

Figure 5. Estimated daily air temperature (°F) for the study area in 2015 water year (months abbreviated).

EPA Criteria

Water temperature criteria for salmonids were published by the U.S. Environmental Protection Agency (EPA) in 2003 for the Pacific Northwest (EPA 2003). Since that time, those criteria have been applied in California. The EPA criteria use the metric 7DADM or maximum seven day average of the daily maximum temperature. EPA established thresholds of 7DADM for various species and life stages of salmonids including passage 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 metric 7DADM should take into account the following: 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 an order of magnitude 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 SNTEMP model to predict maximum daily temperatures is limited.

1.5 Mill Creek Salmonids

Mill Creek SRCS spawning activity generally occurs between an elevation of 1,500 and 5,000 feet, making Mill Creek's spawning habitat among the highest in North America (Yoshiyama et al. 2001; USBR 2002). Some Mill Creek SRCS have been documented spawning at greater elevations, near the boundary of Lassen Volcanic National Park (Killam and Johnson 2013; Reynolds et al. 1993; Yoshiyama et al. 2001). However, recent years have seen few to no SRCS at these higher elevation habitats (M. Johnson, pers. comm. 2015). The Mill Creek SRCS spawning population averaged 882 fish from 1960 to 2003, with a low population estimate of 61 fish in 1993 and a high population estimate of 3,500 fish in 1975 (DWR 2005).

FRCS spawning population estimates dropped from 16,000 fish in 1950 to 150 fish in 1965. The FRCS population estimate in Mill Creek for 2012 was 893 fish (Killam and Johnson 2013). While the estimate increased to 2,488 fish in 2014 (Killam, Johnson and Revnak 2015), it dropped again to 1,033 in 2015 (Killam, Johnson and Revnak 2016). There was an egg taking station on lower Mill Creek between 1902 and 1945 that shipped FRCS eggs to other areas. This station closed in 1945 when the Coleman National Fish Hatchery opened on Battle Creek (Reynolds et al. 1993). Little information is available regarding historic and current populations of LFRCS populations in Mill Creek. However, recent video monitoring shows low but persistent returns of LFRCS to Mill Creek. Twelve LFRCS were counted in the 2013-14 water year, increasing to 31 fish during the 2014-15 water year (Killam, Johnson and Revnak 2015, 2016).

Spawning LFRCS adults have been occasionally observed in the lower reaches of Mill Creek (Reynolds et al. 1993).

Steelhead annual populations averaged 1,100 fish in both 1953 and 1965 population surveys; however, present numbers have since dropped dramatically, only reaching the low hundreds (Reynolds et al. 1993; USFWS 2000). During the 2010-2011 run, 118 steelhead were counted at the Mill Creek video monitoring station (Killam 2002). A total of 113 steelhead were counted for the 2011-2012 run (Killam and Johnson 2013), 122 steelhead counted for the 2012-2013 run (Killam, Johnson and Revnak 2014), 303 steelhead counted for the 2013-2014 run (Killam, Johnson and Revnak 2015), and a total of 100 fish were counted during the 2014-2015 steelhead run (Killam, Johnson, and Revnak 2016).

Migration Timing

The annual timing of when salmonid species life stages are expected to occur in Mill Creek is presented in Table 2. Migrating adult SRCS enter Mill Creek as sexually immature fish from late February through early-August[3], quickly migrate through the lower Mill Creek study reach, move into the deep pools of the upper watershed and hold over the summer, and finally spawning occurs between mid-August and early October (Moyle 2002). FRCS enter Mill Creek from late-September through December to spawn in the valley section of lower Mill Creek. LFRCS migrate into the Sacramento River from mid-October to mid-April (DWR 2005), and occasionally utilize Mill Creek, with peak migration in late-December and January (M. Johnson, pers. comm. 2016). Steelhead spawn in the upper Mill Creek watershed, typically entering the creek from late-September through June, with peak runs in the fall (October–November) and late winter/early spring (January–March).

[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.

Table 2. Adult migration and juvenile presence timing for salmonids in lower Mill 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[4,5,6]												
Juvenile SRCS[7,8]												
Fall-run Chinook Salmon												
Adult FRCS[4,5,6]												
Juvenile FRCS[7,8]												
Late Fall-run Chinook Salmon												
Adult LFRCS[4,5]												
Juvenile LFRCS[7,8]												
Steelhead												
Adult steelhead[4,5]												
Juvenile steelhead[7,8]												

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[4] 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.
[5] 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.
[6] 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.
[7] 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.
[8] 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 Ward Diversion Dam has recorded the upstream movement of SRCS since 2011 (Killam 2012; Killam and Johnson 2013; Killam, Johnson and Revnak 2014, 2015, 2016). This data was used to detect trends between passage, flow, and water temperature. All five years of fish passage data, expressed as cumulative percent, are summarized in Figure 6.

Daily fish counts at the video station were plotted for each year. Fish counts for 2014 and 2015 are provided in Figures 7 and 8, respectively; years 2011 through 2013 are given in Appendix A. In the two critically dry years 2014 and 2015, the estimated number of adults that passed the station was 679 and 127 fish, respectively (Killam, Johnson and Revnak 2015, 2016). Overall passage dates were similar for the two critically dry years, with fish passing Ward Diversion Dam from February 28 to June 20 in 2014, and from March 6 to June 6 in 2015. By April 25 each year, 45 and 50 percent of the fish had passed Ward Diversion Dam in 2014 and 2015, respectively.

Included in Figures 7 and 8 are the average daily flows recorded at the upstream USGS gage and downstream DWR 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 the DWR gage. The longer segmented, orange line refers to the 64°F 7DADM and the dotted orange line refers to the 68°F 7DADM.

Several trends for 2014-2015 stood out: 1) the approximate difference in the flows between the upstream and downstream gage at the end of the SRCS passage season was roughly 100 cfs; 2) less than half of the fish passed prior to the 68°F 7DADM thresholds each year; 3) the pulse flow events coordinated by the Department in each year can be seen by the peaks in DWR gage flows below the steady USGS gage flows; and 4) fish movement upstream was evident in response to the pulse flow events.

The same monitoring data results were plotted for 2011 through 2013 (Appendix A). Coordinated pulse flows did not occur in water years 2011 (wet), 2012 (below normal), or 2013 (dry). In 2011, a smaller number of fish moved into the system than in all the other years except 2015, and all but a few passed through before either 7DADM threshold was exceeded. However, video counts in 2011, a wet year, were less precise than in other years. It is suspected that as a result of the high flows, many fish swam undetected over the dam apron (M. Johnson, pers. comm. 2016). Most fish were through lower Mill Creek before the upper 7DADM threshold was met in 2012. A greater number of fish moved through the study reach after both 7DADM thresholds were exceeded in 2013 than in 2012.

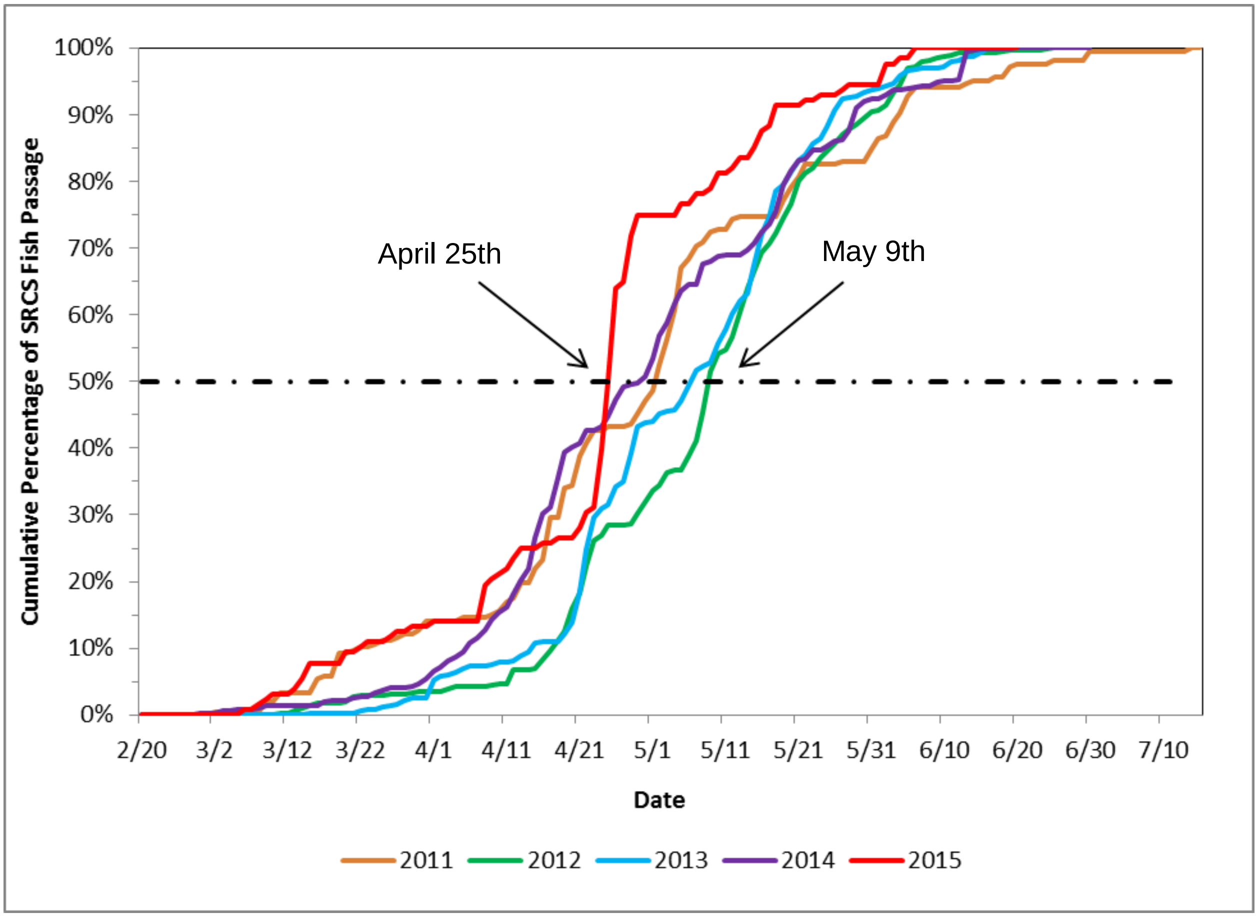

Figure 6. Cumulative adult SRCS passage from the Mill Creek video station, 2011-2015.

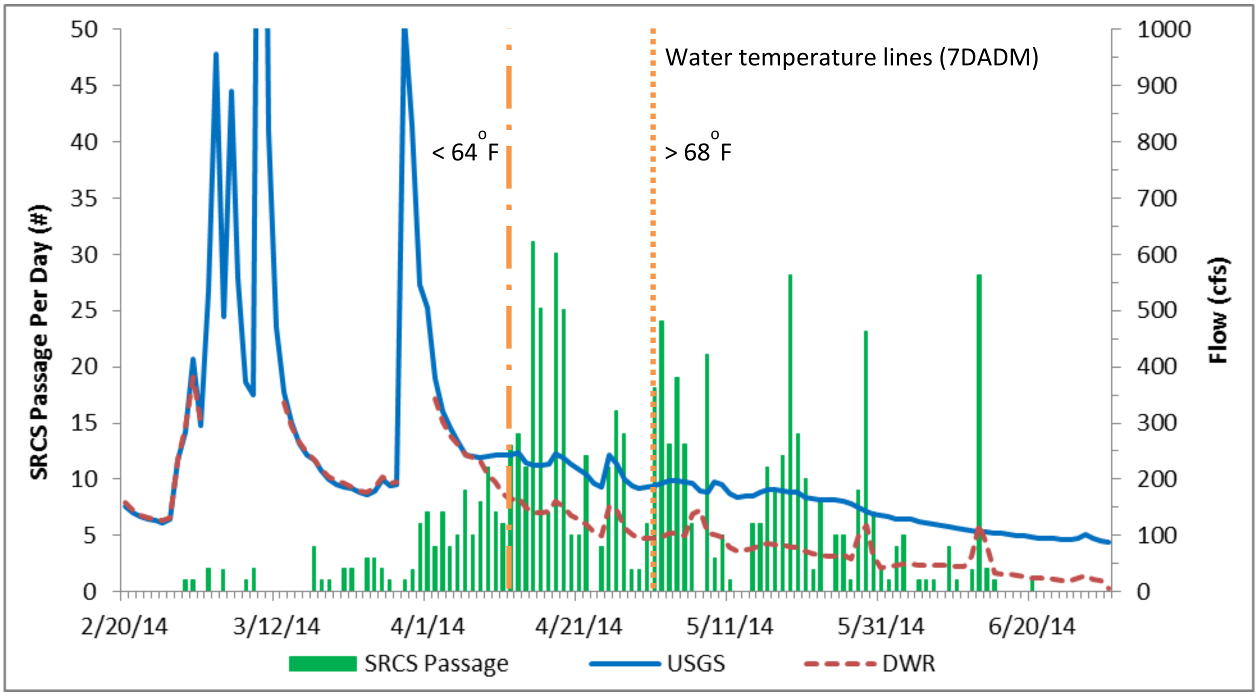

Figure 7. Video station data, average daily flows, and EPA criteria for 2014.

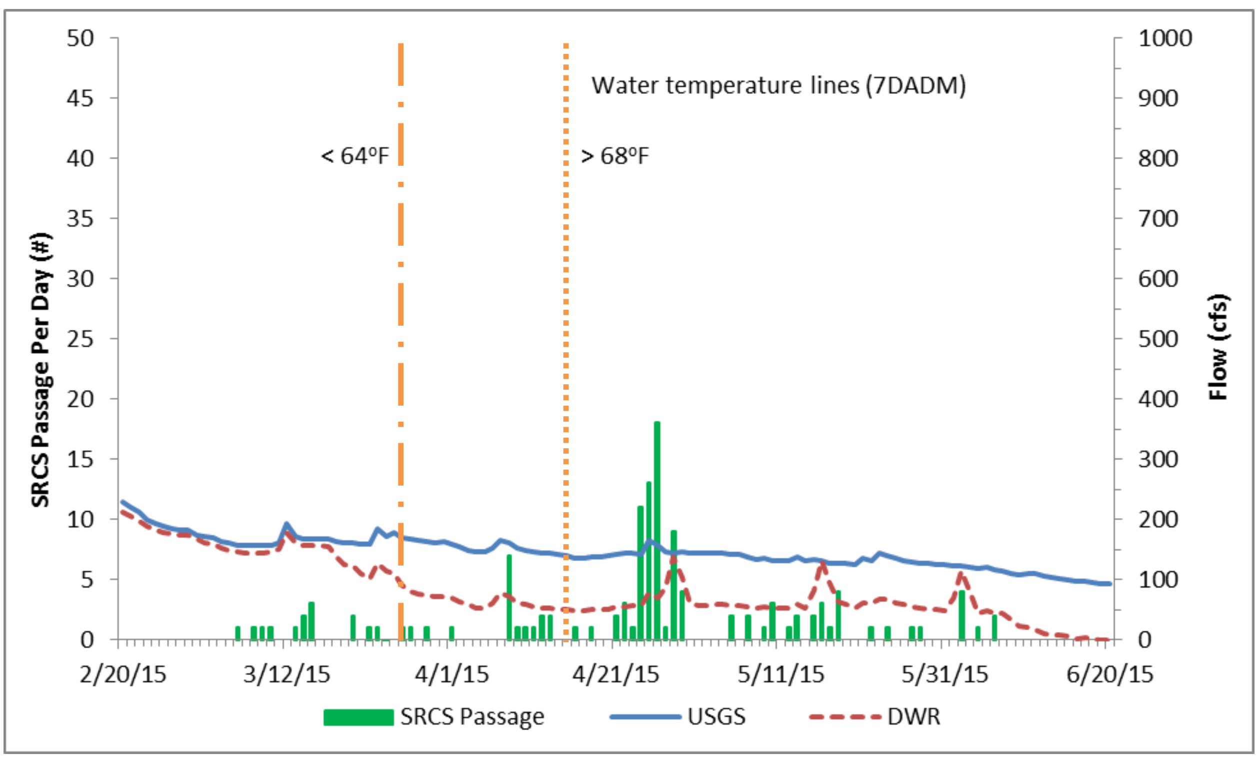

Figure 8. Video station data, average daily flows, and EPA criteria for 2015.

The ability to draw conclusions on SRCS passage from the video monitoring data is limited. Although five years of video data are available, two of these are critically dry years. The effects of water temperature on fish passage are difficult to assess, given that 53 percent of the SRCS had already passed before the 7DADM had exceeded 68°F in 2014, and only 26 percent passed by that time in 2015. The video passage data does suggest that flows supporting upstream passage are needed from late February through at least June, with peak migration occurring in April and May. However, higher flows and lower water temperatures in the later months (i.e. through July) could allow for broader run timing and life history expression.

2.0 METHODS

Selection of appropriate methods for an instream flow assessment is a fundamental step of the Instream Flow Incremental Methodology (IFIM) process (Bovee et al. 1998). While the most commonly applied components of the IFIM process are the hydrology and the biology components (Dunbar et al. 1998), aquatic habitat connectivity is an equally important, and often overlooked element (Fullerton et al. 2010). Aquatic habitat connectivity and unimpeded passage over critical riffles and diversion structures is especially essential for adult SRCS to reach cool-water summer holding pools. For lower Mill Creek, methods were chosen to assess connectivity based on the physical passage of salmonids through shallow critical riffles, and temporal passage conditions by evaluating temperature regimes.

Several critical riffles were identified as potential passage impediments (see section 3.0 Site Selection) and were evaluated to understand the relationship between flow and upstream salmonid migration. Critical Riffle Analysis (CRA) involves selecting the shallowest course from bank to bank across a critical riffle site, and measuring water depth along that course over a wide range of flows to create empirical relationships of the percent total and contiguous width available to migrating fish. In addition to the assessment of standard critical riffles (i.e., depth sensitive riffles with less than 4% gradient and substrate dominated by gravel and cobble), a long transverse riffle located at RM 0.7 identified in Harvey-Arrison (2009) as site CR #4, has historically been observed to impede passage of salmonids. The site, referred to here as Critical Riffle #2 (CR2; Figure 9), is hydraulically complex and required the application of the predictive 2D model River2D.

Figure 9. Critical riffle CR2 at 41 cfs. View facing upstream.

The Department has employed 2D modeling in the past to evaluate hydraulic regimes at potential passage barriers. Holmes et al. (2015) compared fish passage flows derived from River2D modeling with flows derived from the empirical CRA method (Thompson 1972). A high coefficient of determination (r^2=0.93) was found for flows predicted using 2D modeling with flows derived from the CRA method. Cowan and Gard (2016) also evaluated passage conditions for SRCS on Butte Creek at two critical riffles and a braided bedrock- dominated area. The CRA method was used to assess passage in other critical riffles in lower Mill Creek because it directly analyzes the relationship between stream flows, water depth, and water velocity at critical riffle locations (CDFG 2012).

In addition to assessing salmonid passage over critical riffles, the Wetted Perimeter method was conducted at appropriate sites to evaluate if a summer low flow, necessary to maintain critical habitat conditions for ecological function and benthic macroinvertebrate production, could be determined (CDFW 2013b). The Wetted Perimeter method uses a graphical 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 determined by the breakpoint, the threshold below which aquatic habitat conditions for benthic invertebrates rapidly declines (CDFW 2013b), 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. There is a concern that 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 et al. 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 River2D Model

Rivers and streams represent particularly difficult environments to establish predictive computational models because of varying velocity zones, changing slopes, and zones of relatively shallow depth within a habitat unit like an alluvial riffle. Single, straight transect based models like PHABSIM have limited application when the study design seeks to evaluate fish passage by estimating depth and velocity along the shallowest course of a critical riffle. PHABSIM requires the change in height of the water surface elevation (WSEL) across the transect be within 0.1 feet. The water surface profile of the shallowest course across a critical riffle is not straight and the change in height is highly variable.

River2D is a two-dimensional depth averaged finite element hydrodynamic model that is well suited for fish habitat analyses. The flow in defined stream segments like critical riffles can be simulated over a range of flows using 2D depth averaging models like River2D. A 2D hydraulic model simulates depths that vary both longitudinally (upstream and downstream) and laterally (from left bank to right bank). As such, it is a good choice for evaluating depth in a complex hydraulic site, since it can explicitly model how depths vary both longitudinally and laterally.

River2D inputs include the flow at the upstream end of the model reach, bed topography, substrate and cover information, and the WSEL at the downstream end of the site. The data for 2D modeling can be collected with a stratified sampling scheme, with higher intensity sampling in areas with more complex or more quickly varying microhabitat features, and lower intensity sampling in areas with uniformly varying bed topography and uniform substrate and cover. Bed topography and substrate/cover mapping data can be collected at a very low flow, with the only data needed at high flow being WSELs at the upstream and downstream ends of the site, and flow and edge velocities for validation[9] purposes. Substrate and cover are used by River2D, in addition to the bed topography, in calculating bed roughness height.

[9] Validation refers to the comparison of predicted velocities with those measured in the field at matching locations and flow stage.

2.2 Critical Riffle Analysis

Critical Riffle Analysis (CRA) is an empirical method used to determine optimal flow rates 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 Thompson procedure (1972) was developed by the Oregon Department of Fish and Wildlife (ODFW) 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 to be 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. Water depth and velocity data are collected along a given transect at selected flow levels (Figure 10). After data has been collected over a minimum of three flow events containing at least one measurement of adequate depth, and across a range of representative flows, the stream discharge rates and correlating feet of transect meeting the depth and velocity criteria are plotted to determine the flows necessary for salmonid passage.

Figure 10. Critical riffle analysis transect along the shallowest course from bank to bank at a riffle in lower Mill Creek. Stream is flowing from left to right.

In accordance with the Department CRA SOP (CDFG 2012), 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 conditions specified by two evaluation parameters: the percentage of the maximum wetted transect length meeting the life stage-specific depth criteria and the contiguous percentage of the maximum wetted transect length meeting the life stage-specific depth criteria (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.

2.3 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 accurately derive a Manning's n value representative of the low flow period, data collection targeted a flow no greater than the 80 percent exceedance flow, 108 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 11; Annear et al 2004; CDFW 2013b).

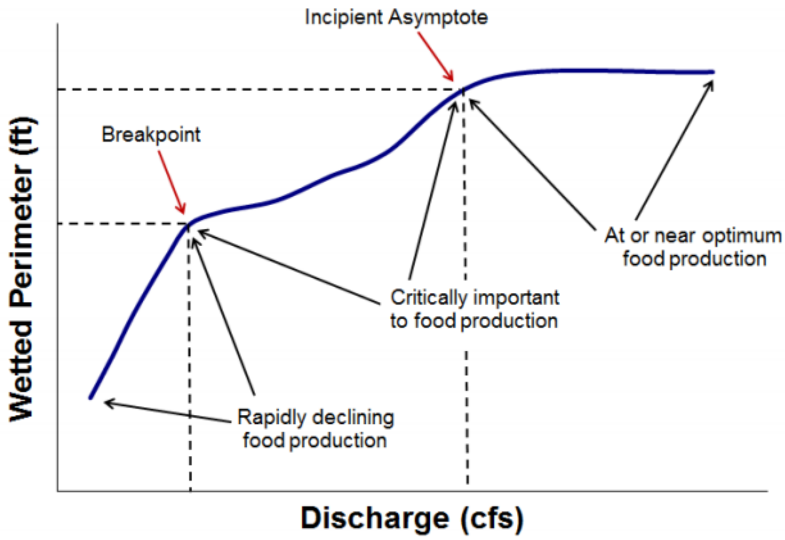

Figure 11. An example of a wetted perimeter-discharge curve (CDFW 2013b).

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 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 (Annear et al. 2004; Gippel and Stewardson 1998). To decrease bias, the flow providing at least 50% 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.

2.4 Temperature Models

There are three main types of water temperature models as follows: 1) segment, 2) network, and 3) higher order models. Stream segment temperature models (SSTEMP) predict the change in average daily temperature between two points. Stream network temperature models (SNTEMP) allow for multiple segments to be joined together forming nodes that define sub-reaches. Water temperature is predicted at each node within the SNTEMP network. Higher order models represent a substantial increase in the complexity over SSTEMP/SNTEMP and can simulate water temperatures on hourly time steps. John Bartholow (2000) of USGS explained the solver in SNTEMP is meant to predict mean daily temperatures. 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.

A SNTEMP water temperature model was prepared to predict the difference in average daily water temperature between unimpaired and impaired flows within the study reach. Mill Creek was divided into three sub-reaches based on the locations of the major diversions: Upper Diversion Dam and Ward Diversion Dam. 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.

SNTEMP is a model type similar to how PHABSIM is a model type used to predict flow habitat relationships for fish. Each one of these model types can be run on different commercially available software programs. The Department uses the software program StreamTemp to run SNTEMP simulations. The SNTEMP model used to estimate water temperature changes within the Mill Creek study reach will be referred to as StreamTemp. StreamTemp executes four submodels: (1) heat transport model, (2) heat flux model, (3) solar model, and (4) shade model, when solving the water temperature change within each sub-reach. 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

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

temperatures were simulated for the same water years to help identify possible trends in 7DADM temperatures with in the study reach.

A second predictive water temperature model was applied to Mill Creek. The Water Temperature Transaction Tool (W3T) is a spreadsheet developed by Watercourse Engineering, Inc. (2013). As a result the model can be run without any special software. W3T may be an option for real time water operations management as it relates water temperature. Concerned water users in the watershed asked the Department to consider the model. 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.

3.0 SITE SELECTION

Sites were selected for each method (i.e., River 2D, 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 any 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 River2D Site Selection

Site CR2 is a long, hydraulically complex transverse riffle that required the application of the predictive model River2D. A 2D model was used at this site in favor of collecting empirical data points at distinct flows for two main reasons: 1) 2D modeling is a more rigorous way to develop the depth, width, and flow relationships where resolution is needed in small increments of flow on the scale of 10 cfs; and 2) CR2 is a broad, wide riffle with a gradient significantly less than 4% and with relatively undefined banks. This characteristic makes it a less than ideal location for CRA because not only is the shallowest course across the site challenging to consistently and accurately identify, but it is extremely difficult to collect empirical data points at a wide enough range of flows to properly characterize the site. Since CR2 is considered the most limiting riffle, based on it consistently measuring the shallowest thalweg depth and previously being identified as a passage impediment to salmonids (Harvey-Arrison 2009), it was imperative that it be assessed in the most robust way possible.

3.2 Critical Riffle Survey and Site Selection

The study reach, defined as lower Mill Creek, extends from the Sacramento River confluence (RM 0.0) upstream to the Upper Diversion Dam (RM 5.4; Figure 12). Reconnaissance surveys were conducted in 2012 and 2013. Throughout the study reach, riffles were identified, numbered, and photographed, and location was recorded. 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). Three depth-sensitive riffles were identified for sampling based on the survey data and historical documentation. All three riffle sites were located in the lower half of the reach below the known diversion points, downstream of the Ward Diversion Dam.

Once field data collection began in 2014, the selected sites were reviewed by field staff to confirm winter flows had not altered the riffle bed structure nor changed the ranking of the depth sensitive riffles. CR2 was still found to be the most critical riffle based on its shallow thalweg depth and historical obstruction to salmonid passage, but was determined to be more appropriate for 2D modeling (see Section 2.1). CR4 was identified by Department Region 1 staff as the second most limiting location to adult salmonid passage. CR6 was selected as a limiting location because it was characteristic of other shallow riffles present in lower Mill Creek. Over the course of field data collection and as flow levels receded, CR6 maintained deep thalweg depths. When compared to the other two critical riffle sites, the critical riffle pathway (shallowest course from bank to bank) was much shorter than those at CR2 and CR4. Depth by percentage was not limited at CR6 at the same flow levels as CR4, and as a result, CR6 was excluded from further data analysis and is excluded from this report.

The study reach was surveyed again in 2015, and two additional critical riffles were identified for study to increase the sample size. Both depth sensitive riffles were selected based on the survey data, and were located downstream of the Ward Diversion Dam.

The selected riffles are described below.

- CR2 was a wide, broad crested transverse riffle approximately 0.7 miles upstream of the mouth, and 2.1 miles downstream of the Ward Diversion Dam (Figure 13). This was the longest critical riffle, having a maximum wetted width of 319 ft.
- CR3 was a transverse riffle approximately 1.4 miles upstream of the mouth, and 1.4 miles downstream of the Ward Diversion Dam (Figure 14). This riffle had a maximum wetted width of 133 ft.
- CR4 was a broad U-shaped riffle that empties into a set of steep steps which converge into a run downstream. It is located approximately 1.8 mile upstream of the mouth, and 1.0 mile downstream of the Ward Diversion Dam (Figure 15). This riffle had a maximum wetted width of 204 ft.
- CR7 was a broad transverse riffle approximately 2.4 miles upstream of the mouth, and 0.4 miles downstream of the Ward Diversion Dam (Figure 16). This riffle had a maximum wetted width of 210.5 ft.

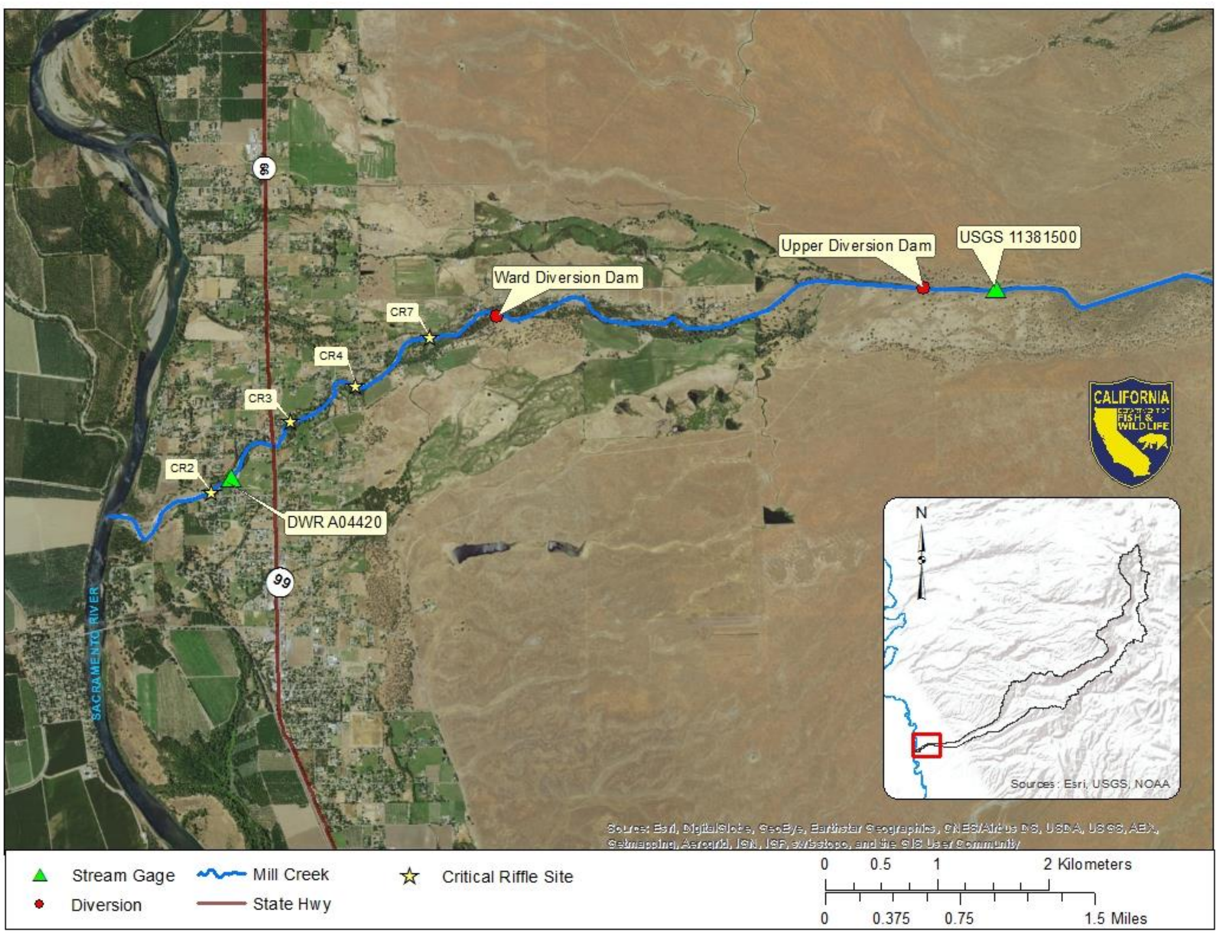

Figure 12. Map of selected critical riffle sites on lower Mill Creek.

Figure 13. CR2 at approximately 64 cfs, looking upstream.

Figure 14. CR3 at approximately 76 cfs, looking downstream.

Figure 15. CR4 at approximately 132 cfs, looking downstream.

Figure 16. CR7 at approximately 158 cfs, looking upstream.

3.3 Wetted Perimeter Site Selection

Sites were selected in lower Mill Creek for Wetted Perimeter analysis between the Sacramento River confluence (RM 0.0) and Ward Diversion Dam (RM 2.8). 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 2013b). Four representative riffles were identified and selected for analysis (Figure 17).

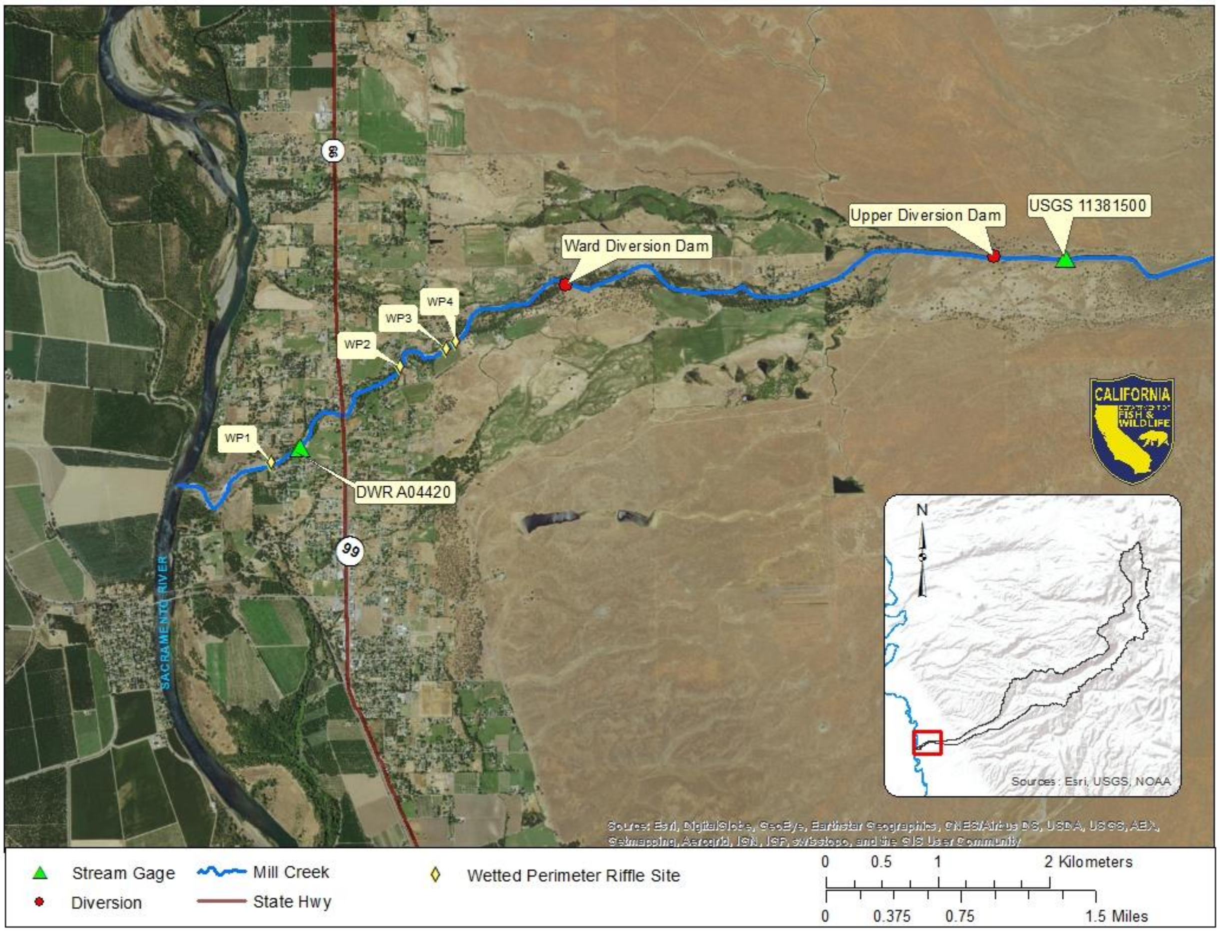

Figure 17. Wetted perimeter riffle site locations on lower Mill Creek.

3.4 Mesohabitat Mapping and Temperature Model Site Selection

For the StreamTemp model, three stream reaches were established based on the locations of stream water diversions and returns, stream hydrology, and gradient (Table 4; Figure 18). W3T was run on the same reaches of Mill Creek as the StreamTemp model. Reach 1 extends upstream from the confluence of Mill Creek with the Sacramento River to the Ward Diversion Dam. Reach 2 extends upstream from Ward Diversion Dam to the Upper Diversion Dam return flow outlet and fish screen. Reach 3 extends upstream from the return flow outlet to the Upper Diversion Dam. Stream gage USGS 11381500 is located approximately 0.5 miles upstream of the Upper Diversion Dam and upstream of any influence of Upper Diversion Dam; Mill Creek is assumed to be unimpaired above the Upper Diversion Dam. Ward Dam backwaters a 475 foot reach, while Upper Dam backwaters a 750 foot reach. While the energy slopes in the backwater reaches are significantly flatter than in the rest of the study area, they are too short to be considered as separate reaches. In addition, the backwater reach of Upper Dam is upstream of the upstream end of the Mill Creek water temperature model.

Table 4. Lower Mill Creek temperature model study reaches from Sacramento River confluence upstream to Upper Diversion Dam.

Reach #	Begin	End
1	Sacramento River confluence	Ward Diversion Dam
2	Ward Diversion Dam	Return flow outlet
3	Return flow outlet	Upper Diversion Dam

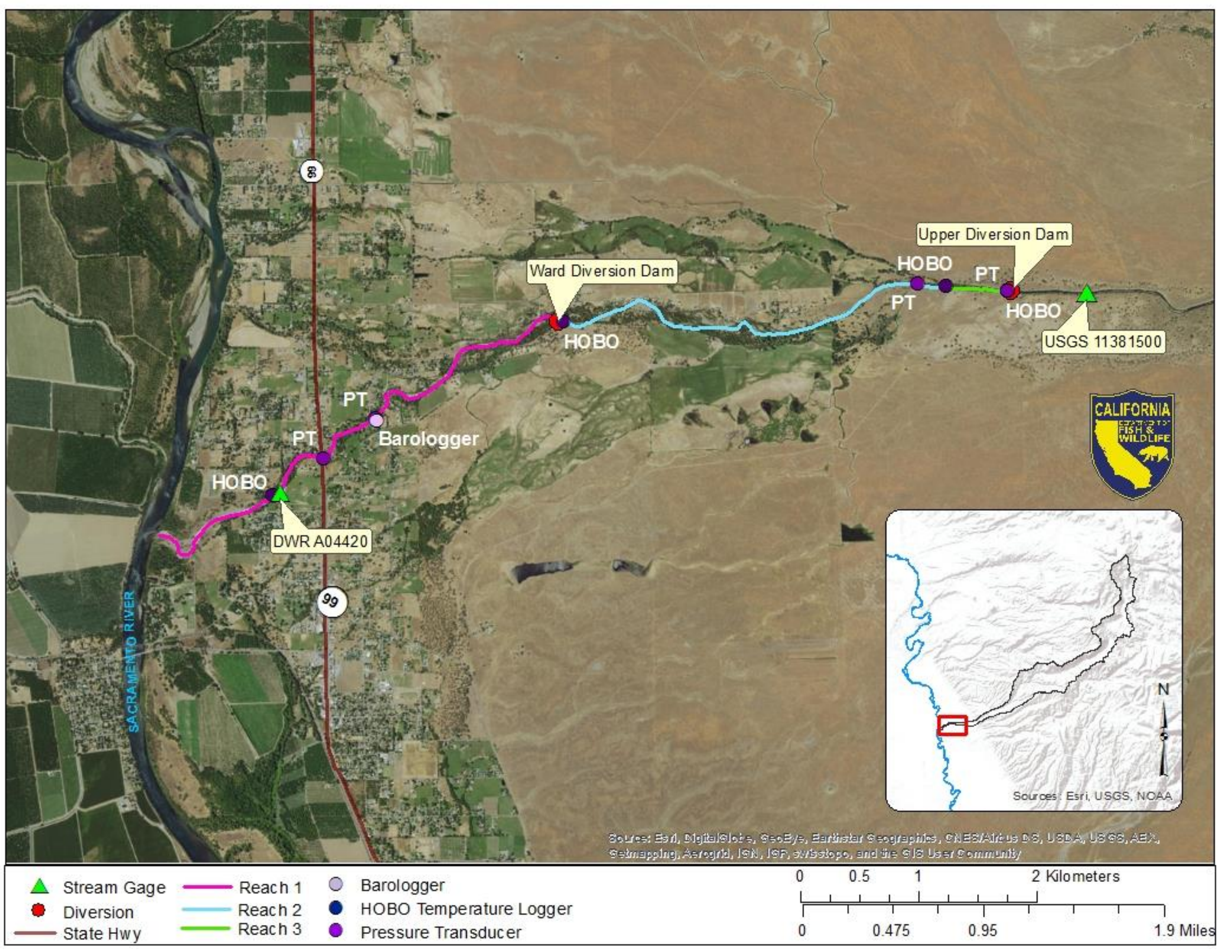

Figure 18. Temperature model study reaches on lower Mill Creek.

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 three reaches was conducted during March 24-25, 2014 by floating downstream in inflatable kayaks and catarafts, 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 percent mesohabitat composition of each reach. An example of the mesohabitat type composition for Reach 3 is shown in Figure 19. 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.

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.

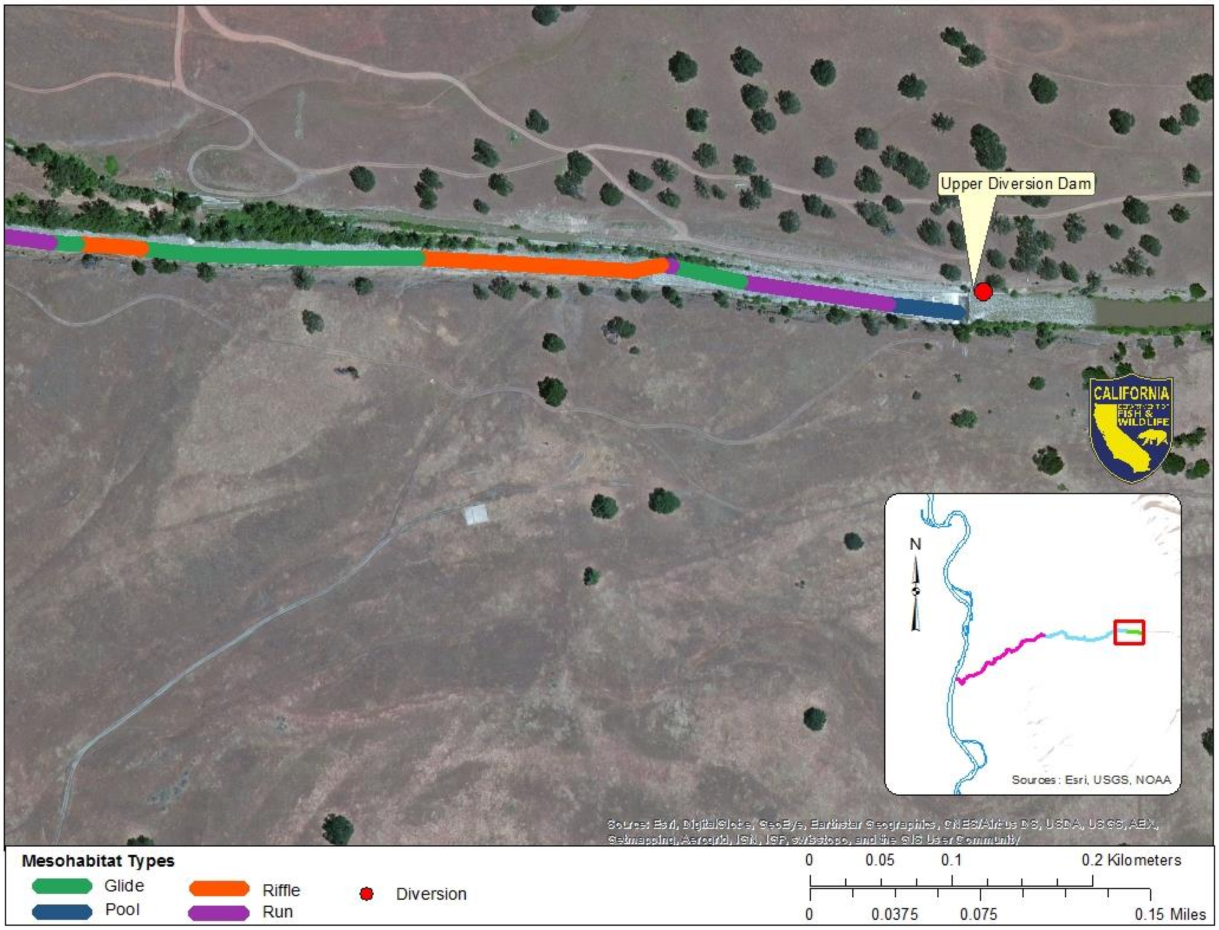

Figure 19. Mesohabitat type composition of Reach 3.

Results of mesohabitat mapping were used to randomly select locations for four transects in Reach 1, eight transects in Reach 2, and four transects in Reach 3. Stratified random sampling in each reach, based on the mesohabitat mapping, was used to help reduce any bias in site selection and to ensure that sites selected adequately characterized the habitats within each Reach. For Reach 1, 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 15-16, 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 mesohabitat characterization of the reaches 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 type was selected to roughly correspond to the mesohabitat characterization of each reach.

Table 6. Mesohabitat composition by percentage.

Habitat Type	Glide	Pool	Riffle	Run
Reach 1	19.4%	7.7%	29.0%	44.0%
Reach 2	14.3%	13.4%	32.1%	40.2%
Reach 3	41.0%	8.4%	31.9%	18.8%

Table 7. Number of transects of each mesohabitat type.

Habitat Type	Glide	Pool	Riffle	Run
Reach 1*	1	1	1	1
Reach 2	1	1	3	3
Reach 3	1	1	1	1

*In addition to the transects in this table, there were three transects located in a riffle and two runs, and two critical riffle discharge measurement transects located in a glide and a run, that were used to develop flow-width and flow-depth relationships for Reach 1.

4.0 DATA COLLECTION

Data collection on the Mill 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 River2D Data Collection

River2D is a 2D computer software model that takes topographic survey data and transforms the points first into a triangular irregular network (TIN) and then into a computational mesh (Mesh). The Mesh is overlain over the TIN and used to solve for a simultaneous mass and energy balance of all mesh elements over a range of flows. The USFWS provide guidance on the performance tolerances required to achieve successful simulations in River2D (USFWS 2011). The topographic survey data and WSEL versus discharge data must be collected with a high level of precision and accuracy to meet the USFWS River2D model simulation performance standards. The measures used to achieve the USFWS standards are described in the following sections and in Appendix B.

River2D inputs include the bed topography, bed roughness height, and WSEL at the downstream end of the site. The relationship between WSEL and discharge must be established at the flow input and output ends of the 2D model site. Transects are established at the upstream and downstream ends of the 2D model site and positioned where the flow is perpendicular to the transect line, relatively undisturbed, and the WSEL is expected to be uniform across the transect over the range of flow levels sampled. Discharge is measured at a minimum of three well-spaced flow levels. During the discharge measuring events the WSEL is recorded at the upstream and downstream transects. The data collected from these measuring events are used to generate a hydraulic rating curve that can be used to predict stage and discharge over a range of flows. A detailed description of the development of the hydraulic rating curves used for the River2D model is provided in Appendix B.

Site Boundaries and Survey Controls

The CR2 River2D study site was established in March 2015. Study site boundaries were placed upstream and downstream of the passage assessment area. The downstream and upstream transects were located to optimize the performance of predictive stage-discharge models where the channel section properties were as close to the following as possible:

- Single-thread channel section, with one primary thalweg;
- Uniform cross-channel WSEL; and
- Velocity perpendicular to the line of the transect.

Straight cross-section transects were placed at the upstream and downstream ends of the study site, and the downstream transect was modeled to provide WSELs as an input to the River2D model. The cross-section transects provide boundary conditions, the basis for calibration, and part of the topography for the River2D model. The upstream transect was used in calibrating the 2D model; bed roughness values are adjusted in the River2D model until the WSEL predicted from the stage-discharge model matched the measured WSEL at the upstream end of the site. Transect pins (headpins and tailpins) were marked on each river bank above the 400 cfs water surface level using rebar driven into the ground and/or lag bolts placed in tree trunks. 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 at the site to serve as the relative vertical elevations to which all elevations (streambed and water surface) were referenced. Horizontal benchmarks, which consisted of rebar driven into the ground, were also established at the site to serve as the horizontal locations to which all horizontal locations (northings and eastings) were referenced. The precise northing and easting coordinates and vertical elevations of two horizontal benchmarks were established for the site using survey- grade Real Time Kinematic (RTK) GPS. The elevations of these benchmarks were tied into the vertical benchmarks on our site using standard surveying techniques (differential leveling).

Stage-Discharge Hydraulic Data Collection at the River2D Site

Hydraulic data for the River2D model were collected in March through July 2015. Flows for calibrating the River2D models were measured onsite. WSELs at the site were collected at five sample events in 2015. Discharge measurements for the site were measured onsite (Table 8). Depth and velocity measurements along the hydraulic control transects were collected at 128 cfs.

Table 8. Sample dates and corresponding flows when water surface elevations were measured for calibration of Mill Creek River2D model.

Date	Flow (cfs)
3/3/15	157.6
4/1/15	64.3
4/28/15	128.0
5/26/15	56.5
7/9/15	1.1

The data collected on the upstream and downstream transect included: WSELs measured to the nearest 0.01 foot (0.003 m) at a minimum of three significantly different stream discharges using differential leveling; wetted streambed elevations determined by subtracting the measured depth from the surveyed WSEL at a measured flow; dry bed elevations to points above bankfull discharge surveyed to the nearest 0.1 foot (0.031 m); mean water column velocities measured at a mid to high-range flow at the points where bed elevations were taken; and substrate and cover classification (Tables 9 and 10) at these same locations and also where dry bed elevations were surveyed. WSELs were measured along both banks and in the middle of each transect. The WSELs at each transect were 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. Starting at the water's edge, water depths, and velocities were measured at set intervals using a wading rod and Marsh-McBirney Model 2000 Flo-Mate (Model 2000) velocity meter. The stations for the dry ground elevation measurements were measured using a fiberglass measuring tape. All substrate and cover data on the transects were assessed by one observer and were made based on the visually-estimated average of multiple grains.

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 20). 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.

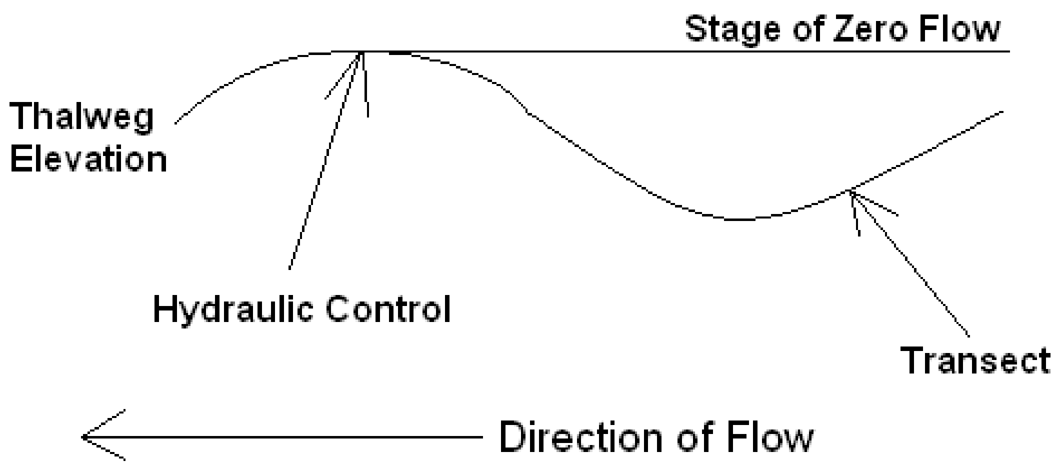

Figure 20. Stage of zero flow diagram.

Table 9. Substrate codes, descriptors, and particle sizes used for Mill Creek River2D model.

Code	Type	Particle Size (inches)
0.1	Sand/Silt	< 0.1
1	Small Gravel	0.1 – 1
1.2	Medium Gravel	1 – 2
1.3	Medium/Large Gravel	1 – 3
2.3	Large Gravel	2 – 3
2.4	Gravel/Cobble	2 – 4
3.4	Small Cobble	3 – 4
3.5	Small Cobble	3 – 5
4.6	Medium Cobble	4 – 6
6.8	Large Cobble	6 – 8
8	Large Cobble	8 – 10
9	Boulder/Bedrock	> 12
10	Large Cobble	10 – 12

Table 10. Cover coding system used for the Mill Creek River2D model.

Cover Category	Cover Code
No cover	0
Cobble	1
Boulder	2
Fine woody vegetation (< 1" diameter)	3
Fine woody vegetation + overhead	3.7
Branches	4
Branches + overhead	4.7
Log (> 1' diameter)	5
Log + overhead	5.7
Overhead cover (> 2' above substrate)	7
Undercut bank	8
Aquatic vegetation	9
Aquatic vegetation + overhead	9.7
Rip-rap	10

Terrain Model Data Collection

Topographic data collection for the River2D site began in March 2015 and was completed in July 2015. RTK GPS and a total station were used to record bed elevation, and horizontal location (i.e., northing and easting, relative to horizontal benchmarks). Substrate and cover codes were assigned to each terrain model point surveyed with the RTK GPS and total station. Sufficient points were collected to characterize the bed topography, substrate, and cover of the site.

Bed topography data were collected between the upstream and downstream transects by obtaining the bed elevation and horizontal location of individual points with a total station or survey-grade RTK GPS, while the cover and substrate were assessed using the same technique used for the transects. The highest densities of bed topography data points were collected within the riffle channels with additional emphasis near the riffle crest. The shallowest course from bank to bank was surveyed with the RTK GPS. The shallowest course from bank to bank can be difficult to identify at flows in the higher end of the sampling range because CR2 was very wide and shallow. To ensure the shallowest course was captured, six possible shallowest courses were surveyed in with the RTK GPS. The model results were later used to identify the most critical course across site CR2 (Figure 21).

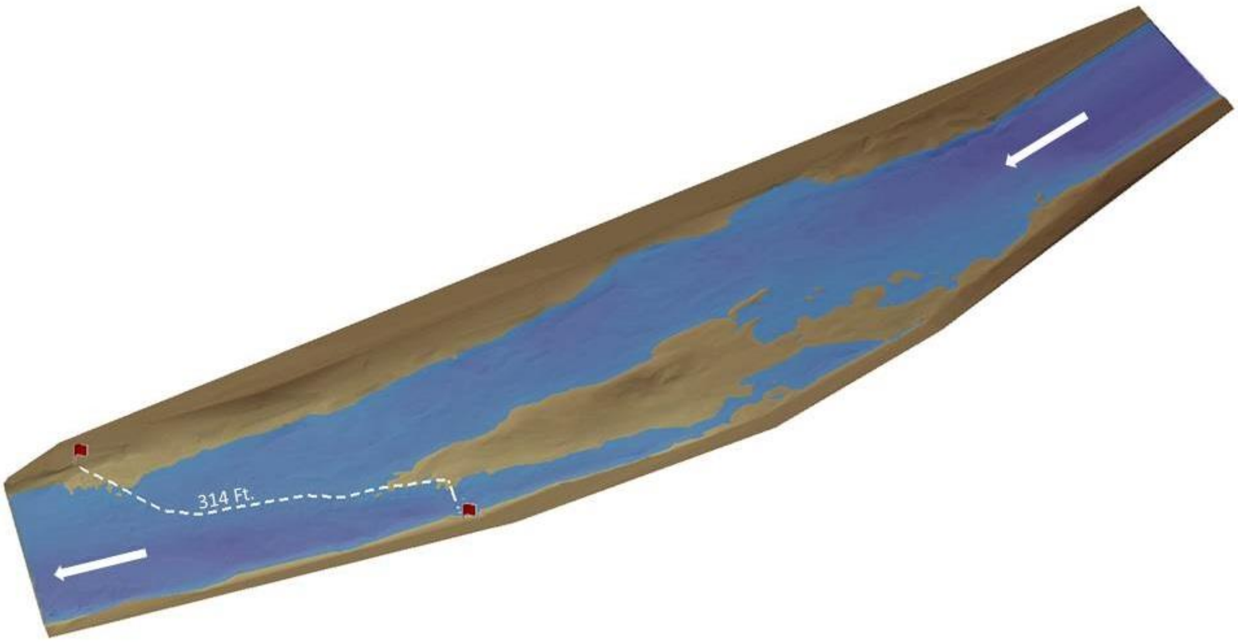

Figure 21. Shallowest course across CR2 displayed in the digital terrain model.

To validate the depths predicted by the River2D model, depth measurements were collected using a wading rod equipped with a Model 2000 velocity meter. The horizontal locations and bed elevations were recorded by taking a measurement with the survey-grade RTK GPS at each point where depth was measured. A minimum of 50 representative points were measured. Validation depths were collected at flows of 1.1, 64.3, 128 and 157.6 cfs.

The number and density of data points collected on each of the two transects and between transects for the River2D model study are presented in Table 11. The overall density of data points collected for the model is presented as well.

Table 11. Number and density of data points collected for the River2D model study site.

Number of Points		**Density of Points (points/m^2)**
Points on Transects	**Points Between Transects**	
70	4,904	0.52

4.2 Critical Riffle Data Collection

CRA data collection was completed consistent with the Department CRA SOP (CDFG 2012). Sampling at CR4 took place from March to June 2014 on the receding limb of the hydrograph. Sampling at CR3 and CR7 was extended from March 2015 to December 2015 as a result of drought conditions which caused low flows and limited opportunities to collect additional relevant measurements during the spring and summer field season. The timing of sampling events was intended to capture the range of discharges needed to adequately bracket and identify passage flows for adult Chinook salmon and steelhead (CDFG 2012). Measurements were taken at six to seven distinct flows, between the 40th and 100th percentile exceedance range (221-40 cfs). A precipitation event provided the opportunity to survey CR4 at the highest sampled flow on April 8, 2014. Sample dates and corresponding flows are summarized in Table 12. Drought conditions precluded sampling of exceedance level flows lower than the ~40th percentile (i.e., greater than 221 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 12. Sample dates and associated flows for critical riffle surveys.

Site	Date	Flow (cfs)
CR3	12/15/15	149.4
	3/17/15	128.4
	5/16/15	113.6
	6/2/15	103.3
	11/3/15	80.7
	4/9/15	64.3
CR4	4/8/14	220.5
	3/26/14	186.1
	5/7/14	126.1
	4/28/14	108.1
	5/13/14	78.6
	5/27/14	52.9
	6/10/14	40.2
CR7	12/15/15	152.6
	3/18/15	124.8
	5/16/15	115.2
	6/2/15	112.8
	11/3/15	85.5
	4/9/15	67.2

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 22 to 25). 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 a handheld GPS.

Water depths were measured along each passage transect to the nearest 0.01 ft with a stadia rod at regular intervals (two foot intervals at CR3 and CR4; three foot intervals at CR7). 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 2013c) at sites adjacent to the riffles.

Figure 22. Transect along CR3 at high flow (149.4 cfs, 12/15/15, top photo) and low flow (64.3 cfs, 4/9/14, bottom photo). View facing upstream.

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.

Figure 23. Transect along CR4 at high flow (220.5 cfs, 4/8/14, top photo) and low flow (40.2 cfs, 6/10/14, bottom photo). View facing downstream.

Transect depth profiles were reviewed for inconsistencies after data collection. The CR3 passage transect sampled on 3/17/15 at 128.4 cfs was found to be taken along a pathway with a substantially different depth profile when compared with the other shallowest courses selected for CR3. The depth profile of the CR7 transect sampled on 6/2/15 at 112.8 cfs was also markedly inconsistent with the other pathways at CR7. These transects were omitted from further CRA analysis.

Figure 24. Transect along CR7 at high flow (152.6 cfs, 12/15/15, top photo) and low flow (67.2 cfs, 4/9/15, bottom photo). Stream flowing from right to left.

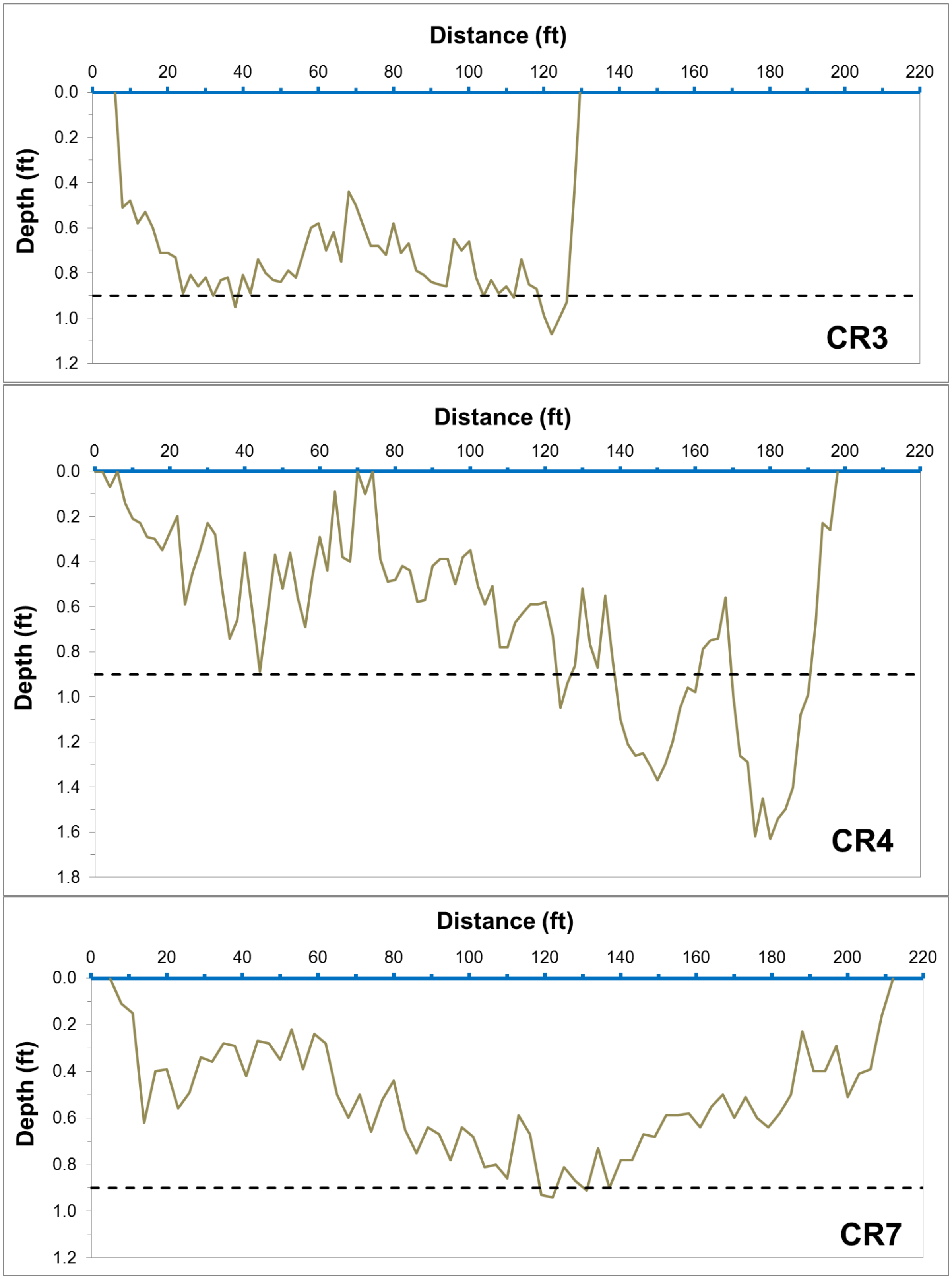

Figure 25. Depth profiles for CR3 (top), CR4 (middle), and CR7 (bottom), surveyed at 149.4 cfs, 220.5 cfs, and 152.6 cfs, respectively. Dotted line indicates 0.9 ft depth.

Velocity was recorded at all sites except for the first sampling event on 3/26/14 at CR4. Velocities within the surveyed areas sampled on this date were assumed to have been below the maximum criteria for adult steelhead and Chinook salmon. The maximum velocity criteria were not exceeded during the second sampling event when flows were higher, 220.5 cfs on 4/8/14, as compared to the flows during the first sampling event, 186.1 cfs. 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.

4.3 Wetted Perimeter Data Collection

Wetted Perimeter transects were established on each riffle site between May 27, 2014 and June 10, 2014 at flows ranging between 41 and 56 cfs (Table 13). Linear transects were installed from the top of each riffle 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 2013d). WSELs were also measured near the left bank, middle channel, and right bank to correlate measured flow to the profile. A stream discharge was collected near each transect using a Model 2000 velocity meter in accordance with the Department’s SOP for Discharge Measurements in Wadeable Streams (CDFW 2013c).

As a surrogate for the energy slope in Manning’s equation, WSELs were measured on July 8, 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 2013c).

Table 13. Wetted perimeter flow parameters.

Riffle Site	Date	Flow (cfs)	Riffle Slope (ft/ft)	Manning's n
WP1	6/9/2014	41	0.007293	0.0739
WP2	6/10/2014	42	0.013052	0.1273
WP3	5/27/2014	56	0.006313	0.0874
WP4	6/10/2014	42	0.017899	0.0732

4.4 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 2013d).

Transect locations were selected though mesohabitat mapping (Figure 26; see Section 3.4). Transect pins and vertical benchmarks were established using the same methods used for the River2D model data collection (see Section 4.1).

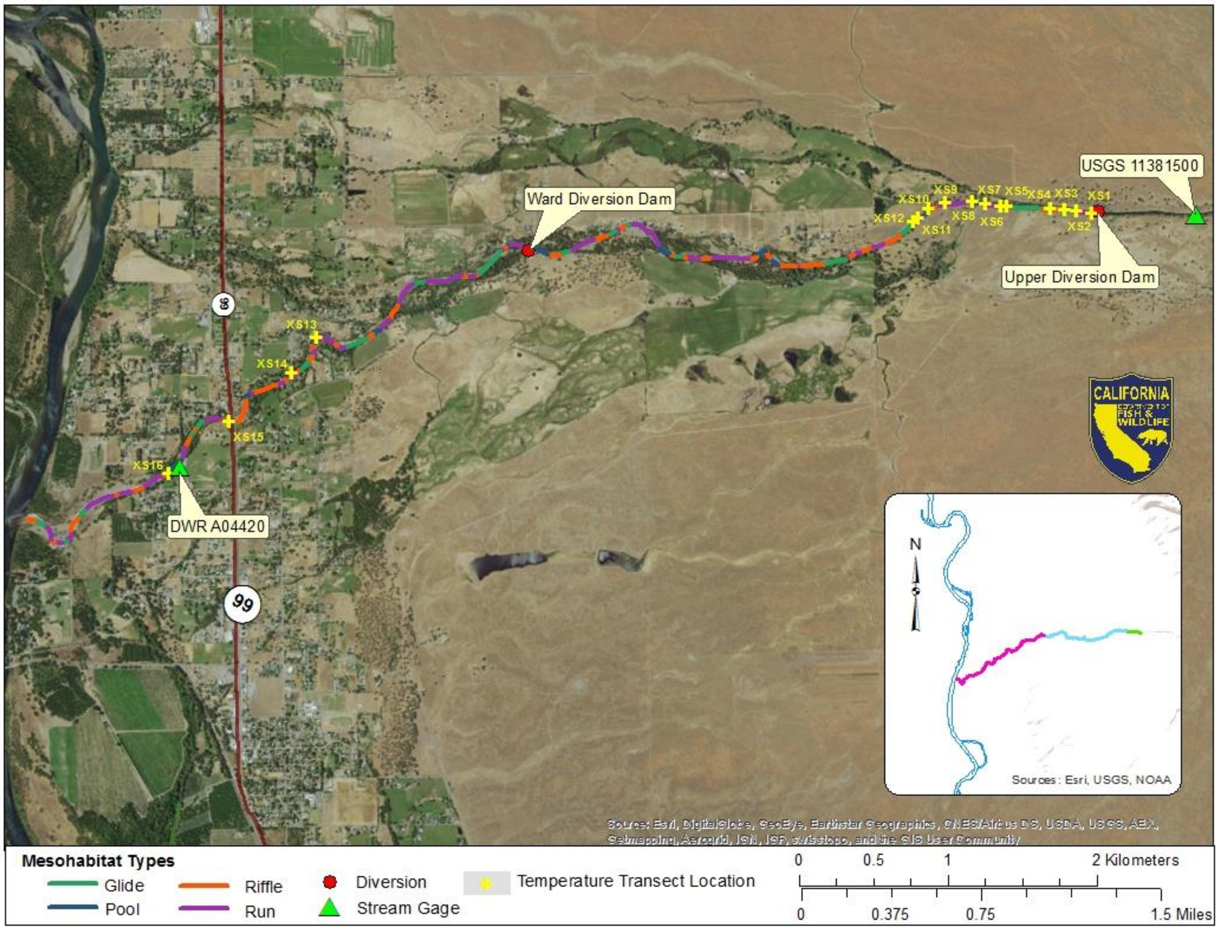

Figure 26. Temperature transects selected through mesohabitat mapping.

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 WSELs and measurements of both wetted and dry streambed elevations using the same methods used for 2D model data collection (see Section 4.1). WSELs at the transects were collected at low, medium, and high flow sample events (Table 14). Discharge measurements for the transects were measured in each reach (Table 14; Appendix B), so that stage-discharge relationships could be developed.

Table 14. 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	152.4	4/16/14	93.0	5/14/14	43.0, 23.8	6/10/14 6/24/14
2	150.9, 166.7	4/15/14	93.5, 101.0	5/13/14	57.6, 66.3	6/9/14
3	141.0	4/16/14	82.8	5/14/14	8.0	6/24/14

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 both the left and right banks, with the staff operating the clinometer standing mid-channel. Measurements were made every 500 feet going downstream through the entire length of all three 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 three 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% of the stream and the average density of that coverage is 50%, the total vegetative density is .25 times .50, which equals 0.125, or 12.5%.

Solinst Model 3001 Levelogger Edge pressure transducers were installed in all three reaches between March 27 and April 15, 2014. For redundancy, two pressure transducers were installed in Reach 1, one near Highway 99 and one near CR4. Because the pressure transducers measure absolute pressure, a Solinst Barologger Edge was also installed on high ground next to Mill Creek to compensate for the atmospheric pressure (see Figure 18). 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 fence T-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 values, 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 one logger installed at the upstream end of Reach 3, between March 26 and April 16, 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 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 10, 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 at the USGS gage on Mill Creek, with the data used to develop regression equations to correct weather data from internet sources to account for local conditions. Data were 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 C. Data collected for transect stage-discharge calibration are presented in Appendix D.

5.0 RESULTS

The results for the four different instream flow assessment methods are presented below. The results of the River2D model and 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 then presented, followed by the StreamTemp model used to predict average daily water temperatures for impaired and unimpaired flow conditions in Mill Creek. The results of maximum daily water temperature simulations are provided in Appendix C.

5.1 Passage Assessment River2D Results

The River2D model was used to estimate the amount of wetted width and depth in CR2 along the shallowest course from bank to bank. Results were generated over the range of flows sampled in the field. The River2D model was used to compute the total and maximum contiguous width at each flow simulated. The width versus flow results for CR2 are summarized in Table 15 and 16 for adult Chinook salmon and steelhead, respectively. The tables are abbreviated, including only the highest flow level where no passage width meeting the depth criteria was detected. The complete results are presented in tabular format in Appendix B (Tables B-9 and B-10). The bottom of the table includes the highest simulated flow level where contiguous width was estimated to still be equal to zero. Flows simulated below this level are not reported here. Simulations were generally run at 10 cfs intervals under 200 cfs, and 20 cfs intervals over 200 cfs. The results are plotted as wetted width on the y-axis and discharge on the x-axis in Figures 27 and 28 for Chinook salmon and steelhead, respectively.

Table 15. Abbreviated CR2 River2D model results for adult Chinook salmon.

Adult spring-run Chinook salmon (minimum depth criteria = 0.9 ft)				
Maximum Wetted Width = 319 ft				
Flow (cfs)	Total Width (ft)	Percent Total Width	Contiguous Width (ft)	Percent Contiguous Width
390	160	50.2%	112	35.1%
380	152	47.6%	104	32.6%
360	148	46.4%	102	32.0%
340	142	44.5%	100	31.3%
320	138	43.3%	99	31.0%
300	126	39.5%	94	29.5%
280	116	36.4%	60	18.8%
260	94	29.5%	48	15.0%
240	70	21.9%	48	15.0%
220	52	16.3%	36	11.3%
200	38	11.9%	20	6.3%
190	28	8.8%	18	5.6%
180	24	7.5%	18	5.6%
170	14	4.4%	6	1.9%
160	12	3.8%	6	1.9%
150	7	2.2%	4	1.3%
140	2	0.6%	2	0.6%
130	0	0.0%	0	0.0%

Table 16. Abbreviated CR2 River2D model results for adult steelhead.

Adult steelhead (minimum depth criteria = 0.7 ft)				
Maximum Wetted Width = 319 ft				
Flow (cfs)	**Total Width (ft)**	**Percent Total Width**	**Contiguous Width (ft)**	**Percent Contiguous Width**
390	178	55.8%	148	46.4%
380	168	52.7%	142	44.5%
360	162	50.8%	112	35.1%
340	160	50.2%	112	35.1%
320	158	49.5%	112	35.1%
300	152	47.6%	104	32.6%
280	148	46.4%	102	32.0%
260	138	43.3%	100	31.3%
240	136	42.6%	98	30.7%
220	126	39.5%	94	29.5%
200	96	30.1%	48	15.0%
190	80	25.1%	48	15.0%
180	70	21.9%	48	15.0%
170	60	18.8%	42	13.2%
160	48	15.0%	36	11.3%
150	40	12.5%	20	6.3%
140	30	9.4%	18	5.6%
130	22	6.9%	16	5.0%
120	14	4.4%	6	1.9%
110	11	3.4%	4	1.3%
100	7	2.2%	4	1.3%
90	2	0.6%	1	0.3%
70	0	0.0%	0	0.0%

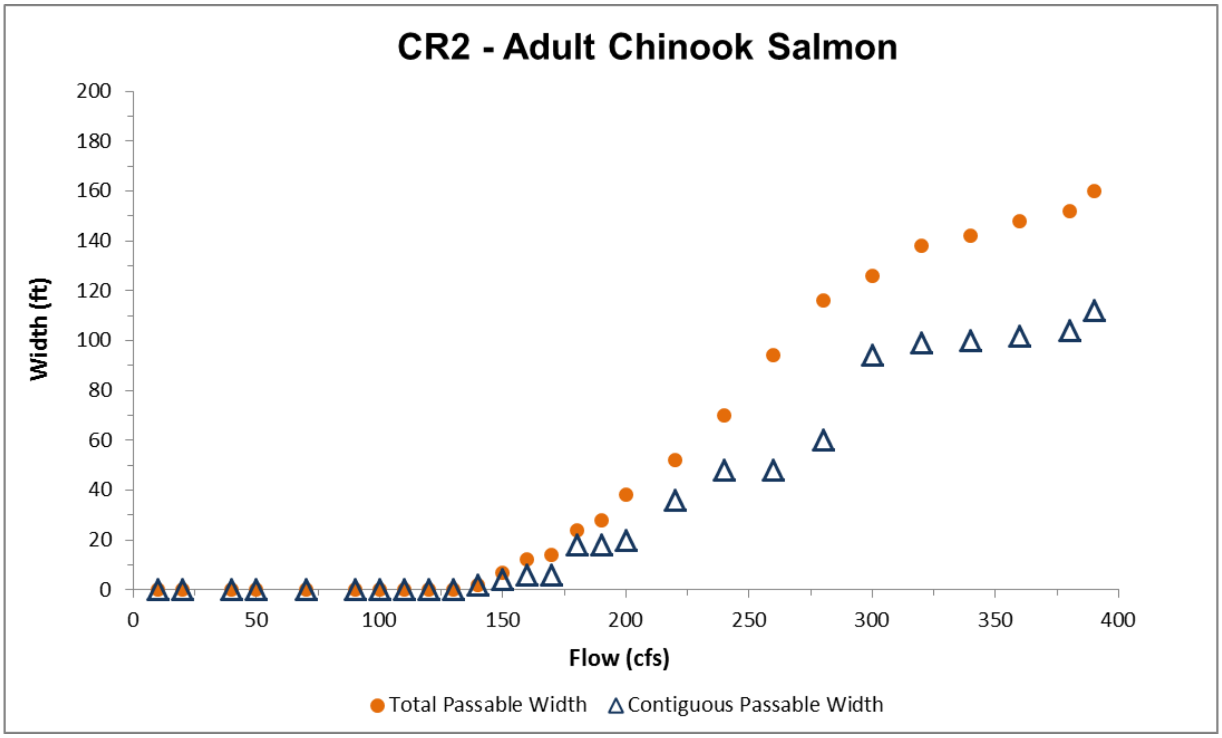

Figure 27. CRA River2D predicted results for adult Chinook salmon at CR2.

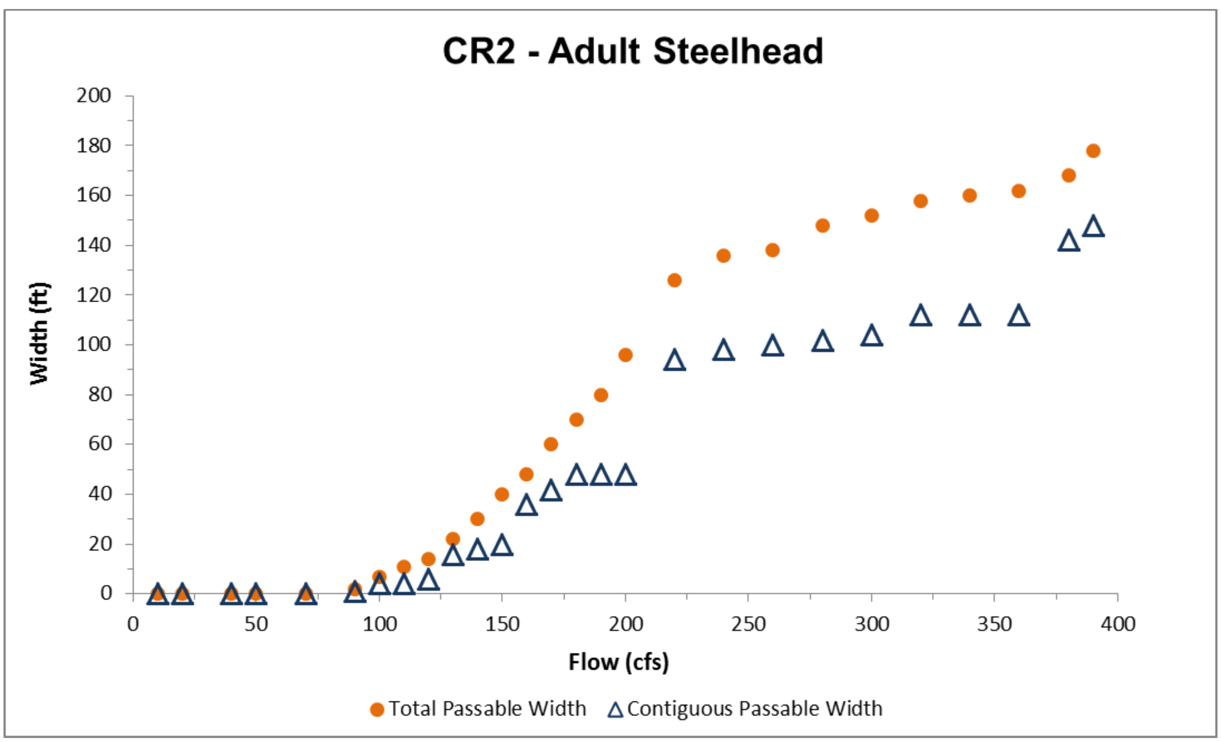

Figure 28. CRA River2D predicted results for adult steelhead at CR2.

5.2 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 (CDFG 2012). Even though 2014 and 2015 were critically dry years, staff were able to sample sites at enough distinct flows to meet the field sampling requirements. However, at CR3, only four of the five events sampled resulted in depth profiles where at least one point along the shallowest course met the minimum depth criteria for adult Chinook salmon. At CR7, only four of the five events sampled were collected at flows high enough to evaluate conditions for adult steelhead, and only three of the five flows sampled contained passable depths for adult Chinook salmon. Points collected at flow levels where the minimum depth criteria were not met could not be used to generate the best-fit regression. The CRA data are summarized in Table 17.

Best-fit regressions of flow versus width were developed for CR3, CR4, and CR7 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 E.

Table 17. Field data, with total and contiguous wetted widths as a function of flow, where adult steelhead and adult Chinook salmon depth criteria are met for CR3, CR4, and CR7.

			Adult Steelhead (0.7 ft criteria)				Adult Chinook Salmon (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 (%)
CR3	12/15/15	149.4	86	64.7%	40	30.1%	16	12.0%	8	6.0%
	5/16/15	113.6	74	55.6%	18	13.5%	14	10.5%	10	7.5%
	6/2/15	103.3	54	40.6%	26	19.5%	6	4.5%	2	1.5%
	11/3/15	80.7	26	19.5%	8	6.0%	1	0.8%	1	0.8%
	4/9/15	64.3	6	4.5%	6	4.5%	0	0.0%	0	0.0%
CR4	4/8/14	220.5	72	36.4%	30	15.2%	48	24.2%	22	11.1%
	3/26/14	186.1	82	41.4%	44	22.2%	54	27.3%	28	14.1%
	5/7/14	126.1	50	25.3%	22	11.1%	24	12.1%	14	7.1%
	4/28/14	108.1	58	29.3%	24	12.1%	28	14.1%	12	6.1%
	5/13/14	78.6	34	17.2%	18	9.1%	26	13.1%	18	9.1%
	5/27/14	52.9	12	6.1%	6	3.0%	6	3.0%	4	2.0%
	6/10/14	40.2	14	7.1%	12	6.1%	10	5.1%	6	3.0%
CR7	12/15/15	152.6	42	20.0%	27	12.8%	12	5.7%	6	2.9%
	3/18/15	124.8	54	25.7%	27	12.8%	3	1.4%	3	1.4%
	5/16/15	115.2	33	15.7%	30	14.3%	6	2.9%	3	1.4%
	11/3/15	85.5	15	7.1%	15	7.1%	0	0.0%	0	0.0%
	4/9/15	67.2	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 18 to 23). The tables are abbreviated to include only the flow levels which increase the amount of width meeting the depth criteria. The bottom of each table begins with 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 E (Tables E-1 to E-6).

Table 18. Abbreviated CR3 rating curve results for adult Chinook salmon. Total width versus flow (top), and contiguous width versus flow (bottom).

Adult Chinook Salmon (minimum depth criteria = 0.9 ft)					
Maximum Wetted Width = 133 ft					
Flow (cfs)	Total Width (ft)	Percent Total Width	Flow (cfs)	Total Width (ft)	Percent Total Width
345	110	83%	190	58	44%
340	104	78%	185	52	39%
330	102	77%	180	44	33%
315	98	74%	175	38	29%
295	96	72%	170	34	26%
285	94	71%	165	30	23%
280	92	69%	160	24	18%
270	90	68%	150	22	17%
260	86	65%	145	16	12%
250	82	62%	135	10	8%
245	74	56%	125	8	6%
240	72	54%	110	6	5%
230	70	53%	105	4	3%
225	66	50%	85	2	2%
205	64	48%	80	0	0%
195	60	45%	-	-	-
Flow (cfs)	Contiguous Width (ft)	Percent Contiguous Width	Flow (cfs)	Contiguous Width (ft)	Percent Contiguous Width
345	56	42%	160	10	8%
295	46	35%	135	8	6%
250	40	30%	110	6	5%
235	34	26%	105	4	3%
230	32	24%	85	2	2%
190	20	15%	80	0	0%
170	12	9%	-	-	-

Table 19. Abbreviated CR4 rating curve results for adult Chinook salmon. Total width versus flow (top), and contiguous width versus flow (bottom).

Adult Chinook Salmon (minimum depth criteria = 0.9 ft)					
Maximum Wetted Width = 204 ft					
Flow (cfs)	**Total Width (ft)**	**Percent Total Width**	**Flow (cfs)**	**Total Width (ft)**	**Percent Total Width**
550	124	61%	280	58	28%
540	122	60%	250	56	27%
530	120	59%	240	54	26%
520	118	58%	235	52	25%
510	116	57%	225	50	25%
500	112	55%	195	48	24%
480	108	53%	185	46	23%
470	106	52%	180	44	22%
460	104	51%	175	42	21%
455	100	49%	150	38	19%
445	98	48%	135	34	17%
435	94	46%	130	32	16%
410	86	42%	100	30	15%
400	84	41%	95	28	14%
375	80	39%	85	26	13%
365	78	38%	80	24	12%
350	74	36%	75	20	10%
320	72	35%	70	18	9%
315	70	34%	55	14	7%
310	66	32%	50	12	6%
295	64	31%	45	10	5%
290	62	30%	35	8	4%
Flow (cfs)	**Contiguous Width (ft)**	**Percent Contiguous Width**	**Flow (cfs)**	**Contiguous Width (ft)**	**Percent Contiguous Width**
505	92	45%	175	22	11%
500	86	42%	135	18	9%
470	62	30%	80	16	8%
460	56	27%	75	14	7%
315	30	15%	50	12	6%
310	28	14%	45	10	5%
280	26	13%	35	6	3%
250	24	12%	-	-	-

Table 20. Abbreviated CR7 rating curve results for adult Chinook salmon. Total width versus flow (top), and contiguous width versus flow (bottom).

Adult Chinook Salmon (minimum depth criteria = 0.9 ft)		
Maximum Wetted Width = 210.5 ft		
Flow (cfs)	**Total Width (ft)**	**Percent Total Width**
565*	60	29%
535*	57	27%
510*	48	23%
390*	42	20%
350	39	19%
300	36	17%
265	27	13%
250	24	11%
185	18	9%
175	15	7%
145	12	6%
135	9	4%
120	6	3%
115	3	1%
110	0	0%
Flow (cfs)	**Contiguous Width (ft)**	**Percent Contiguous Width**
535*	36	17%
390*	27	13%
250	15	7%
120	6	3%
115	3	1%
110	0	0%
*Flows modeled above 381 cfs have less confidence		

Table 21. Abbreviated CR3 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 = 133 ft					
Flow (cfs)	**Total Width (ft)**	**Percent Total Width**	**Flow (cfs)**	**Total Width (ft)**	**Percent Total Width**
300	122	92%	130	70	53%
270	118	89%	125	66	50%
260	116	87%	110	64	48%
250	114	86%	105	60	45%
240	112	84%	100	52	39%
210	110	83%	95	44	33%
205	104	78%	90	34	26%
195	102	77%	85	30	23%
190	98	74%	80	22	17%
170	96	72%	75	16	12%
165	94	71%	70	10	8%
160	92	69%	65	8	6%
155	90	68%	55	6	5%
145	86	65%	50	4	3%
140	74	56%	40	2	2%
135	72	54%	35	0	0%
Flow (cfs)	**Contiguous Width (ft)**	**Percent Contiguous Width**	**Flow (cfs)**	**Contiguous Width (ft)**	**Percent Contiguous Width**
300	122	92%	105	20	15%
270	60	45%	90	12	9%
260	58	44%	85	10	8%
210	56	42%	70	8	6%
170	46	35%	55	6	5%
145	40	30%	50	4	3%
135	34	26%	40	2	2%
130	32	24%	35	0	0%

Table 22. Abbreviated CR4 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 = 204 ft					
Flow (cfs)	Total Width (ft)	Percent Total Width	Flow (cfs)	Total Width (ft)	Percent Total Width
550	168	82%	255	84	41%
540	166	81%	240	80	39%
530	164	80%	235	78	38%
520	160	78%	225	74	36%
470	158	77%	200	72	35%
460	152	75%	195	70	34%
455	148	73%	190	66	32%
445	146	72%	185	64	31%
435	142	70%	180	62	30%
425	136	67%	175	58	28%
410	134	66%	150	56	27%
390	130	64%	145	54	26%
385	126	62%	140	52	25%
365	124	61%	135	50	25%
360	122	60%	115	48	24%
350	120	59%	110	46	23%
345	118	58%	105	44	22%
335	116	57%	100	42	21%
330	112	55%	85	38	19%
315	108	53%	75	34	17%
310	106	52%	70	32	16%
300	104	51%	50	30	15%
295	100	49%	45	26	13%
290	98	48%	40	24	12%
280	94	46%	35	18	9%
265	86	42%	-	-	-
Flow (cfs)	Contiguous Width (ft)	Percent Contiguous Width	Flow (cfs)	Contiguous Width (ft)	Percent Contiguous Width
470	118	58%	175	26	13%
335	92	45%	150	24	12%
330	86	42%	100	22	11%
310	62	30%	75	18	9%
300	56	27%	40	16	8%
195	30	15%	35	12	6%
190	28	14%	-	-	-

Table 23. Abbreviated CR7 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 = 210.5 ft					
Flow (cfs)	Total Width (ft)	Percent Total Width	Flow (cfs)	Total Width (ft)	Percent Total Width
350	108	51%	120	42	20%
335	105	50%	110	39	19%
300	102	48%	100	36	17%
280	96	46%	90	27	13%
265	87	41%	75	18	9%
235	78	37%	70	15	7%
210	75	36%	65	12	6%
200	63	30%	60	9	4%
185	60	29%	55	6	3%
175	57	27%	50	0	0%
165	48	23%	-	-	-
Flow (cfs)	Contiguous Width (ft)	Percent Contiguous Width	Flow (cfs)	Contiguous Width (ft)	Percent Contiguous Width
350	84	40%	120	27	13%
300	81	38%	90	15	7%
280	75	36%	55	6	3%
175	36	17%	50	0	0%

Depths were measured at two foot increments along the critical path at CR3 and CR4. At CR7, measurements were recorded along the critical path at three foot increments. Stage-discharge relationships in Appendix E (Figures E-1 to E-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 depth criteria are plotted with the total and contiguous wetted widths measured in the field (Figures E-4 to E-15).

5.3 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). Four riffles were selected in lower Mill 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 F). 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 24).

Table 24. Wetted perimeter breakpoint and incipient asymptote flows (cfs).

Name	Breakpoint (cfs)	Incipient Asymptote (cfs)
WP1	40	87
WP2	11	21
WP3	22	42
WP4	44	81

5.4 Temperature Model Results

Input data from several sources including climate 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 Mill Creek during the spring for water years 2008 through 2014. Those results are presented below. The results of the W3T model are given in Appendix C, 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 C; along with a comparison of the modeled simulated flow runs to 7DADM values at the downstream end of Reach 1.

Pressure Transducer and Temperature Logger Data

Flows generated from the pressure transducer data are shown in Figures 29 and 30, while measured water temperatures are shown in Figures 31 and 32. The measured 7DADM at the downstream end of Reach 1 first reached 64°F on April 12, 2014 and March 29, 2015, and reached 68°F on May 1, 2014 and April 20, 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 7, May 29, and June 13 (Figure 29). Peaks in 2015 are visible on April 28, May 16, June 2, and June 10 (Figure 30).

Each reach was equipped with two loggers at the downstream end. Data from one of the temperature loggers at the downstream end of Reach 3 indicated that it was no longer submerged after June 29, 2014. As a result, water temperatures used to calibrate the downstream end of Reach 3 were the water temperatures recorded at the other temperature logger for the period of June 30 to July 29, 2014. Similarly, data from one of the temperature loggers at the downstream end of Reach 1 indicated that it was no longer submerged after June 29, 2014. As a result, the calibration water temperatures used for the downstream end of Reach 1 were the water temperatures recorded at the other temperature logger for the period of June 30 to July 29, 2014. The spatial distribution of water temperatures was as expected, with water temperatures increasing downstream.

One of the temperature loggers at the downstream end of Reach 3 was lost during high flows in the winter of 2015, and was replaced with a new temperature logger on March 3, 2015. As a result, the validation water temperatures used for the downstream end of Reach 3 were the water temperatures recorded at the other temperature logger for the period of February 15 to March 2, 2015. Data from one of the temperature loggers at the downstream end of Reach 2 indicated that it was no longer submerged after June 11, 2015. As a result, the validation water temperatures used for the downstream end of Reach 2 were the water temperatures recorded at the other temperature logger for the period of June 12 to July 5, 2014. One of the temperature loggers at the downstream end of Reach 1 was removed on March 3, 2015 at the request of the landowner at that location. As a result, the validation water temperatures used for the downstream end of Reach 1 were the water temperatures recorded at the other temperature logger for the period of March 3 to July 5, 2014.

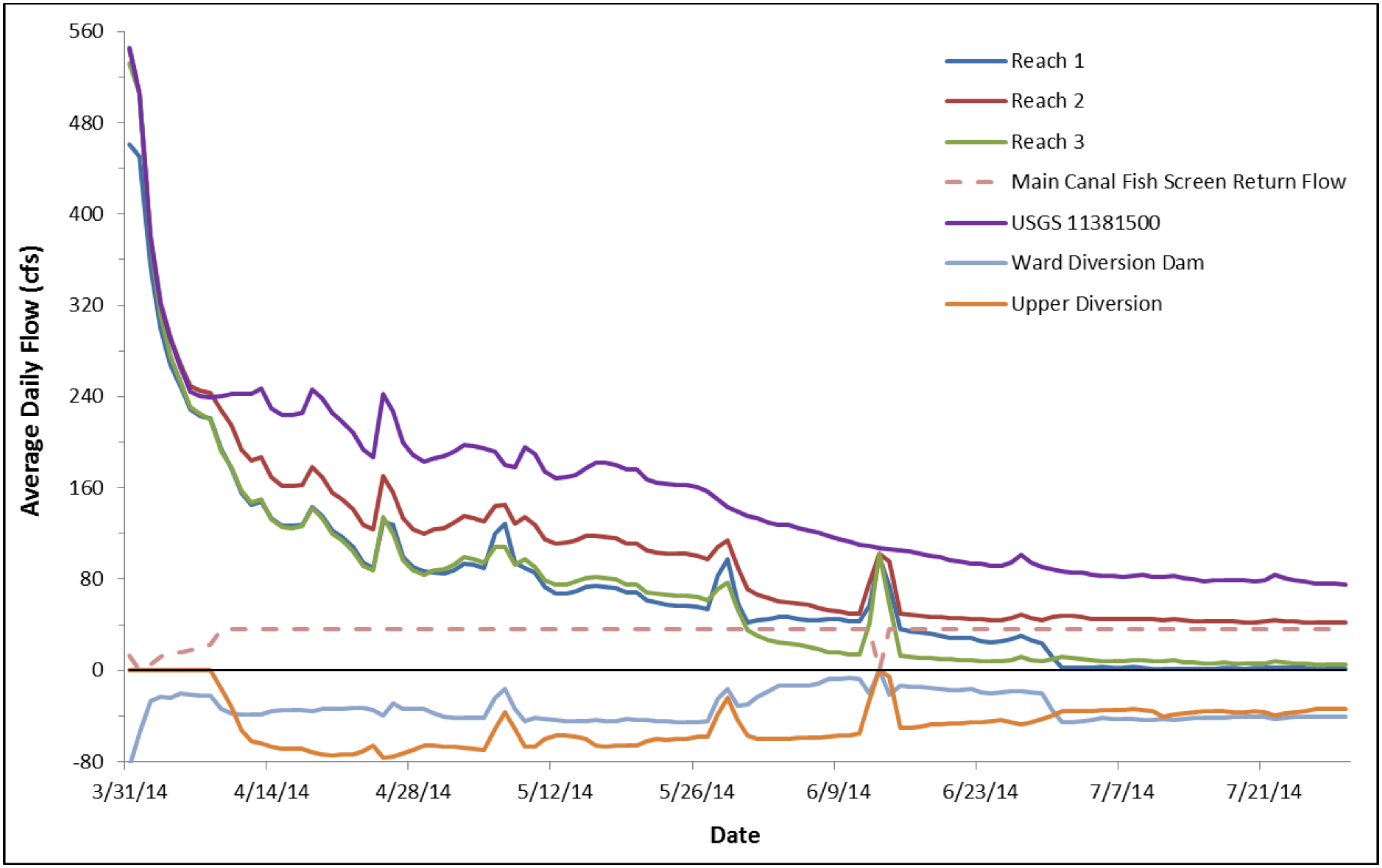

Figure 29. Mill Creek 2014 flow data from pressure transducers and USGS 11381500. Flows are plotted as positive values, while diversions are plotted as negative values.

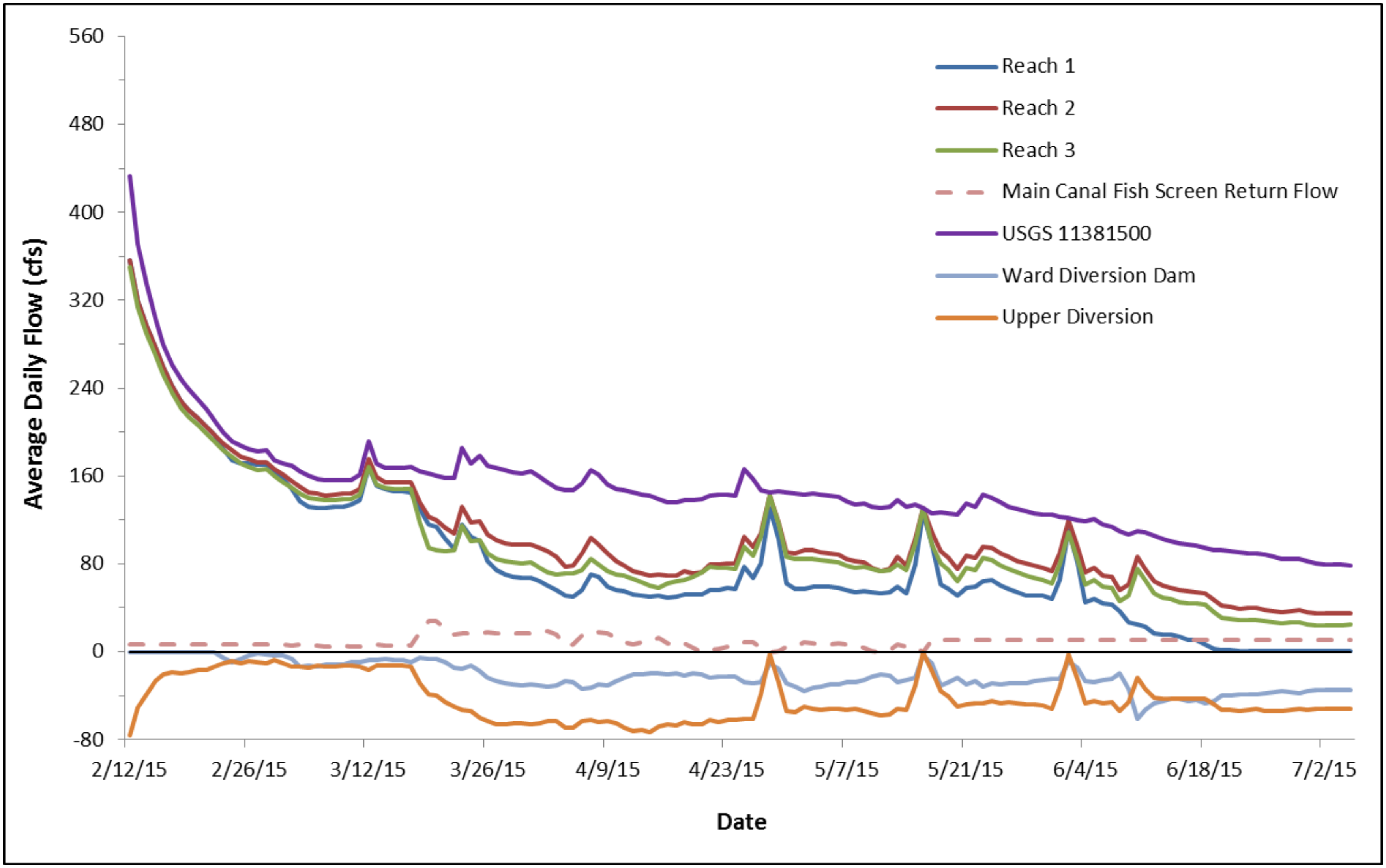

Figure 30. Mill Creek 2015 flow data from pressure transducers and USGS 11381500. Flows are plotted as positive values, while diversions are plotted as negative values.

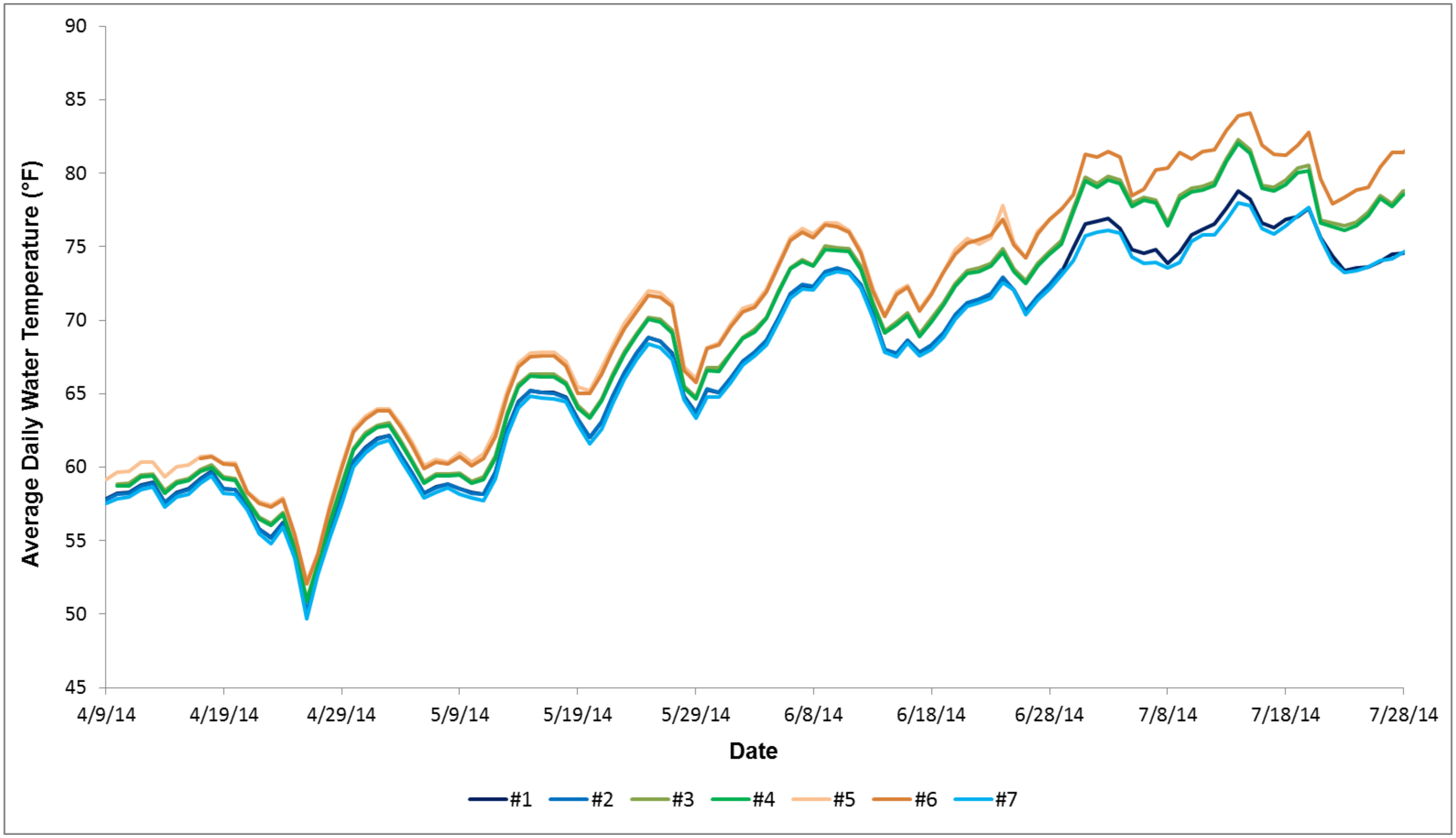

Figure 31. Mill Creek 2014 measured water temperatures. Temperature loggers 1 and 2 were at the downstream end of Reach 3, loggers 3 and 4 at the downstream end of Reach 2, loggers 5 and 6 at the downstream end of Reach 1, and logger 7 was at the upstream end of Reach 3.

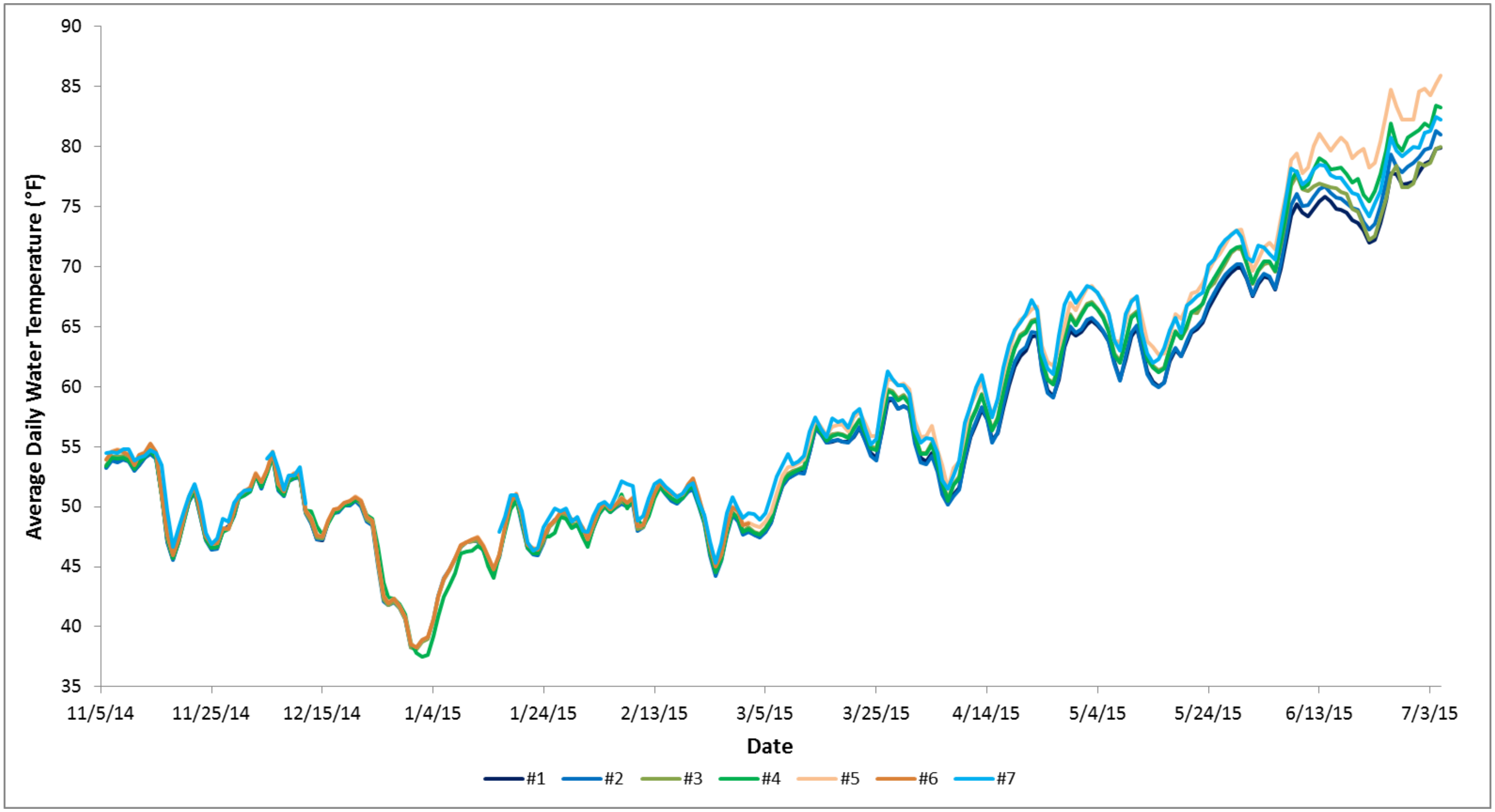

Figure 32. Mill Creek 2015 measured water temperatures. Temperature loggers 1 and 2 were at the downstream end of Reach 3, loggers 3 and 4 at the downstream end of Reach 2, loggers 5 and 6 at the downstream end of Reach 1, and logger 7 was at the upstream end of Reach 3.

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 33 through 36, mean daily water temperature values were generally lower for unimpaired flows versus impaired flows during the latter half of the SRCS migration. 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 1.0 °F and the peak difference was 12.5 °F. In comparison, in the wet year of 2011, mean daily water temperatures remained similar through July with a median difference of 0.3 °F and a peak difference of 1.8 °F.

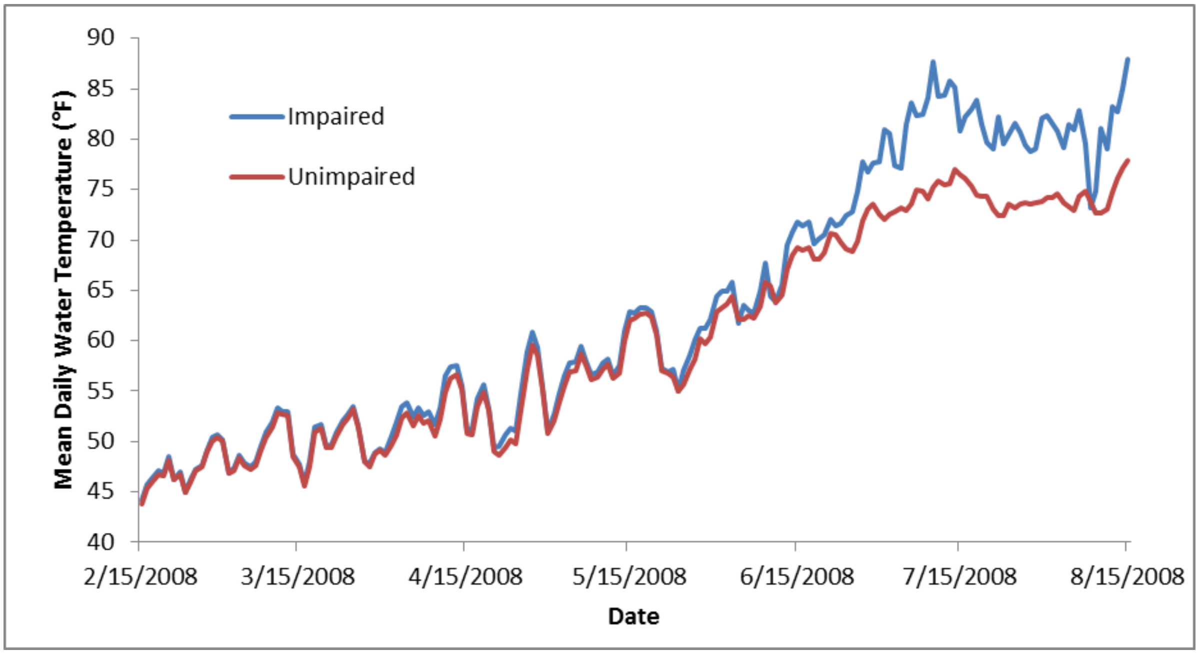

Figure 33. Predicted mean daily water temperature (°F) at the downstream end of Reach 1 for impaired and unimpaired flows during season of migration in 2008.

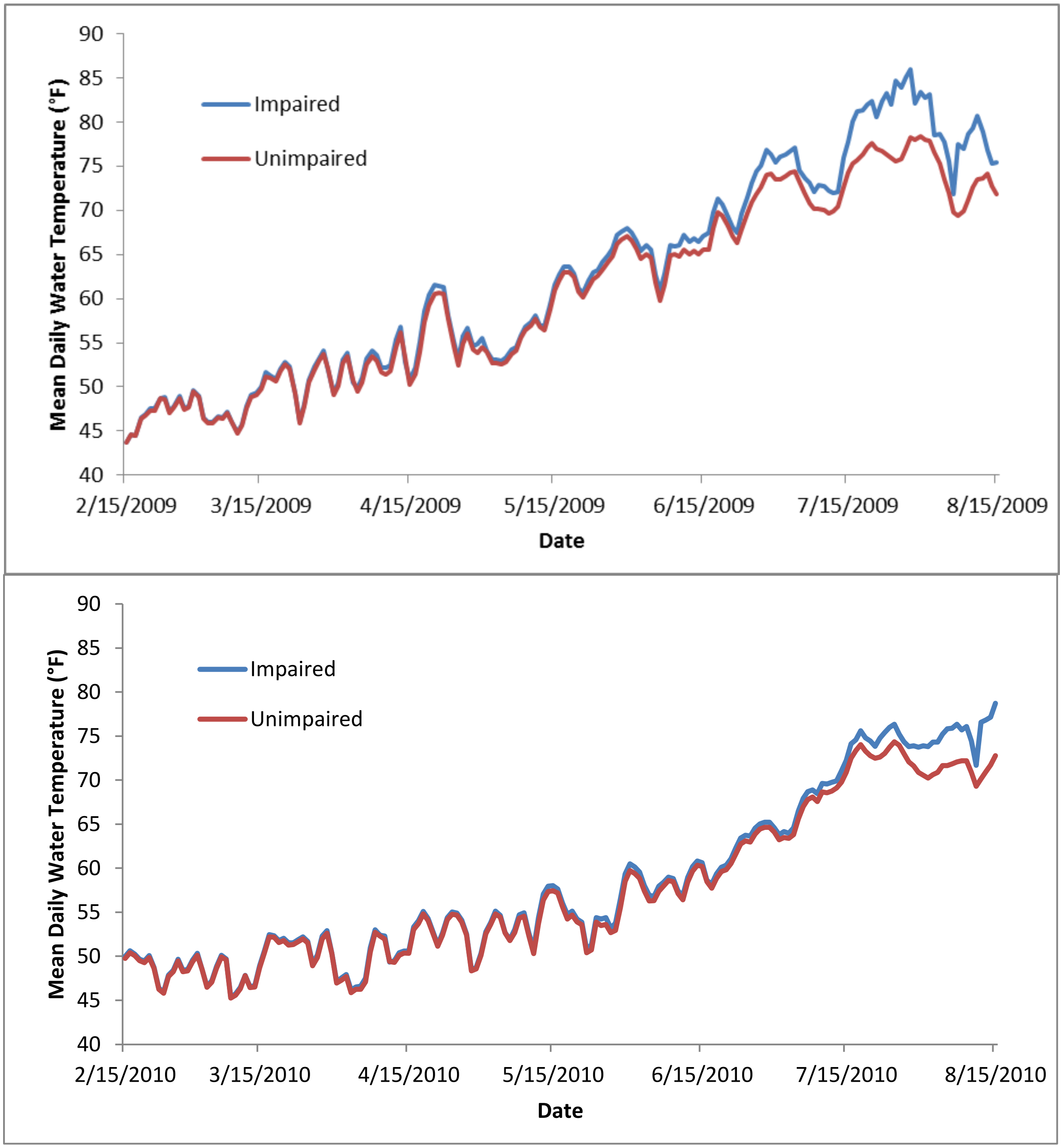

Figure 34. Predicted mean daily water temperature (°F) at the downstream end of Reach 1 for impaired and unimpaired flows during season of migration in 2009-2010.

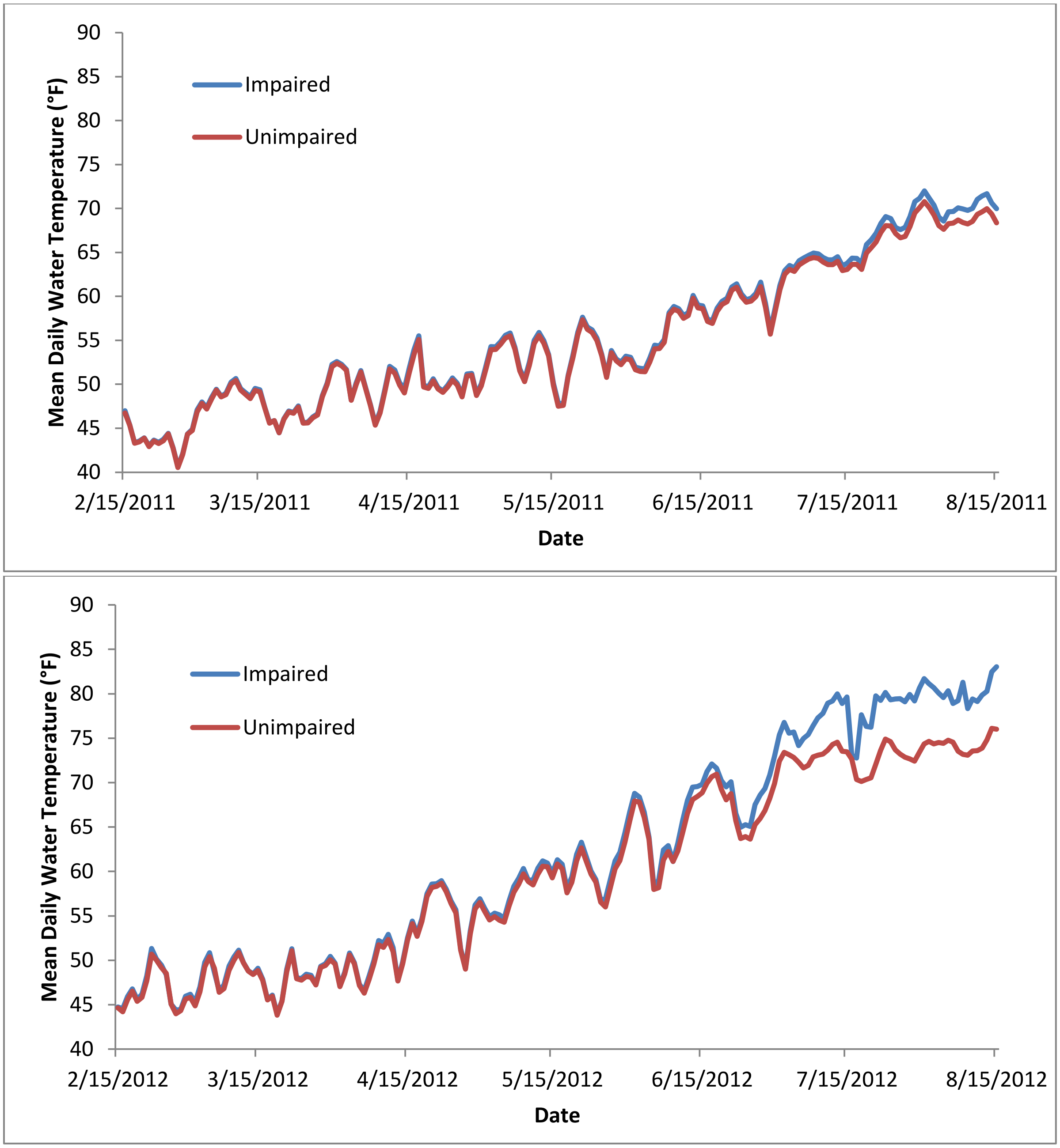

Figure 35. Predicted mean daily water temperature (°F) at the downstream end of Reach 1 for impaired and unimpaired flows during season of migration in 2011-2012.

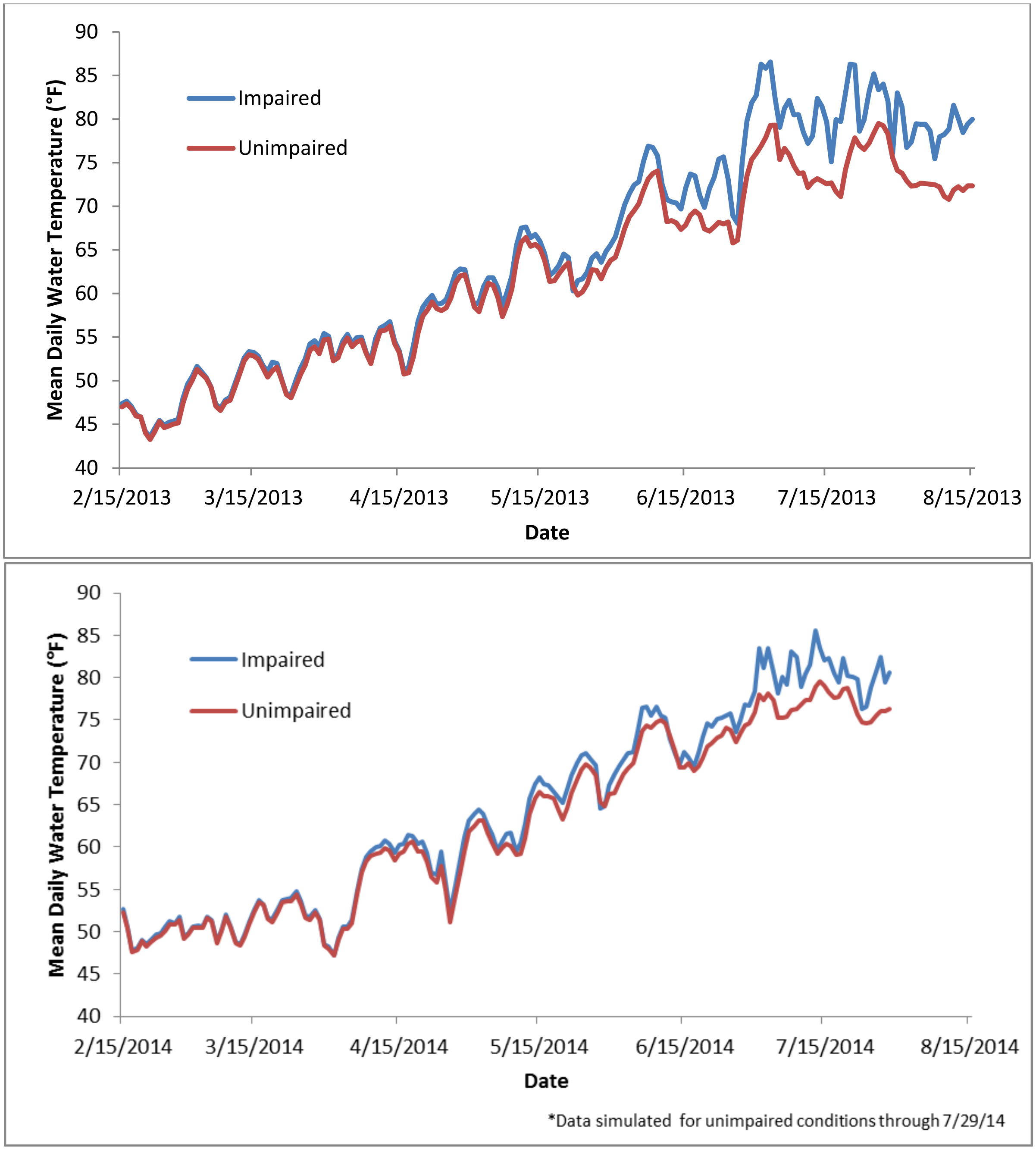

Figure 36. Predicted mean daily water temperature (°F) at the downstream end of Reach 1 for impaired and unimpaired flows during season of migration in 2013-2014.

6.0 DISCUSSION

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

6.1 River2D Passage Assessment at CR2

In 2014, the CRA method was applied to site CR2. The site proved to be a poor candidate for the CRA assessment for two main reasons. First, the site lacked a defined bed to bank transition. As flow levels rose, the wetted width increased but the amount of total and contiguous depth meeting the criteria for steelhead or Chinook salmon remained constant. This trend caused the amount of total and contiguous width by percent to decrease as the flow level increased. The second reason CR2 was found to be a poor candidate for the CRA method was the site's hydraulic complexity. Specifically, the change in water surface slope along the shallowest course changed with flow level. This impacted the CRA data collection because the location and length of the shallowest course changed between sampling events. This variation in pathways increased the amount of uncertainty in finding a relationship between flow and depth over the shallowest course.

The model River2D was chosen to model CR2 and allow the shallowest course to be evaluated over a range of flows. The passable depth versus discharge results are given in the previous section. The model performed well in calibration of the water surface to discharge at the site boundaries and in validation of depth within the site boundary (refer to Appendix B). Variations in measured versus predicted depths were observed along the shallowest course line in some simulations. Froude number (FN) was used as an indicator of the reliability of the model to predict depth. Below a FN of 1.0 the hydraulic condition is subcritical and the variation in the water surface is assumed to be minimal. As the FN approaches 1.0, the hydraulic condition transitions from subcritical to supercritical. In supercritical conditions (FN > 1) the reliability of the model to predict depth diminishes.

The FN can be output as a graphical display in River2D. The FN graphic display was reviewed in River2D to identify points in the flow simulations where the Froude number exceeded 1.0, possibly affecting the model's ability to estimate passable width. The simulation with the highest maximum Froude number (Max F) was 200 cfs (see Appendix B). The graphic display of FN for 200 cfs is given below in Figure 37.

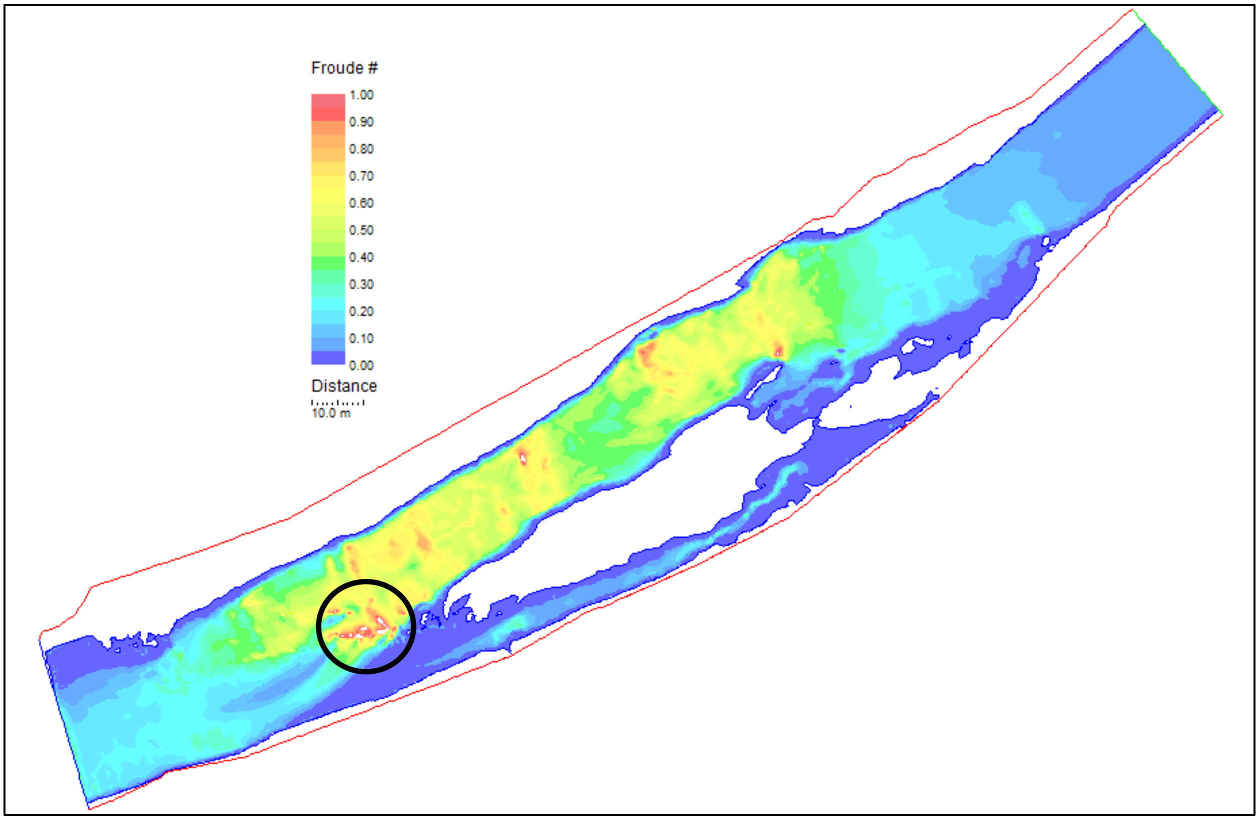

Figure 37. River2D graphic display of Froude number at 200 cfs.

The only portions of the shallowest course where the FN exceeded 1.0 are the small white areas marked by the black circle. As expected, the FN exceeded 1.0 along the shallowest portion of the shallowest course, where velocities were high and depths were low. The depths in the yellow area were least likely to be considered in the estimation of passable width.

6.2 Critical Riffle Passage Assessment

Assessment of the riffles was based on the Thompson (1972) methodology, an empirical method commonly used to evaluate passage flows (Bjornn and Reiser 1991; Reiser et al. 2006; Holmes et al. 2015). The purpose of the methodology and associated transect width metrics is to provide flow conditions for physical movement of salmonids through critical riffle locations. Although Thompson (1972) cautions that the relationship between transect flow conditions and the relative ability of a fish to pass have not been evaluated, the 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 is meant to consider maximum velocity as well as depth and width. The maximum allowable velocity for adult Chinook through low gradients riffles is 8.0 ft/s (Thompson 1972). The River2D outputs were reviewed to confirm velocity was not a limiting factor to upstream migration of SRCS through CR2. No limiting velocities were encountered during any of the CRA sampling events at CR3, CR4, or CR7 for any of the life stages considered.

CRA was used to assess flow, depth, width, and velocity at critical riffle sites. CRA is dependent on a sufficient number of flow sample events, at a representative and appropriate range of flows, to build a robust relationship between the habitat passage metrics and flow. Each riffle site was surveyed at five to seven 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 criteria. While the intent of field surveys was to bracket flows meeting criteria for passage, drought conditions resulting in low flows limited opportunities to collect additional relevant measurements during the field season at CR3 and CR7. Sampled events captured a range of flows from 40 to 221 cfs, approximating the 40^{th} to 100^{th} percentile of exceedance flows. Though target sampling flows for CRA are between the 20^{th} to 80^{th} exceedance probability range (CDFG 2012), flows approaching the 20^{th} percentile (~410 cfs) at Mill Creek riffle sites would have been hazardous and un-wadeable for field crews.

6.3 Wetted Perimeter

A Wetted Perimeter breakpoint defines the threshold below which aquatic habitat conditions for benthic macroinvertebrates, rapidly declines (CDFW 2013b). The Wetted Perimeter method only addresses low flows and is restricted to streams 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 be used or the flow corresponding to at least 50 percent of the wetted perimeter being covered in streams less than 50 feet wide, and between 60 to 70 percent covered in larger streams, whichever is higher. All four sites were wider than 50 feet. For three of the four wetted perimeter sites analyzed, the breakpoint flow was higher than the 60 percent wetted perimeter flow. The exception was WP4, which had a breakpoint flow of 44 cfs providing 57 percent wetted perimeter and a 60 percent wetted perimeter flow of 47 cfs.

The four wetted perimeter sites evaluated varied in geomorphic shape (Appendix F). Since sites were selected based on their structure and their representativeness of riffle habitat types in lower Mill 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. If the 60 percent wetted perimeter flow of 47 cfs is selected for WP4, as recommended by Annear et al. (2004), then the average low flow threshold for benthic macroinvertebrate production in lower Mill Creek is 30 cfs.

6.4 Temperature Models

StreamTemp outputs for impaired versus unimpaired mean daily water temperatures show the magnitude of change to be slight until the latter half of the SRCS migration season (i.e., mid-February through early August; Figures 33 through 36). 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 comparison, 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 Mill Creek (presented in Appendix C), indicate that 7DADM values will be exceeded earlier in drier water year types compared to wetter water year types.

7.0 CONCLUSION

Conditions that could potentially limit upstream migration of Chinook salmon and steelhead were evaluated for lower Mill Creek. Four passage limiting riffle sites were identified in the creek below the most downstream diversion. CRA data were collected at the sites during 2014-2015 to evaluate passage limiting conditions based on flow depth, width, and velocity. River2D was used to develop flow versus width and depth relationships, needed to assess passage at CR2 using the CRA method. Passage conditions at riffle CR3, CR4, and CR7 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 adult steelhead and adult 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 15 and 16 for CR2, and Tables 18 through 23 for CR3, CR4, and CR7. The Wetted Perimeter method was also used to determine a minimum instream flow for the summer low flow period.

A predictive SNTEMP temperature model, StreamTemp, was developed for the lower migratory reach of Mill 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. It was found that 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 not found to be substantial in the simulations except 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 maintain healthy conditions for fish and wildlife in lower Mill Creek. Subsequent recommendations will be developed separately from the scientific process presented above, and are not incorporated into this technical report.

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REFERENCES

Alley, D.W. 1996. IFIM Modeling of Critical Riffles, With Recommended Passage Flows for Chinook Salmon in Lower Mill Creek, Tehama County, California, 1995.

Annear, T., I. Chisholm, H. Beecher, A. Locke, and 12 other authors. 2004. Instream Flows for Riverine Resource Stewardship, Revised Edition. Instream Flow Council, Cheyenne, Wyoming.

Armentrout, S., H. Brown, S. Chappell, M. Everett-Brown, J. Fites, J. Forbes, M. McFarland, J. Riley, K. Roby, A. Villalovos, R. Walden, D. Watts, and M.R. Williams. 1998. Watershed Analysis for Mill, Deer and Antelope Creeks. Appendix E – Anadromous Fish Habitat. Almanor Ranger District. Lassen National Forest.

Bartholow, J. M. 2000. The Stream Segment and Stream Network Temperature Models: A Self-Study Course, Version 2.0. U.S. Department of the Interior, U.S. Geological Survey. Open-File Report 99-112. March 2000. Fort Collins, CO. 282 pp.

Bjornn, T.C., and D.W Reiser. 1991. Chapter 4. Habitat Requirements of Salmonids in Streams. In: Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. American Fisheries Society Special Publication 19: 83-138.

Bovee, K.D., B.L. Lamb, J.M. Bartholow, C.B. Stalnaker, J. Taylor, and J. Henriksen. 1998. Stream Habitat Analysis Using the Instream Flow Incremental Methodology: U.S. Geological Survey Information and Technology Report 1998-0004. 130 pp.

California Department of Fish and Game (CDFG). 1998. A Status Review of the Spring-Run Chinook Salmon (*Oncorhynchus tshawytscha*) in the Sacramento River Drainage. Report to the Fish and Game Commission. Candidate Species Status Report 98-01. June 1998.

California Department of Fish and Game (CDFG). 2006. California Department of Fish and Game Guidelines for Instream Flow Assessment and Resource Protection: Appendix A: Guidelines to the Application and Use of the Physical Habitat Simulation System. 16 pp.

California Department of Fish and Game (CDFG). 2012 [Updated 2015]. Critical Riffle Analysis for Fish Passage in California. California Department of Fish and Game Instream Flow Program Standard Operating Procedure DFW-IFP-001, 26 pp. Available at: https://www.wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/SOP

California Department of Fish and Wildlife (CDFW). 2013a, Standard Operating Procedure for Flow Duration Analysis in California. Department of Fish and Wildlife Instream Flow Program Standard Operating Procedure DFW-IFP-005, 16 pp. Available at: https://www.wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/SOP

California Department of Fish and Wildlife (CDFW). 2013b.Standard Operating Procedure for the Wetted Perimeter Method in California. California Department of Fish and Wildlife Instream Flow Program Standard Operating Procedure DFW-IFP-004, 19 pp. August 2013. Available at: https://www.wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/SOP

California Department of Fish and Wildlife (CDFW). 2013c. Standard Operating Procedure for Discharge Measurements in Wadeable Streams in California. California Department of Fish and Wildlife Instream Flow Program Standard Operating Procedure CDFW-IFP-002, 24 pp. Available at: https://www.wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/SOP

California Department of Fish and Wildlife (CDFW). 2013d, Standard Operating Procedure for Streambed and Water Surface Elevation Data Collection in California. Department of Fish and Wildlife Instream Flow Program Standard Operating Procedure DFW-IFP-003, 24 pp. Available at: https://www.wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/SOP

Cowan, W. and M. Gard. 2016. Instream Flow Evaluation of upstream Spring-run Chinook Salmon Passage in Butte Creek, California. Department of fish and Wildlife. Stream Evaluation Report No. 16-1. February 2016.

Department of Water Resources (DWR). 2016. Water Conditions in California DWR Bulletin 120. California Cooperative Snow Surveys. Chronological Reconstructed Sacramento and San Joaquin Valley Water Year Hydrologic Classification Indices. WSIHIST (01/19/16 1412). Available at: http://cdec.water.ca.gov/snow/bulletin120/index2.html

Department of Water Resources (DWR). 2005. Chapter 3. Existing Habitat Conditions and Status of Fish Populations. In: Fish Passage Improvement. An Element of CALFED's Ecosystem Restoration Program. Bulletin 250. Fish Passage Improvement Program. Sacramento, CA.

Department of Water Resources (DWR). 2009. Central Valley Spring-run Chinook Salmon and Steelhead in the Sacramento River Basin. Background Report. November 2009.

Dunbar, M.J., A. Gustard, M.C. Acreman, and C.R.N. Elliott. 1998. Overseas Approaches to Setting River Flow Objectives. Environment Agency Research and Development Technical Report W145. Institute of Hydrology: Wallingford, U.K.

Environmental Protection Agency (EPA). 2003. EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards. EPA 910-B-03-002. Region 10, Office of Water, Seattle, WA.

Flosi, G., S. Downie, J. Hopelain, M. Bird, R. Coey, and B.Collins. 2010. California Salmonid Stream Habitat Restoration Manual. Fourth edition. California Department of Fish and Game, Wildlife and Fisheries Division. Available at: http://www.dfg.ca.gov/fish/resources/habitatmanual.asp

Fullerton, A. H., K.M. Burnett, E.A. Steel, R.L Flitcroft, G.R. Pess, B.E. Feist, C.E. Torgersen, D.J. Miller, and B.L. Sanderson. 2010. Hydrological connectivity for riverine fish: measurement challenges and research opportunities. *Freshwater Biology* 55: 2215-2237.

Gippel, C. and E. Stewardson. 1998. Use of Wetted Perimeter in Defining Minimum Environmental Flows. *Regulated Rivers: Research & Management* 14: 53-67.

Harvey-Arrison, C. 2009. Surface Flow Criteria for Salmon Passage Lower Mill Creek Watershed Restoration Project. California Department of Fish and Game, Upper Sacramento River Salmon and Steelhead Assessment Project Report.

Holmes, R.W., D.E. Rankin, M. Gard, and E. Ballard. 2014. Instream Flow Evaluation. Steelhead Passage and Connectivity of Riverine and Lagoon Habitats. Big Sur River, Monterey County. California Department of Fish and Wildlife. Stream Evaluation Report 14-3.

Holmes, R.W., D.E. Rankin, E. Ballard, and M. Gard. 2015. Evaluation of steelhead passage flows using hydraulic modeling on an unregulated coastal California river. *River Research and Applications* DOI: 10.1002/rra.2884

Johnson, M., and K. Merrick. 2012. Juvenile Salmonid Monitoring using Rotary Screw Traps in Deer Creek and Mill Creek, Tehama County, California Summary Report: 1994 to 2010. Red Bluff, California.

Killam, D. 2012. Chinook Salmon Populations of the Upper Sacramento River Basin in 2011. RBFO Technical Report No. 03-2012. California Department of Fish and Wildlife- Northern Region, Red Bluff Fisheries Office.

Killam, D., and M. Johnson. 2013. Chinook Salmon Populations of the Upper Sacramento River Basin in 2012. RBFO Technical Report No. 02-2013. California Department of Fish and Wildlife- Northern Region, Red Bluff Fisheries Office.

Killam, D., M. Johnson, and R. Revnak. 2014. Chinook Salmon Populations of the Upper Sacramento River Basin in 2013. RBFO Technical Report No. 02-2014. California Department of Fish and Wildlife- Northern Region, Red Bluff Fisheries Office.

Killam, D., M. Johnson, and R. Revnak. 2015. Chinook Salmon Populations of the Upper Sacramento River Basin in 2014. RBFO Technical Report No. 03-2015. California Department of Fish and Wildlife- Northern Region, Red Bluff Fisheries Office.

Killam, D., M. Johnson, and R. Revnak. 2016. Chinook Salmon Populations of the Upper Sacramento River Basin in 2015. RBFO Technical Report No. 03-2016. California Department of Fish and Wildlife- Northern Region, Red Bluff Fisheries Office.

Kondolf, G.M. 2001. Fluvial Geomorphic Study on Mill Creek Tehama County, California.

McEwan, D.R. and T. Jackson. 1996. Steelhead restoration and management plan for California. California Department of Fish and Game. 234 p.

Molls, T. 2000. NCH Hydraulic Calculator (HydroCalc), Version 2.0. Northwest Hydraulic Consultants, Inc. West Sacramento, CA. Available at: http://www.hydrocalc2000.com/index.php

Moyle, P. B. 2002. Inland Fishes of California. Berkeley, CA: University of California Press. 517 p.

National Marine Fisheries Service (NMFS). 2014. Recovery Plan for the Evolutionarily Significant Units of Sacramento River Winter-run Chinook Salmon and Central Valley Spring-run Chinook Salmon and the Distinct Population Segment of California Central Valley Steelhead. California Central Valley Area Office. July 2014.

R2 Resource Consultants. 2008. Appendix G: Approach for Assessing Effects of Policy Element Alternatives on Upstream Passage and Spawning Habitat Availability. Administrative Draft prepared for the California State Water Resources Control Board, Division of Water Rights as part of the North Coast Instream Flow Policy: Scientific Basis and Development of Alternatives Protecting Anadromous Salmonids. March 14, 2008.

Reiser, D.W., C.M. Huang, S. Beck, M. Gagner, and D. Jeanes. 2006. Defining flow windows for upstream passage of anadromous salmonids at cascades and falls. *Transactions of the American Fisheries Society* 135: 668–679.

Reynolds F.L., T.J. Mills, R. Benthin and A. Low. 1993. Restoring Central Valley Streams: A Plan for Action. California Department of Fish and Game, Inland Fisheries Division. Sacramento River Watershed Program (SRWP).

Sacramento River Watershed Program (SRWP). 2010. Mill Creek Watershed. In: A Roadmap to Watershed Management. October 2010. P. 110-114. Available at: www.sacriver.org

Snider, W.M., D.B. Christophel, B.L. Jackson and P.M. Bratovich. 1992. Habitat characterization of the Lower American River. California Department of Fish and Game, Sacramento, CA.

Spina, A.P., M.R. McGoogan, and TS. Gaffney. 2006. Influence of surface-water withdrawal on juvenile steelhead and their habitat in a south-central California nursery stream. *California Fish and Game* 92(2): 81-90.

State Water Resources Control Board (SWRCB). 2010. Instream Flow Studies for the Protection of Public Trust resources: A prioritized Schedule and Estimate of Costs. December 2010. Sacramento, CA. Available at: http://www.waterboards.ca.gov/publications_forms/publications/legislative/docs/2011/instream_flow2010.pdf

Theurer, F.D., K.A. Voos, and W.J. Miller. 1984. Instream water temperature model. Instream Flow Information Paper 16. U.S. Fish and Wildlife Service FWS/OBS-84/15.

Thompson, K.E. 1972. Determining streamflows for fish life. In: Proceedings of the Instream Flow Requirement Workshop. Pacific N.W. River Basins Commission. Portland, OR. P. 31-50.

U.S. Bureau of Reclamation (USBR). 2002. Temporary forbearance of a Water Right Entitlement Held by the Orange Cove Irrigation District on Mill Creek, Tehama County, California. Environmental Assessment.

U.S. Department of Agriculture (USDA). 1992. Lassen National Forest. Final Environmental Impact Statement for the Land and Resource Management Plan.

U.S. Fish and Wildlife Service (USFWS). 2000. Draft Finding of No Significant Impact. Anadromous Fish Restoration Actions in Lower Mill Creek Tehama County, California. Sacramento, CA: U.S. Fish and Wildlife Service.

U.S. Fish and Wildlife Service (USFWS). 2001. Final Restoration Plan for the

Anadromous Fish Restoration Program: A Plan to Increase Natural Production of Anadromous Fish in the Central Valley of California.

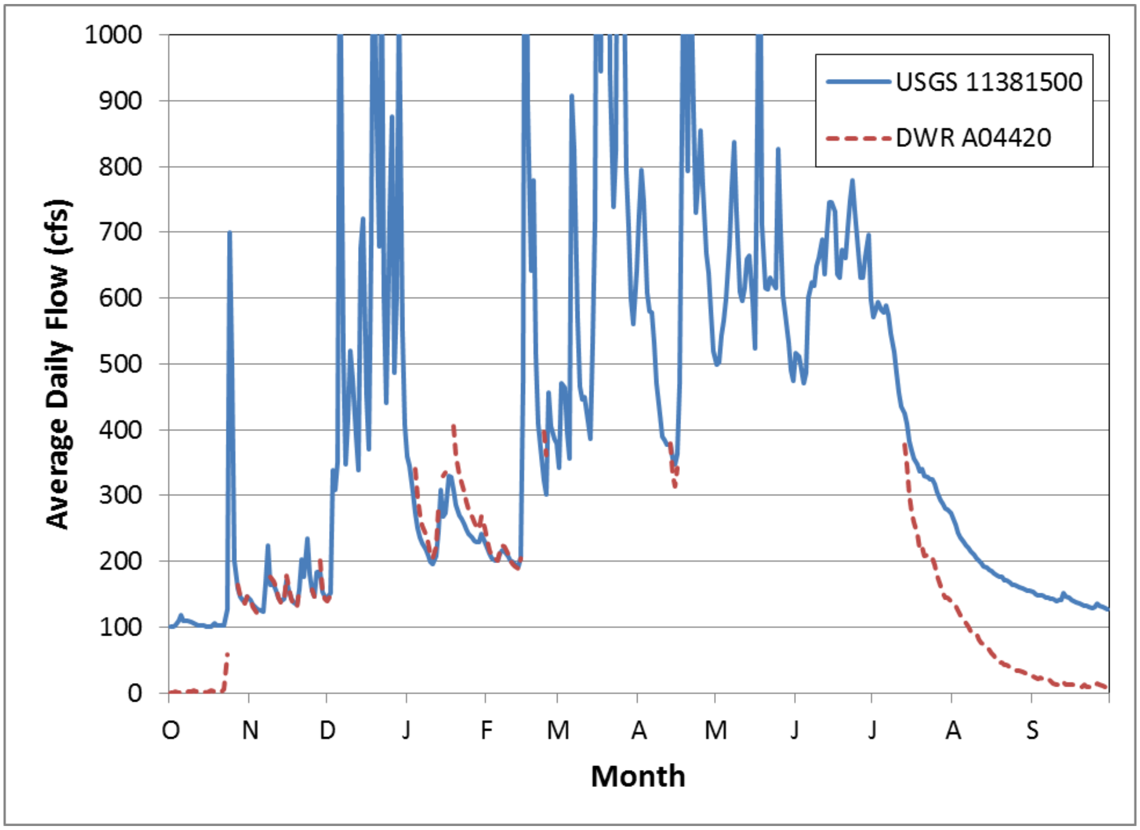
U.S. Fish and Wildlife Service (USFWS). 2011. Sacramento Fish and Wildlife Office Standards for Physical Habitat Simulation Studies. U.S. Fish and Wildlife Service Sacramento Office. Sacramento, California. 17 p.

Watercourse Engineering, Inc. 2013. Water temperature transaction tool (W3T): technical and user's guide (v1.0). A report for the National Fish and Wildlife Foundation. Davis, CA: Watercourse Engineering, Inc.

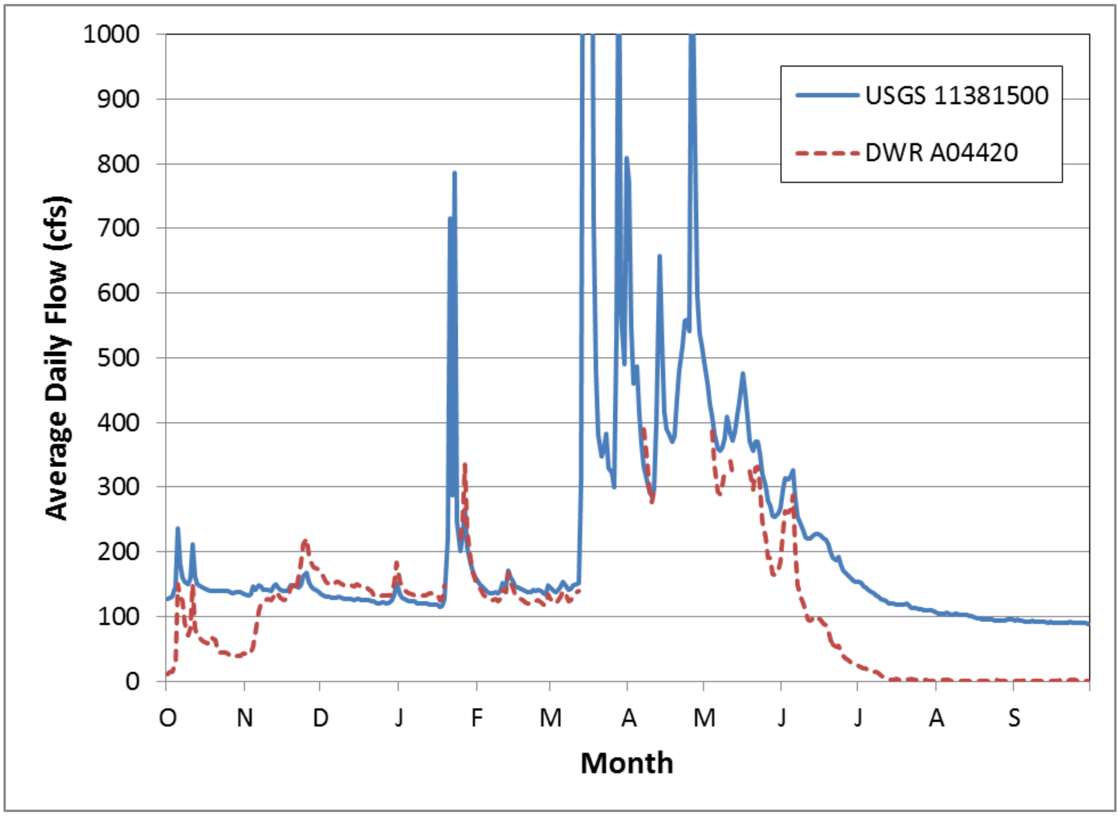
Yoshiyama, R. M., E. R. Gerstung, F. W. Fisher, and P. B. Moyle. 2001. Historical and present distribution of Chinook salmon in the Central Valley. In R. Brown, ed. Contributions to the biology of Central Valley salmonids. CDFG Fish Bulletin 179. P. 71-176.

Appendix A. Monitoring Data

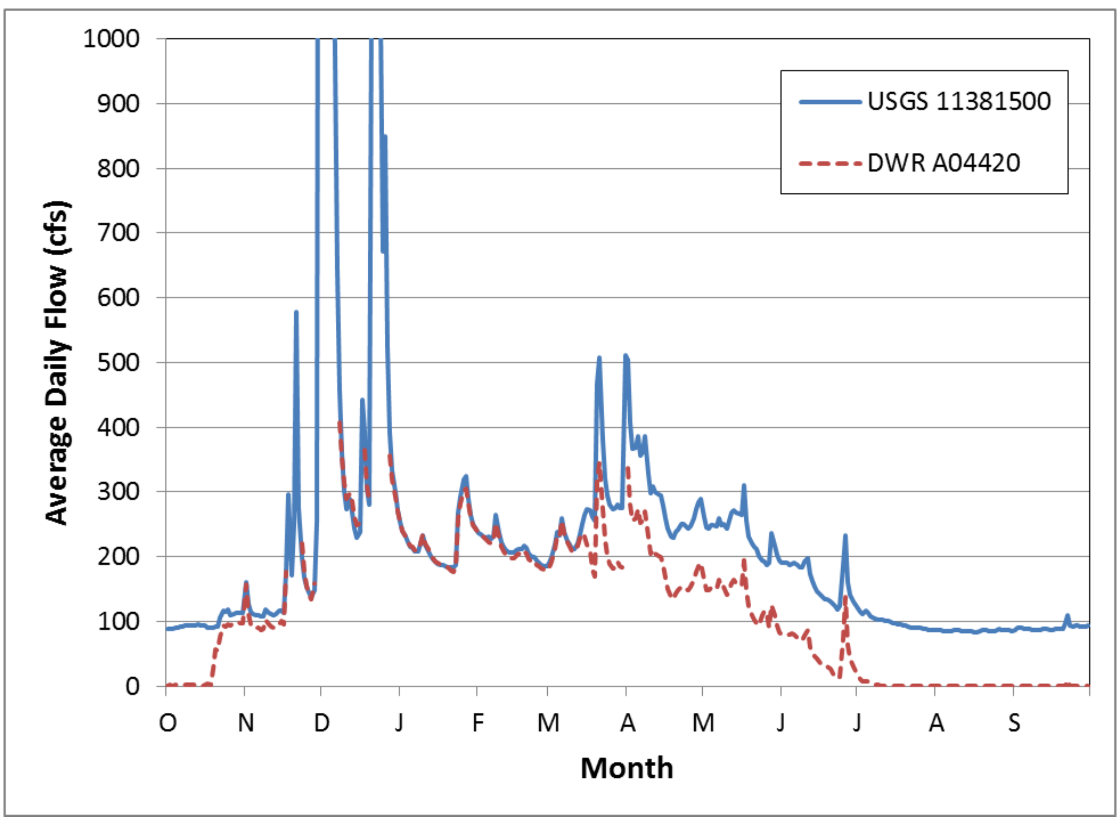
Average Daily Flow



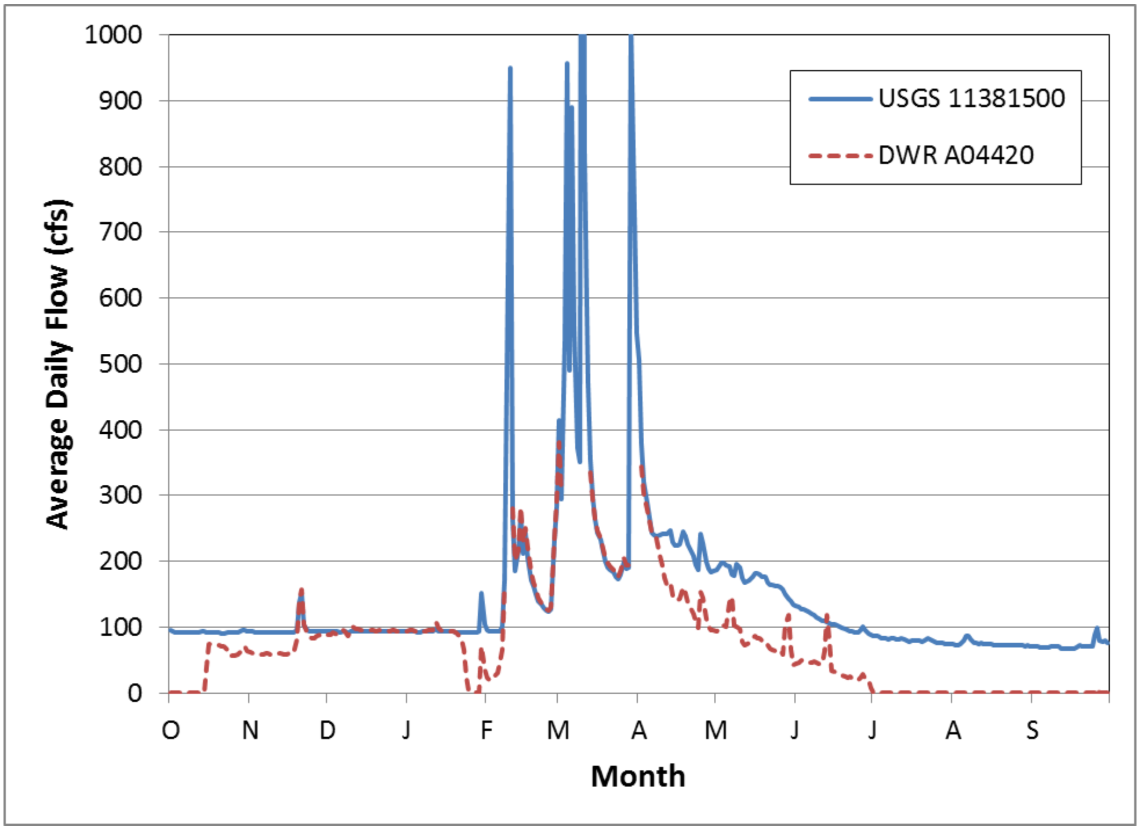
Average daily flow levels (cfs) at monitoring gages for water year 2011.



Average daily flow levels (cfs) at monitoring gages for water year 2012.

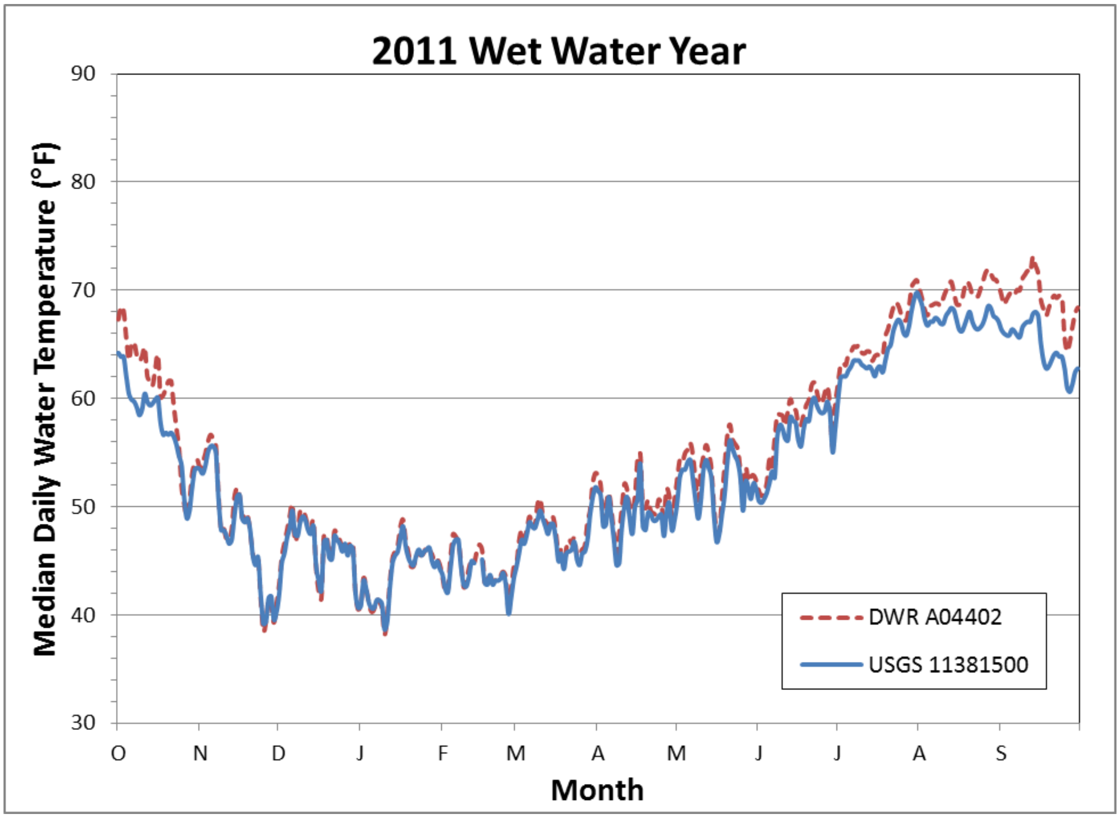


Average daily flow levels (cfs) at monitoring gages for water year 2013.

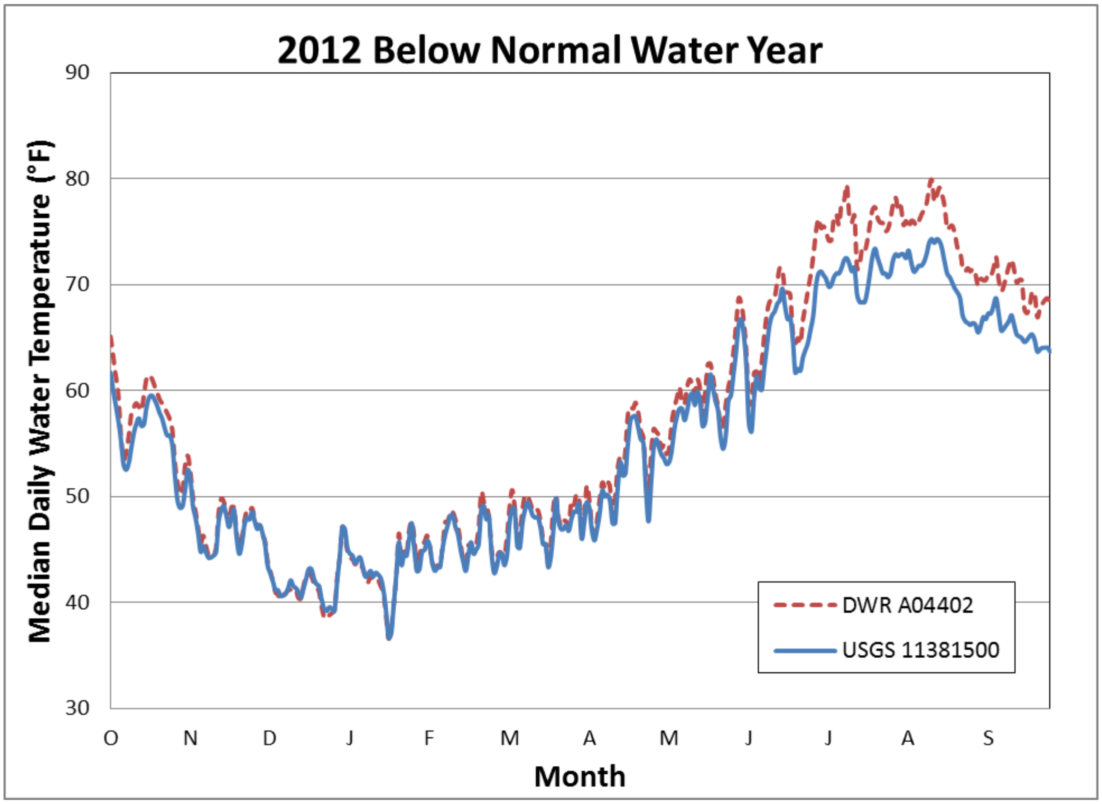


Average daily flow levels (cfs) at monitoring gages for water year 2014.

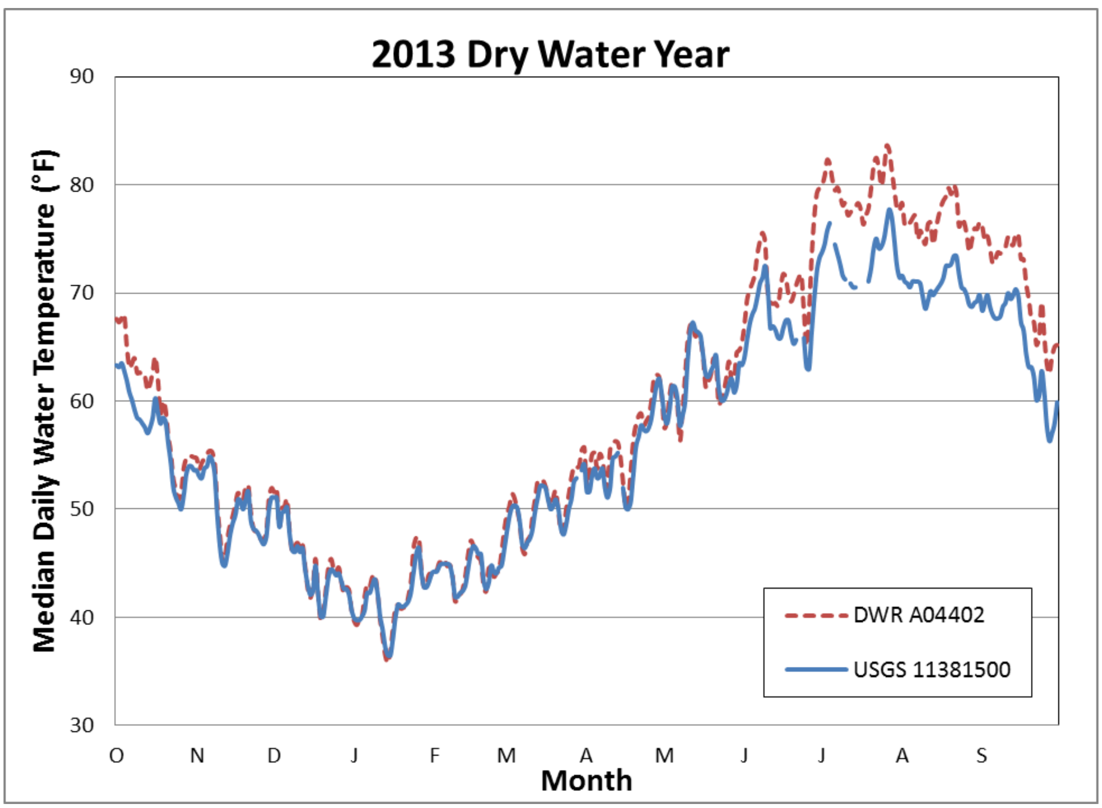
Median Daily Water Temperature



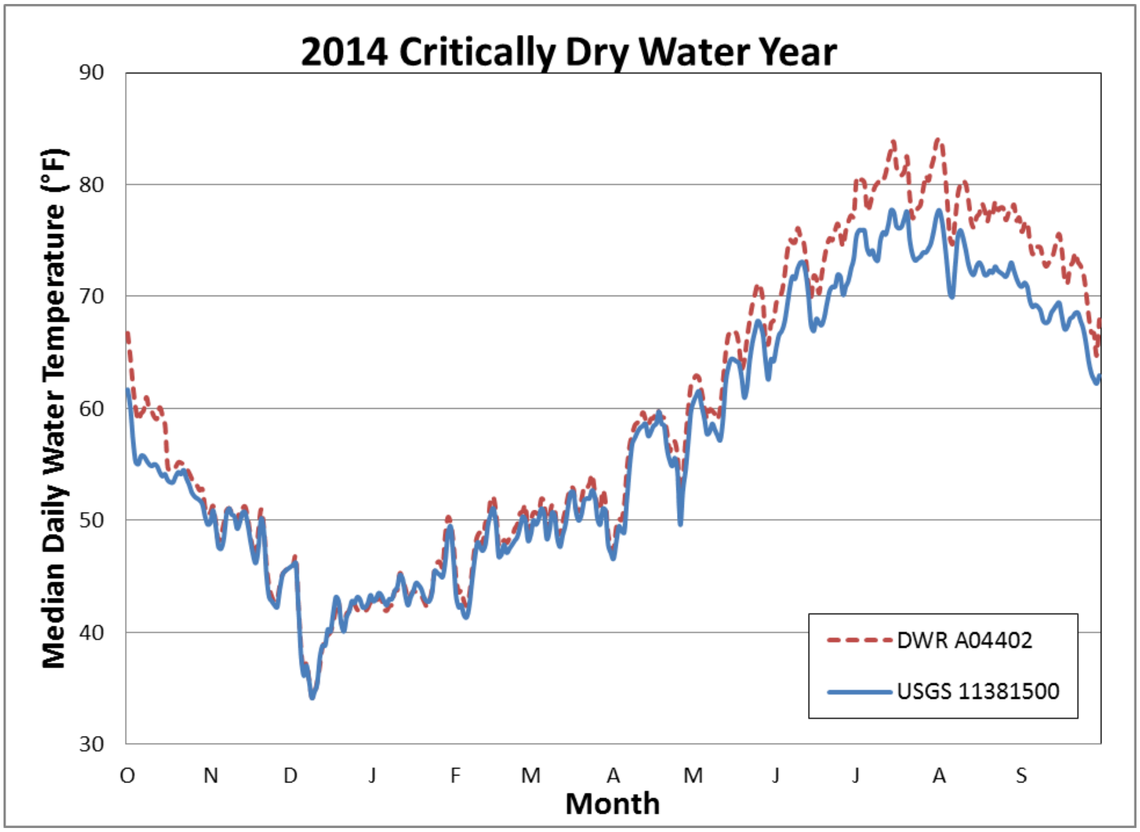
Median daily water temperature (°F) in Mill Creek for water year 2011.



Median daily water temperature (°F) in Mill Creek for water year 2012.

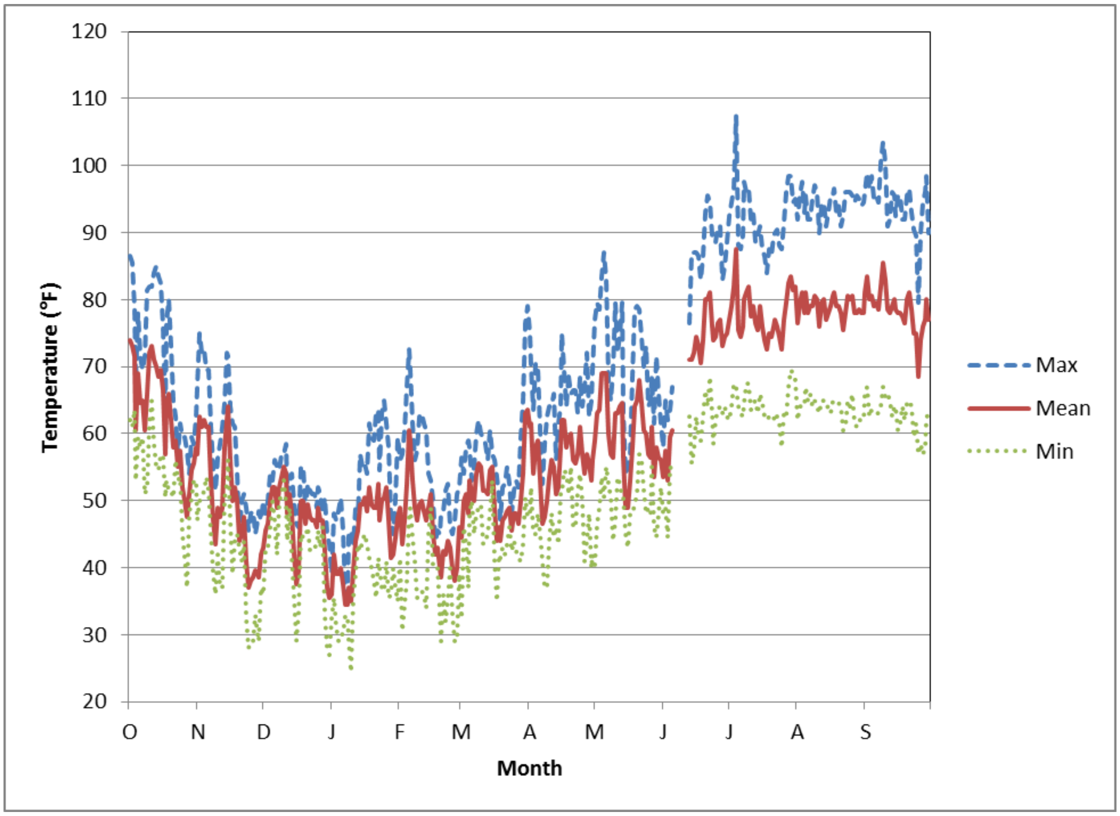


Median daily water temperature (°F) in Mill Creek for water year 2013.

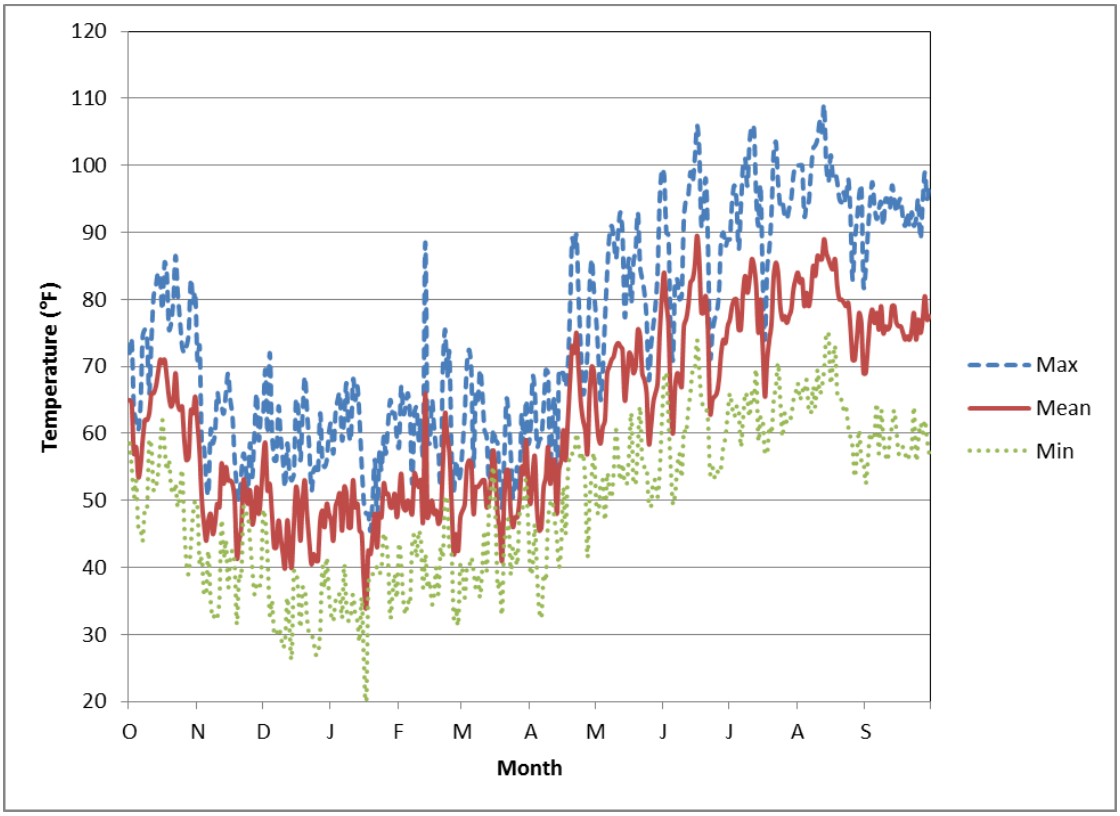


Median daily water temperature (°F) in Mill Creek for water year 2014.

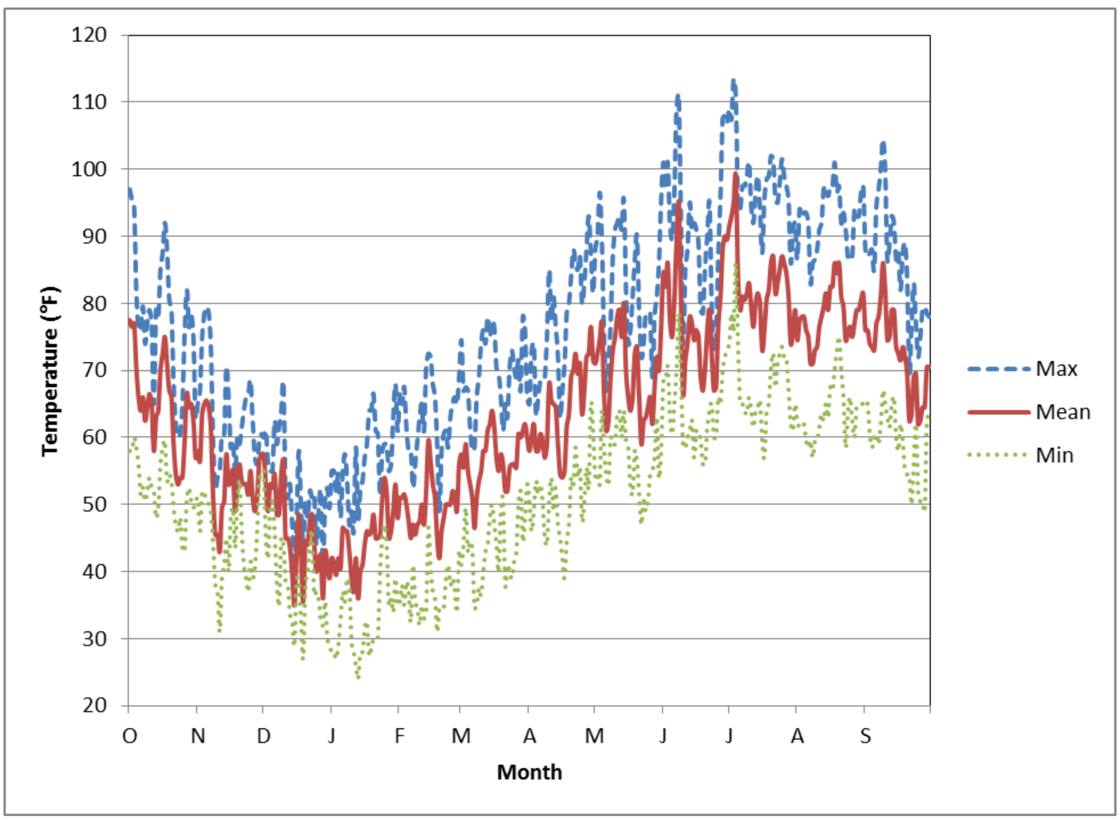
Daily Air Temperature



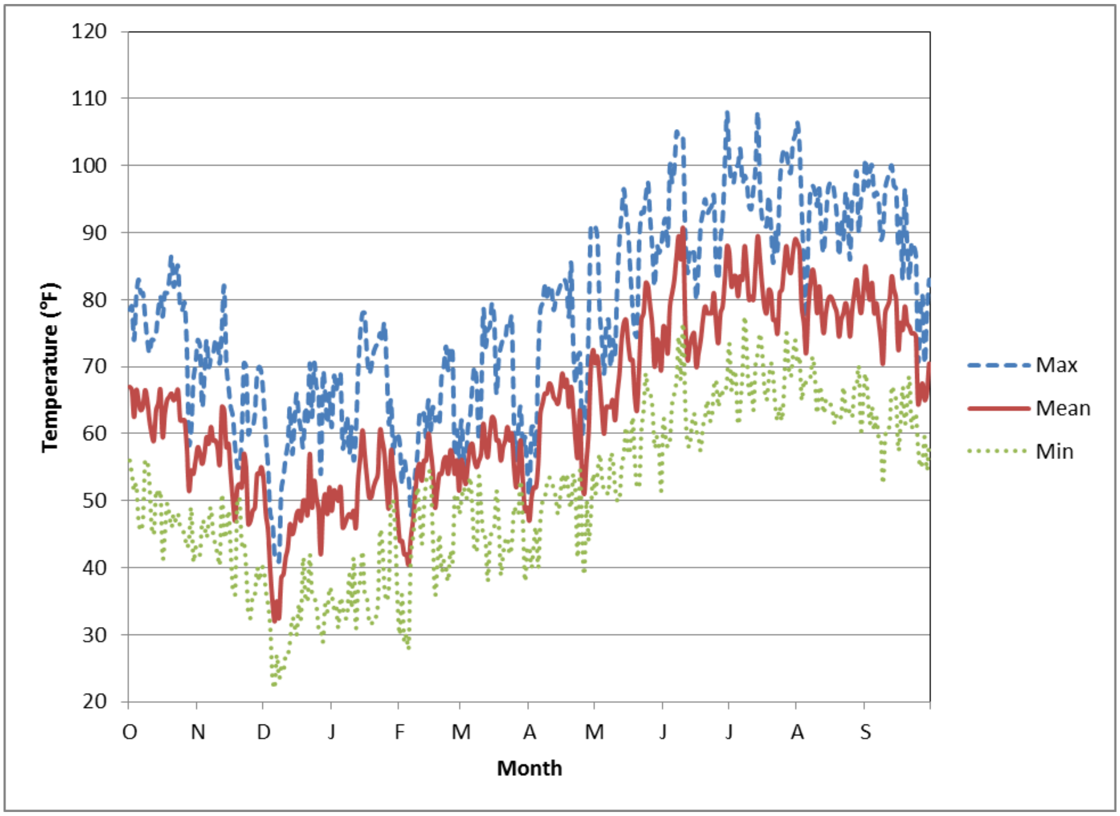
Estimated daily air temperature (°F) for the study area in water year 2011.



Estimated daily air temperature (°F) for the study area in water year 2012.

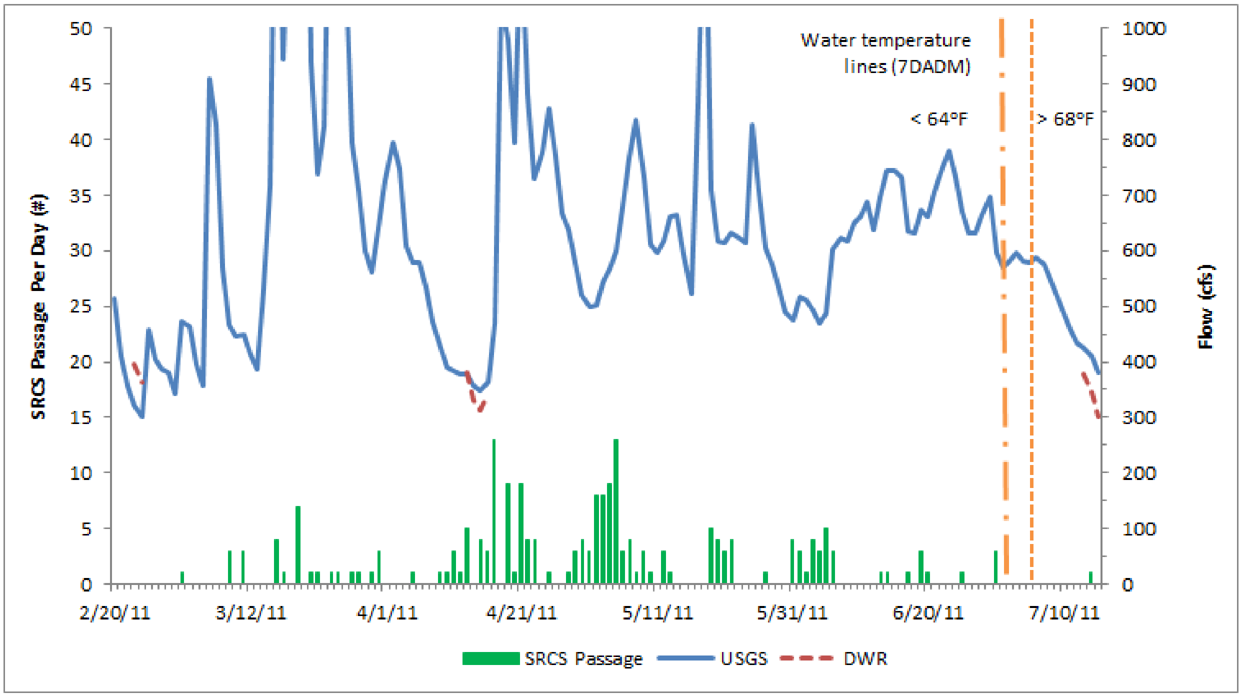


Estimated daily air temperature (°F) for the study area in water year 2013.

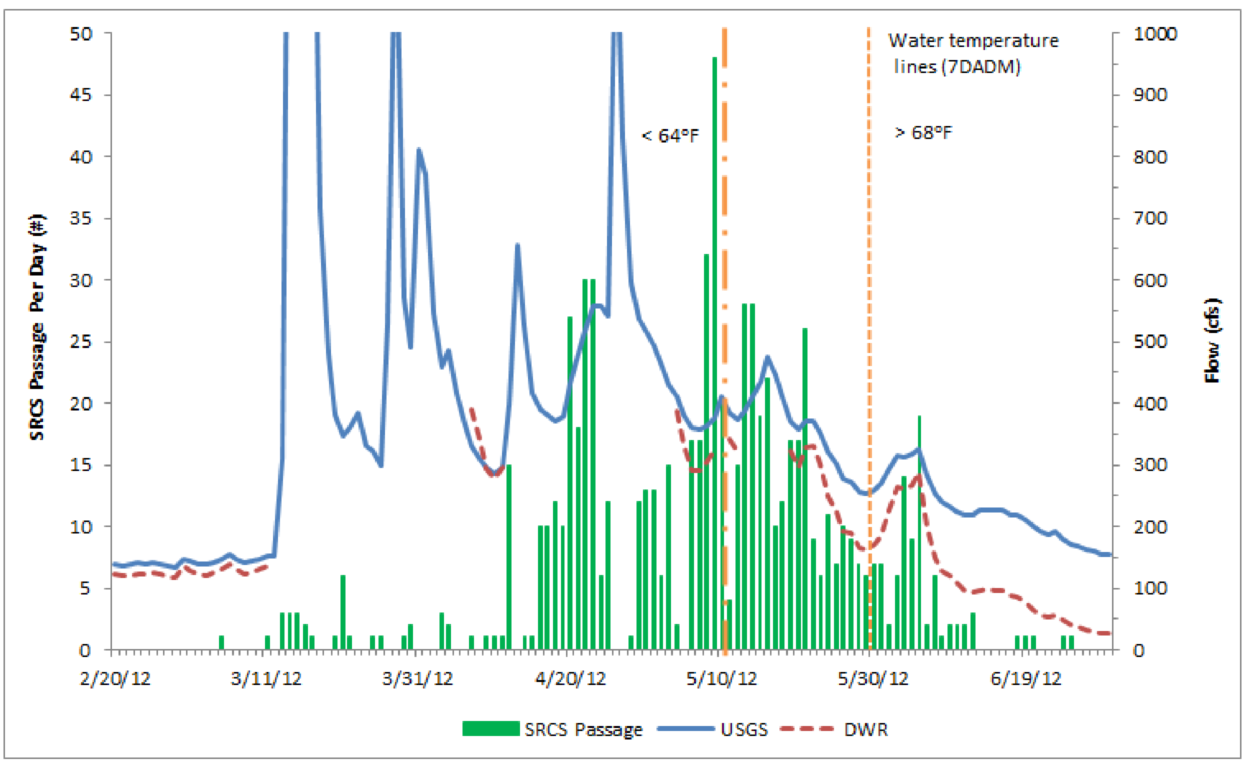


Estimated daily air temperature (°F) for the study area in water year 2014.

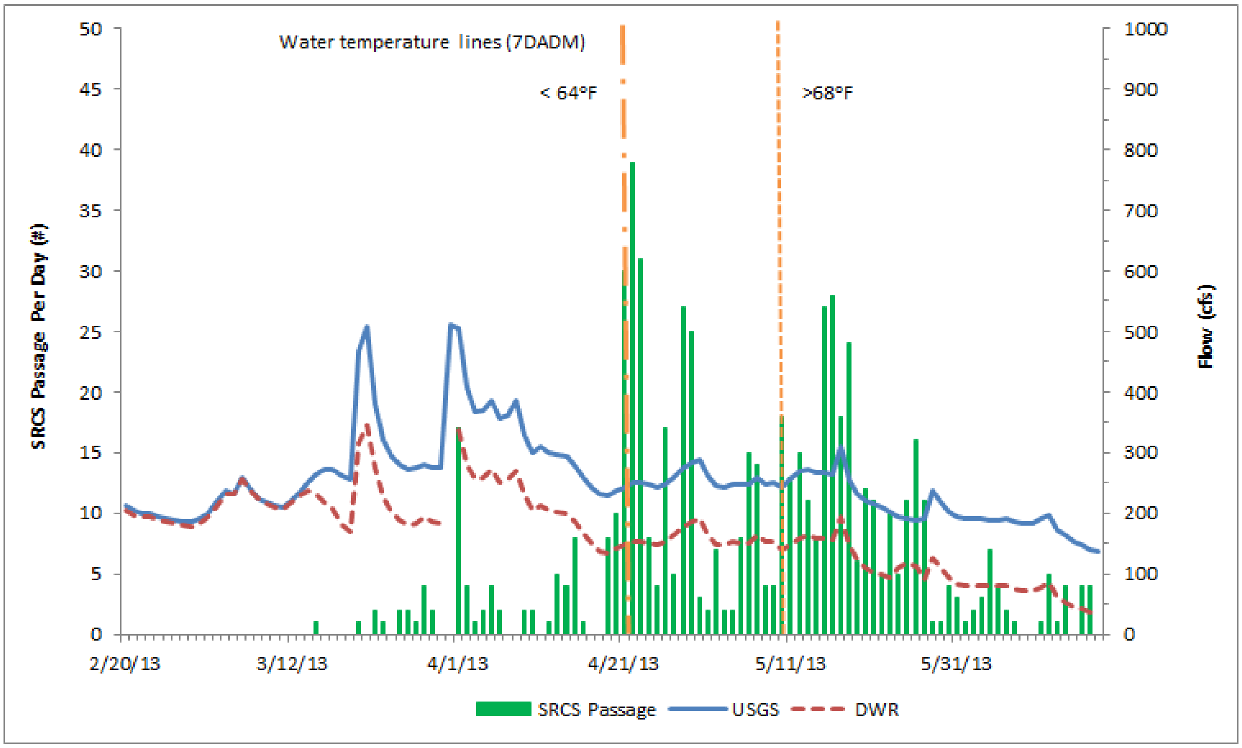
Fish Passage, Flow, and Water Temperature Criteria



Video station data, average daily flows, and EPA criteria for 2011.



Video station data, average daily flows, and EPA criteria for 2012.



Video station data, average daily flows, and EPA criteria for 2013.

Appendix B. Two-Dimensional Hydraulic Model Construction and Calibration

Model construction included seven phases as follows:

1) Development of stage-discharge relationship boundary conditions for the two-dimensional (2D) model using PHABSIM;
2) Development of a digital terrain model for the site;
3) Building best fit computational mesh for the site terrain model;
4) 2D model calibration fitting upstream discharge with downstream water surface elevation (WSEL);
5) Depth validation;
6) Hydraulic simulations at numerous flows; and
7) Passage transect delineation.

WSEL and Discharge Calibration

Physical Habitat Simulation (PHABSIM) is a model that can be used to simulate a relationship between streamflow and physical habitat for various life stages of a species of fish. For this study, it was utilized to develop rating curves from field measurements as inputs to and calibration data for the River2D model. Stage-discharge relationships were developed at two transects: one at the downstream end of the River2D site and one at the upstream end of the River2D site. The stage discharge relationship at the downstream transect was used as the downstream WSEL boundary condition in River2D and the stage discharge relationship at the upstream transect was used to calibrate the River2D model.

PHABSIM contains the three utilities for developing stage discharge relationships described above: Instream Flow Group Model #4 (*IFG4*; regression), Manning's stage discharge (*MANSQ*; Manning's n), and Water Surface Profile Model (*WSP*; water surface via step-back computation). IFG4 uses three or more measured stage and discharge pairs, along with the stage of zero flow (SZF), to develop a relationship between stage and discharge based on the following equation:

$$WSEL - SZF = aQ^b$$

The above equation is converted to log-log format and a log-log linear relationship is fit to the data.

MANSQ operates under the assumption that the condition of the channel and the nature of the streambed control WSELs. *MANSQ* uses transect survey data and three or more measured stage and discharge pairs to develop a relationship between stage and discharge based on Manning's Equation. *WSP*, the water surface profile model, calculates the energy loss between transects to determine WSELs. *WSP* requires data from the transect of interest and one downstream, at least three stages at both transects, and the three corresponding flows to perform a step backwater calculation (similar to HEC-RAS) to develop the stage discharge relationship. Generally, users first attempt to generate a stage discharge relationship using *IFG4*. Then if the *IFG4* equation does not fit the data well, they then attempt *MANSQ* and finally *WSP*.

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 (0.031 m) difference between measured and simulated WSELs[11]. *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[12] and flow; and 3) there is no more than a 0.1 foot (0.031 m) difference between measured and simulated WSELs. The first three *IFG4* criteria are not applicable to *WSP*.

IFG4 was selected as the method to predict WSELs at the upstream and downstream transects because it is the most versatile and the *IFG4* results met the performance criteria given above. By calibrating the upstream and downstream transects with *IFG4*, WSELs could be predicted for the transects at the various simulation flows being modeled with River2D.

Velocity Adjustment Factors (VAFs)[13] were examined for all of the simulated flows as a potential indicator of problems with the stage-discharge relationship. The acceptable range of VAF values is 0.2 to 5.0, and the expected pattern for VAFs is a monotonic increase with an increase in flows (USFWS 1994).

River2D models were calibrated using the highest simulation flow. The highest simulated WSELs predicted by PHABSIM for the upstream and downstream transects were used for the initial upstream boundary condition (in addition to flow) and the downstream boundary condition. The PHABSIM-predicted WSEL for the upstream transect at the highest simulation flow was used to ascertain calibration of the River2D model at the highest simulation flow. After the River2D model was calibrated at the highest simulation flow, the WSELs predicted by PHABSIM for the downstream transect, for each simulation flow, were used as an input for the downstream boundary

[11] The first three criteria are from U.S. Fish and Wildlife Service (1994), while the fourth criterion is our own criterion.
[12] The reach multiplier is used to vary Manning’s n as a function of discharge.
[13] VAFs are used in PHABSIM to adjust velocities (see Milhous et al. 1989), but in this study are only used as an indicator of potential problems with the stage-discharge relationship.

condition for River2D model production files, for the simulation flows. The following describes the PHABSIM WSEL calibration process for the upstream and downstream transects.

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 the WSELs predictions. All data were compiled and checked before entry into SEFA data files. A table of substrate and cover ranges/values was created to determine the substrate and cover for each vertical/cell (e.g., if the substrate size class was 2-4 inches (5 to 10 cm) on a transect from station 50 to 70, all of the verticals with station values between 50 and 70 were given a substrate coding of 2.4). Dry bed elevation data were entered into the spreadsheet to extend the bed profile up the banks, above the WSEL of the highest flow to be modeled. Spreadsheet data were then converted into SEFA data files.

All of the measured WSELs were checked to make sure that water was not flowing uphill. At each measured flow, the slope for each transect was computed 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 five WSEL sets at low, medium, and high flows were used. If WSELs were available for several closely spaced flows, the WSEL that corresponded with the velocity set or the WSEL collected at the lowest flow was used in the PHABSIM data files. Calibration flows in the data files were the flows measured on site.

The SZF, an important parameter used in calibrating the stage discharge relationship, was determined for each transect and entered into SEFA. 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. In some cases, data collected in between transects showed a higher thalweg elevation than either transect; in these instances the higher thalweg elevation was used as the SZF for the upstream transect. The rating curves developed in SEFA for CR2, XS1[14] and XS2 are presented below in Figures B-1 through B-3.

[14] XS1 refers to the downstream transect for the site, while XS2 refers to the upstream transect for the site. XS is an abbreviation for transect.

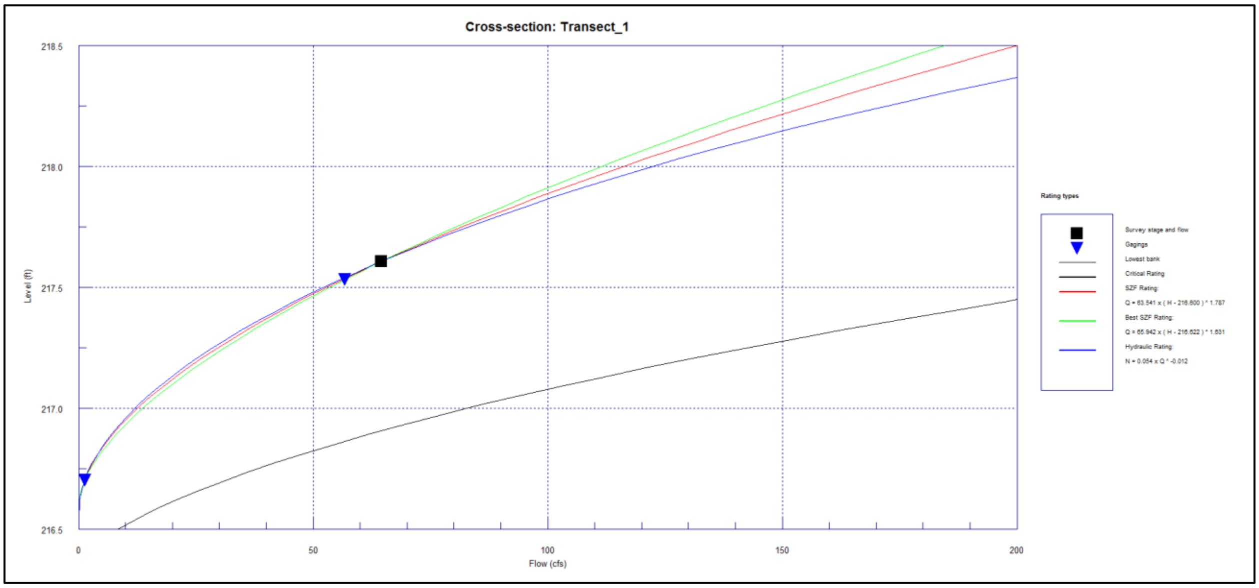


Figure B-1. CR2 XS1 high flow regime rating curve from SEFA.

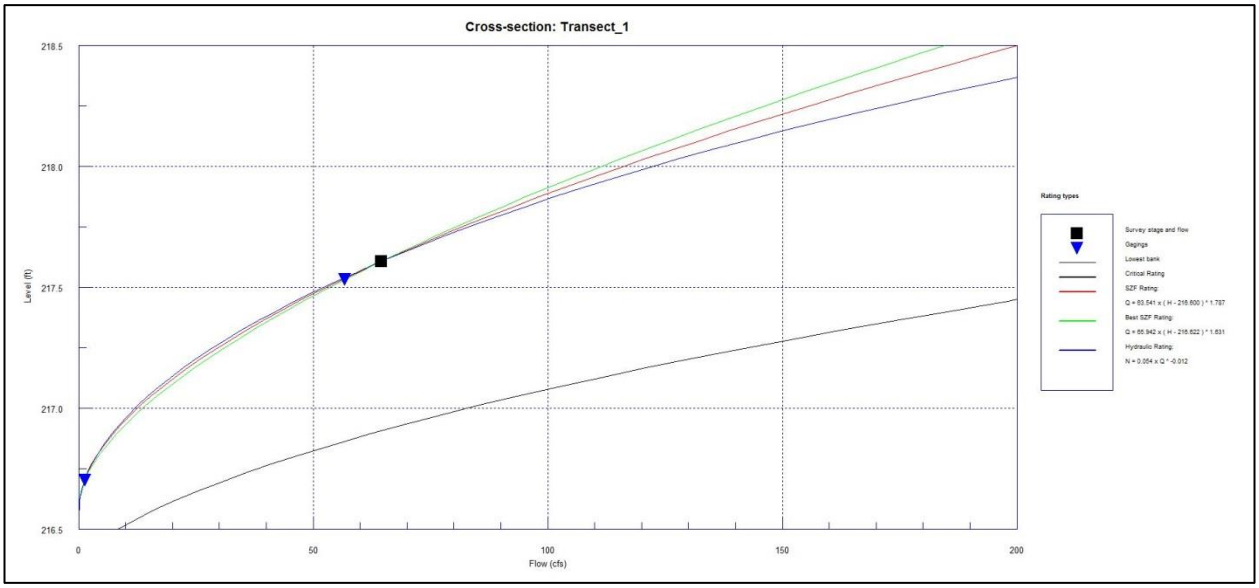


Figure B-2. CR2 XS1 low flow regime rating curve from SEFA.

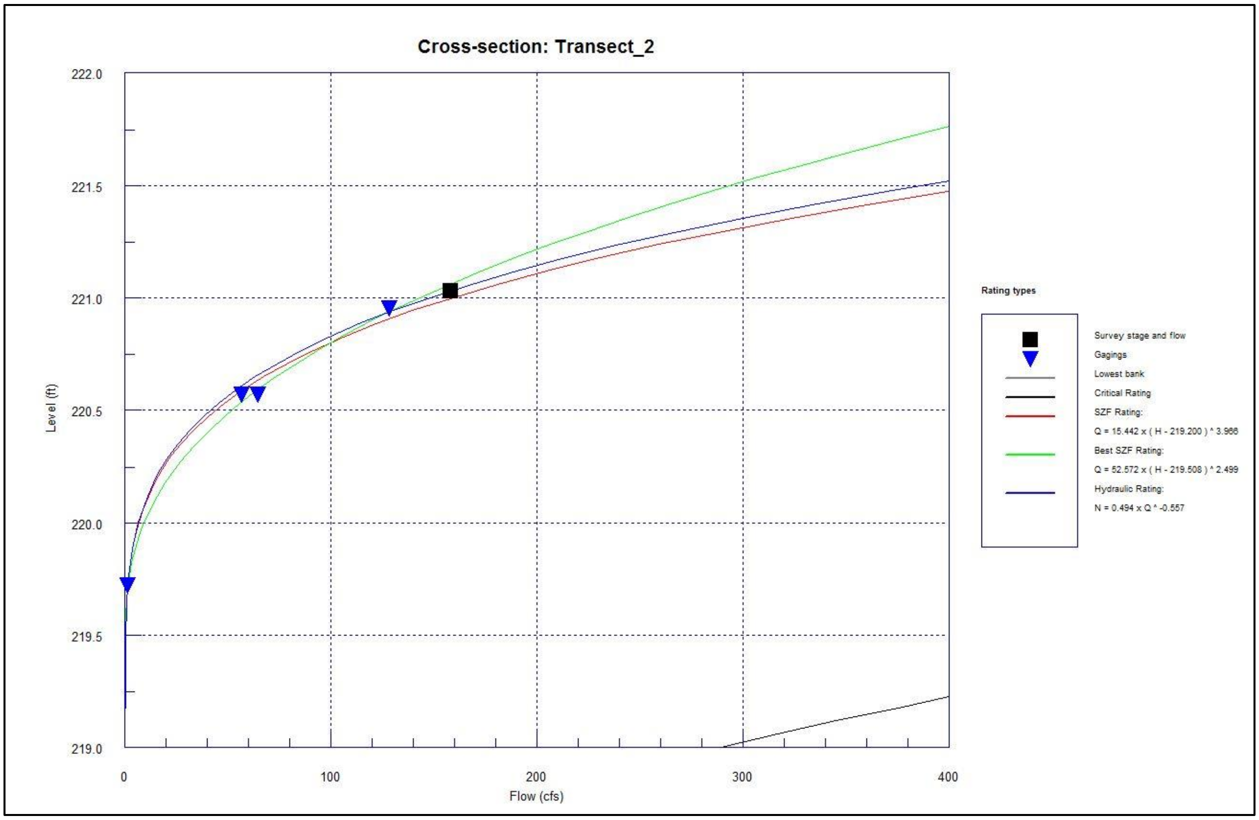


Figure B-3. CR2 XS2 rating curve from SEFA.

Rating curves were developed for the StreamTemp model using the same techniques and tools as used for the River2D model. The results for the rating curves developed for River2D and StreamTemp are presented in Appendix D.

River2D Model Construction

After the simulated WSELs are generated, construction of the River2D model, using the collected bed topography data, can begin. The total station and Real Time Kinematic Global Positioning System (RTK GPS) data, and the PHABSIM transect data were combined in a spreadsheet to create input files (bed and substrate) for the 2D modeling program. An artificial extension one channel-width-long was added upstream of the topography data collected, upstream of the study site, to enable the flow to be distributed by the model when it reached the study area. This extension minimized boundary conditions influencing the flow distribution at the upstream transect and within the study site. The bed file contains the horizontal location (northing and easting), bed elevation, and initial bed roughness value for each point. The initial bed roughness value for each point was determined from the substrate and cover codes for that point and the corresponding bed roughness values in Table B-1, with the bed roughness value for each point computed as the sum of the substrate bed roughness value and the cover bed roughness value for the point. The resulting initial bed roughness value for each point was therefore a combined matrix of the substrate and cover roughness values. The bed roughness values for substrate in Table B-1 were computed as five times the average particle size[15]. The bed roughness height values for cover in Table B-1 were computed as five times the average cover size, where the cover size was measured on the Sacramento River on a representative sample of cover elements of each cover type. The bed file was exported from the spreadsheet as an ASCII file.

Table B-1. Initial bed roughness height values for the respective substrate and cover codes used in the Mill Creek River2D model.

Substrate Code	Bed Roughness (m)	Cover Code	Bed Roughness (m)
0.1	0.05	0.1	0
1	0.1	1	0
1.2	0.2	2	0
1.3	0.25	3	0.11
2.3	0.3	3.7	0.2
2.4	0.4	4	0.62
3.4	0.45	4.7	0.96
3.5	0.5	5	1.93
4.6	0.65	5.7	2.59
6.8	0.9	7	0.28
8	1.25	8	2.97
9	0.05, 0.76, 2[16]	9	0.29
10	1.4	9.7	0.57
-	-	10	3.05

[15] Five times the average particle size is approximately the same as 2 to 3 times the d85 particle size, which is recommended as an estimate of bed roughness height (Yalin 1977).

[16] For substrate code 9, we used a bed roughness of 0.76 and 2, respectively, for cover codes 1 and 2, and a bed roughness of 0.05 for all other cover codes. The bed roughness value for cover code 1 (cobble) was estimated as five times the assumed average size of cobble (6 inches [0.15 m]). The bed roughness values for cover code 2 (boulder) was estimated as five times the assumed median size of boulders (1.3 feet [0.4 m]). Bed roughness values of zero were used for cover codes 0.1, 1 and 2 for all other substrate codes, since the roughness associated with the cover was included in the substrate roughness.

A utility program, R2D_BED (Steffler 2002), was used to define the study area boundary and to refine the raw topographical data finite element computational mesh (TIN) by defining breaklines[17] following longitudinal features such as thalwegs, tops of bars, and bottoms of banks. The first step in refining the TIN was to conduct a quality assurance/quality control process, consisting of a point-by-point inspection to eliminate quantitatively wrong points, and a qualitative process where features constructed in the TIN were checked against aerial and site photographs to make sure landforms were correctly represented. Breaklines were also added along lines of constant elevation.

An additional utility program, R2D_MESH (Waddle and Steffler 2002), was used to define the inflow and outflow boundaries and create the finite element computational mesh for the River2D model. R2D_MESH uses the final bed file as an input. The first stage in creating the computational mesh was to define mesh breaklines[18] which coincided with the final bed file breaklines. Additional mesh breaklines were then added between the initial mesh breaklines, and then additional nodes were added as needed to improve the fit between the mesh and the final bed file and to improve the quality of the mesh, as measured by the Quality Index (QI) value. An ideal mesh (all equilateral triangles) would have a QI of 1.0. A QI value of at least 0.2 is considered acceptable (Waddle and Steffler 2002). The QI is a measure of how much the least equilateral mesh element deviates from an equilateral triangle. The final step with the R2D_MESH software was to generate the computational mesh (cdg) file.

River2D Model Calibration

Following construction, the River2D model is calibrated to determine that the model is reliably simulating the flow-WSEL relationship established through the PHABSIM calibration process using the measured WSELs. The cdg files were opened in the River2D software, where the computational bed topography mesh was used together with the following elements to compute the depths, velocities, and WSELs throughout each site: the WSEL at the bottom of the site, the flow entering the site, and the bed elevations and roughness heights of the computational mesh. The basis for the current form of River2D is given in Ghanem et al. (1995). The computational mesh was run to steady state at the highest flow simulated. The resulting WSELs predicted by River2D at the upstream end of the site were then compared to the WSELs predicted by PHABSIM at the upstream transect. Calibration was considered to have been achieved when the WSELs predicted by River2D at the upstream transect were within 0.1 foot (0.031 m) of the WSEL predicted by PHABSIM. In cases where the simulated WSELs at the highest simulation flow varied across the channel by more than 0.1 foot (0.031 m), the highest measured flow within the range of simulated flows for River2D calibration was used.

[17] Breaklines are a feature of the R2D_Bed program which force the TIN of the bed nodes to linearly interpolate bed elevation and bed roughness values between the nodes on each breakline and force the TIN to fall on the breaklines (Steffler 2002).

[18] Mesh breaklines are a feature of the R2D_MESH program which force edges of the computation mesh elements to fall on the mesh breaklines and force the TIN of the computational mesh to linearly interpolate the bed elevation and bed roughness values of mesh nodes between the nodes at the end of each breakline segment (Waddle and Steffler 2002).

The bed roughness heights of the computational mesh elements were modified by multiplying them by a constant bed roughness multiplier (BR Mult) until the WSELs predicted by River2D at the upstream end of the site matched the WSELs predicted by PHABSIM at the top transect. The same BR Mult was used for all flows. The minimum groundwater depth was adjusted to a value of 0.05 m to increase the stability of the model. The values of all other River2D hydraulic parameters were left at their default values (upwinding coefficient = 0.5, groundwater transmissivity = 0.1, groundwater storativity = 1, and eddy viscosity parameters ε_1 = 0.01, ε_2 = 0.5, and ε_3 = 0.1).

The upstream transect was calibrated using the methods described above, varying the BR Mult until the simulated WSEL at the upstream transect matched the measured WSEL at the upstream transect. A stable solution generally has a solution change (Sol Δ) of less than 0.00001 and a net flow (Net Q) of less than 1% (Steffler and Blackburn 2002). WSELs predicted by the 2D model are expected to be within 0.1 foot (0.031 m) of the WSEL measured at the upstream transect[19].

Depth averaging models like River2D are most readily applied to subcritical stream conditions, maximum Froude Number (Max F) of less than 1.0 (<1.0)[20]. The parameter Max F is often used as a calibration tool to verify the simulated flow regime was subcritical and the water surface at any given point was stable. As stream gradients increase flow conditions transition from subcritical to transient to supercritical. Froude number (FN) is greater than 1.0 (>1.0) in supercritical conditions. Depths are more variable at any given point in supercritical conditions. River2D is capable of predicting depths in subcritical, supercritical, and transient conditions, but because of the variable water surface, predicted depths are less reliable than predictions made in subcritical areas, Max F <1.0.

River2D Model Depth Validation

Depth validation is the final step in the preparation of the hydraulic model for use in passage simulation. Depths predicted by River2D were compared with measured depths along the upstream and downstream control transects (at 128 cfs), along two possible critical riffle paths (at 157.6 and 64.3 cfs), and at 50 randomly selected sites within the modeled area (at 1.1 cfs) to determine the accuracy of the model's predictions of depths. The validation results are provided in the Depth Validation Statistics section below and include the plots from the control transects and the critical riffle path.

River2D Model Simulation Flow Runs

After the River2D model is calibrated, the flow and downstream WSEL in the calibrated cdg file are changed to provide initial boundary conditions for simulating hydrodynamics

[19] We have selected this standard because it is a standard used for PHABSIM (U. S. Fish and Wildlife Service 2000).

[20] This criterion is based on the assumption that flow in low gradient streams is usually subcritical, where the Froude number is less than 1.0 (Peter Steffler, personal communication).

of the site at the simulation flows. The cdg file for each flow contained the WSEL predicted by PHABSIM at the downstream transect at that flow. The River2D model was run at simulated flows between 10 cfs and 390 cfs. Each discharge was run in River2D to steady state. Again, a stable solution generally has a Sol Δ value of less than 0.00001 and a Net Q of less than 1%. In addition, Max F was used to evaluate model performance.

River2D Passage Transect Delineation

River2D was used to develop the flow versus width and depth relationships needed to assess passage in CR2 using the Critical Riffle Analysis (CRA) method (CDFG 2012). The shallowest course from bank to bank was recorded in the field using a RTK GPS (Figure B-4). Because it was difficult to assess in the field what the true shallowest course was for CR2, as a result of it being very wide and shallow, we recorded data in the field for six possible shallowest courses. The surveyed points were converted to a CSV file of x, y locations for each course. The CSV files were used to extract depth values from the River2D model's various flows.

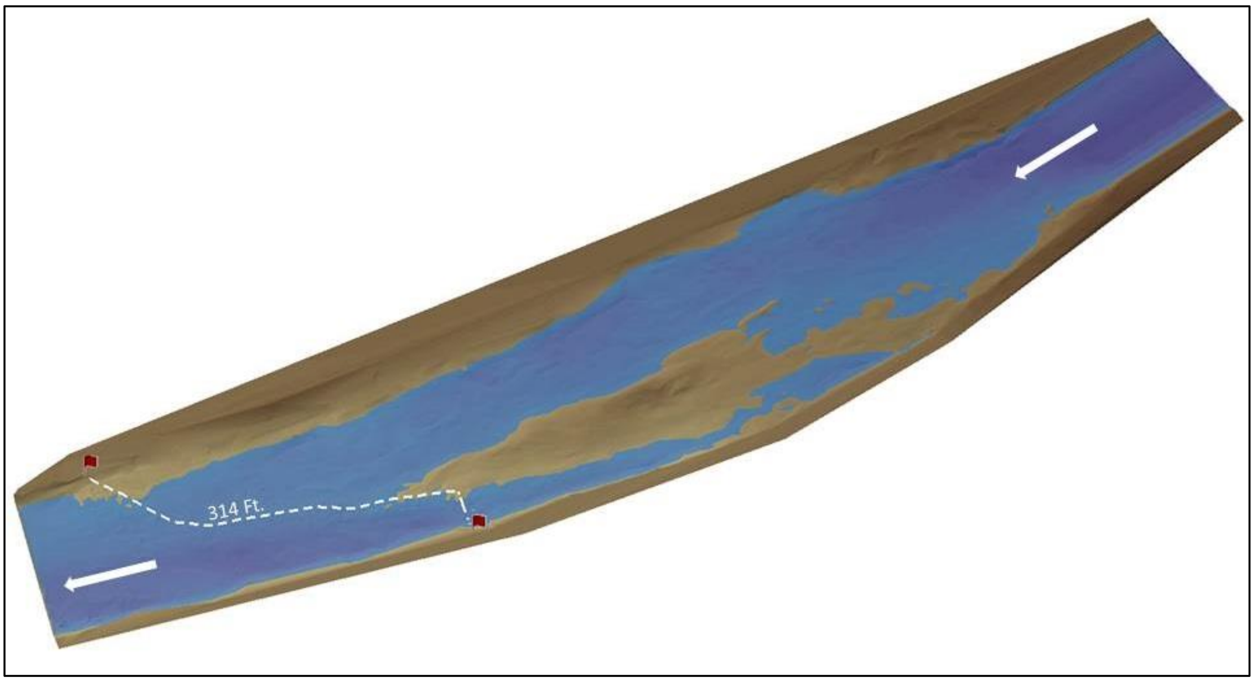


Figure B-4. Example of the shallowest course of CR2 from bank to bank.

River2D Model Development for Passage Assessment Results

The outcomes of the River2D model with respect to WSEL calibration, construction, overall model calibration, depth validation, and simulated flow runs are discussed below.

PHABSIM WSEL Calibration

There were no problems found with water appearing to flow uphill due to measurement error or inaccuracies for the study site. A total of five WSEL sets at low, medium, and high flows were used for the site. For XS1, the calibration had to be broken into two flow ranges (less than and greater than 64.3 cfs) to meet most of the criteria described in the methods for *IFG4.* For one of the two transects, *IFG4* met the criteria described in the methods for *IFG4* (Appendix D). 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 D), with the exception of the beta value for XS1 for the low flow range, which was less than 2.0. Neither of the transects deviated significantly from the expected pattern of VAFs (Figure B-5). XS1 at flows less than 220 cfs and XS2 at the lowest three flows deviated slightly from the expected pattern of VAFs. VAF values for both transects (ranging from 1.002 to 1.01) were all within an acceptable range (Table B-2).

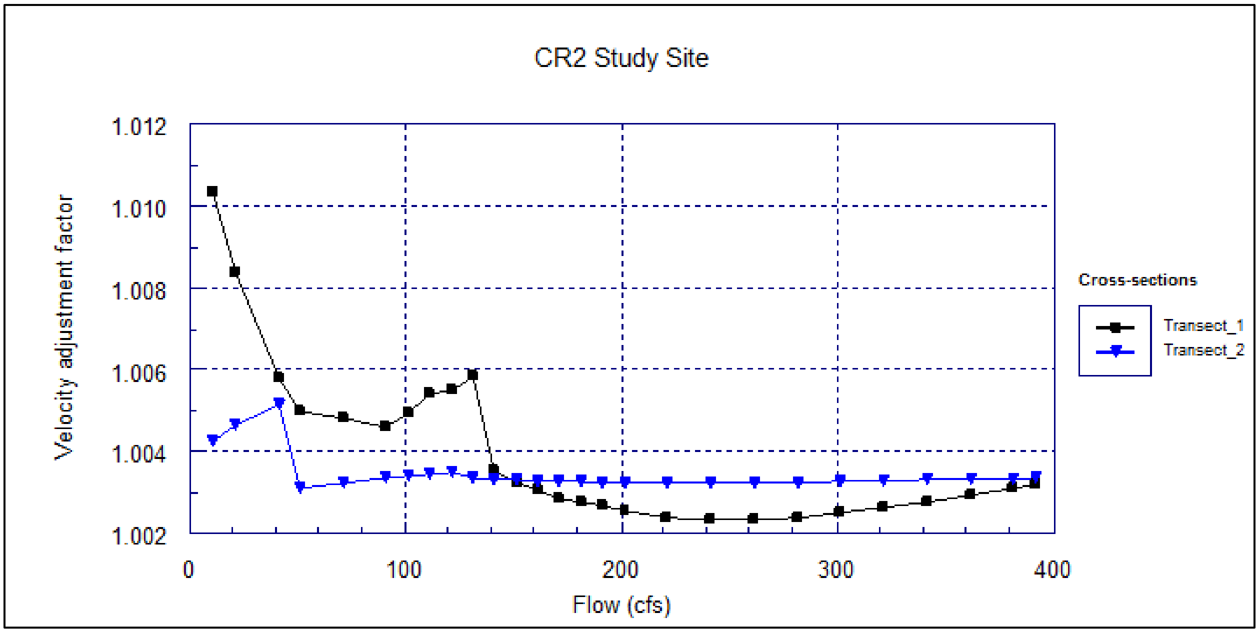


Figure B-5. Flow vs. VAF.

Table B-2. VAFs for CR2 XS1 and XS2.

	Velocity Adjustment Factors	
Flow (cfs)	**XS1**	**XS2**
10	1.01	1.003
40	1.006	1.003
70	1.004	1.003
100	1.005	1.003
120	1.006	1.003
140	1.006	1.004
160	1.004	1.004
180	1.003	1.004
200	1.003	1.004
240	1.003	1.004
280	1.002	1.004
320	1.002	1.004
360	1.002	1.005
390	1.002	1.005

River2D Model Construction

The bed topography of the site is shown in Figure B-6. The finite element computational mesh (TIN) for the study site is shown in Figure B-7. The mesh had a QI value of 0.30 (Table B-3). The percentage of the original bed nodes for which the mesh differed by less than 0.1 foot (0.03 m) from the elevation of the original bed nodes was 93% (Table B-3).

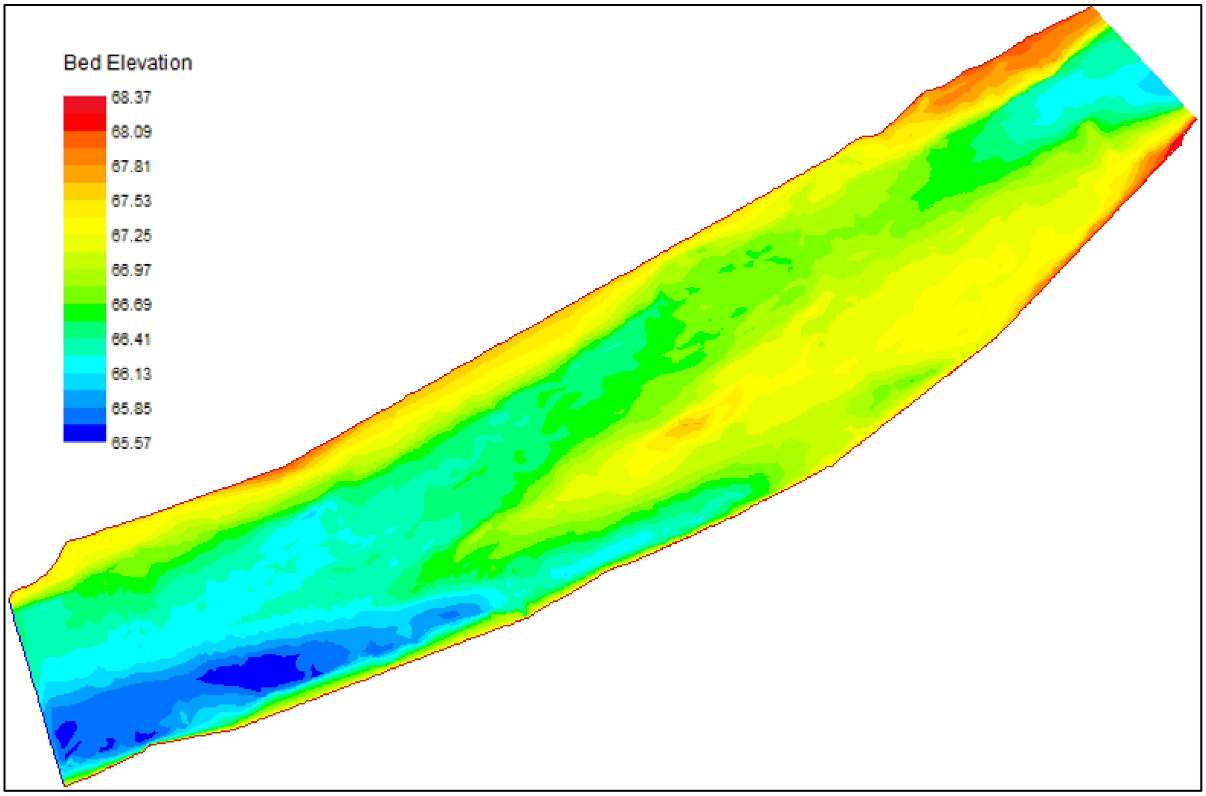


Figure B-6. CR2 bed topography. Elevation in meters.

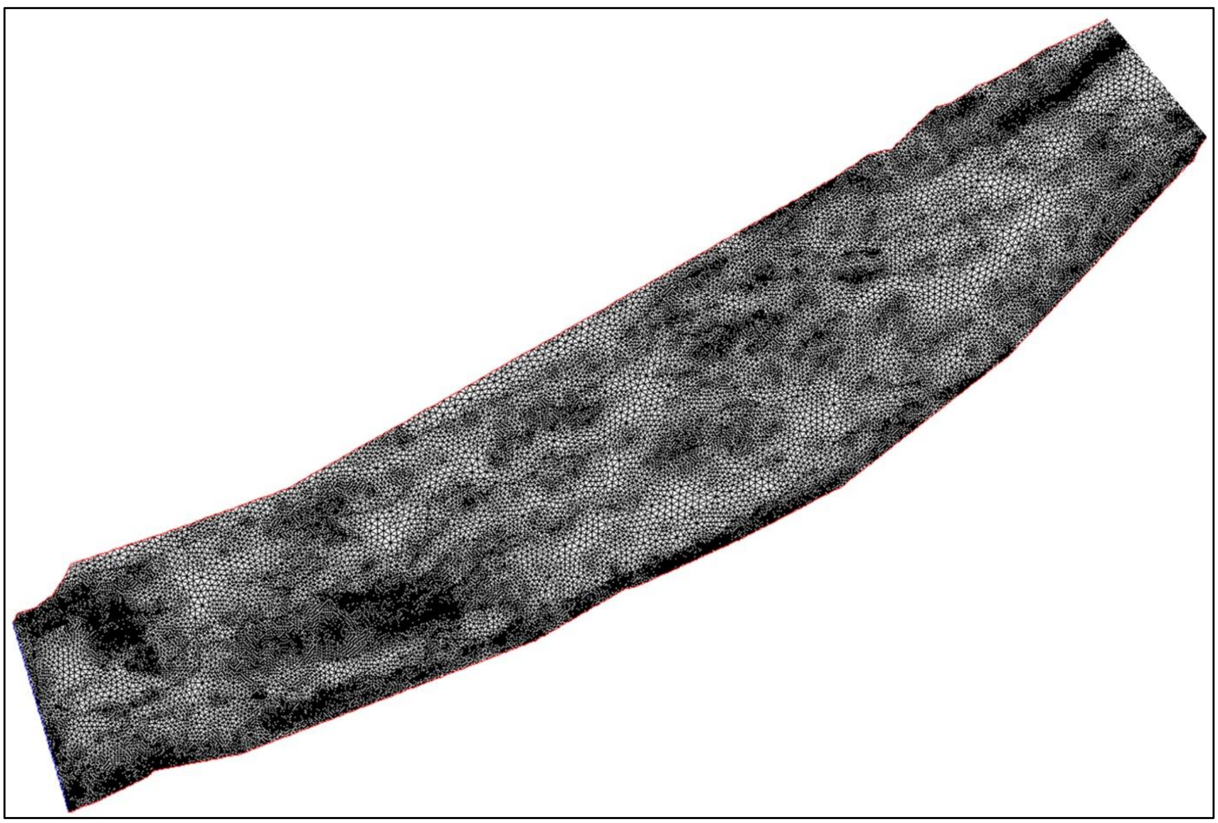


Figure B-7. CR2 site computational mesh.

Table B-3. CR2 River2D Calibration Statistics[21].

% Nodes within 0.1'	Nodes	QI	Net Q	Sol Δ	Max F
93%	30,387	0.30	0.1%	0.000006	1.26

River2D Model Calibration

The calibrated cdg file had a solution change of less than 0.00001, with the net flow (Q) less than 1% (Table B-3). The calibrated cdg file for the study site had a maximum Froude Number of greater than 1.0 (Table B-4). The study site had a calibrated cdg file with WSELs that were within 0.1 foot (0.031 m) of the PHABSIM predicted WSELs (Table B-5).

[21] QI = Quality Index, Net Q = Net Flow, Sol Δ = Solution change, Max F = Maximum Froude Number

Table B-4. CR2 River2D Simulation Statistics.

CR2 2D Model			
Flow (cfs)	**Net Q**	**Sol Δ**	**Max F**
390	0.1%	0.000006	1.26
380	0.1%	0.000005	1.28
360	0.1%	0.000006	1.28
340	0.1%	0.000001	1.25
320	0.1%	0.000002	1.28
300	0.1%	0.000002	1.31
280	0.2%	0.000004	1.35
260	0.7%	0.000005	1.42
240	0.7%	0.000004	1.59
220	0.8%	0.000002	1.77
200	1.7%	<0.000001	2.01
190	1.4%	<0.000001	2.00
180	1.2%	0.000003	1.71
170	1.1%	0.000003	1.53
160	1.4%	0.000005	1.56
150	1.4%	0.000006	1.53
140	1.7%	0.000005	1.48
130	1.6%	0.000004	1.37
120	1.6%	0.000004	1.44
110	1.1%	0.000002	1.55
100	1.1%	0.000002	1.47
90	0.8%	0.000002	1.45
70	1.0%	0.000002	1.28
50	1.1%	0.000003	1.36
40	1.4%	0.000001	1.49
20	2.7%	0.000008	0.95
10	5.8%	<0.000001	0.87

Table B-5. CR2 XS2 simulated vs. measured WSELs, absolute value, in feet.

XS	BR Mult[22]	Average	Standard Deviation	Maximum
2	0.3	0.01	0.01	0.02

River2D Model Depth Validation

There was a very strong correlation (0.95) between predicted and measured depths (Table B-6). Comparisons of measured versus predicted depths for the model are presented in Figure B-8. Although the randomly collected depth measurements were slightly variable when compared to model simulations at CR2 (Table B-7), the results of the measured versus simulated depths on the cross section transects were generally consistent with the highest frequencies of differences being observed within ± 0.10 ft for XS1 and ± 0.20 ft for XS2 (Figures B-9 and B-10). For the critical riffle measurements, depths were consistently over-predicted in the westernmost 20 to 30 feet of the channel (Figures B-11 and B-12). For the rest of the channel, differences between measured and simulated depths were generally within ± 0.10 ft.

Table B-6. Correlation between simulated and measured depths.

Number of Observations	Correlation Between Measured and Simulated Depths
377	0.95

[22] BR Mult = Bed Roughness Multiplier

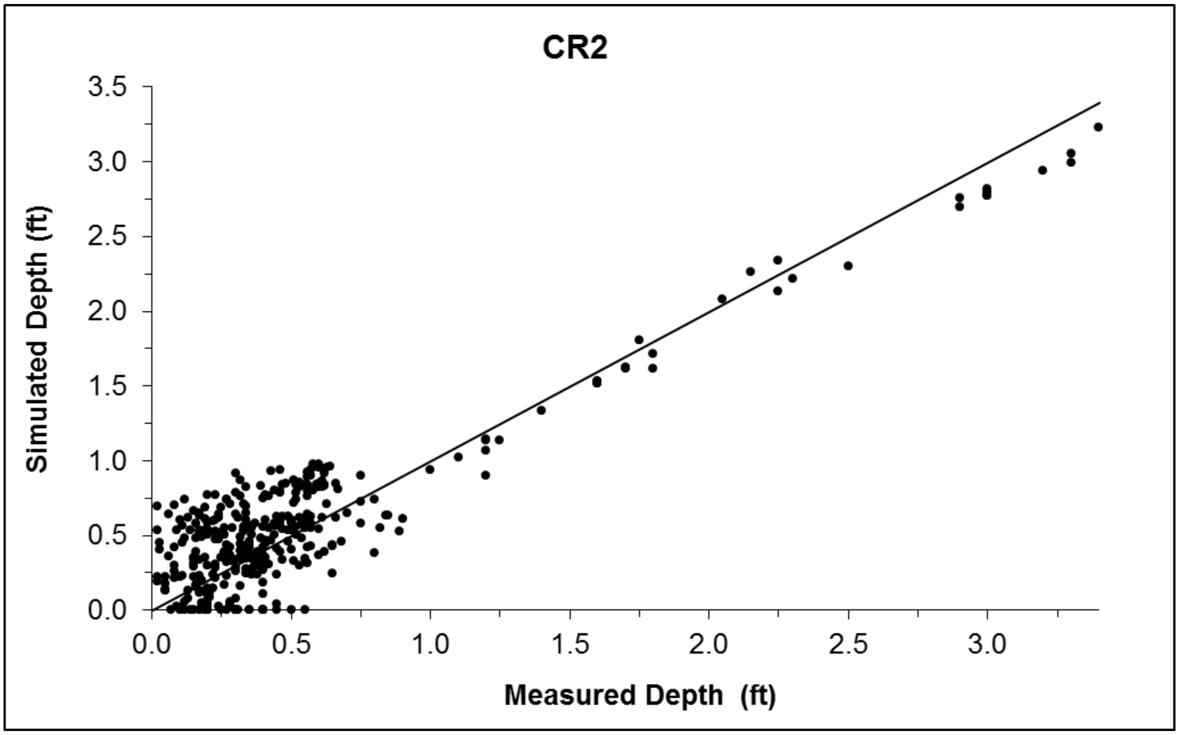


Figure B-8. CR2 simulated vs. measured depths.

Table B-7. Difference (measured vs. predicted depths, absolute value, in feet).

Average	Standard Deviation	Maximum
0.2	0.1	0.7

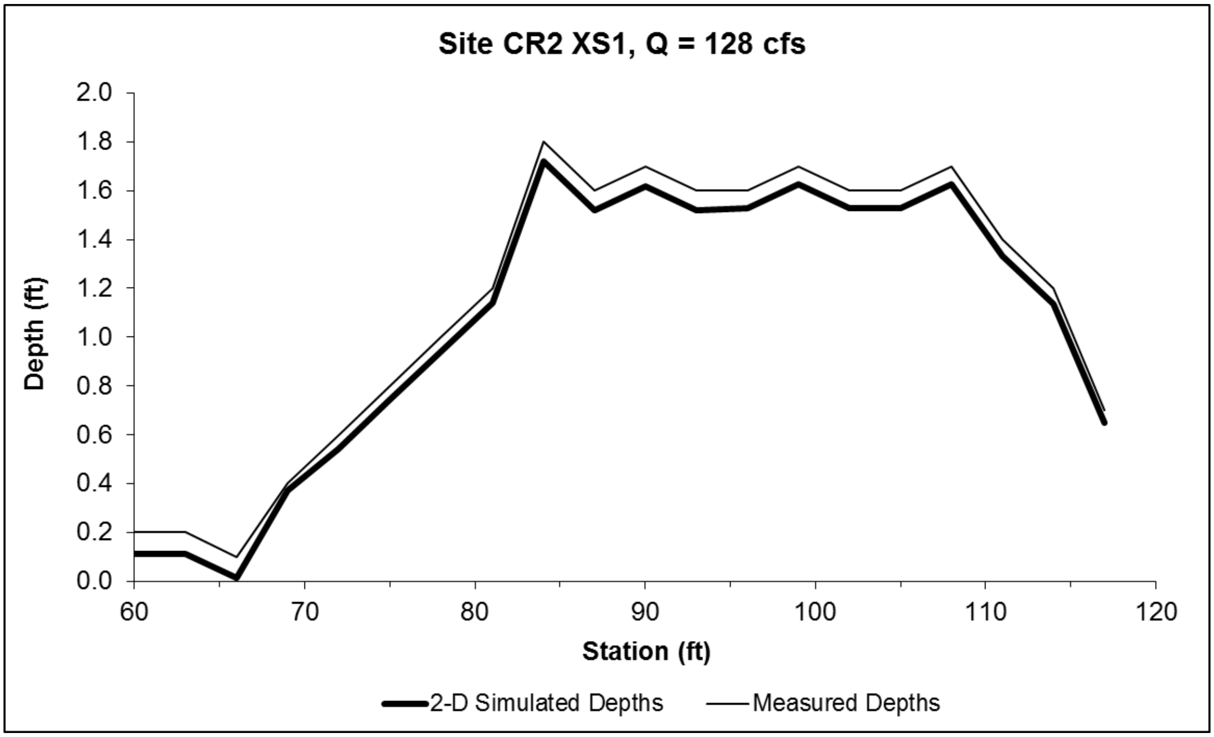


Figure B-9. CR2 XS1 simulated vs. measured depths at 128 cfs.

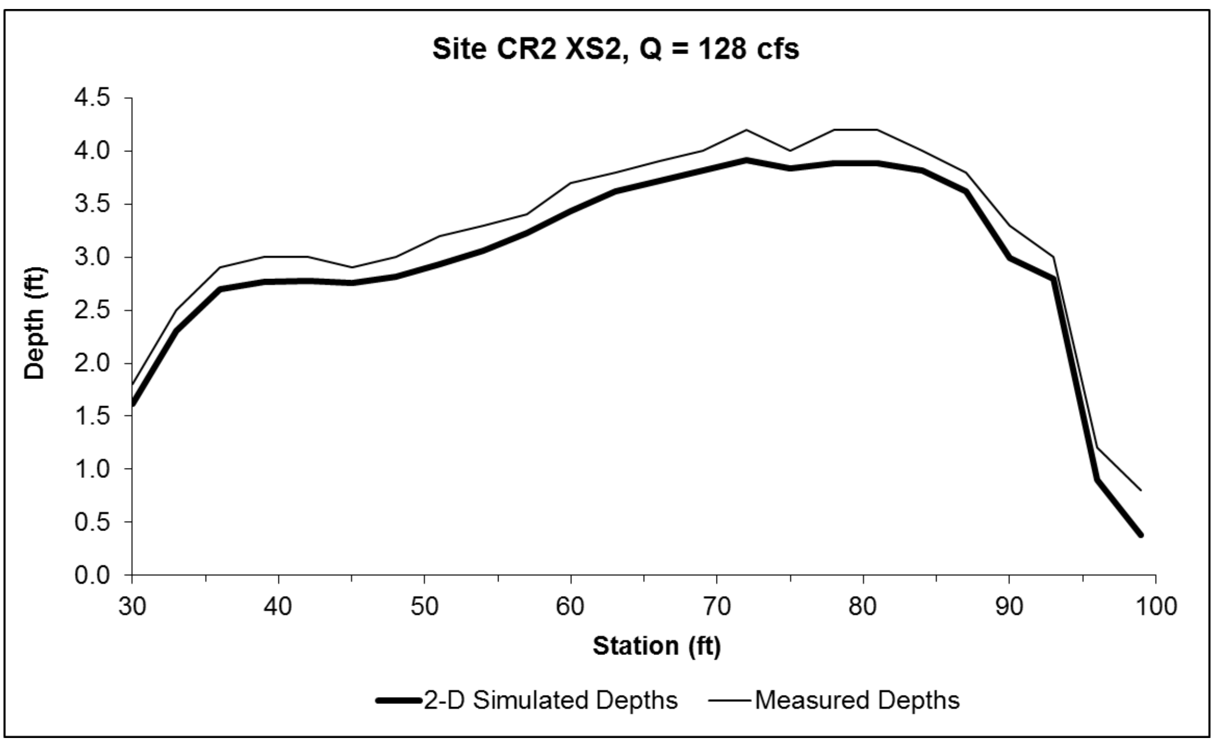


Figure B-10. CR2 XS2 simulated vs. measured depths at 128 cfs.

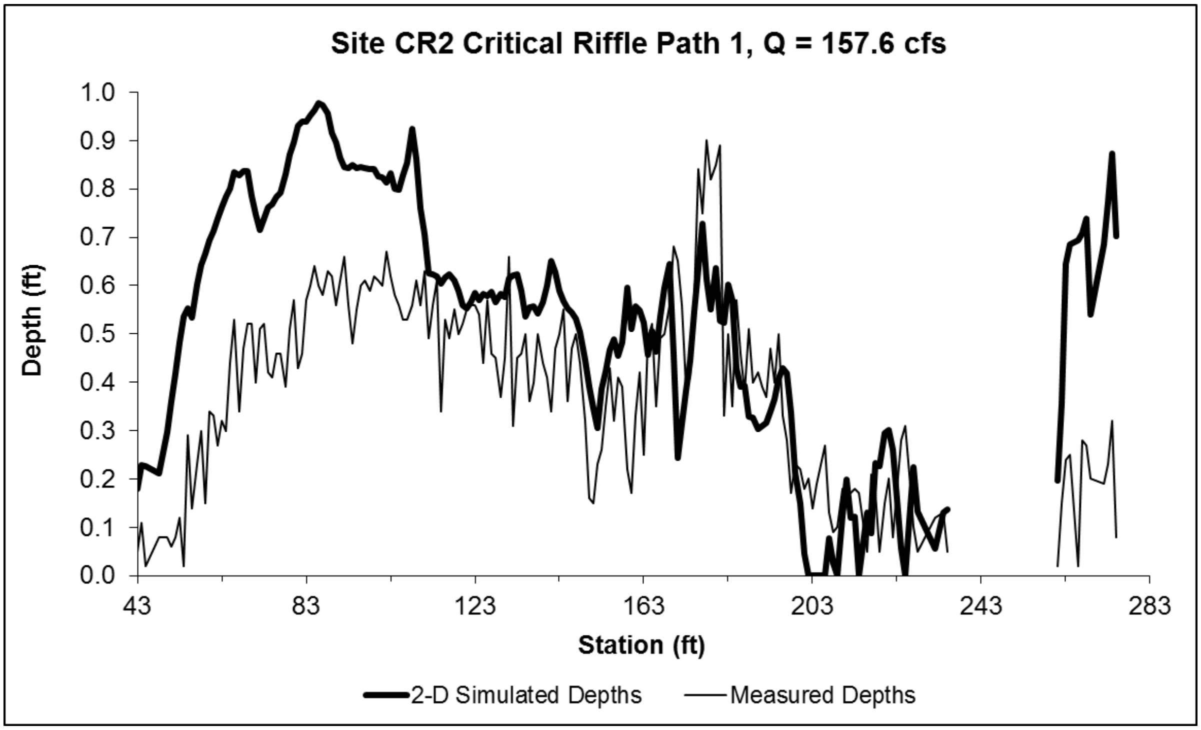


Figure B-11. CR2 Critical riffle path simulated vs. measured depths at 157.6 cfs.

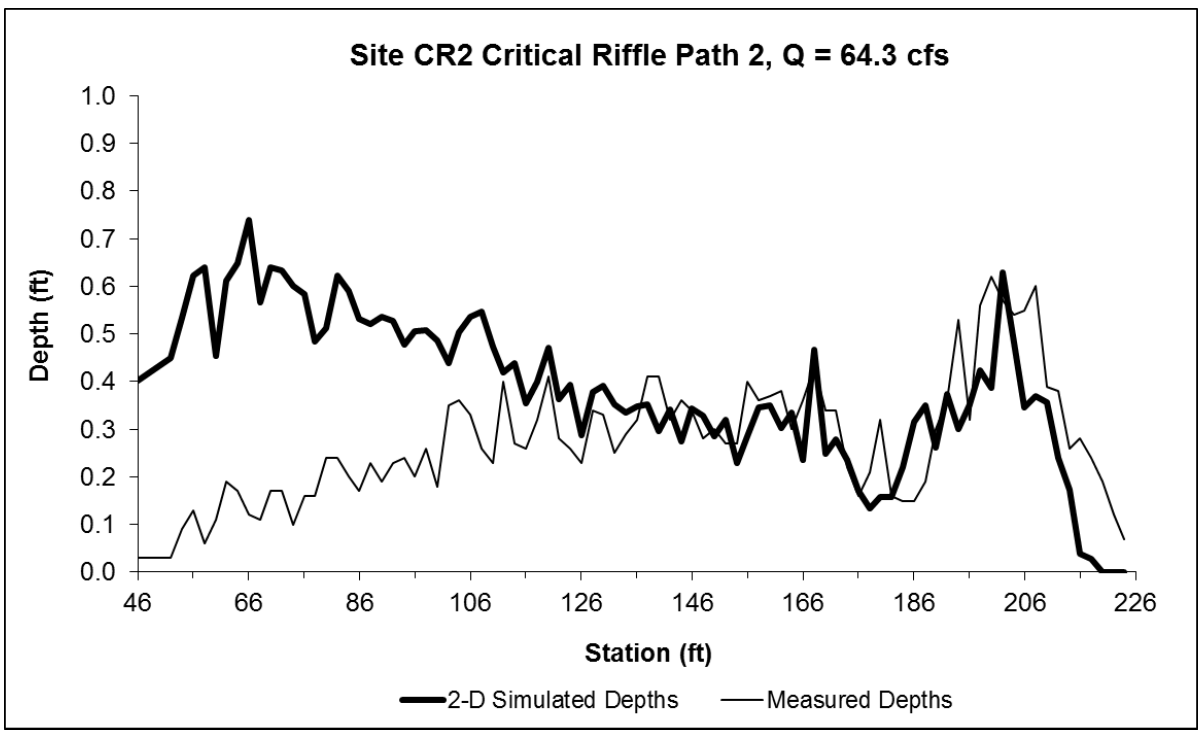


Figure B-12. CR2 critical riffle path simulated vs. measured depths at 64.3 cfs.

River2D Model Simulation Flow Runs
Simulation flows were 10, 20, 40, 50 cfs, 50 to 90 cfs by 20 cfs increments, 90 to 200 cfs by 10 cfs increments, 200 to 380 cfs by 20 cfs increments, and 390 cfs. Overall, the model simulation performance was within acceptable ranges. For example, all corresponding solution changes (Sol Δ) were less than 0.00001 (Table B-4). Net flow values (net Q) were less than 1% for 10 of 27 flows and only exceeded 5% for the lowest flow. Maximum Froude values exceeded a value of 1 at all but the lowest two flows (Table B-4).

River2D Model Discussion

A 2D model was developed to assess wetted width, flow depth, and velocity at CR2. The performance of the River2D model when applied to CR2 is discussed below.

PHABSIM WSEL Calibration
The low beta value for the low flow calibration range of XS1 was due to an unusually strong downstream hydraulic control; given that this transect could be calibrated for flows between 10 and 390 cfs and that the beta value for the high flow calibration range was in the expected range, the calibration of this transect is considered to be acceptable. The slight deviation in the expected pattern of VAFs for lower flows for XS1 and the three lowest flows for XS2 were due to strong backwater effects of the hydraulic controls. These slight deviations from the expected pattern of VAFs are considered to be acceptable since the transects were only used to develop stage-discharge relationships for the River2D model.

River2D Model Construction
In most cases, the portions of the mesh where there was greater than a 0.1 foot (0.03 m) difference between the mesh and final bed file were in steep areas; in these areas, the mesh would be within 0.1 foot (0.03 m) vertically of the bed file within 1.0 foot (0.3 m) horizontally of the bed file location. Given that a 1-foot (0.3 m) horizontal level of accuracy occurred, such areas would have an adequate fit of the mesh to the bed file.

River2D Model Calibration
The calibration simulation was considered to be acceptable for CR2, even though Max F was greater than 1.0. Plots of FN were evaluated for CR2 at each simulation flow to identify areas where River2D predicted transient or supercritical flow. The maximum FN output for all the simulations was 2.01 at 200 cfs. The proportion of nodes with FN values >1.0 in each site is summarized in Table B-8.

Table B-8. Frequency of nodes with Froude number (FN) >1.0.

Flow (cfs)[23]	Number of Nodes	Number of Nodes FN>1	Nodes FN>1/All Nodes
200	30,387	3	0.13%

Nodes with FN >1.0 were present in CR2. Staff compared the location of the shallowest course for CR2 (Figure B-4) to determine whether the areas of FN >1.0 occurred where River2D was used to predict passage depths. Although CR2 had a very low percentage of nodes with FN >1.0, some of these nodes occurred along the shallowest course line. In addition, there was a node with a FN >2.0 along the shallowest course line at flows of 190 and 200 cfs (Figure 37 in the main report). High velocity and low depth conditions were observed in this portion of the riffle crest (Figure B-13).

Field staff did not observe supercritical flow and hydraulic jumps while collecting calibration data. All attempts were made to reduce the Net Q and the results included in the report represent staff efforts to reach the best calibration of the complex CR2 site.

Figure B-13. Area of CR2 where River2D predicted supercritical flow. View facing downstream at a flow of approximately 150 cfs.

[23] Flows in the column represent where a minimum of one foot of width was available to migrating adult SRCS along a continuous path through each site.

River2D Model Depth Validation
Differences in magnitude of depths, in most cases, are due to aspects of the bed topography that were not captured in the data collection, and differences between the underlying bed topography and the computational mesh. Differences between measured and simulated depths for the critical riffle paths likely reflect small changes in the bed topography between when the depths were measured (March 3 and April 1, 2015) and when most of the bed topography data were collected (July 2015). Although the maximum flow during the intervening time period was only 138 cfs, the bed topography data collected for the critical riffle on March 3 supports that there were some minor changes to the bed topography of the critical riffle path during that time period. Specifically, the bed elevations collected on March 3 were in general 0.3 feet higher than the surrounding bed elevations collected in July, and as a result the bed topography data collected on March 3 was not used to develop the bed topography of the site. The most likely cause of the discrepancy between the depths measured on April 1 and the simulated depths is deposition of substrate downstream of the critical riffle on the west side of the channel, which would have raised the WSEL on that portion of the critical riffle. We have no means to test this hypothesis, since topography data was only collected for the critical riffle path on April 1. However, since the River2D model was validated for CR2, we conclude that the depth validation was acceptable for this site.

Results are only shown for the two critical riffle maps where we measured depths along the critical riffle. For the other critical riffle paths that were mapped in the field, we did not measure depths due to time constraints. As a result, we are only able to compare simulated and measured depths for the two critical riffle maps where we measured depths. The standard practice for River2D studies is to collect depth validation data at one flow. We exceeded this practice for this study by collecting depth validation data at four flows (157.6, 128, 64.3 and 1.1 cfs).

River2D Model Simulation Flow Runs
For CR2, field staff did not observe supercritical flow and hydraulic jumps while collecting calibration data. In the case of CR2 at 10 cfs, where the Net Q exceeded the 5% level, attempts were made to reduce Net Q and the results included in the report represent the best calibration results attainable at this complicated site. We consider that a level of uncertainty applies to the results from this production file. The standard practice for River2D is to use the same Bed Roughness Multiplier value for all flows, so the roughness heights are the same for low and high flows. River2D calculates roughness values (Chézy coefficients) from depth and roughness heights, so the roughness values do vary with flow.

River2D Outputs

Table B-9. River2D model run results of total and contiguous width in feet meeting the minimum depth criteria for adult Chinook salmon for site CR2.

Adult Chinook Salmon (minimum depth criteria = 0.9 ft)		
Maximum Wetted Width = 319 ft		
Flow (cfs)	**Total Passable Width (ft)**	**Contiguous Passable Width (ft)**
390	160	112
380	152	104
360	148	102
340	142	100
320	138	99
300	126	94
280	116	60
260	94	48
240	70	48
220	52	36
200	38	20
190	28	18
180	24	18
170	14	6
160	12	6
150	7	4
140	2	2
130	0	0
120	0	0
110	0	0
100	0	0
90	0	0
70	0	0
50	0	0
40	0	0
20	0	0
10	0	0

Table B-10. River2D model run results of total and contiguous width in feet meeting the minimum depth criteria for adult steelhead for site CR2.

Adult Steelhead (minimum depth criteria = 0.7 ft)		
Maximum Wetted Width = 319 ft		
Flow (cfs)	Total Passable Width (ft)	Contiguous Passable Width (ft)
390	178	148
380	168	142
360	162	112
340	160	112
320	158	112
300	152	104
280	148	102
260	138	100
240	136	98
220	126	94
200	96	48
190	80	48
180	70	48
170	60	42
160	48	36
150	40	20
140	30	18
130	22	16
120	14	6
110	11	4
100	7	4
90	2	1
70	0	0
50	0	0
40	0	0
20	0	0
10	0	0

References

California Department of Fish and Wildlife (CDFW). 2015. Critical Riffle Analysis for Fish Passage in California. California Department of Fish and Wildlife Instream Flow Program Standard Operating Procedure DFW-IFP-001, 26 pp. October 2012, updated February 2015. Available at: https://www.wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/SOP

Ghanem, A., P. Steffler, F. Hicks and C. Katopodis. 1995. Two-Dimensional Modeling of Flow in Aquatic Habitats. *Water Resources Engineering Report* 95-S1, Department of Civil Engineering, University of Alberta, Edmonton, Alberta. March 1995.

Jowett, I., T. Payne and R. Milhous. 2013. SEFA System for Environmental Flow Analysis. Software Manual Version 1.2. Pukekohe, New Zealand.

Milhous, R.T., M. Updike, and D. Schneider. 1989. Physical habitat simulation system reference manual. Version II. Instream Flow Information Paper No. 26 U.S. Fish and Wildlife Service Biological Report 89(16).

Steffler, P. 2002. River2D_Bed. Bed Topography File Editor. User's manual. University of Alberta, Edmonton, Alberta. 32 pp. Available at: http://www.River2D.ualberta.ca/download.htm

Steffler, P. and J. Blackburn. 2002. River2D: Two-dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat. Introduction to Depth Averaged Modeling and User's Manual. University of Alberta, Edmonton, Alberta. 120 pp. Available at: http://www.River2D.ualberta.ca/download.htm

U.S. Fish and Wildlife Service (USFWS). 1994. Using the computer based physical habitat simulation system (PHABSIM). Fort Collins, CO: U.S. Fish and Wildlife Service.

Waddle, T. and P. Steffler. 2002. R2D_Mesh - Mesh Generation Program for River2D Two Dimensional Depth Averaged Finite Element. Introduction to Mesh Generation and User's manual. U.S. Geological Survey, Fort Collins, CO. 32 pp. Available at: http://www.River2D.ualberta.ca/download.htm

Yalin, M.S. 1977. Mechanics of Sediment Transport. Pergamon Press, New York.

Appendix C. StreamTemp Model Construction, Calibration, and Validation

Water Temperature Model Construction

All data were compiled and checked before entry into the System for Environmental Flow Analysis (SEFA) data files. A separate SEFA file was constructed for each reach. Water surface elevations (WSELs), transect slopes, and stage of zero flow (SZF) were determined using the same methods used for 2D model calibration (see Appendix B). A total of three to four WSEL sets at low, medium, and high flows were used. Calibration flows in the data files were the flows measured in each reach. *IFG4*, *MANSQ*, and *WSP* models were assessed using the same criteria used for Physical Habitat Simulation (PHABSIM) WSEL calibration (see Appendix B).

After the transect stage-discharge relationships were calibrated, the SEFA files were used to generate wetted width and average depth for flows of 20 to 380 cfs for Reach 1, 30 to 375 cfs for Reach 2, and 30 to 345 cfs for Reach 3 (Appendix D). 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 used to compute the width parameters (width A constant, width B coefficient and maximum width[24]) in StreamTemp[25]. 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 2.3).

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 height using the following formula:

Vegetation height = 0.5 x maximum width x tan (vegetation shade angle)

Vegetation crown widths were calculated by multiplying the vegetation height by 0.57[26]. Data to compute topographic shade angles were developed from a digital terrain model in GIS. 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

[24] The maximum width used in StreamTemp was calculated from the log-log regression equation using the highest simulated flow.
[25] StreamTemp is a commercially produced software (Payne and Associates 2005) that incorporates the modeling procedures used in SNTEMP.
[26] 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 Mill Creek.

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:

$$\text{Topographic shade angle} = \text{Atan}\left(\frac{\text{horizon elevation - stream channel elevation}}{\text{distance}}\right)$$

The reach 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 3 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 Mill Creek is located 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 nodes and reaches. Nodes were defined at the upstream and downstream end of each reach. The next step in entering data into the StreamTemp data files is to input the reach channel geometry parameters for each reach. Next, a time series of hydrology data were entered into StreamTemp, including diversion flows at the Ward Diversion Dam, computed as the difference between Reach 1 and 2 flow data from the pressure transducers, and return flows from the main canal fish screen, computed as the difference between Reach 2 and 3 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 3 (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 10 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 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°F; 5) number of predicted errors greater than 1.0°F less than 10 percent; and 6) minimal bias. 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.

For validation, Reach 1 was broken up into two subreaches, one downstream and one upstream of the DWR A04420 gage, located 0.4 miles downstream of Highway 99 and 0.8 miles upstream of the Sacramento River, respectively. The Mill 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 5, 2015, and by comparing simulated water temperatures at the downstream end of the upper subreach of Reach 1 to the measured water temperatures at the DWR gage, for the period of January 14, 2008 to April 9, 2014[27]. For the 2008 to 2013 validation, water temperatures from USGS 11381500 were used for the water temperatures at the upstream end of the model. The total diversions were computed as the difference between flows from the USGS and DWR gage. The diversions from the Upper Diversion Dam and Ward Diversion Dam were calculated from the flows from the USGS gage and the flows from the pressure transducers in Reaches 1 and 2 for the time period of March 31 to July 29, 2014. Based on these calculated diversions, the diversion at the upper diversion dam was zero for total diversions less than 25 cfs. For total diversions greater than 25 cfs,

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

the following equation was derived to predict diversions at the upper diversion dam, from a linear regression of the above calculated diversions:

Upper Diversion Dam diversion = 1.9 + (0.6 x total diversions)

The return flow from the main canal fish screen was set to 36.3 cfs[28] when the Upper Diversion Dam was diverting and to zero when the Upper Diversion Dam was not diverting. The diversion at Ward Diversion Dam was calculated by subtracting the Upper Diversion Dam diversion from the total diversions. The 2015 validation was conducted using flow and water temperature data collected in 2015, using the same methods described above for calibration data collection.

To further evaluate model performance, Mill 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 were used for W3T as for StreamTemp, except that hourly meteorological data were downloaded from the RAWS website (RAWS 2015). Meteorological data used in the W3T 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 with water appearing to flow uphill due to measurement error or inaccuracies were found for any of the transects. A total of three WSEL sets at low, medium, and high flows were used for all transects, except for Transect 15 where four WSEL sets were used. For all but one transect, *IFG4* met the criteria described in the methods for *IFG4* (Appendix D). 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 D), with the exception of Transect 4, where the beta value was less than 2.0 and the difference between the measured and predicted WSELs at the medium and high flows were greater than 0.10. *MANSQ* was even worse than *IFG4* for the difference between the measured and predicted WSELs, and *WSP* could not be used because Transect 4 was the downstream-most transect in Reach 3. As a result, Transect 5 was used to represent riffles in Reach 3, since the upstream portion of the riffle encompassing Transect 5 was located in Reach 3.

[28] This was the average difference between measured Reach 2 and 3 flows in 2014.

The 2014 rating curve for the pressure transducer at Highway 99 in Reach 1 (Figure C-1) was developed from 13 flow measurements made in Reach 1, ranging from 2.7 to 247.3 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 23.8 cfs, and greater than 23.8 cfs.

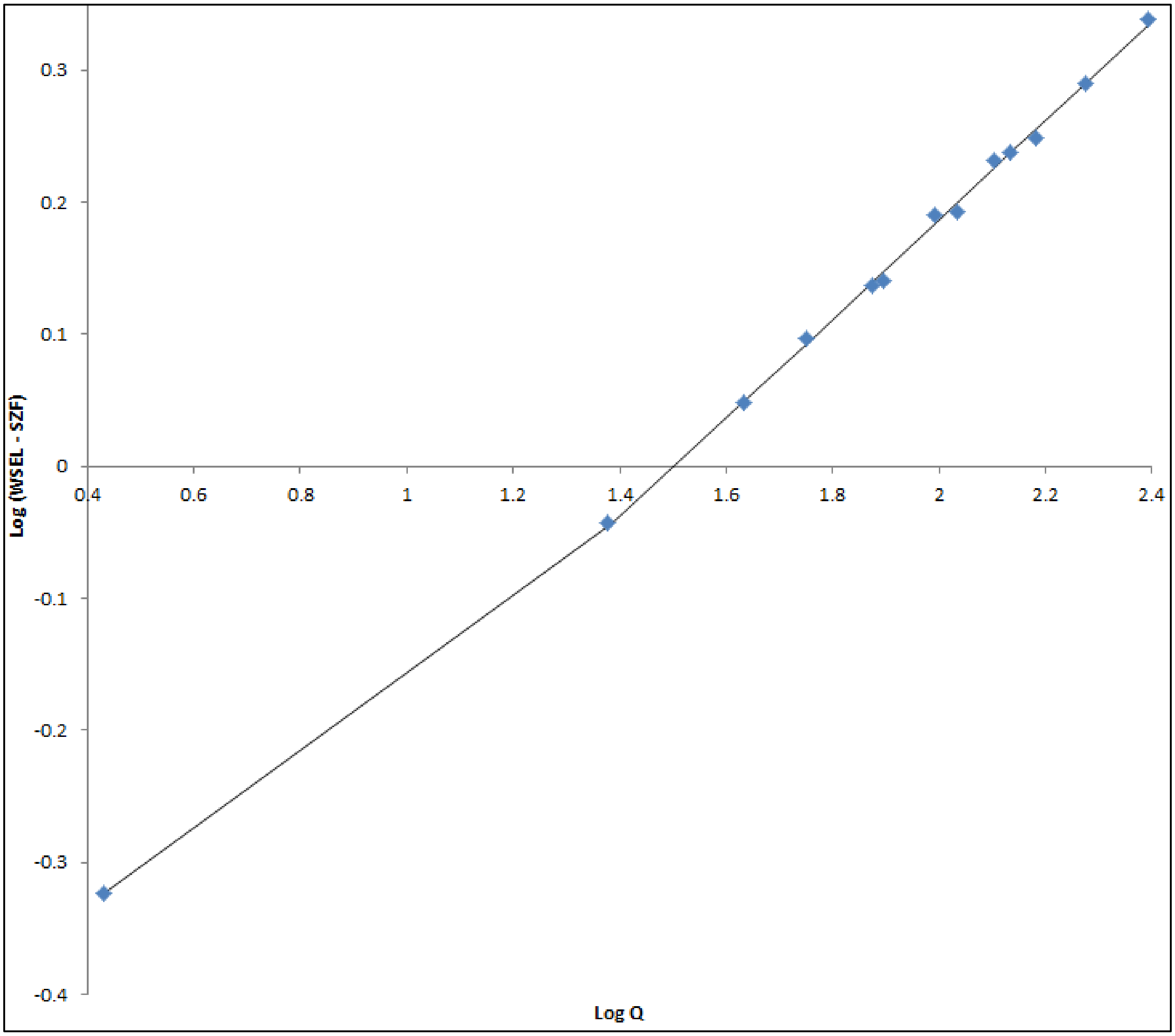


Figure C-1. 2014 Reach 1 at HWY 99 rating curve.

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:

$$\text{Flows} < 23.8 \text{ cfs: } \log(\text{flow}) = 1.521 + 3.374 \times \log(\text{stage} - 95.98)$$

$$\text{Flows} > 23.8 \text{ cfs: } \log(\text{flow}) = 1.501 + 2.672 \times \log(\text{stage} - 95.98)$$

The 2014 rating curve for the pressure transducer near CR4 in Reach 1 (Figure C-2) was developed from 11 flow measurements made in Reach 1, ranging from 2.7 to 247.3 cfs, along with the pressure transducer data at the times that the flow measurements

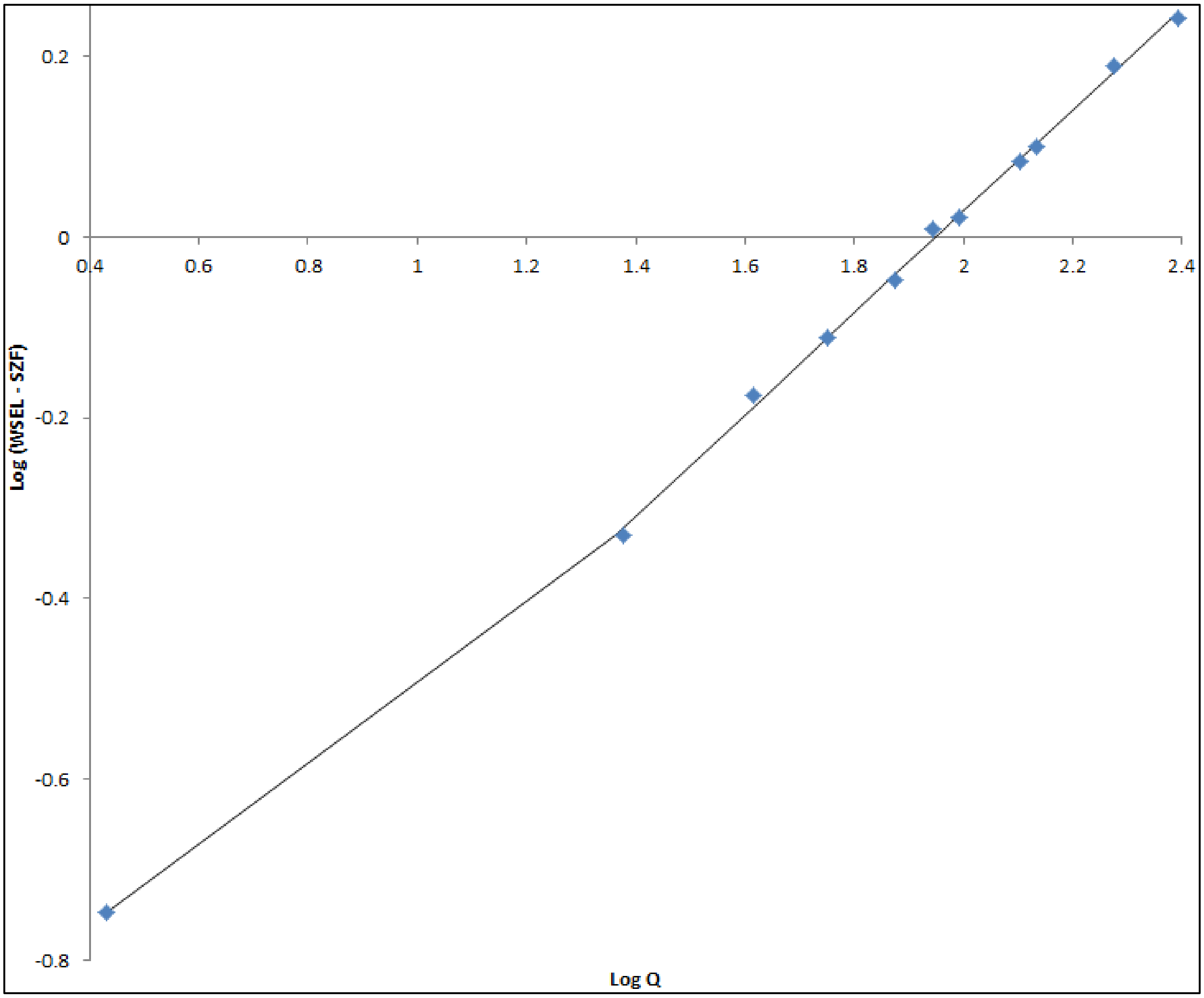


Figure C-2. 2014 Reach 1 near CR4 rating curve.

were made. The data indicated that there were two distinct log-log linear portions of the rating curve: up to 23.8 cfs, and greater than 23.8 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 < 23.8 cfs: log (flow) = 2.128 + 2.271 x log (stage – 96.97)

Flows > 23.8 cfs: log (flow) = 1.950 + 1.777 x log (stage – 96.97)

Unfortunately, we were unable to develop a rating curve in 2014 for Reach 2 as a result of faulty data collection. As a result, Reach 2 flows were calculated by adding the return flow from the main canal fish screen to the Reach 3 flows from the pressure transducer in Reach 3. We felt this was sufficiently accurate because return fish flows are relatively constant. As noted above, the return flow from the main canal fish screen in 2014 was

36.3 cfs when the Upper Diversion Dam was operating and zero when the Upper Diversion Dam was not operating.

The 2014 rating curve for the pressure transducer in Reach 3 (Figure C-3) was developed from six flow measurements made in Reach 3, ranging from 8 to 233.1 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 65.9 cfs, and greater than 65.9 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:

$$\text{Flows} < 65.9 \text{ cfs: } \log(\text{flow}) = 1.208 + 4.551 \times \log(\text{stage} - 96.5)$$

$$\text{Flows} > 65.9 \text{ cfs: } \log(\text{flow}) = 1.479 + 2.399 \times \log(\text{stage} - 96.5)$$

The Reach 3 pressure transducer was lost during high flows in the winter of 2015, and as a result the Reach 1 pressure transducer near CR4 was moved to Reach 3 on March 3, 2015. In addition, it was discovered that the pressure transducers for Reaches 1 and 3 stopped recording data on May 17, 2015. As a result, Reach 3 flows for the period of February 15 to March 2, 2015 were calculated by subtracting 6.3 cfs (the difference between measured Reach 2 and 3 flows on March 3, 2015) from Reach 2 flows. Reach 3 flows for the period of May 18 to July 5, 2015 were calculated by subtracting 10.7 cfs (the average difference between measured Reach 2 and 3 flows during that time period) from Reach 2 flows. For Reach 1, stage values recorded at the DWR gage were used together with flows measured in Reach 1 to develop a corrected rating curve for the DWR gage. The corrected rating curve was then used together with stage values from the DWR gage to calculate Reach 1 flows for the period of May 18 to July 5, 2015.

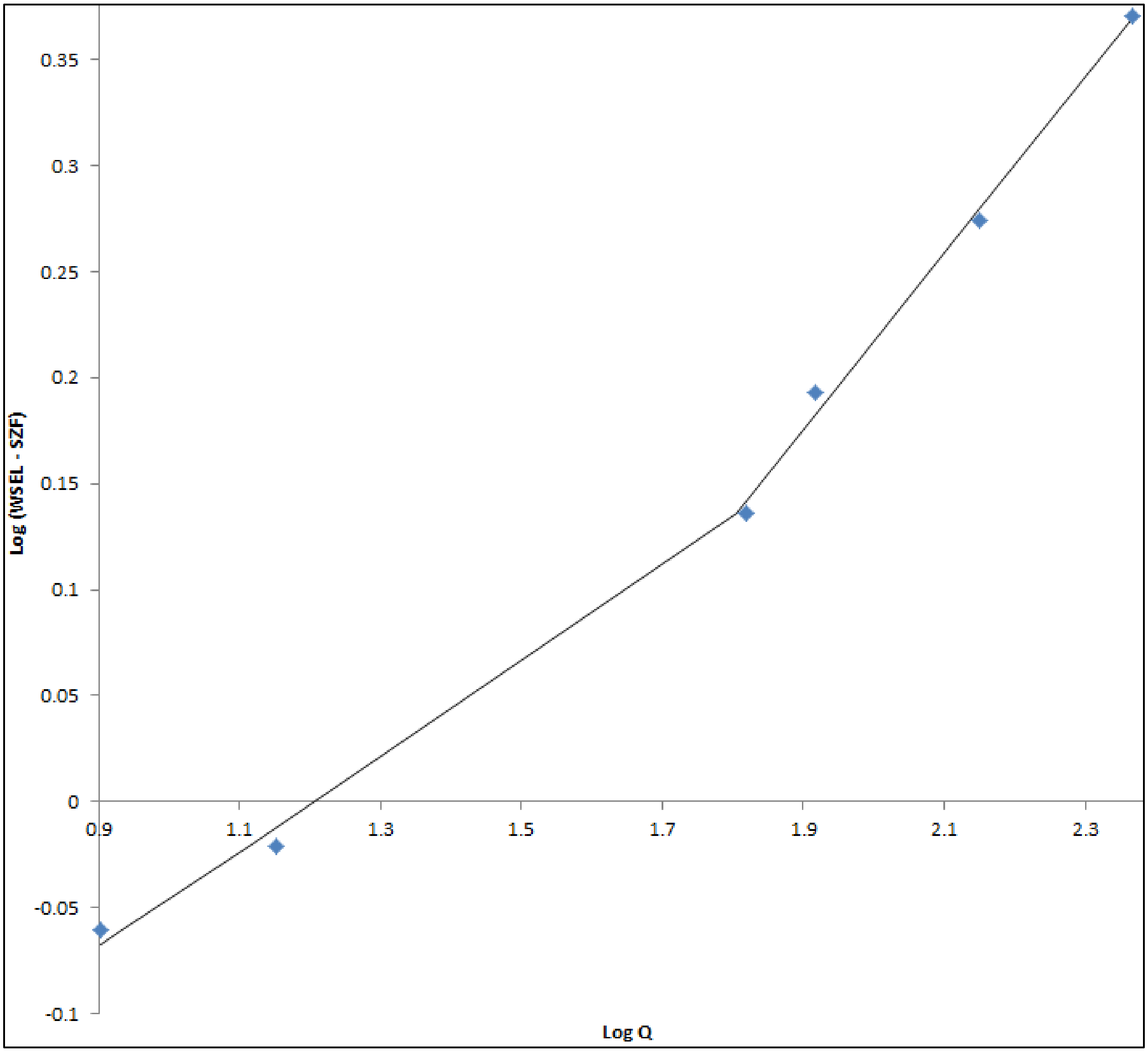


Figure C-3. 2014 Reach 3 rating curve.

The 2015 rating curve for the pressure transducer in Reach 1 (Figure C-4) was developed from three flow measurements made in Reach 1, ranging from 56.5 to 157.6 cfs, along with the pressure transducer data corresponding to the times of the field flow measurements. The resulting regression equation was as follows:

$$\text{Log (flow)} = 1.347 + 2.778 \times \log(\text{stage} - 98.6)$$

The 2015 rating curve for the pressure transducer in Reach 2 (Figure C-5) was developed from five flow measurements made in Reach 2, ranging from 31.9 to 164.7 cfs, along with the pressure transducer data corresponding to the times of the field flow measurements. The data indicated that there were two distinct log-log linear portions of the rating curve: up to 89.1 cfs, and greater than 89.1 cfs. Accordingly, the rating curve

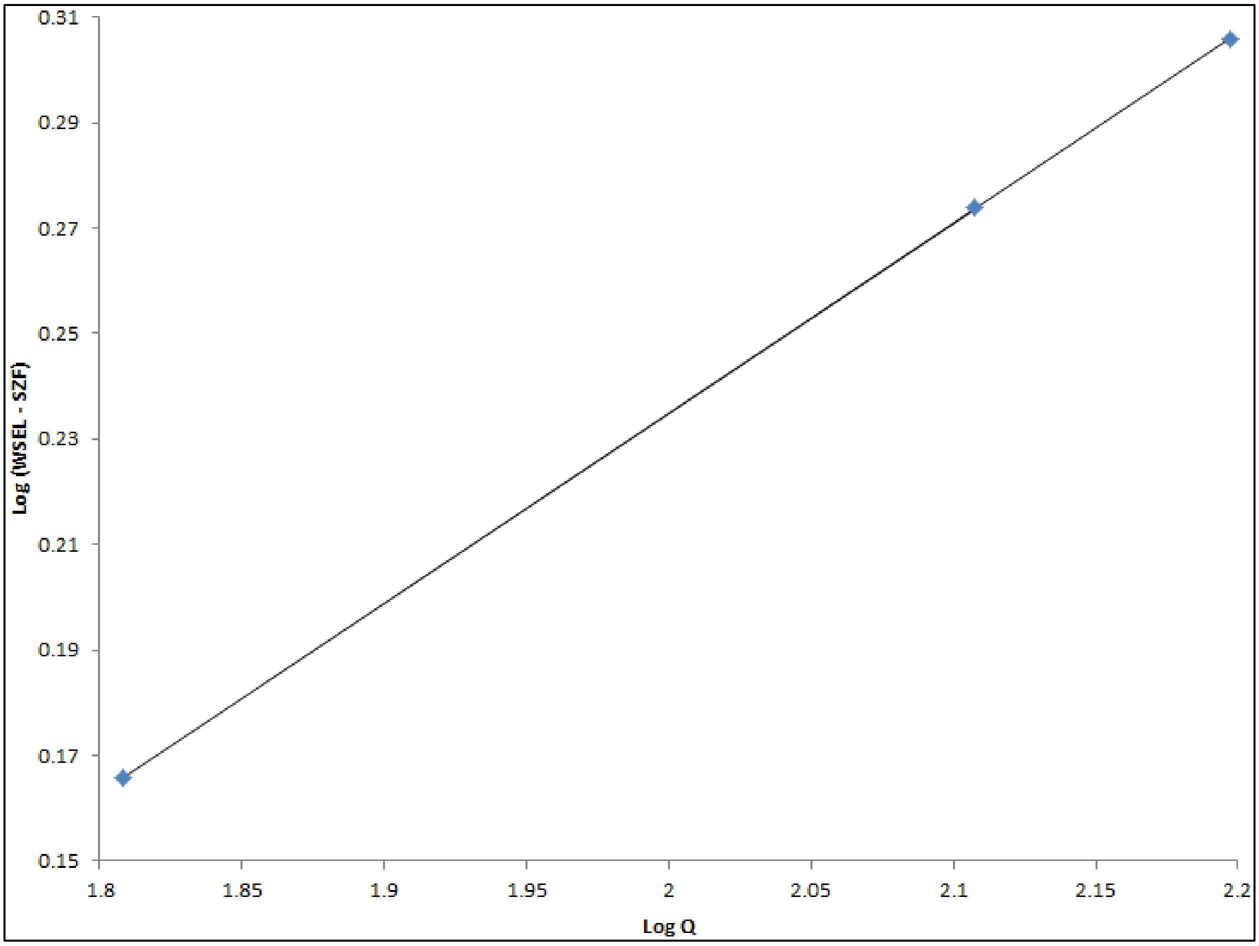


Figure C-4. 2015 Reach 1 rating curve.

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 < 89.1 cfs: log (flow) = 1.949 + 1.316 x log (stage – 99.0)

Flows > 89.1 cfs: log (flow) = 1.950 + 2.225 x log (stage – 99.0)

The 2015 rating curve for the pressure transducer in Reach 3 (Figure C-6) was developed from three flow measurements made in Reach 3, ranging from 75.9 to 158.4 cfs, along with the pressure transducer data corresponding to the times of the field flow measurements. The resulting regression equation was as follows:

Log (flow) = 1.492 + 2.254 x log (stage – 98.5)

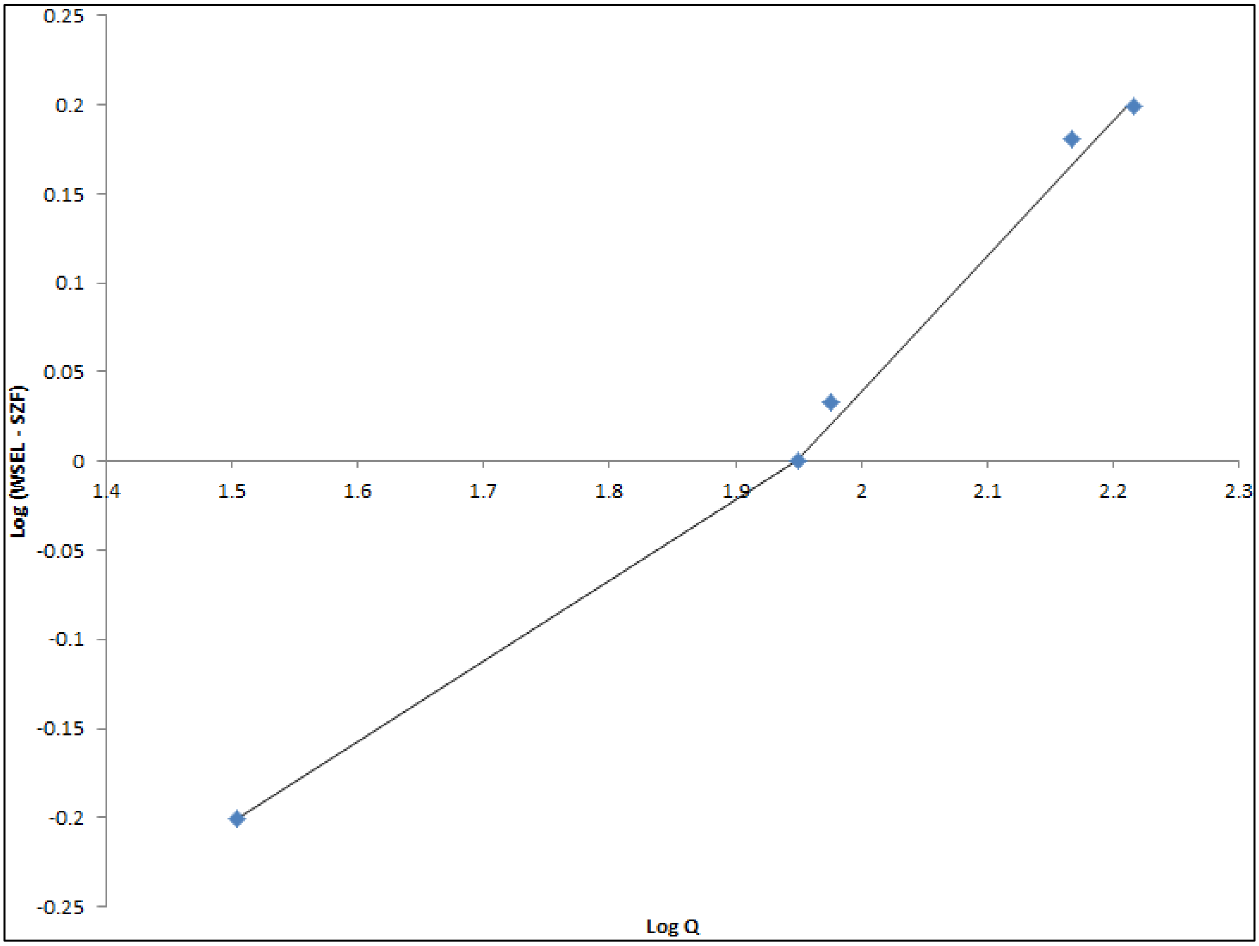


Figure C-5. 2015 Reach 2 rating curve.

The rating curve for the DWR gage (Figure C-7) was developed from three flow measurements made in Reach 1, ranging from 0.2 to 128 cfs, along with the DWR gage height data corresponding to the times of field flow measurements. The resulting regression equation was as follows:

Log (flow) = 1.730 + 2.533 x log (stage – 4.3)

The flow-width and flow-depth relationships for each reach are given 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 C-1 and C-2.

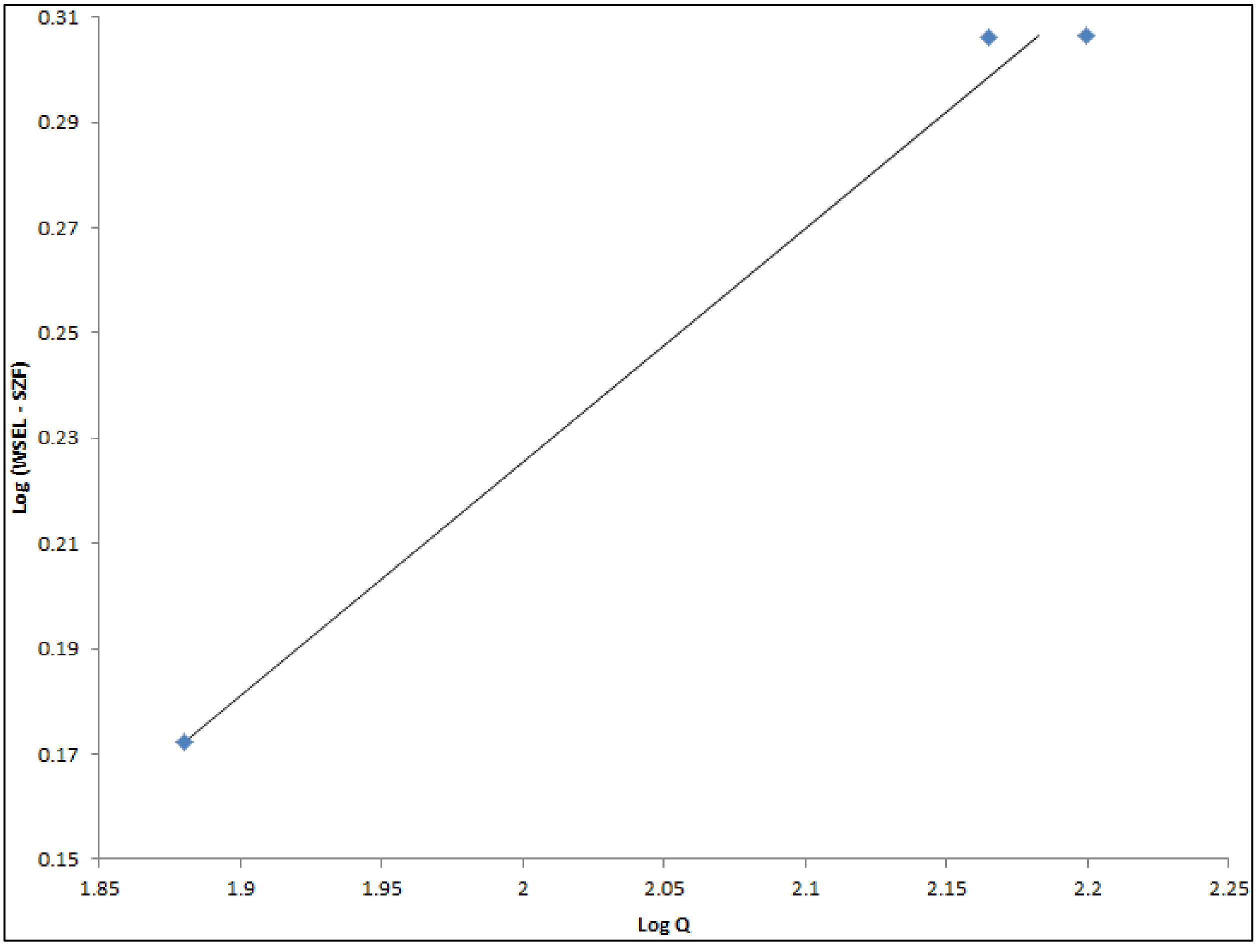


Figure C-6. 2015 Reach 3 rating curve.

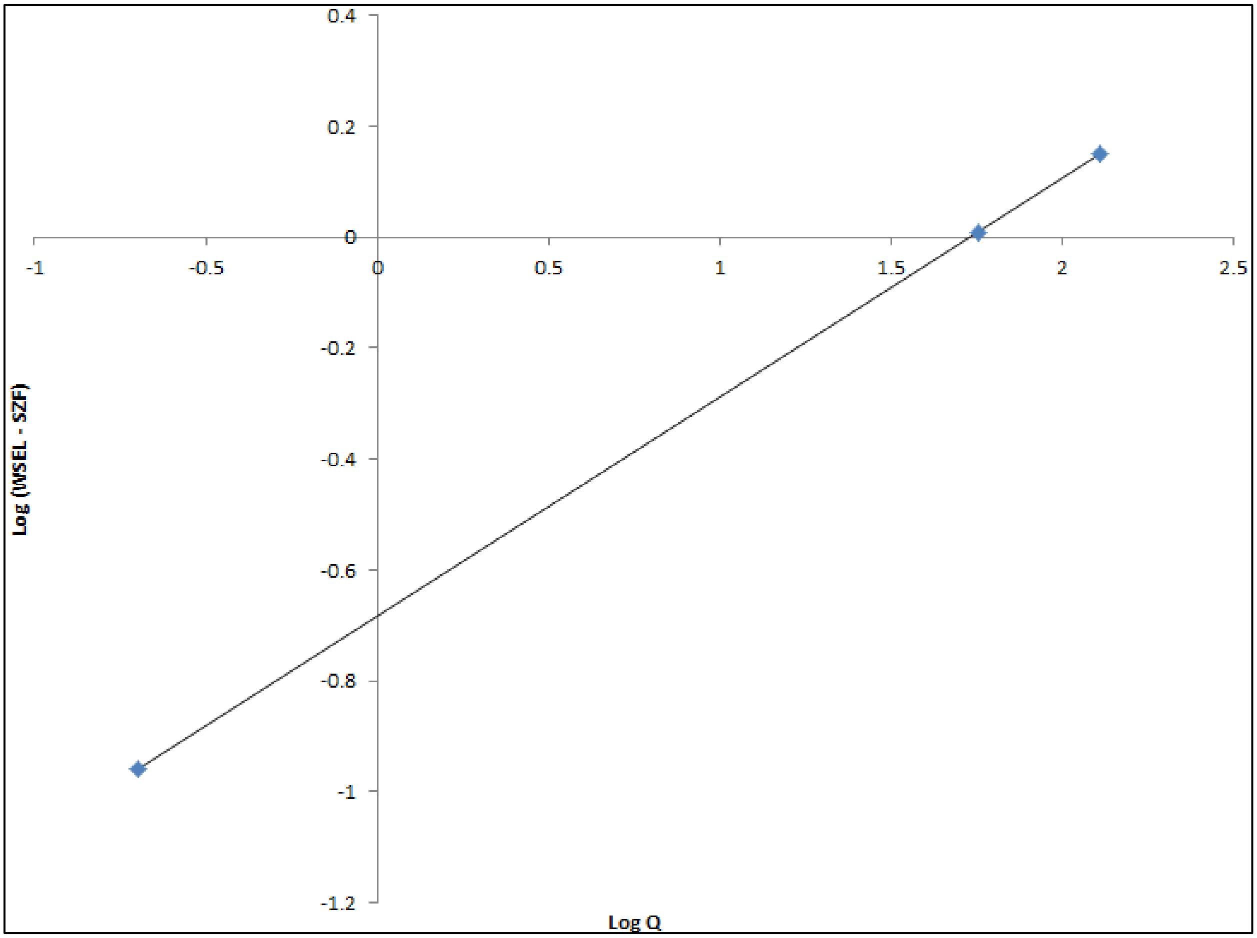


Figure C-7. 2015 Rating curve near DWR A04420.

Table C-1. Initial values of global ST parameters.

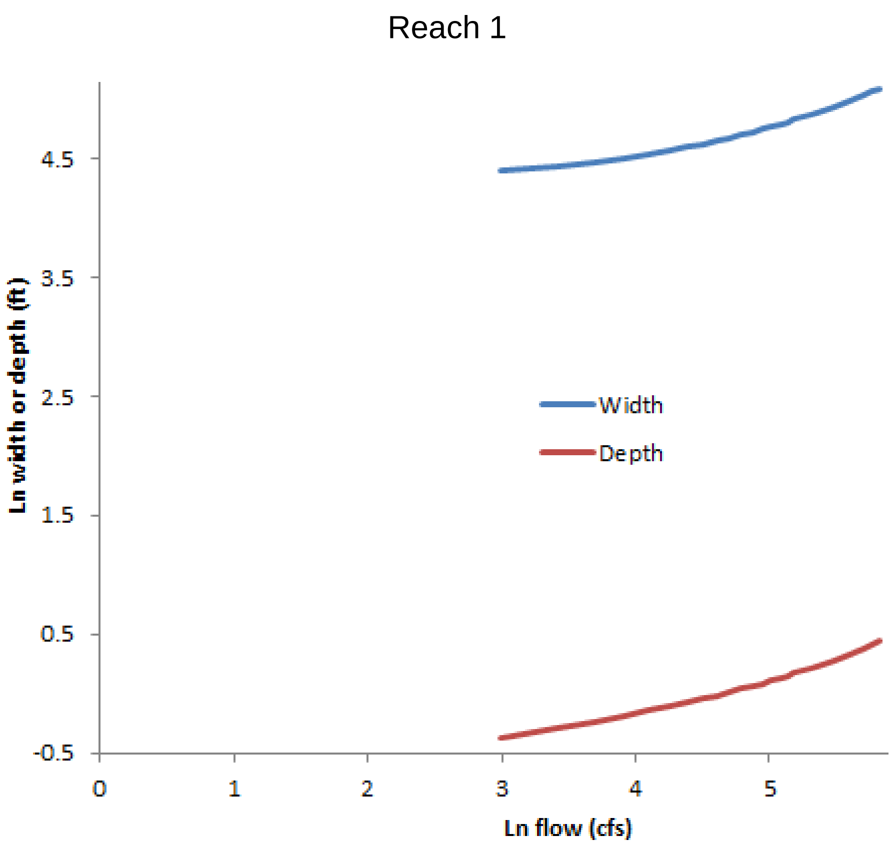
Parameter / Variable	Value	Constant	Coefficient
Average Annual Air Temperature (°F)	62.3	-	-
Bowen Ratio	0.000619	-	-
Evaporation Factor A	40	-	-
Evaporation Factor B	15	-	-
Evaporation Factor C	0	-	-
Dust	4	-	-
Ground Reflection	17	-	-
Air Temperature (°F)	-	0.3109	1.011
Wind Speed (ft/s)	-	0.3699	0.1779
Relative Humidity	-	0	1.0377
Percent Sunshine	-	0	1
Solar Radiation	-	0	1

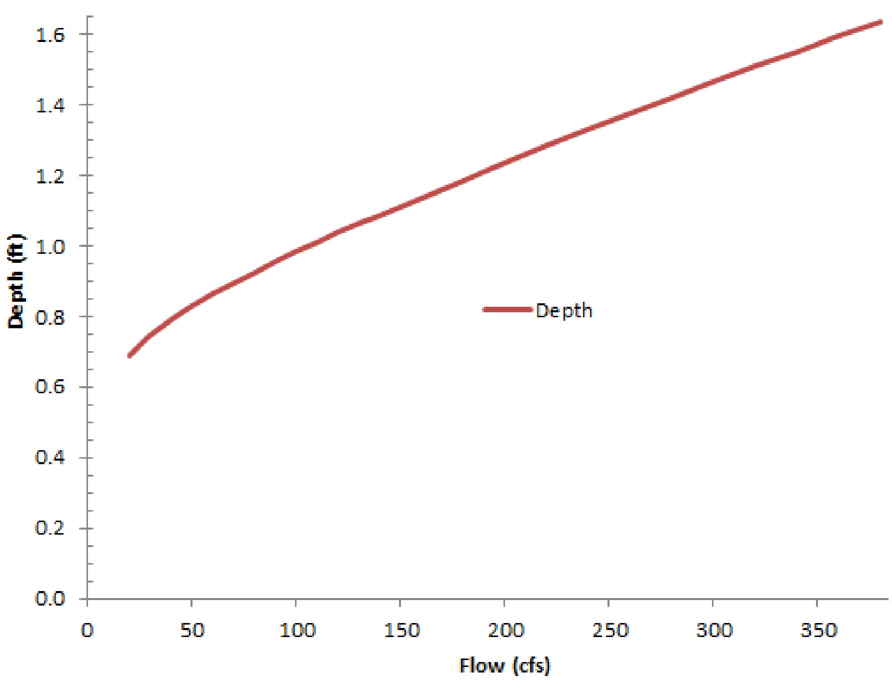
Table C-2. Initial values of reach-specific StreamTemp parameters.

Parameter	Reach 1	Reach 2	Reach 3
Thermal Gradient	1.65	1.65	1.65
Left Bank Vegetation Height	38	13	21
Right Bank Vegetation Height	63	15	18
Left Bank Vegetation Density	15	14	26
Right Bank Vegetation Density	17	21	5
Left Bank Topographic Shade	5/4[29]	6	8
Right Bank Topographic Shade	6	8	20
Left Bank Vegetation Crown Width	22	8	12
Right Bank Vegetation Crown Width	36	8	10
Width A Constant	31.80	29.47	34.89
Width B Coefficient	0.269	0.095	0.083
Maximum Width (ft)	158	52	57
Residual Depth (ft)	0.57	0.62	0.87
Slope	0.005	0.008	0.007
Manning’s n	0.11	0.10	0.11

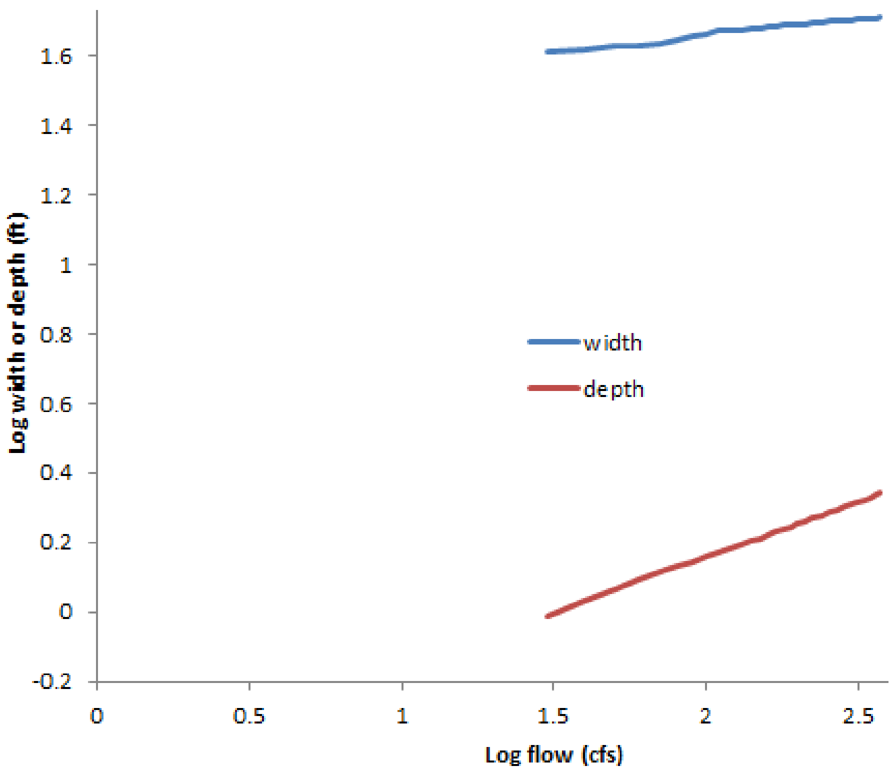
[29] The first value is for the upper subreach of Reach 1, while the second value is for the lower subreach of Reach 1.

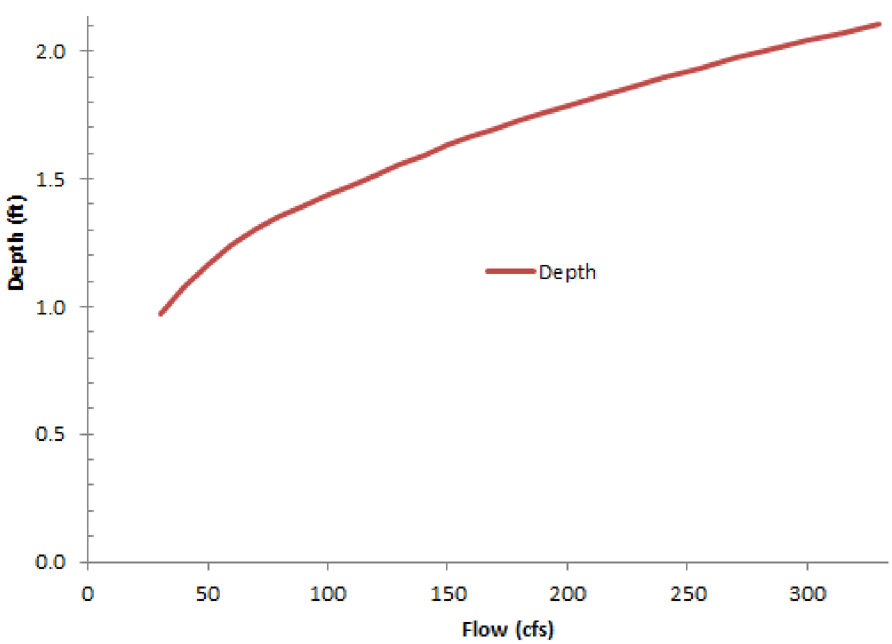
Flow-width and Flow-depth Relationships



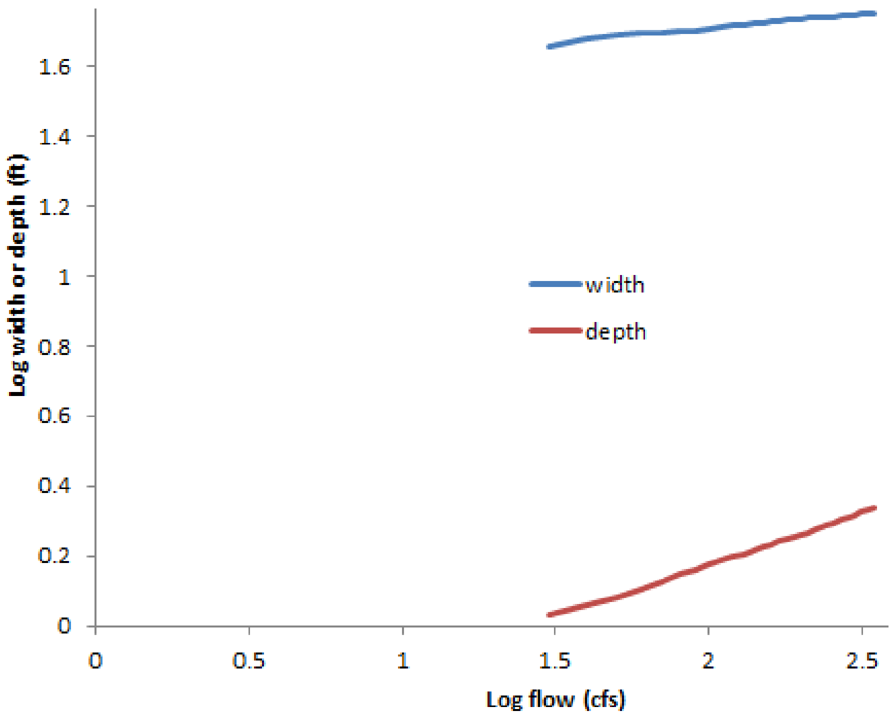


Reach 2

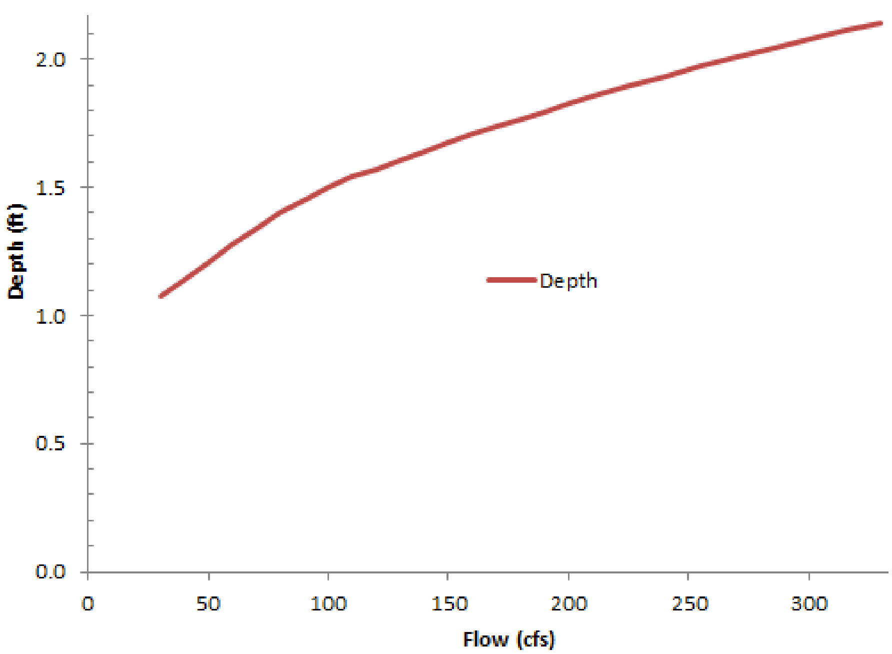

1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Log width or depth (ft)
width
depth
0
0.5
1
1.5
2
2.5
Log flow (cfs)


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

Reach 3



Log width or depth (ft)
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
Log flow (cfs)
width
depth



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

Water Temperature Model Calibration, Validation, and Additional Criteria
The calibrated values of universal parameters and reach-specific parameters are shown in Tables C-3 and C-4. The calibration to 2014 monitoring data 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 C-5). The calibrated model had a correlation coefficient of 0.9945, a mean error of -0.09°F, a probable error of 0.57°F, a maximum error of 3.25°F, 17.4% of the predicted errors less than 1.0°F, and a bias of 0.031. As shown in Figures C-8 to C-10, 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 C-3. Calibrated values of universal StreamTemp parameters.

Parameter / Variable	Value	Constant	Coefficient
Average Annual Air Temperature (°F)	62.3	-	-
Bowen Ratio	0.000619	-	-
Evaporation Factor A	40	-	-
Evaporation Factor B	15	-	-
Evaporation Factor C	0	-	-
Dust	4	-	-
Ground Reflection	17	-	-
Air Temperature (°F)	-	0.3109	1.011
Wind Speed (ft/s)	-	0.3699	0.1779
Relative Humidity	-	0	1.0377
Percent Sunshine	-	0	1
Solar Radiation	-	0	0.8

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

Parameter	Reach 1	Reach 2	Reach 3
Thermal Gradient	1.65	1.65	1.65
Left Bank Vegetation Height	38	13	21
Right Bank Vegetation Height	63	15	18
Left Bank Vegetation Density	30	7	52
Right Bank Vegetation Density	34	11	10
Left Bank Topographic Shade	5/4[30]	6	8
Right Bank Topographic Shade	6	8	20
Left Bank Vegetation Crown Width	31	6	17
Right Bank Vegetation Crown Width	51	7	15
Width A Constant	31.80	29.47	34.89
Width B Coefficient	0.269	0.095	0.083
Maximum Width (ft)	158	52	57
Residual Depth (ft)	0.57	0.62	0.87
Slope	0.005	0.008	0.007
Manning's n	0.03	0.03	0.04

Table C-5. Calibrated StreamTemp model performance.

Parameter (°F)	Reach 1	Reach 2	Reach 3
Mean Error for Daily Mean Temperature	0.1	-0.5	0.3
Error Range for Daily Mean Temperature	-1.5 to 3.2	-2.6 to 1.3	-0.3 to 1.5
Mean Error for 7DADM	-2.4	-2.5	0.002
Error Range for 7DADM	-4.9 to 1.0	-6.3 to 0.7	-1.3 to 1.1

[30] The first value is for the upper subreach of Reach 1, while the second value is for the lower subreach of Reach 1.

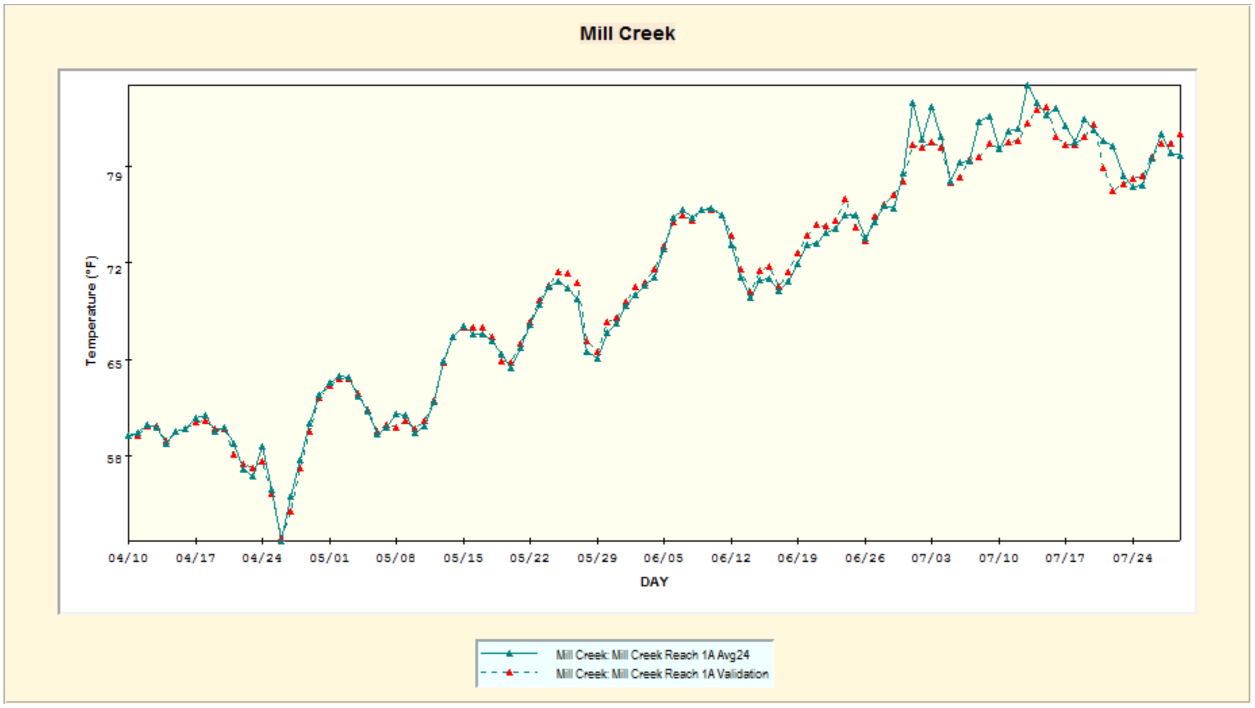


Figure C-8. StreamTemp model calibration result for the downstream end of Reach 1.

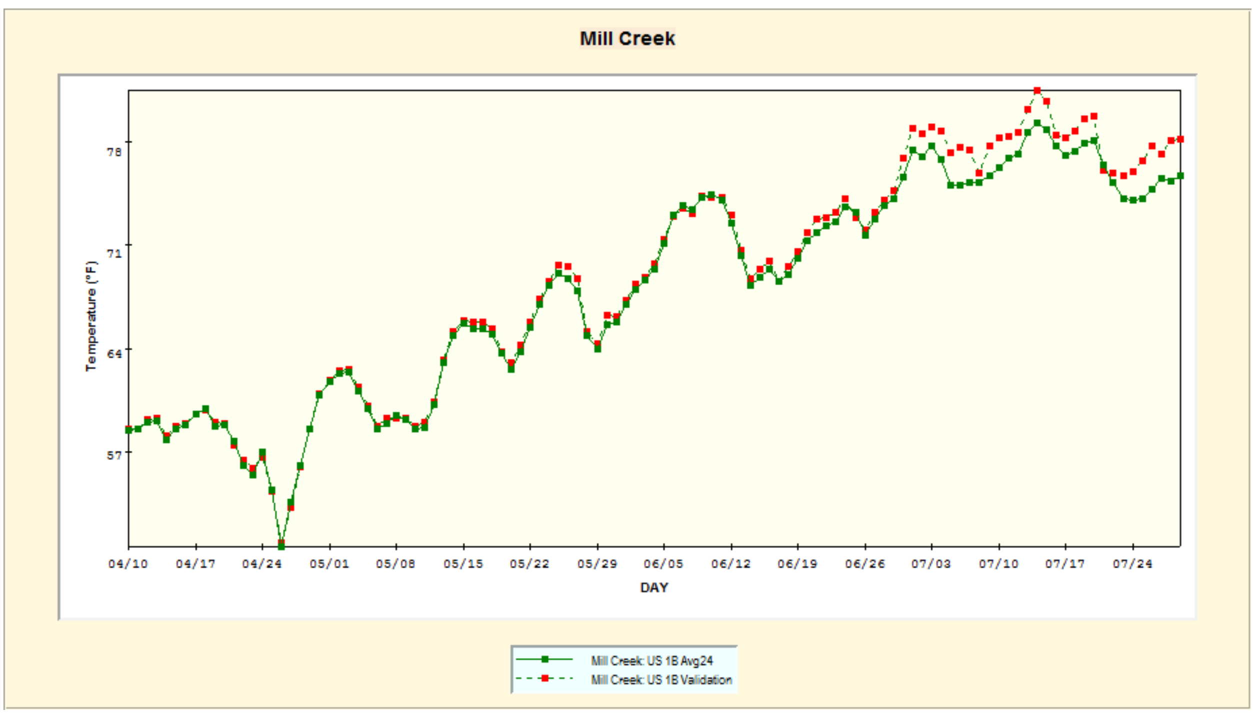


Figure C-9. StreamTemp model calibration result for the upstream end of Reach 1.

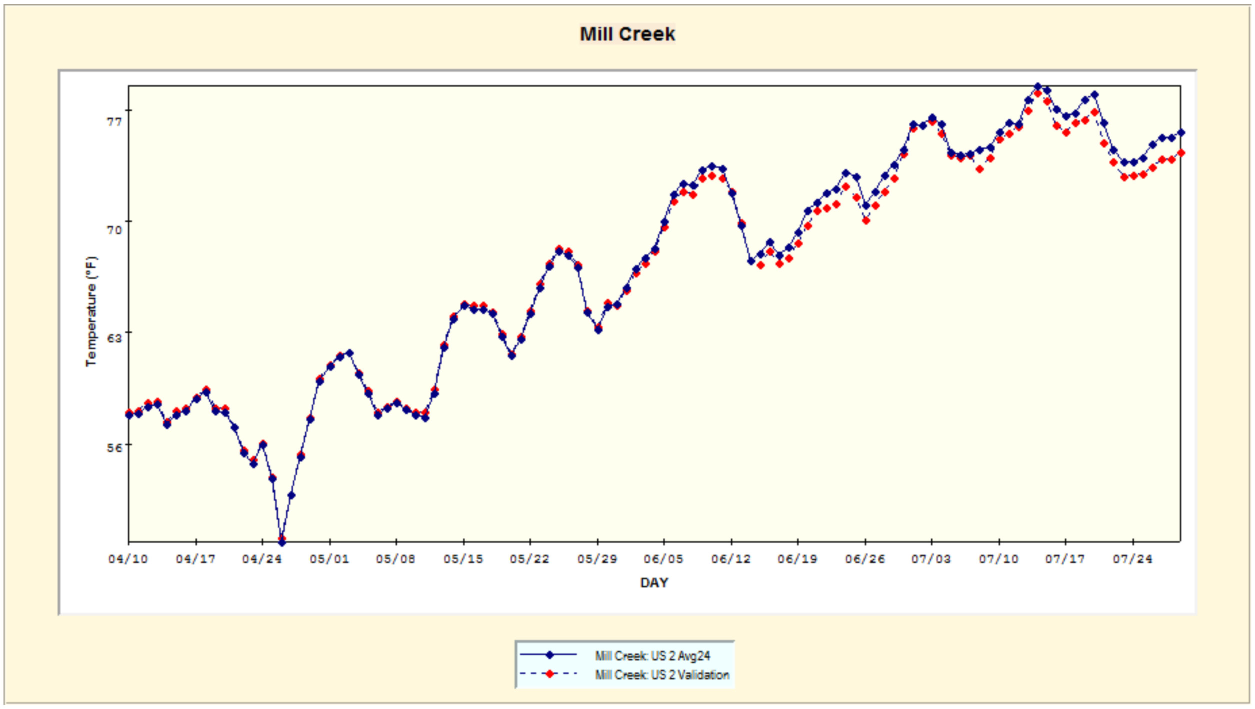


Figure C-10. StreamTemp model calibration result for Reach 2.

When validating the model to the 2008 to 2013 monitoring data, the error in mean daily water temperature ranged from -5.5 to 10.1°F (average of 0.2°F), and the error on 7DADM ranged from -7.4 to 7.9°F (average of -0.6°F). The StreamTemp model had a correlation coefficient of 0.993, a mean error of 0.161°F, a probable error of 0.993°F, a maximum error of 10.1°F, 27% of the predicted errors less than 1.0°F, and a bias of 0.0208. 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 -2.7 to 6.8°F (average of -0.4°F) and the error on 7DADM ranged from -7.3 to 2.1°F (average of -1.4°F). As shown in Figure C-11, the StreamTemp model generally tracked the 2008 to 2013 mean daily measured water temperatures.

When validating the model to the monitoring network data collected in 2015, as shown in Table C-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 0.9978, a mean error of 0.025°F, a probable error of 0.468°F, a maximum error of 4.104°F, 8.04% of the predicted errors less than 1.0°F, and a bias of 0.0227. As shown in Figures C-12 to C-14, 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 1.

As shown in Figures C-15 and C-16, 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.

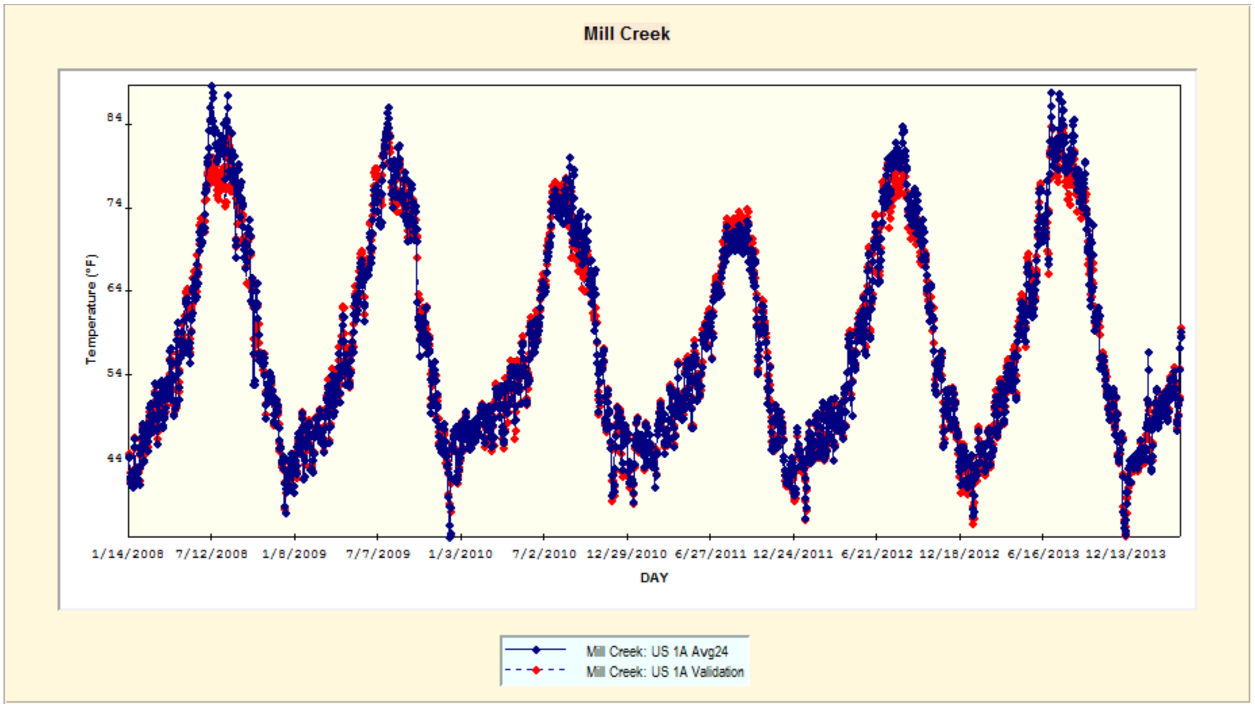


Figure C-11. StreamTemp model validation result for 2008 through 2013.

Table C-6. 2015 StreamTemp model validation performance.

Parameter (°F)	Reach 1	Reach 2	Reach 3
Mean Error for Daily Mean Temperature	0.2	0.01	-0.1
Error Range for Daily Mean Temperature	-2.0 to 4.1	-0.8 to 2.5	-0.5 to 0.3
Mean Error for 7DADM	-2.6	-1.6	-0.4
Error Range for 7DADM	-4.5 to 0.4	-3.7 to 1.1	-1.4 to 0.4

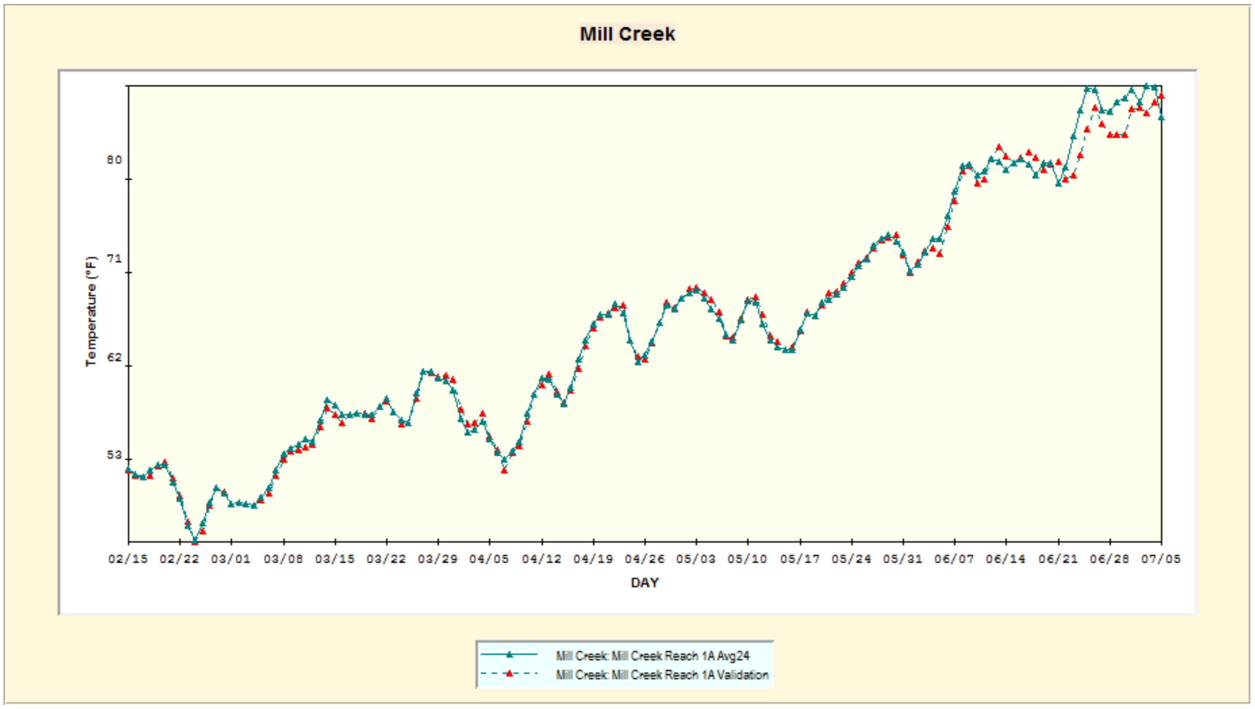


Figure C-12. StreamTemp model validation result at the downstream end of Reach 1 in 2015.

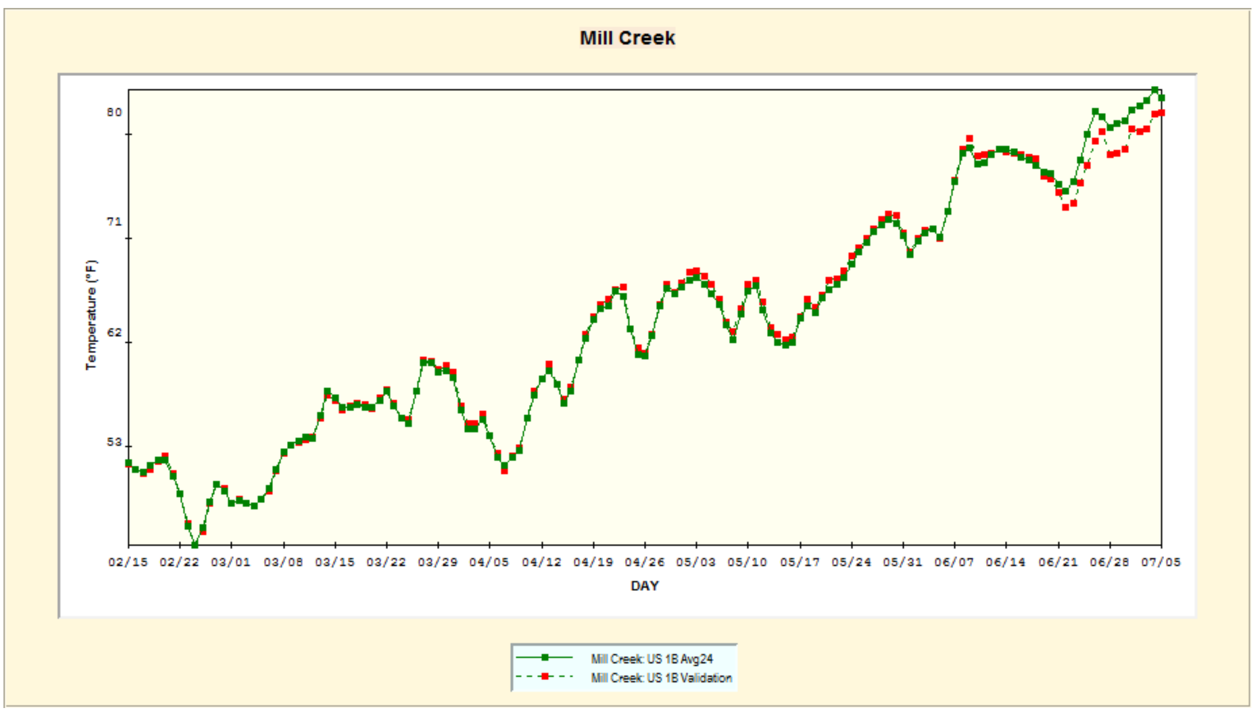


Figure C-13. StreamTemp model validation result at the upstream end of Reach 1 in 2015.

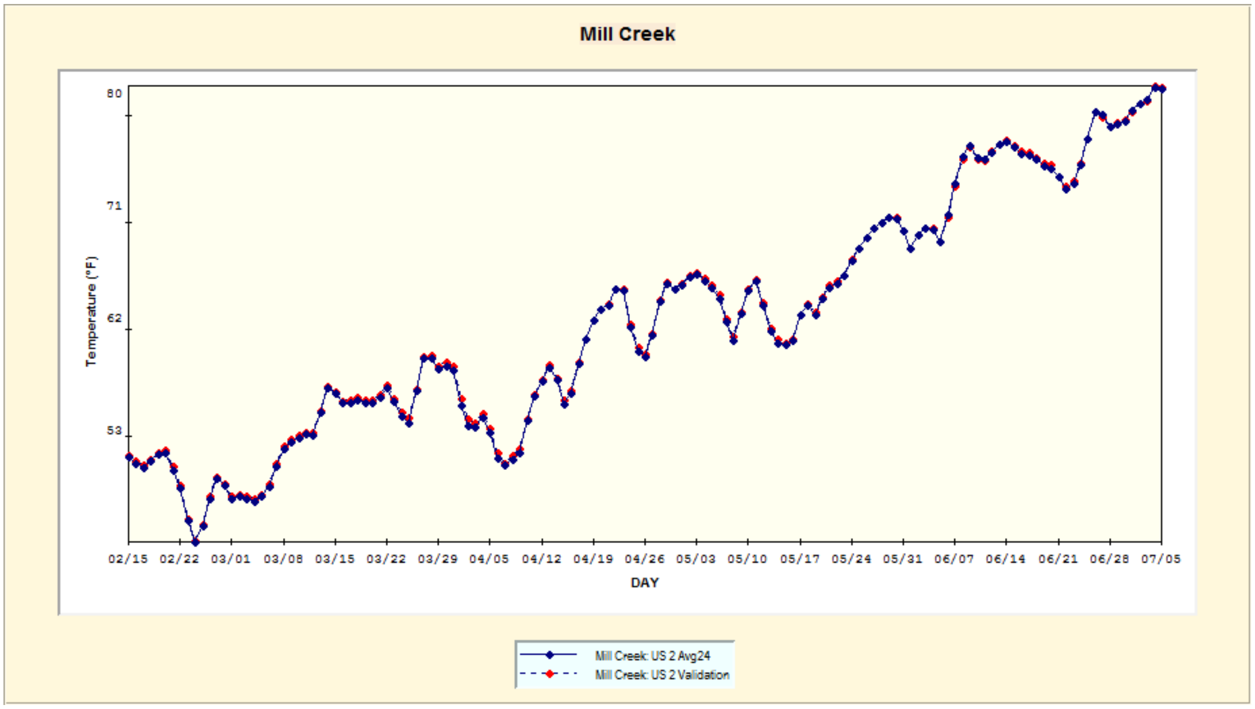


Figure C-14. StreamTemp model validation result for Reach 2 in 2015.

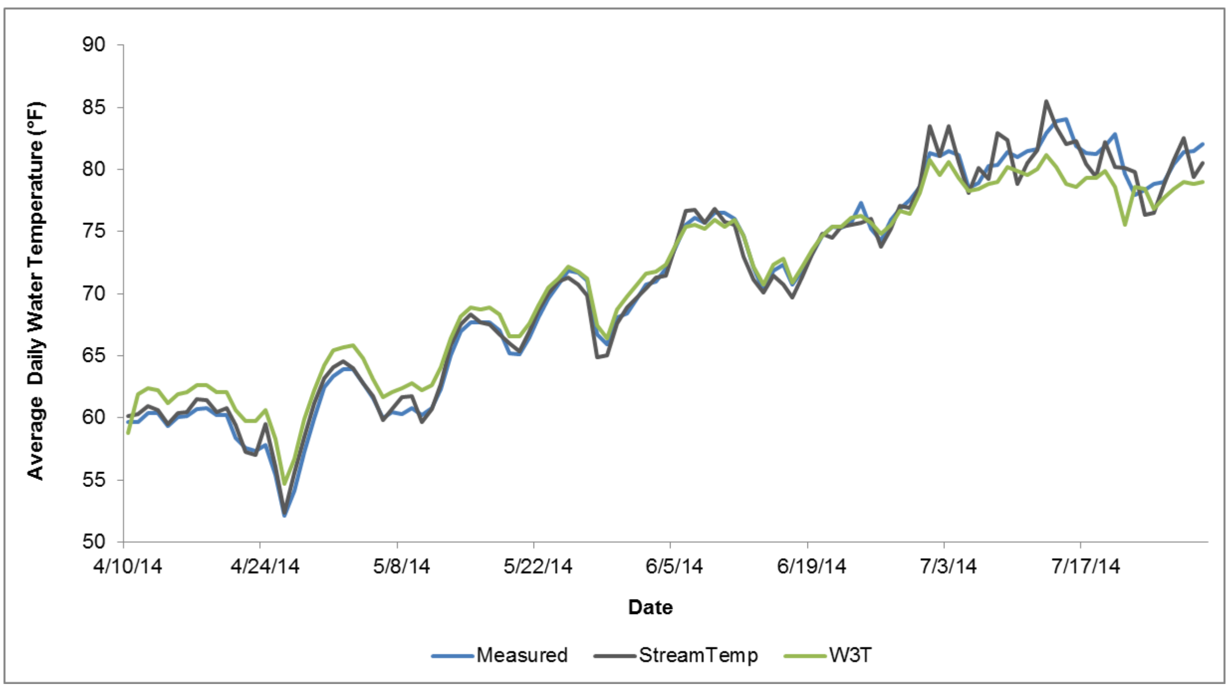


Figure C-15. Comparison of predicted mean daily water temperatures from the StreamTemp and W3T models at the downstream end of Reach 1 in 2014.

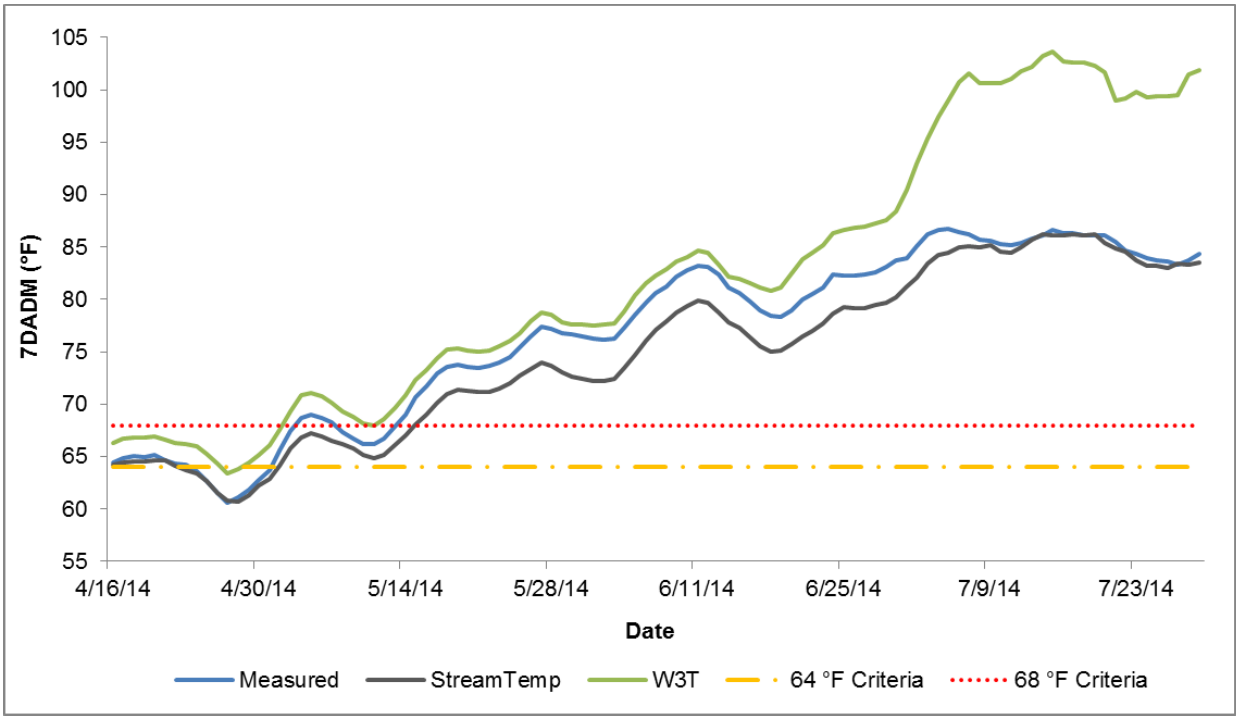


Figure C-16. Comparison of predicted 7DADM water temperatures from the StreamTemp and W3T models at the downstream end of Reach 1 in 2014.

Model Simulated Flow Runs

Water temperatures were simulated for unimpaired conditions for the period of January 14, 2008 to July 29, 2014 by setting all diversions equal to zero. As shown in Figures C-17 through C-20, 7DADM values at the downstream end of Reach 1 first exceeded 64°F between April 30 in drier years and July 5 in wetter years, for both impaired and unimpaired flows. 7DADM values reached 68°F an average of 14 days later (range 2 to 26 days); exceeding 68°F between May 14 in drier years and July 22 in wetter years, for both impaired and unimpaired flows.

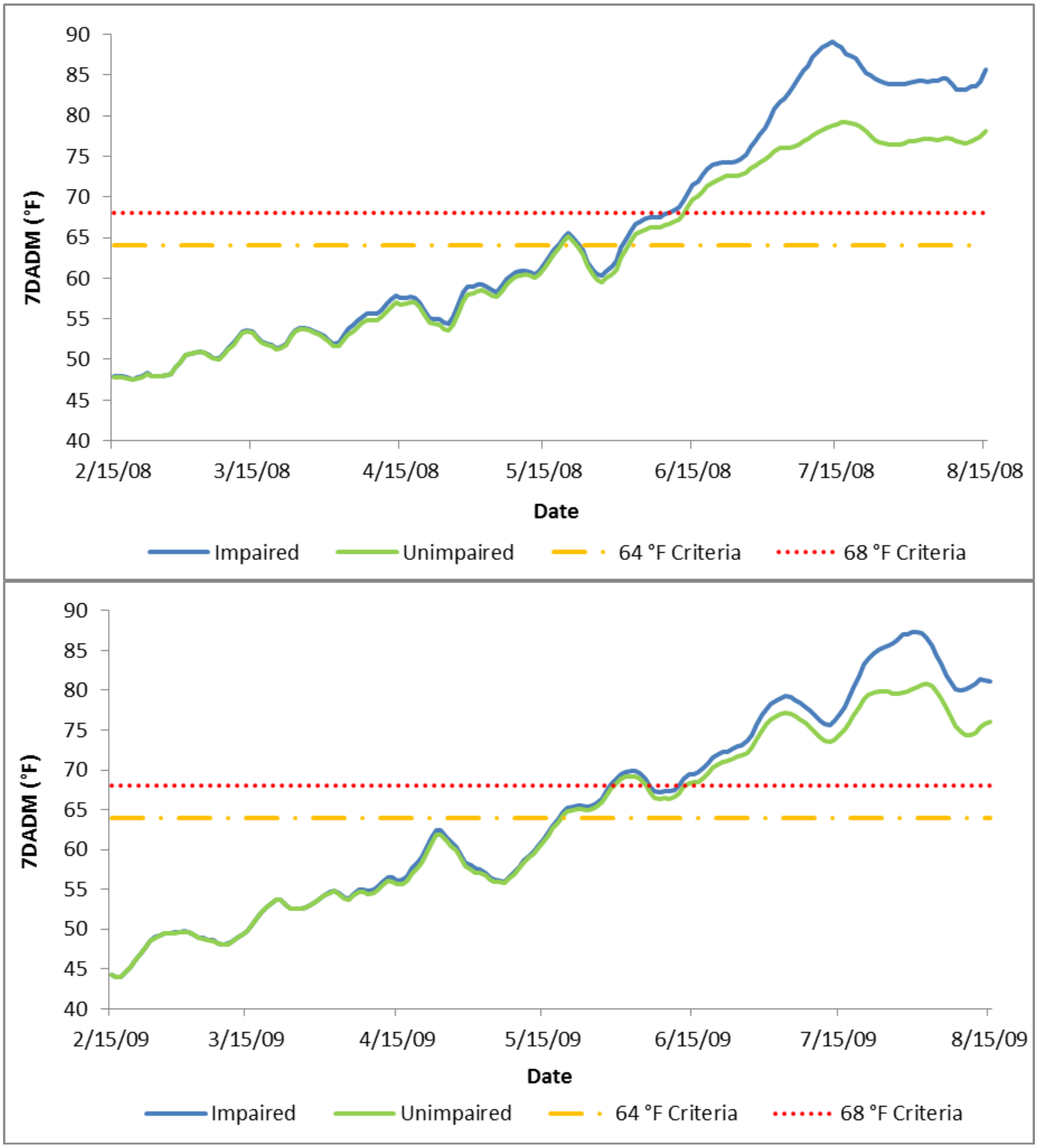


Figure C-17. Predicted 7DADM at the downstream end of Reach 1 for impaired and unimpaired flows during season of migration in 2008-2009.

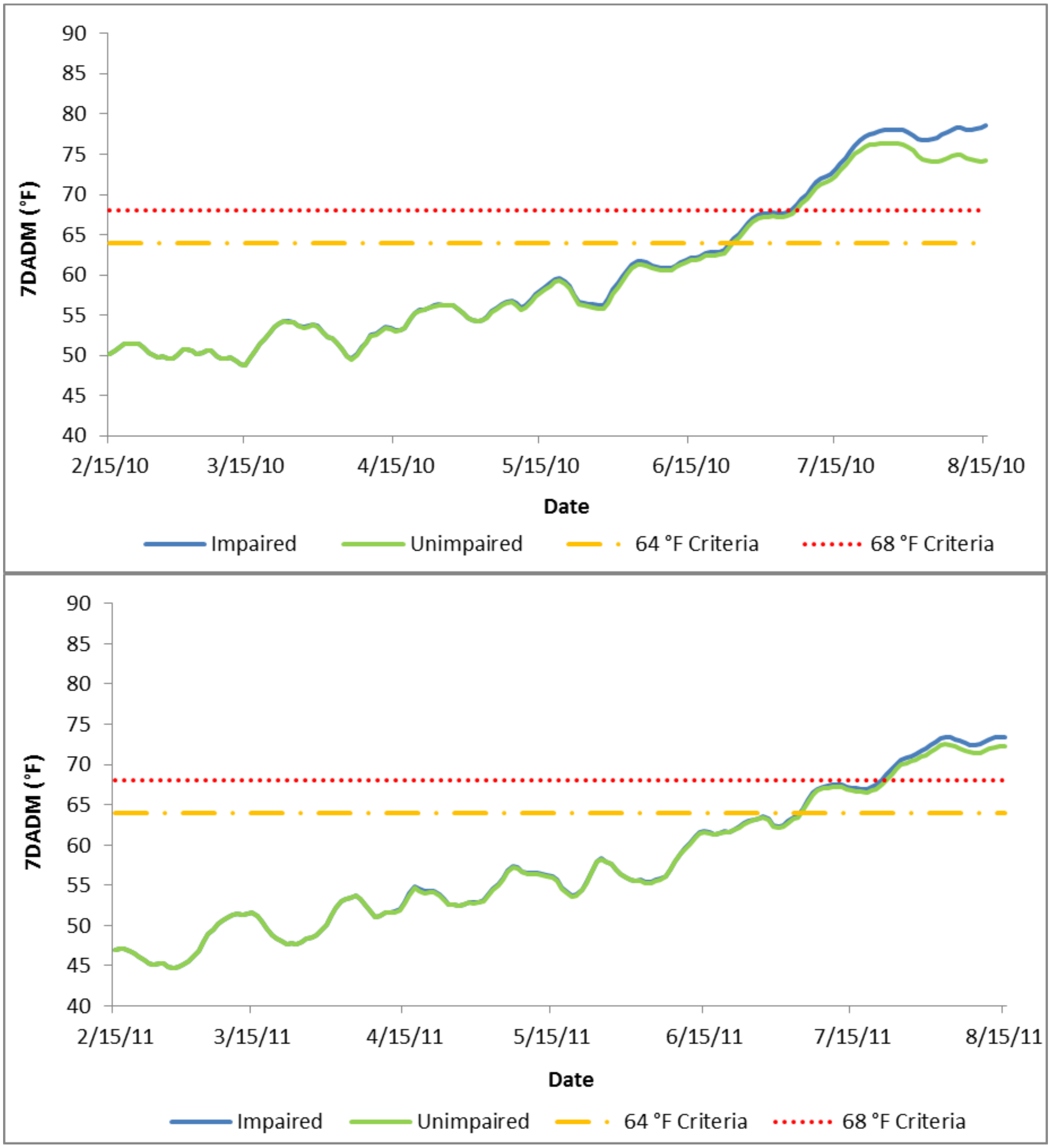


Figure C-18. Predicted 7DADM at the downstream end of Reach 1 for impaired and unimpaired flows during season of migration in 2010-2011.

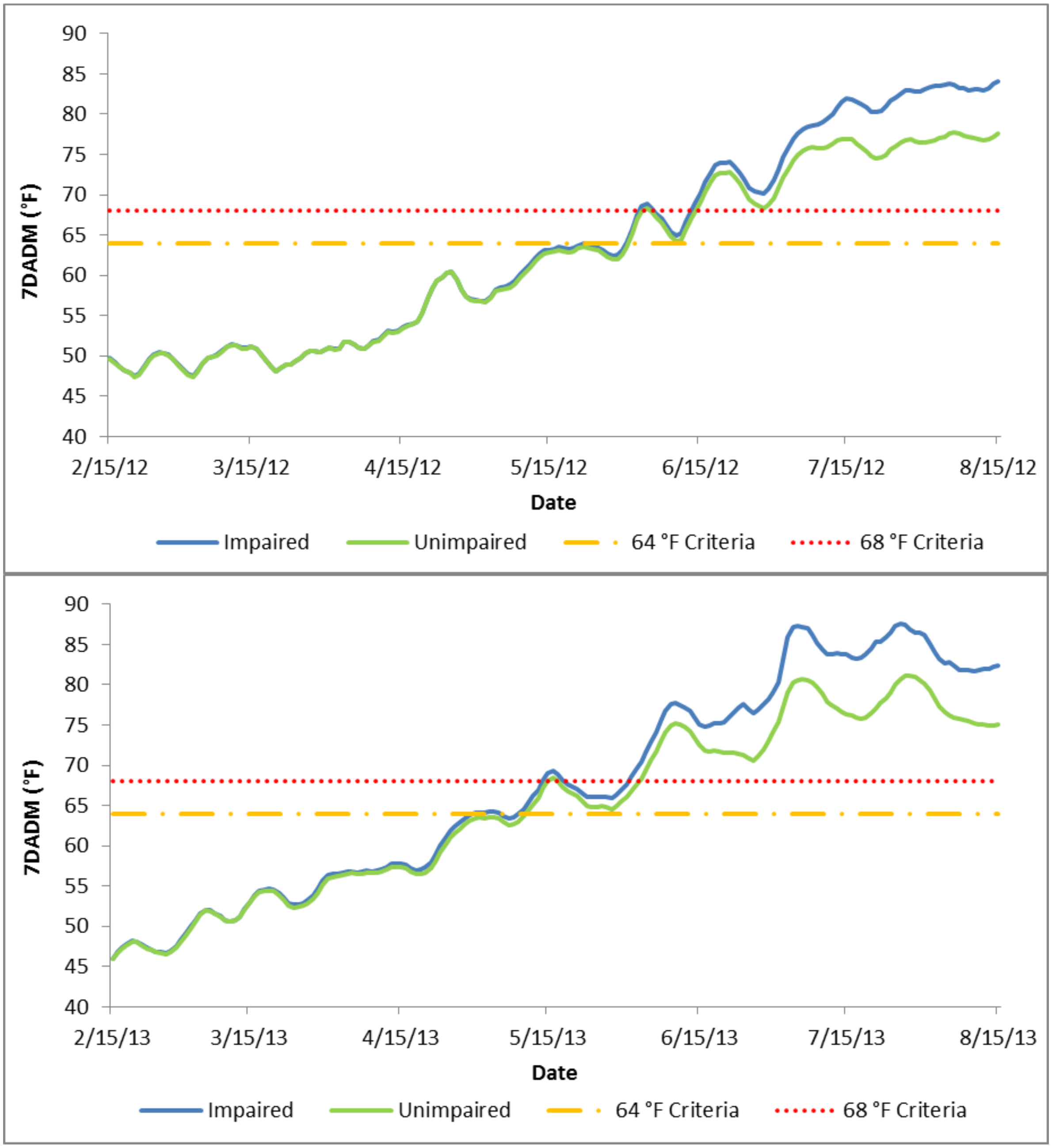


Figure C-19. Predicted 7DADM at the downstream end of Reach 1 for impaired and unimpaired flows during season of migration in 2012-2013.

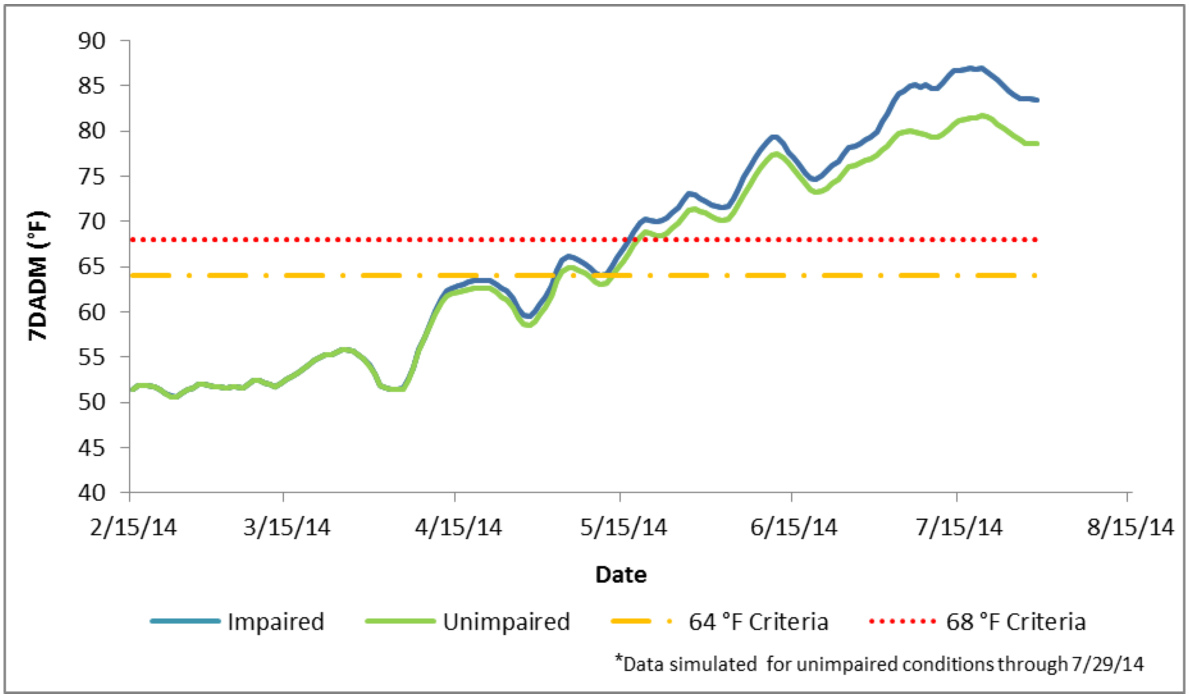


Figure C-20. Predicted 7DADM at the downstream end of Reach 1 for impaired and unimpaired flows during season of migration in 2014.

Water Temperature Model Discussion

The calibration of Transect 4 was not accepted because it did not meet the standards for either *IFG4* or *MANSQ* and it could not be calibrated with *WSP*. We concluded that this transect was placed in a location which was not appropriate for a PHABSIM transect due to the substantial differences in measured WSELs across the transect (by as much as 0.27 feet). Given that there was not a usable riffle transect in Reach 3, and furthermore that 29 percent of Reach 3 was comprised of riffles, we concluded that the best solution would be to use Transect 5 (in Reach 2) to represent riffles in Reach 3. Transect 5 was considered to be representative of riffles in Reach 3, given that the upstream portion of the riffle encompassing Transect 5 was located in Reach 3.

In calibrating the StreamTemp model, the adjustment of parameters was restricted to ranges deemed reasonable given the underlying data and its level of accuracy. 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 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 parameters that affect 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.

References

Kimmerer, W. and J. Carpenter. 1989. Desabla-Centerville project (FERC 803) Butte Creek interim temperature modeling study. Prepared for Pacific Gas and Electric by BioSystems Analysis, Inc. Tiburon, CA.

Payne and Associates. 2005. StreamTemp Version 1.0.4 and TRPA Stream Temperature User Manual. Arcata, CA: Thomas R. Payne and Associates.

Remote Automatic Weather Stations on-line database (RAWS). 2015. Available: http://www.raws.dri.edu/wraws/ncaF.html. Accessed: October 23, 2014.

Watercourse Engineering, Inc. (2013). Water temperature transaction tool (W3T): technical and user's guide (v1.0). A report for the National Fish and Wildlife Foundation. Davis, CA: Watercourse Engineering, Inc.

Appendix D. SEFA WSEL Calibration

Transect Stage-Discharge Calibration Parameters Used

Site/Reach	Transect	Flow Range (cfs)	Calibration Flows (cfs)	SZF
CR2	1	10-64.3	1.1, 56.5, 64.3	216.6
CR2	1	64.3-390	64.3, 128, 157.6	216.6
CR2	2	10-390	1.1, 56.5, 64.3, 128, 157.6	219.2
3	1	30 – 345	8, 82.8, 141	96.50
3	2	30 – 345	8, 82.8, 141	95.47
3	3	30 – 345	8, 82.8, 141	94.91
3	4	30 – 345	8, 82.8, 141	96.69
2	5	30 – 375	57.6, 101, 166.7	93.70
2	6	30 – 375	57.6, 101, 166.7	96.30
2	7	30 – 375	57.6, 101, 166.7	91.54
2	8	30 – 375	57.6, 101, 166.7	94.42
2	9	30 – 375	66.3, 93.5, 150.9	96.00
2	10	30 – 375	66.3, 93.5, 150.9	95.44
2	11	30 – 375	66.3, 93.5, 150.9	94.30
2	12	30 – 375	66.3, 93.5, 150.9	94.10
1	13	20 – 380	43, 93, 152.4	96.53
1	14	20 – 380	43, 93, 152.4	96.53
1	15	20 – 380	23.8, 43, 93, 152.4	95.98
1	16	20 – 380	43, 93, 152.4	94.79

CR2 Results

	BETA	%MEAN	Calculated vs Given[31] Discharge (%)			Difference[32] (measured vs. predicted WSELs)		
XS	COEFF.	ERROR	1.1	56.5	64.3	1.1	56.5	64.3
1	1.79	0.4	0.5	0.4	0.4	0.00	0.01	0.00

	BETA	%MEAN	Calculated vs Given Discharge (%)			Difference (measured vs. predicted WSELs)		
XS	COEFF.	ERROR	64.3	128	157.6	64.3	128	157.6
1	2.48	2.6	0.5	3.9	3.2	0.00	0.02	0.02

	BETA	%MEAN	Calculated vs Given Discharge (%)					Difference (measured vs. predicted WSELs)				
XS	COEFF.	ERROR	1.1	56.5	64.3	128	157.6	1.1	56.5	64.3	128	157.6
2	3.97	8.9	4.9	4.7	16.3	11.0	7.7	0.01	0.02	0.06	0.04	0.03

	BETA	%MEAN	Calculated vs Given[33] Discharge (%)			Difference[34] (measured vs. predicted WSELs)		
XS	COEFF.	ERROR	8	82.8	141	8	82.8	141
1	3.79	6.6	2.4	9.5	7.8	0.01	0.04	0.04
2	2.62	6.9	2.6	9.9	8.2	0.01	0.06	0.06
3	2.53	1.5	0.4	2.2	1.8	0.00	0.01	0.01
4	1.97	9.3	4.0	13.2	11.0	0.01	0.13	0.14

	BETA	%MEAN	Calculated vs Given Discharge (%)			Difference (measured vs. predicted WSELs)		
XS	COEFF.	ERROR	57.6	101	166.7	57.6	101	166.7
5	4.11	6.0	5.6	8.7	3.7	0.03	0.05	0.03
6	3.69	2.6	2.1	3.9	1.9	0.01	0.02	0.02
7	3.73	3.1	2.5	4.7	2.2	0.01	0.03	0.02
8	3.58	0.8	0.6	1.3	0.6	0.01	0.01	0.00

[31] Given refers to measured flows.
[32] Units of Difference are feet.
[33] Given refers to measured flows.
[34] Units of Difference are feet.

	BETA	%MEAN	Calculated vs Given Discharge (%)			Difference (measured vs. predicted WSELs)		
XS	**COEFF.**	**ERROR**	66.3	93.5	150.9	66.3	93.5	150.9
9	2.86	0.4	0.4	0.6	0.3	0.00	0.00	0.00
10	3.07	5.1	3.3	7.9	4.2	0.02	0.04	0.02
11	3.42	4.1	2.8	6.3	3.2	0.01	0.03	0.02
12	3.05	2.8	2.1	4.3	2.1	0.01	0.03	0.02
	BETA	**%MEAN**	**Calculated vs Given Discharge (%)**			**Difference (measured vs. predicted WSELs)**		
XS	**COEFF.**	**ERROR**	43	93	152.4	43	93	152.4
13	3.94	3.9	2.7	5.7	3.2	0.01	0.02	0.01
14	2.80	8.4	7.1	11.9	6.0	0.02	0.06	0.03
16	4.42	7.8	6.6	11.2	5.8	0.03	0.06	0.03

	BETA	%MEAN	Calculated vs Given Discharge (%)				Difference (measured vs. predicted WSELs)			
XS	**COEFF.**	**ERROR**	23.8	43	93	152.4	23.8	43	93	152.4
15	3.01	3.4	1.4	4.7	5.2	2.1	0.00	0.02	0.02	0.01

Appendix E. Critical Riffle Rating Curve Analysis

Best-fit regressions of flow versus width were developed for Critical Riffles CR3, CR4, and CR7 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 flows were calculated using the following equation:

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

The average depth at each flow event was calculated using the locations along the transects that remained inundated by water at all of the measured 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 four 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.

The stage-discharge relationships were used to expand the transect data to a greater range of representative flows. The rating curve for CR3 was developed from four of the measured flows. The flow of 113.6 cfs was excluded from the rating curve as it had a deeper profile, and the pathway did not appear to align with the other events. The resulting regression equation was as follows:

$$\log(\text{stage}-98.93) = -0.629 + 0.304 \times \log(\text{flow})$$

The rating curve for CR4 was calculated from the five 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 portion of the rating curve was found to apply. The resulting regression equation was as follows:

$$\log(\text{stage}-98.37) = -0.373 + 0.250 \times \log(\text{flow})$$

The rating curve for CR7 was calculated from all five measured flows. The data indicated that there were two distinct log-log linear portions of the rating curve: up to 110 cfs, and greater than 110 cfs. Accordingly, the rating curve was developed by performing regressions for the data in each of the above two flow ranges. The resulting regression equations were as follows:

$$\text{Flows} < 110 \text{ cfs: } \log(\text{stage}-99.06) = -0.729 + 0.334 \times \log(\text{flow})$$

$$\text{Flows} > 110 \text{ cfs: } \log(\text{stage}-99.06) = -0.390 + 0.167 \times \log(\text{flow})$$

The slope of rating curves often shift with flows; in PHABSIM, it is common to have to break rating curves up 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, as was the case for CR7. Because the slope of the rating curve for CR4 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 CR3, CR4, and CR7 are shown below (Figures E-1 to E-3). 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.

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 E-4 to E-9). 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 E-10 to E-15). The rating curve was used to estimate the total and maximum contiguous width at each flow in 5 cfs intervals (Tables E-1 to E-12). The bottom of each table begins with 40% of the lowest measured flow used in each rating curve.

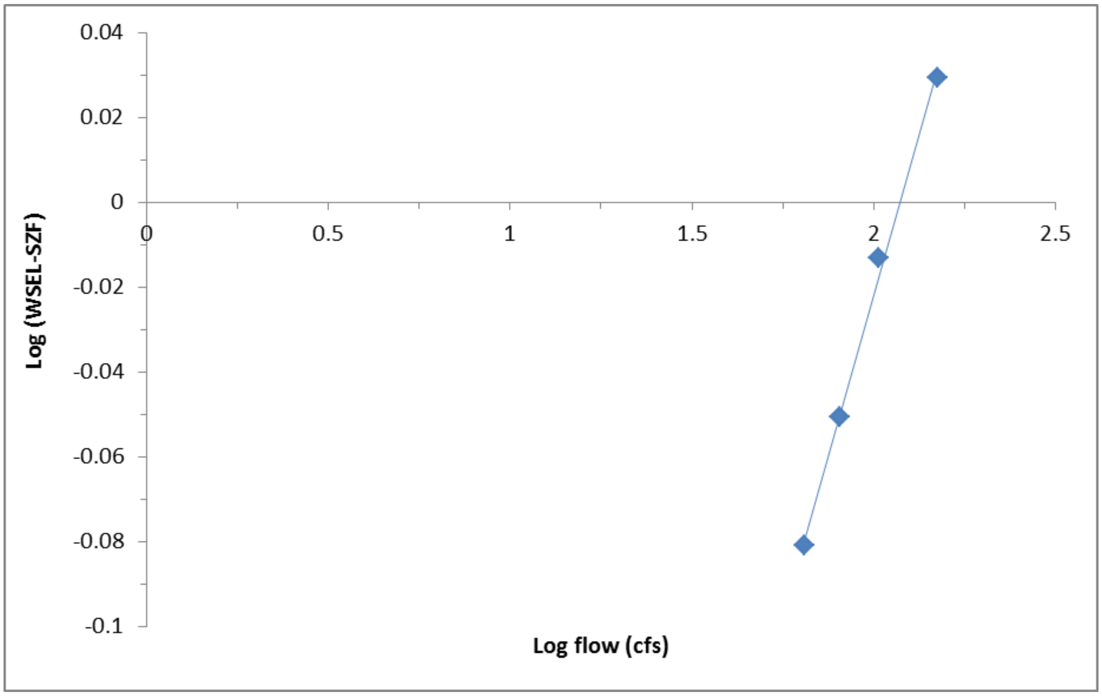


Figure E-1. Rating curve for CR3.

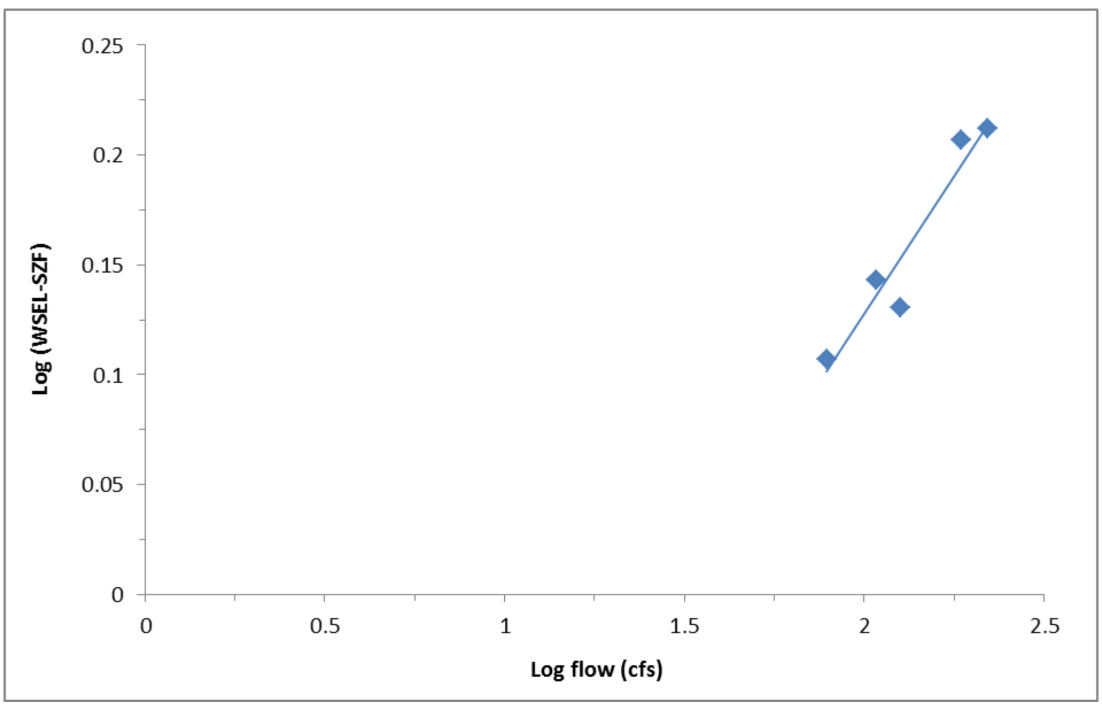


Figure E-2. Rating curve for CR4.

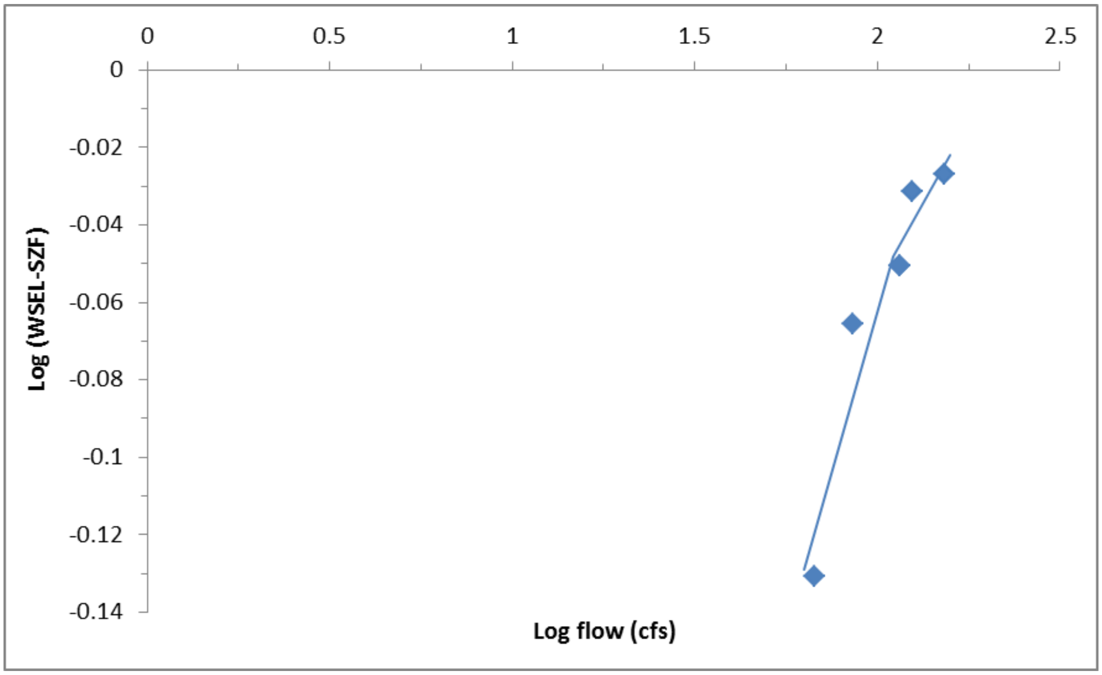


Figure E-3. Rating curve for CR7.

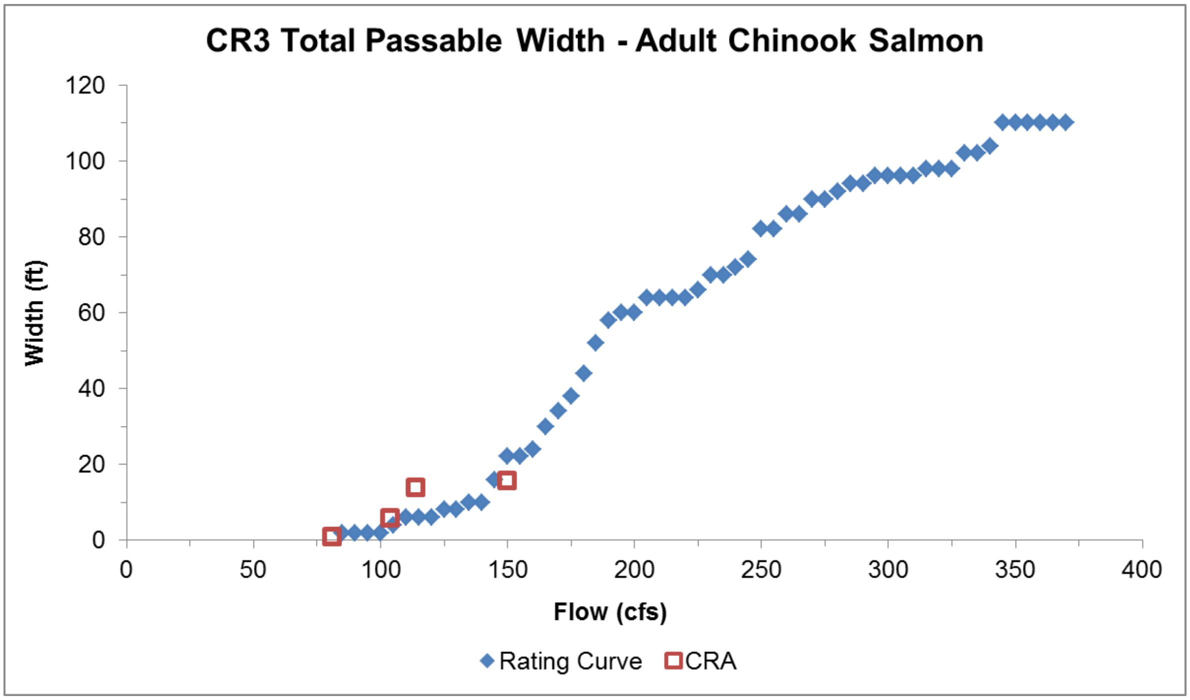


Figure E-4. Rating curve results of total passable width as a function of flow for the 0.9 ft minimum body depth criteria for adult Chinook salmon at CR3. The red boxes indicate field-collected data.

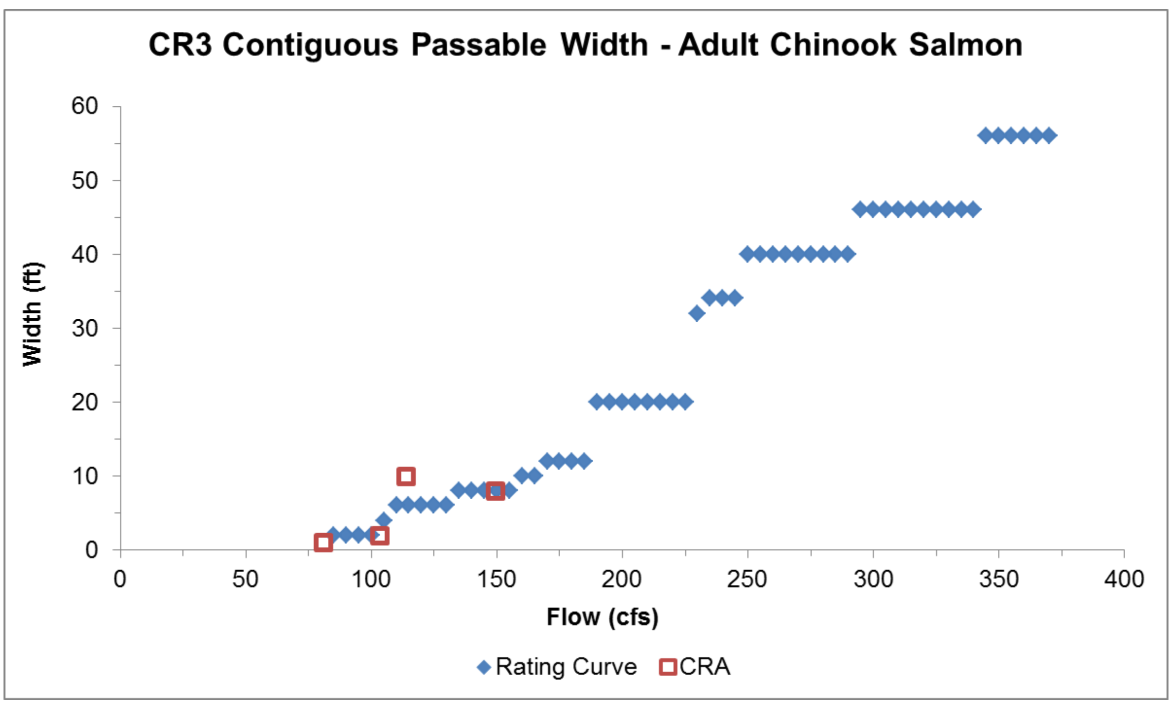


Figure E-5. Rating curve results of contiguous passable width as a function of flow for the 0.9 ft minimum body depth criteria for adult Chinook salmon at CR3. The red boxes indicate field-collected data.

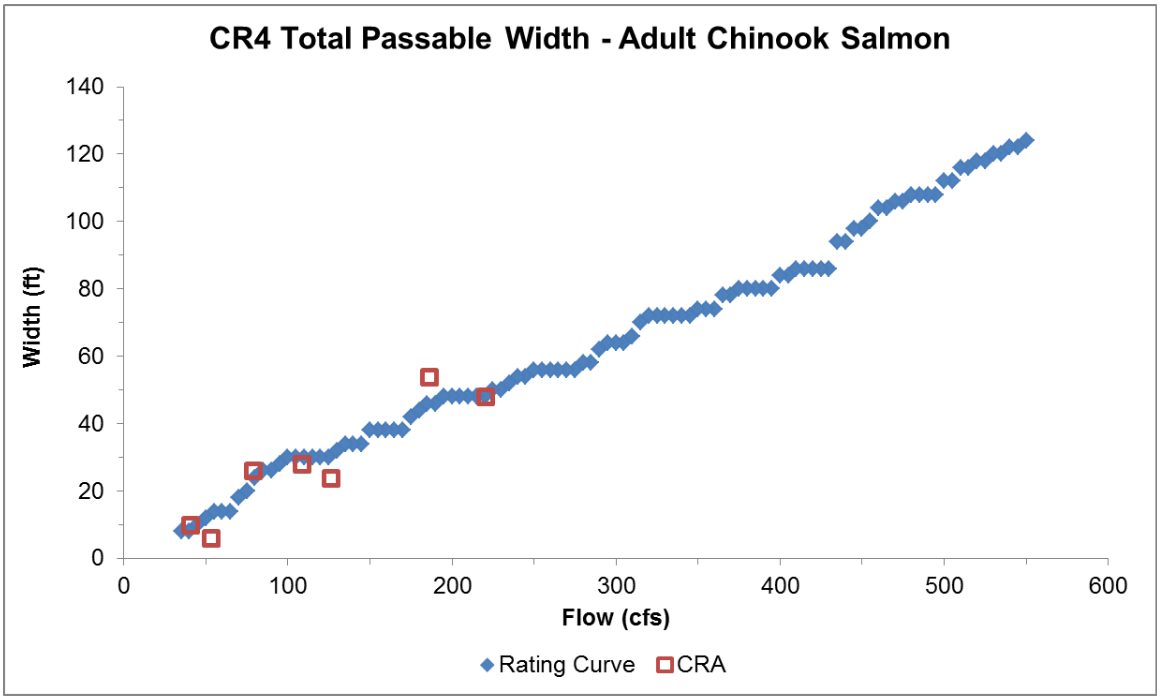


Figure E-6. Rating curve results of total passable width as a function of flow for the 0.9 ft minimum body depth criteria for adult Chinook salmon at CR4. The red boxes indicate field-collected data.

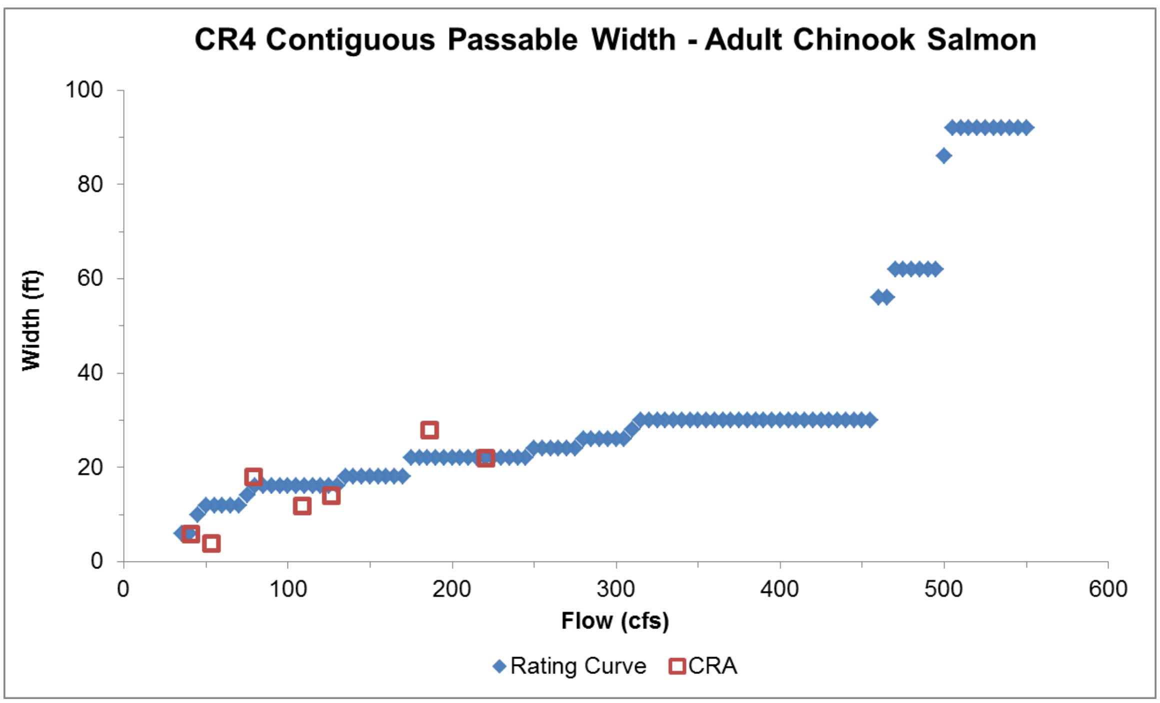


Figure E-7. Rating curve results of contiguous passable width as a function of flow for the 0.9 ft minimum body depth criteria for adult Chinook salmon at CR4. The red boxes indicate field-collected data.

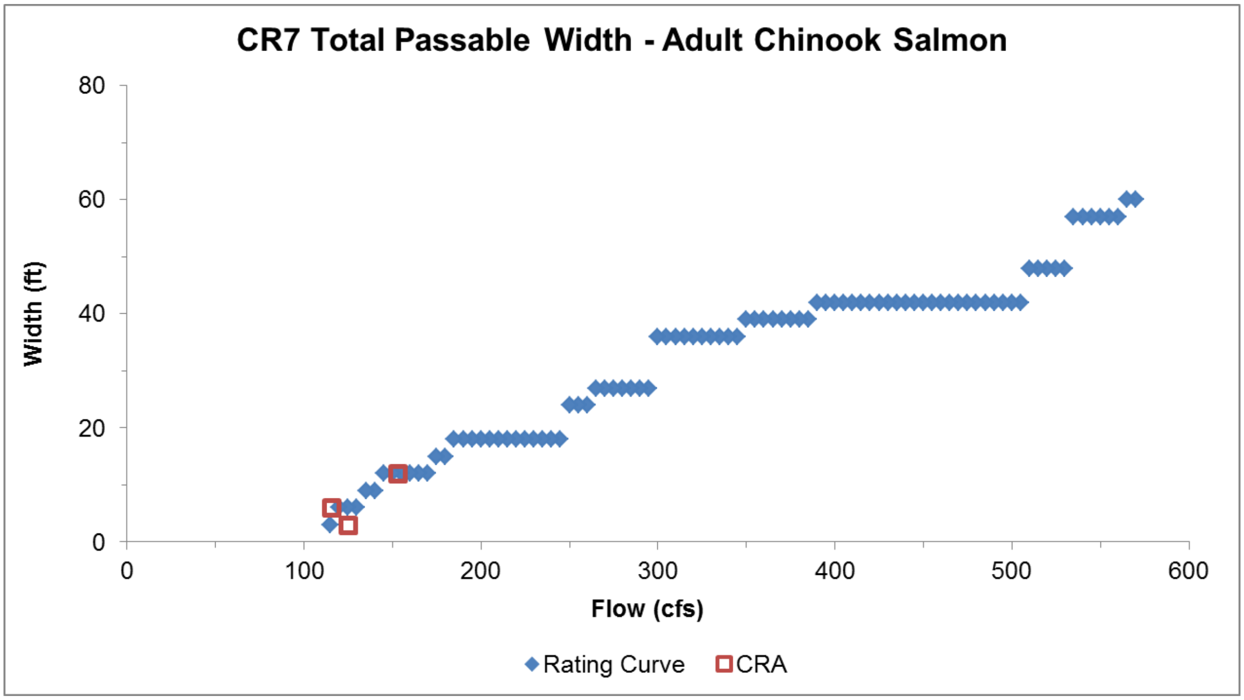


Figure E-8. Rating curve results of total passable width as a function of flow for the 0.9 ft minimum body depth criteria for adult Chinook salmon at CR7. The red boxes indicate field-collected data.

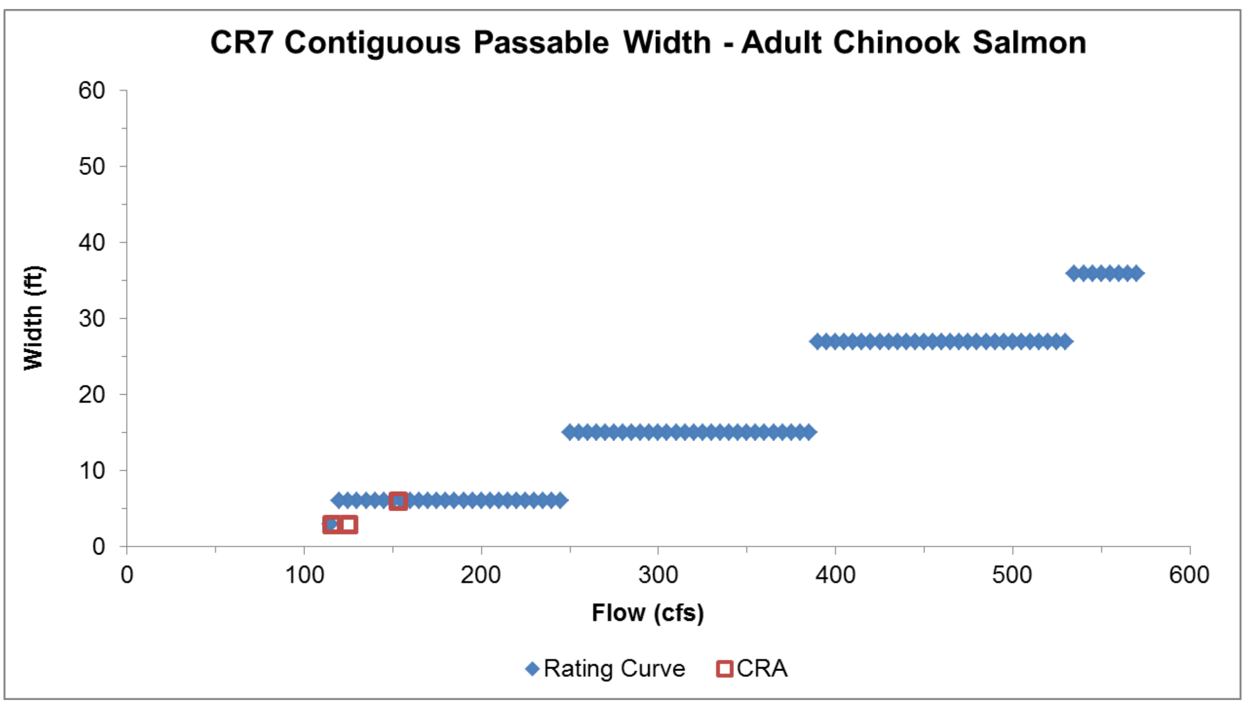


Figure E-9. Rating curve results of contiguous passable width as a function of flow for the 0.9 ft minimum body depth criteria for adult Chinook salmon at CR7. The red boxes indicate field-collected data.

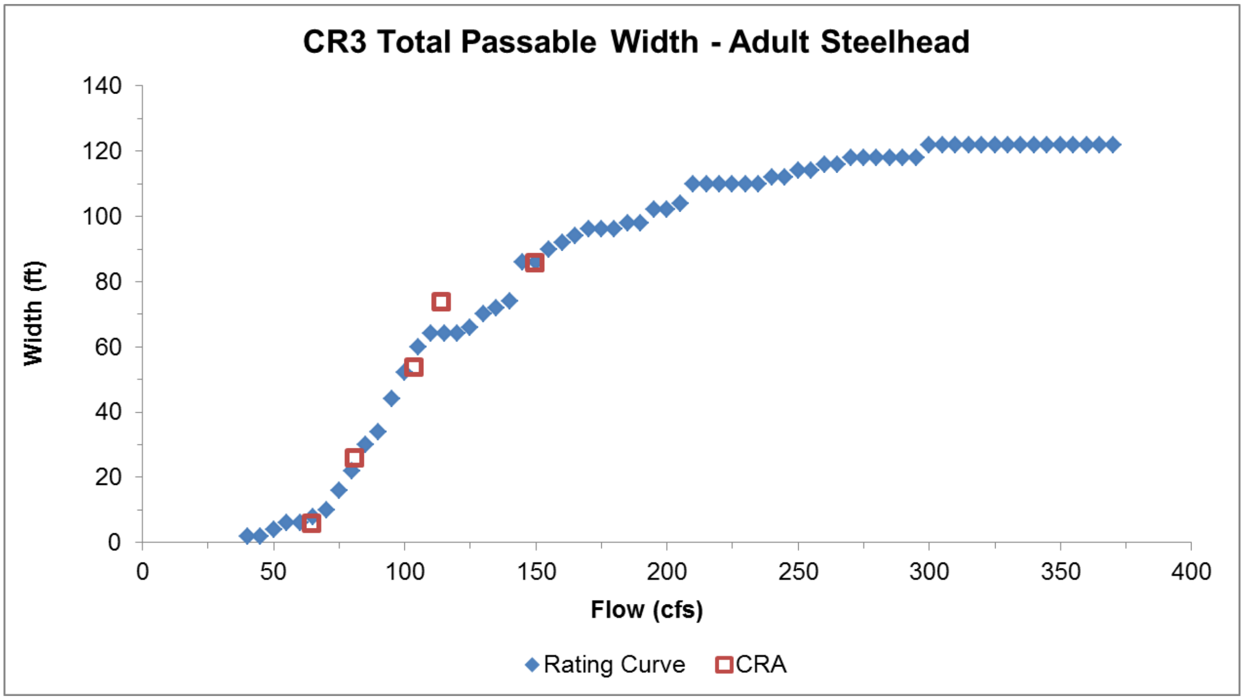


Figure E-10. Rating curve results of total passable width as a function of flow for the 0.7 ft minimum body depth criteria for adult steelhead at CR3. The red boxes indicate field-collected data.

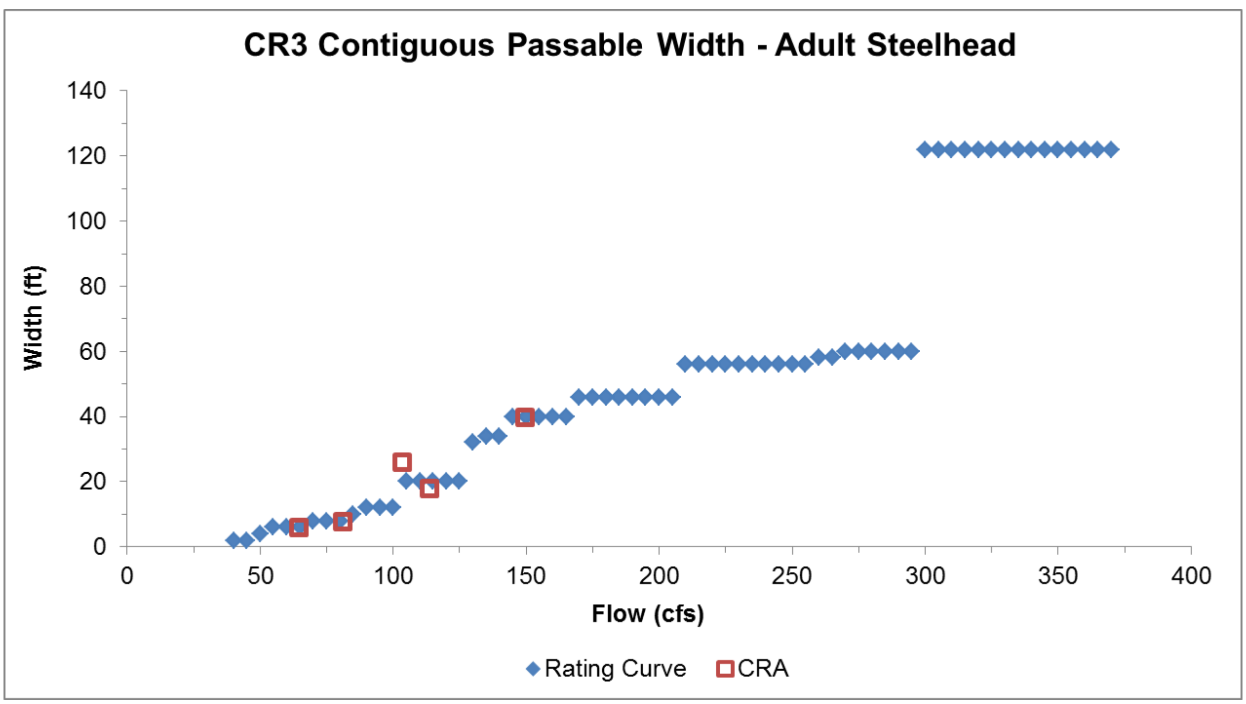


Figure E-11. Rating curve results of contiguous passable width as a function of flow for the 0.7 ft minimum body depth criteria for adult steelhead at CR3. The red boxes indicate field-collected data.

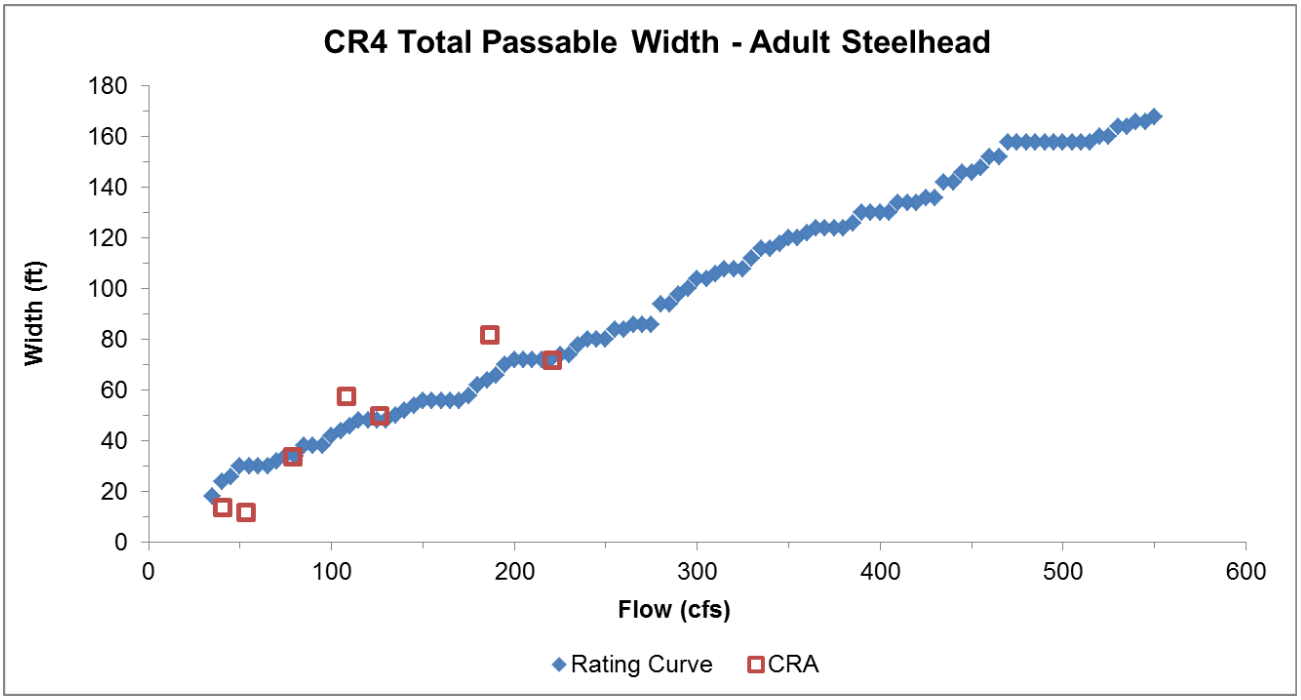


Figure E-12. Rating curve results of total passable width as a function of flow for the 0.7 ft minimum body depth criteria for adult steelhead at CR4. The red boxes indicate field-collected data.

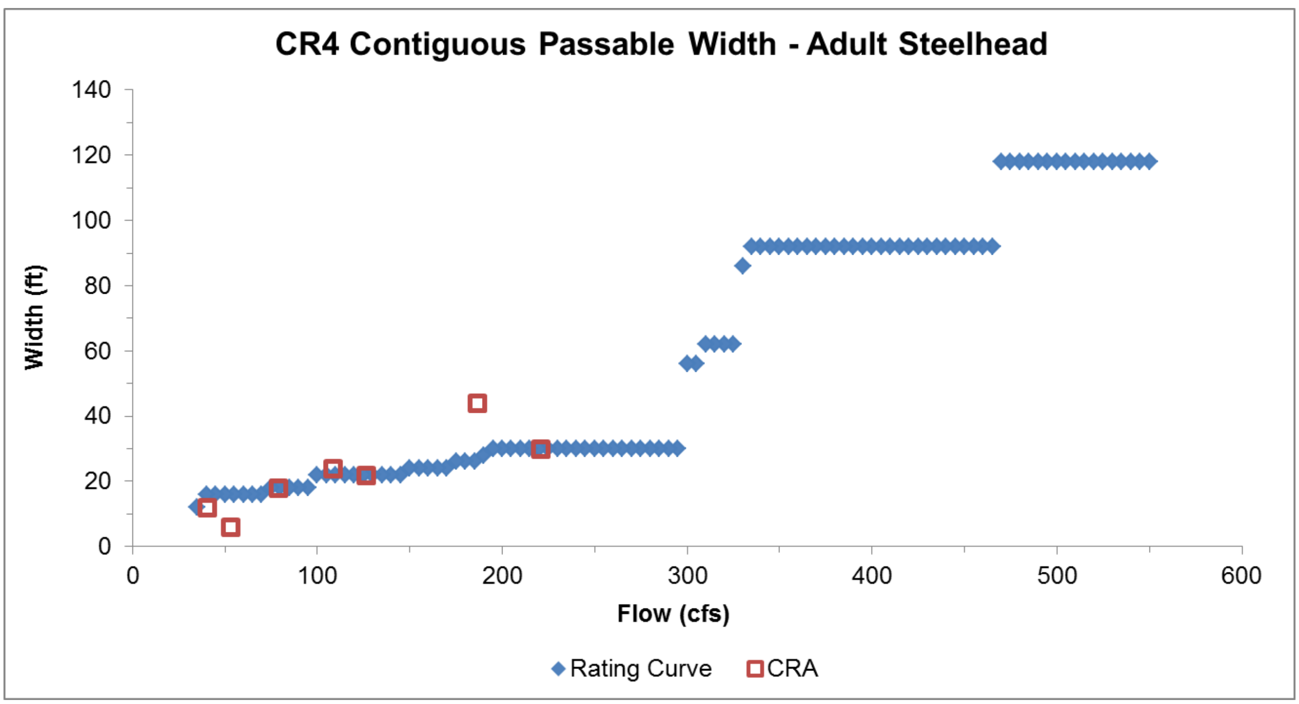


Figure E-13. Rating curve results of contiguous passable width as a function of flow for the 0.7 ft minimum body depth criteria for adult steelhead at CR4. The red boxes indicate field-collected data.

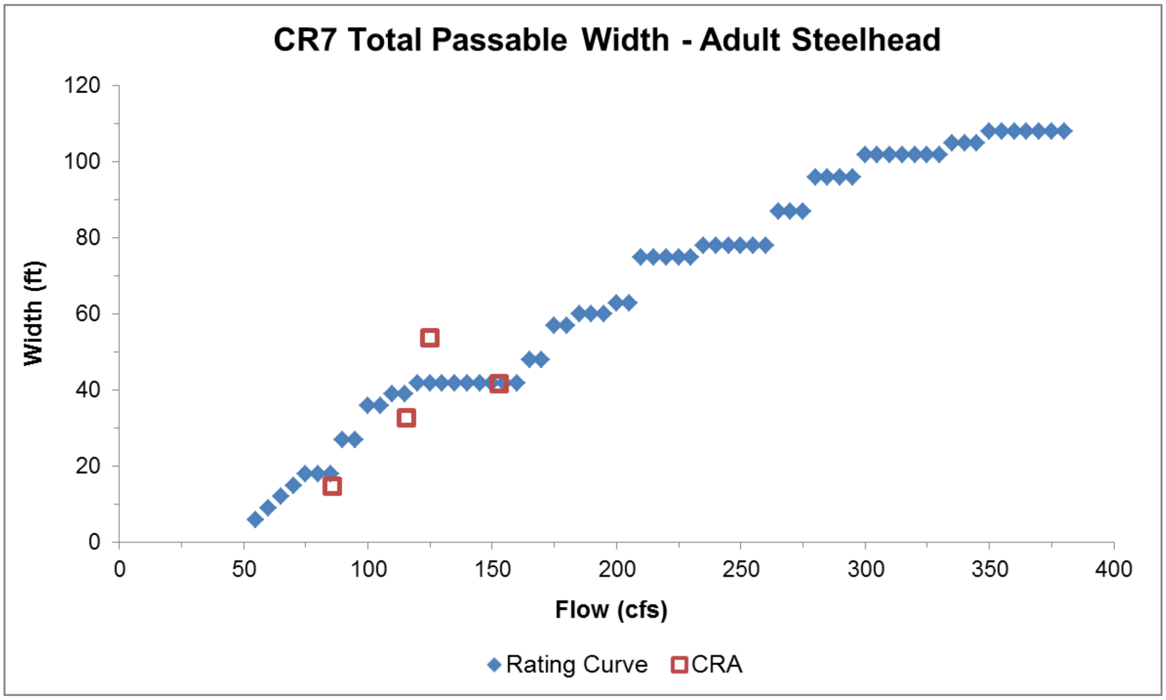


Figure E-14. Rating curve results of total passable width as a function of flow for the 0.7 ft minimum body depth criteria for adult steelhead at CR7.The red boxes indicate field-collected data.

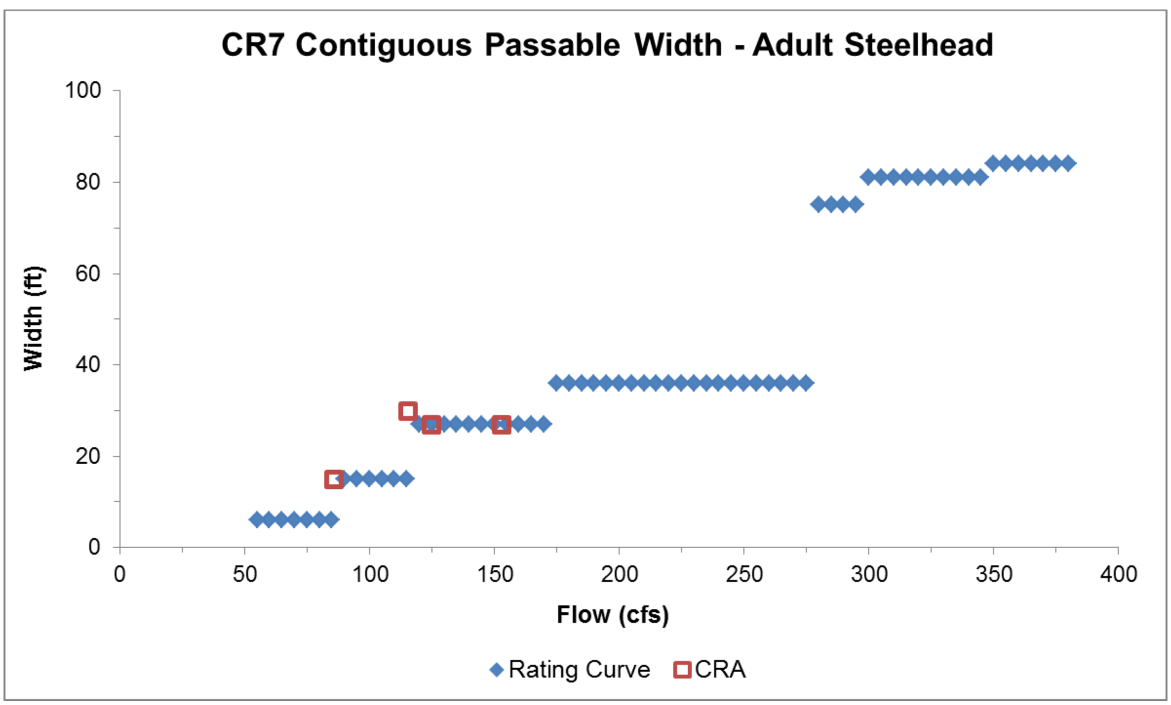


Figure E-15. Rating curve results of contiguous passable width as a function of flow for the 0.7 ft minimum body depth criteria for adult steelhead at CR7.The red boxes indicate field-collected data.

Table E-1. CR3 rating curve results for adult Chinook salmon, total width (ft).

Adult Chinook Salmon (minimum depth criteria = 0.9 ft)					
Maximum Wetted Width = 133 ft					
Flow (cfs)	**Total Width (ft)**	**Flow (cfs)**	**Total Width (ft)**	**Flow (cfs)**	**Total Width (ft)**
370	110	255	82	140	10
365	110	250	82	135	10
360	110	245	74	130	8
355	110	240	72	125	8
350	110	235	70	120	6
345	110	230	70	115	6
340	104	225	66	110	6
335	102	220	64	105	4
330	102	215	64	100	2
325	98	210	64	95	2
320	98	205	64	90	2
315	98	200	60	85	2
310	96	195	60	80	0
305	96	190	58	75	0
300	96	185	52	70	0
295	96	180	44	65	0
290	94	175	38	60	0
285	94	170	34	55	0
280	92	165	30	50	0
275	90	160	24	45	0
270	90	155	22	40	0
265	86	150	22	35	0
260	86	145	16	30	0

Table E-2. CR3 rating curve results for adult Chinook salmon, contiguous width (ft).

Adult Chinook Salmon (minimum depth criteria = 0.9 ft)					
Maximum Wetted Width = 133 ft					
Flow (cfs)	Contiguous Width (ft)	Flow (cfs)	Contiguous Width (ft)	Flow (cfs)	Contiguous Width (ft)
370	56	255	40	140	8
365	56	250	40	135	8
360	56	245	34	130	6
355	56	240	34	125	6
350	56	235	34	120	6
345	56	230	32	115	6
340	46	225	20	110	6
335	46	220	20	105	4
330	46	215	20	100	2
325	46	210	20	95	2
320	46	205	20	90	2
315	46	200	20	85	2
310	46	195	20	80	0
305	46	190	20	75	0
300	46	185	12	70	0
295	46	180	12	65	0
290	40	175	12	60	0
285	40	170	12	55	0
280	40	165	10	50	0
275	40	160	10	45	0
270	40	155	8	40	0
265	40	150	8	35	0
260	40	145	8	30	0

Table E-3. CR4 rating curve results for adult Chinook salmon, total width (ft).

Adult Chinook Salmon (minimum depth criteria = 0.9 ft)					
Maximum Wetted Width = 204 ft					
Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)
550	124	375	80	200	48
545	122	370	78	195	48
540	122	365	78	190	46
535	120	360	74	185	46
530	120	355	74	180	44
525	118	350	74	175	42
520	118	345	72	170	38
515	116	340	72	165	38
510	116	335	72	160	38
505	112	330	72	155	38
500	112	325	72	150	38
495	108	320	72	145	34
490	108	315	70	140	34
485	108	310	66	135	34
480	108	305	64	130	32
475	106	300	64	125	30
470	106	295	64	120	30
465	104	290	62	115	30
460	104	285	58	110	30
455	100	280	58	105	30
450	98	275	56	100	30
445	98	270	56	95	28
440	94	265	56	90	26
435	94	260	56	85	26
430	86	255	56	80	24
425	86	250	56	75	20
420	86	245	54	70	18
415	86	240	54	65	14
410	86	235	52	60	14
405	84	230	50	55	14
400	84	225	50	50	12
395	80	220	48	45	10
390	80	215	48	40	8
385	80	210	48	35	8
380	80	205	48	-	-

Table E-4. CR4 rating curve results for adult Chinook salmon, contiguous width (ft).

Adult Chinook Salmon (minimum depth criteria = 0.9 ft)					
Maximum Wetted Width = 204 ft					
Flow (cfs)	**Contiguous Width (ft)**	**Flow (cfs)**	**Contiguous Width (ft)**	**Flow (cfs)**	**Contiguous Width (ft)**
550	92	375	30	200	22
545	92	370	30	195	22
540	92	365	30	190	22
535	92	360	30	185	22
530	92	355	30	180	22
525	92	350	30	175	22
520	92	345	30	170	18
515	92	340	30	165	18
510	92	335	30	160	18
505	92	330	30	155	18
500	86	325	30	150	18
495	62	320	30	145	18
490	62	315	30	140	18
485	62	310	28	135	18
480	62	305	26	130	16
475	62	300	26	125	16
470	62	295	26	120	16
465	56	290	26	115	16
460	56	285	26	110	16
455	30	280	26	105	16
450	30	275	24	100	16
445	30	270	24	95	16
440	30	265	24	90	16
435	30	260	24	85	16
430	30	255	24	80	16
425	30	250	24	75	14
420	30	245	22	70	12
415	30	240	22	65	12
410	30	235	22	60	12
405	30	230	22	55	12
400	30	225	22	50	12
395	30	220	22	45	10
390	30	215	22	40	6
385	30	210	22	35	6
380	30	205	22	-	-

Table E-5. CR7 rating curve results for adult Chinook salmon, total width (ft).

Adult Chinook Salmon (minimum depth criteria = 0.9 ft)					
Maximum Wetted Width = 210.5 ft					
Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)
570	60	390	42	210	18
565	60	385	39	205	18
560	57	380	39	200	18
555	57	375	39	195	18
550	57	370	39	190	18
545	57	365	39	185	18
540	57	360	39	180	15
535	57	355	39	175	15
530	48	350	39	170	12
525	48	345	36	165	12
520	48	340	36	160	12
515	48	335	36	155	12
510	48	330	36	150	12
505	42	325	36	145	12
500	42	320	36	140	9
495	42	315	36	135	9
490	42	310	36	130	6
485	42	305	36	125	6
480	42	300	36	120	6
475	42	295	27	115	3
470	42	290	27	110	0
465	42	285	27	105	0
460	42	280	27	100	0
455	42	275	27	95	0
450	42	270	27	90	0
445	42	265	27	85	0
440	42	260	24	80	0
435	42	255	24	75	0
430	42	250	24	70	0
425	42	245	18	65	0
420	42	240	18	60	0
415	42	235	18	55	0
410	42	230	18	50	0
405	42	225	18	45	0
400	42	220	18	40	0
395	42	215	18	35	0

Table E-6. CR7 rating curve results for adult Chinook salmon, contiguous width (ft).

Adult Chinook Salmon (minimum depth criteria = 0.9 ft)					
Maximum Wetted Width = 210.5 ft					
Flow (cfs)	Contiguous Width (ft)	Flow (cfs)	Contiguous Width (ft)	Flow (cfs)	Contiguous Width (ft)
570	36	390	27	210	6
565	36	385	15	205	6
560	36	380	15	200	6
555	36	375	15	195	6
550	36	370	15	190	6
545	36	365	15	185	6
540	36	360	15	180	6
535	36	355	15	175	6
530	27	350	15	170	6
525	27	345	15	165	6
520	27	340	15	160	6
515	27	335	15	155	6
510	27	330	15	150	6
505	27	325	15	145	6
500	27	320	15	140	6
495	27	315	15	135	6
490	27	310	15	130	6
485	27	305	15	125	6
480	27	300	15	120	6
475	27	295	15	115	3
470	27	290	15	110	0
465	27	285	15	105	0
460	27	280	15	100	0
455	27	275	15	95	0
450	27	270	15	90	0
445	27	265	15	85	0
440	27	260	15	80	0
435	27	255	15	75	0
430	27	250	15	70	0
425	27	245	6	65	0
420	27	240	6	60	0
415	27	235	6	55	0
410	27	230	6	50	0
405	27	225	6	45	0
400	27	220	6	40	0
395	27	215	6	35	0

Table E-7. CR3 rating curve results for adult steelhead, total width (ft).

Adult Steelhead (minimum depth criteria = 0.7 ft)					
Maximum Wetted Width = 133 ft					
Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)
370	122	255	114	140	74
365	122	250	114	135	72
360	122	245	112	130	70
355	122	240	112	125	66
350	122	235	110	120	64
345	122	230	110	115	64
340	122	225	110	110	64
335	122	220	110	105	60
330	122	215	110	100	52
325	122	210	110	95	44
320	122	205	104	90	34
315	122	200	102	85	30
310	122	195	102	80	22
305	122	190	98	75	16
300	122	185	98	70	10
295	118	180	96	65	8
290	118	175	96	60	6
285	118	170	96	55	6
280	118	165	94	50	4
275	118	160	92	45	2
270	118	155	90	40	2
265	116	150	86	35	0
260	116	145	86	30	0

Table E-8. CR3 rating curve results for adult steelhead, contiguous width (ft).

Adult Steelhead (minimum depth criteria = 0.7 ft)					
Maximum Wetted Width = 133 ft					
Flow (cfs)	Contiguous Width (ft)	Flow (cfs)	Contiguous Width (ft)	Flow (cfs)	Contiguous Width (ft)
370	122	255	56	140	34
365	122	250	56	135	34
360	122	245	56	130	32
355	122	240	56	125	20
350	122	235	56	120	20
345	122	230	56	115	20
340	122	225	56	110	20
335	122	220	56	105	20
330	122	215	56	100	12
325	122	210	56	95	12
320	122	205	46	90	12
315	122	200	46	85	10
310	122	195	46	80	8
305	122	190	46	75	8
300	122	185	46	70	8
295	60	180	46	65	6
290	60	175	46	60	6
285	60	170	46	55	6
280	60	165	40	50	4
275	60	160	40	45	2
270	60	155	40	40	2
265	58	150	40	35	0
260	58	145	40	30	0

Table E-9. CR4 rating curve results for adult steelhead, total width (ft).

Adult Steelhead (minimum depth criteria = 0.7 ft)					
Maximum Wetted Width = 204 ft					
Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)
550	168	375	124	200	72
545	166	370	124	195	70
540	166	365	124	190	66
535	164	360	122	185	64
530	164	355	120	180	62
525	160	350	120	175	58
520	160	345	118	170	56
515	158	340	116	165	56
510	158	335	116	160	56
505	158	330	112	155	56
500	158	325	108	150	56
495	158	320	108	145	54
490	158	315	108	140	52
485	158	310	106	135	50
480	158	305	104	130	48
475	158	300	104	125	48
470	158	295	100	120	48
465	152	290	98	115	48
460	152	285	94	110	46
455	148	280	94	105	44
450	146	275	86	100	42
445	146	270	86	95	38
440	142	265	86	90	38
435	142	260	84	85	38
430	136	255	84	80	34
425	136	250	80	75	34
420	134	245	80	70	32
415	134	240	80	65	30
410	134	235	78	60	30
405	130	230	74	55	30
400	130	225	74	50	30
395	130	220	72	45	26
390	130	215	72	40	24
385	126	210	72	35	18
380	124	205	72	-	-

Table E-10. CR4 rating curve results for adult steelhead, contiguous width (ft).

Adult Steelhead (minimum depth criteria = 0.7 ft)					
Maximum Wetted Width = 204 ft					
Flow (cfs)	**Contiguous Width (ft)**	**Flow (cfs)**	**Contiguous Width (ft)**	**Flow (cfs)**	**Contiguous Width (ft)**
550	118	375	92	200	30
545	118	370	92	195	30
540	118	365	92	190	28
535	118	360	92	185	26
530	118	355	92	180	26
525	118	350	92	175	26
520	118	345	92	170	24
515	118	340	92	165	24
510	118	335	92	160	24
505	118	330	86	155	24
500	118	325	62	150	24
495	118	320	62	145	22
490	118	315	62	140	22
485	118	310	62	135	22
480	118	305	56	130	22
475	118	300	56	125	22
470	118	295	30	120	22
465	92	290	30	115	22
460	92	285	30	110	22
455	92	280	30	105	22
450	92	275	30	100	22
445	92	270	30	95	18
440	92	265	30	90	18
435	92	260	30	85	18
430	92	255	30	80	18
425	92	250	30	75	18
420	92	245	30	70	16
415	92	240	30	65	16
410	92	235	30	60	16
405	92	230	30	55	16
400	92	225	30	50	16
395	92	220	30	45	16
390	92	215	30	40	16
385	92	210	30	35	12
380	92	205	30	-	-

Table E-11. CR7 rating curve results for adult steelhead, total width (ft).

Adult Steelhead (minimum depth criteria = 0.7 ft)					
Maximum Wetted Width = 210.5 ft					
Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)	Flow (cfs)	Total Width (ft)
380	108	260	78	140	42
375	108	255	78	135	42
370	108	250	78	130	42
365	108	245	78	125	42
360	108	240	78	120	42
355	108	235	78	115	39
350	108	230	75	110	39
345	105	225	75	105	36
340	105	220	75	100	36
335	105	215	75	95	27
330	102	210	75	90	27
325	102	205	63	85	18
320	102	200	63	80	18
315	102	195	60	75	18
310	102	190	60	70	15
305	102	185	60	65	12
300	102	180	57	60	9
295	96	175	57	55	6
290	96	170	48	50	0
285	96	165	48	45	0
280	96	160	42	40	0
275	87	155	42	35	0
270	87	150	42	-	-
265	87	145	42	-	-

Table E-12. CR7 rating curve results for adult steelhead, contiguous width (ft).

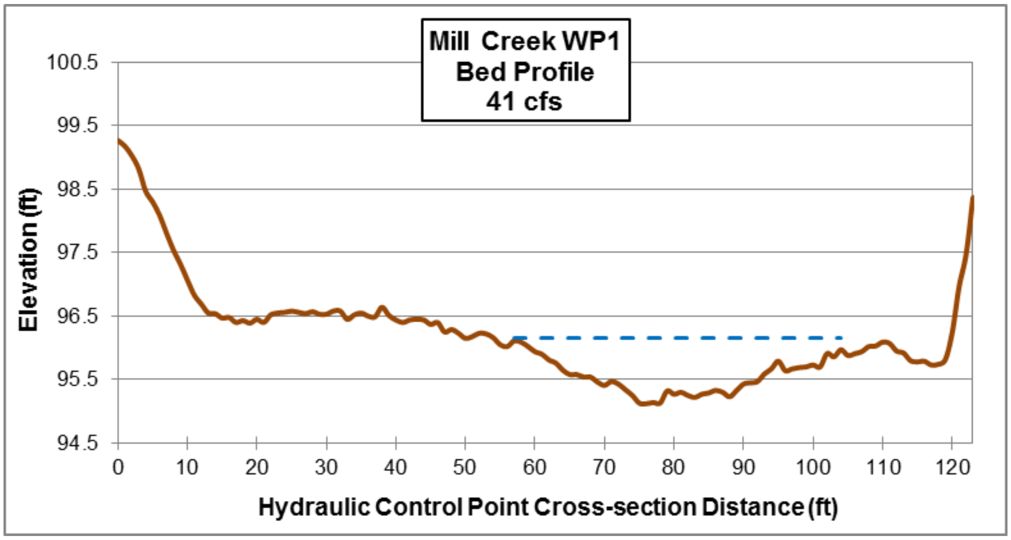
Adult Steelhead (minimum depth criteria = 0.7 ft)					
Maximum Wetted Width = 210.5 ft					
Flow (cfs)	**Contiguous Width (ft)**	**Flow (cfs)**	**Contiguous Width (ft)**	**Flow (cfs)**	**Contiguous Width (ft)**
380	84	260	36	140	27
375	84	255	36	135	27
370	84	250	36	130	27
365	84	245	36	125	27
360	84	240	36	120	27
355	84	235	36	115	15
350	84	230	36	110	15
345	81	225	36	105	15
340	81	220	36	100	15
335	81	215	36	95	15
330	81	210	36	90	15
325	81	205	36	85	6
320	81	200	36	80	6
315	81	195	36	75	6
310	81	190	36	70	6
305	81	185	36	65	6
300	81	180	36	60	6
295	75	175	36	55	6
290	75	170	27	50	0
285	75	165	27	45	0
280	75	160	27	40	0
275	36	155	27	35	0
270	36	150	27	-	-
265	36	145	27	-	-

References

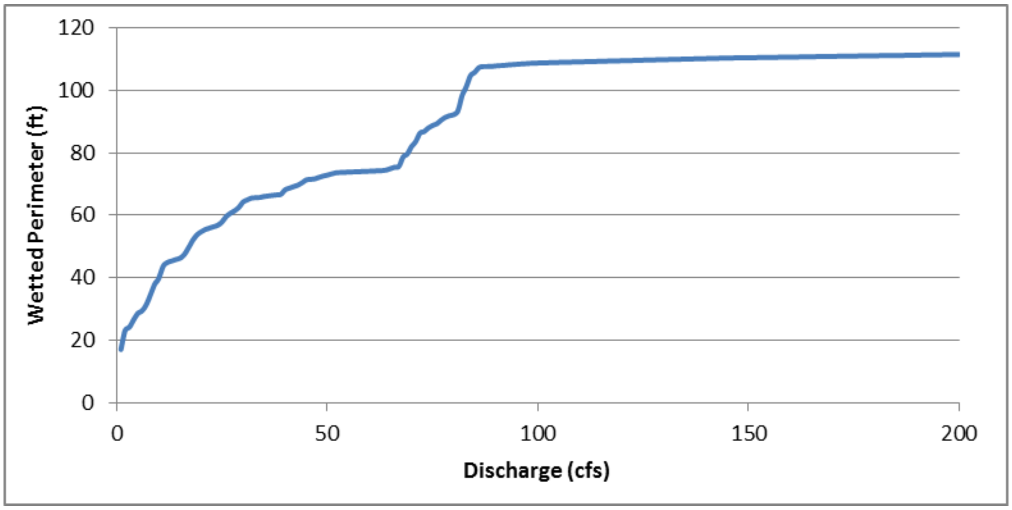
Sauer, V.B. 2002. Standards for the analysis and processing of surface-water data and information using electronic methods: U.S. Geological Survey Water-Resources Investigations Report 01-4044, 91 p.

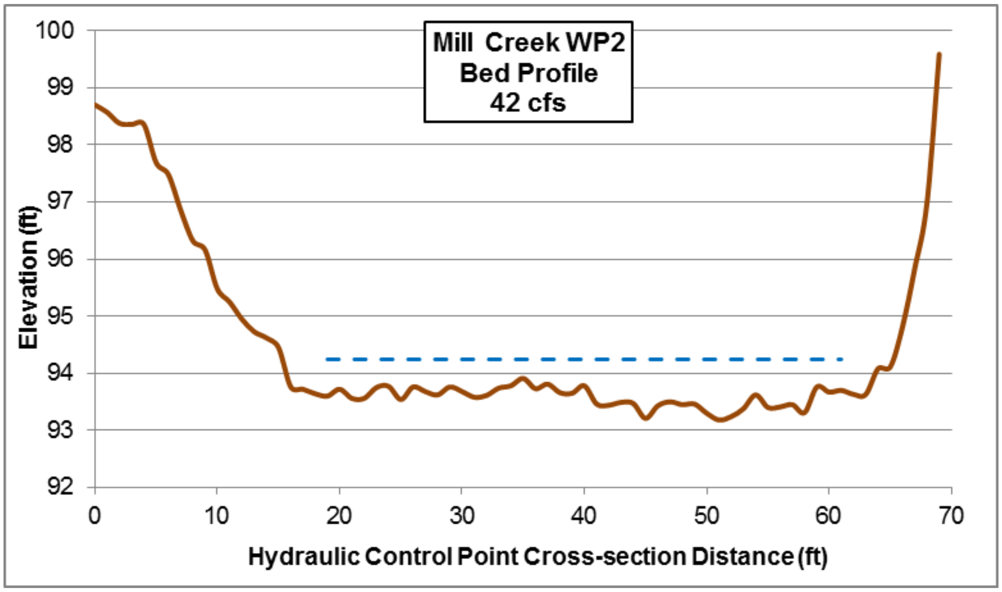
Waddle, T.J. (ed.). 2012. PHABSIM for Windows user's manual and exercises. Open-File Report 2001-340. Fort Collins, CO: U.S. Geological Survey. 288 p.

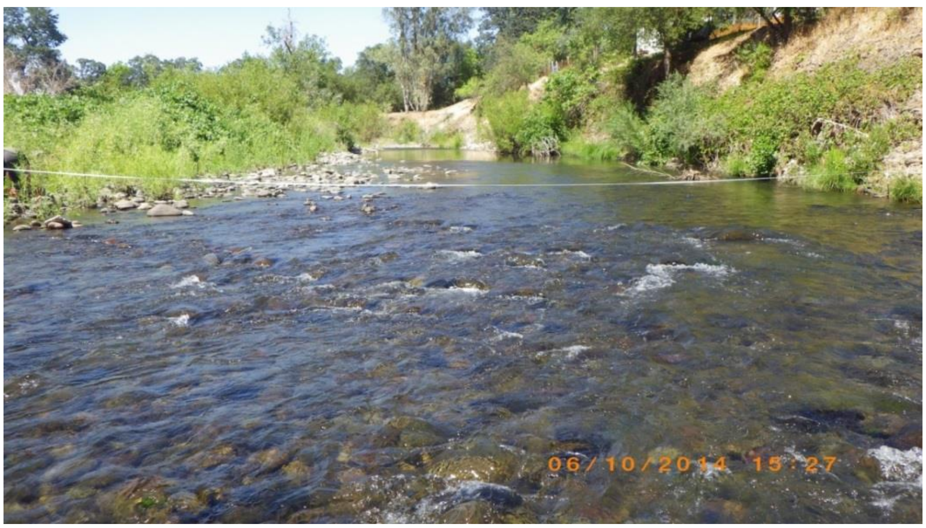
Appendix F. Wetted Perimeter Profiles



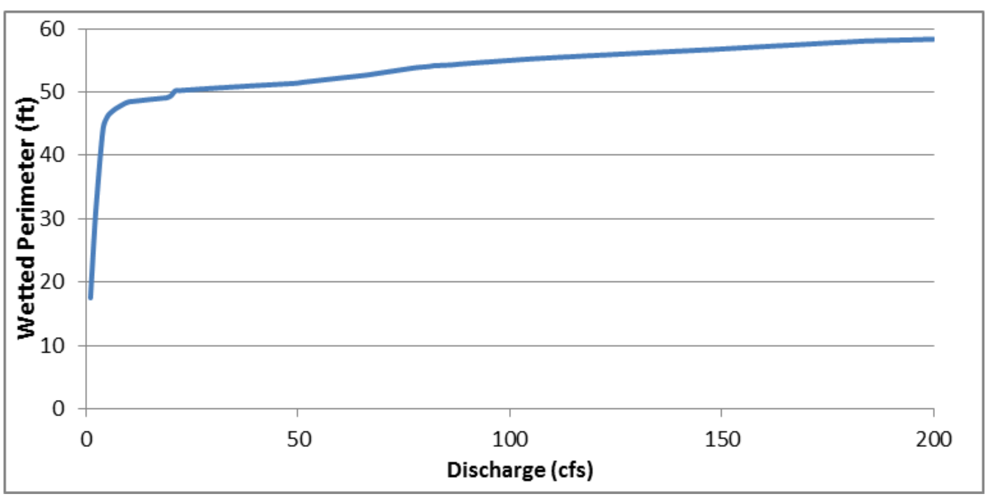
WP1: View upstream at 41 cfs

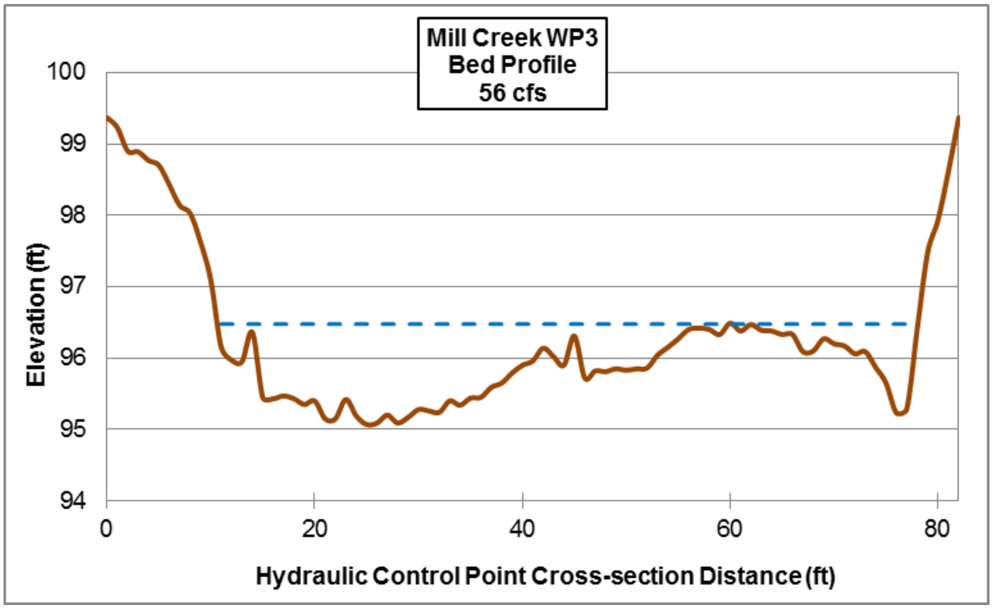




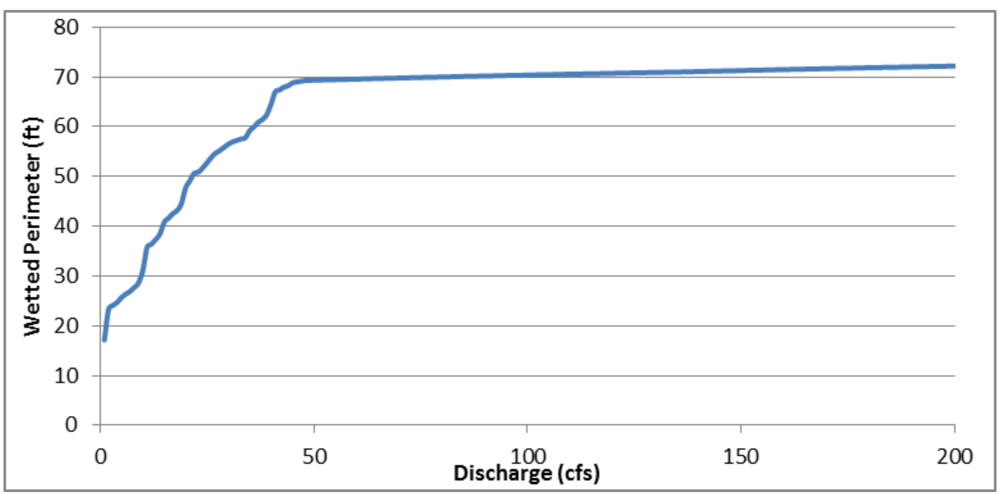


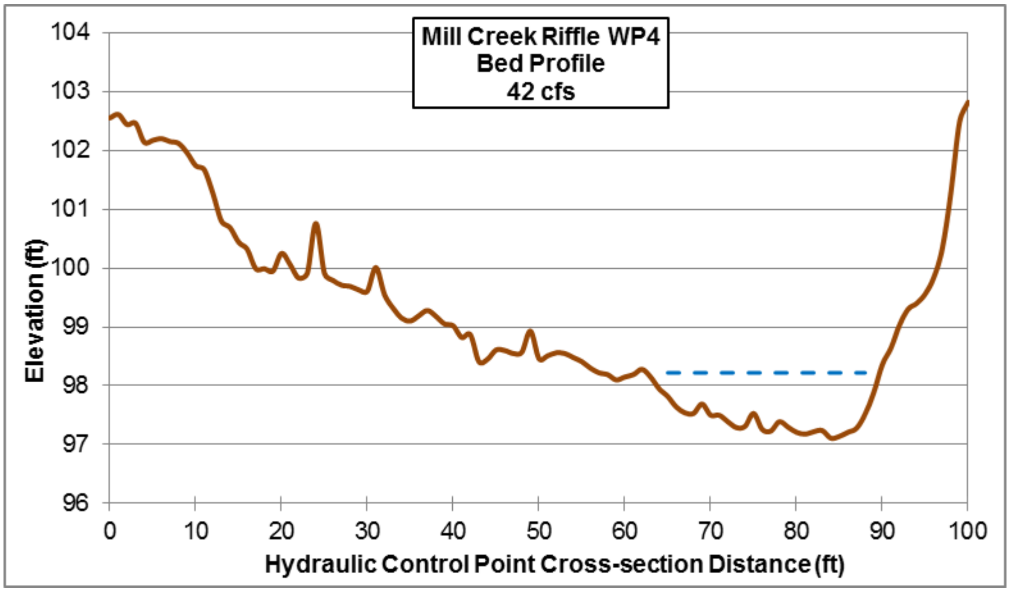
WP2: View upstream at 42 cfs.





WP3: View downstream at 56 cfs.





WP4: View upstream at 42 cfs.