CALIFORNIA TROUT

SPROUL CREEK INSTREAM FLOW STUDY FINAL REPORT

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1 INTRODUCTION

1.1 Background and Purpose of the Study

California Trout (CalTrout) and several project partners conducted water resource investigations in Sproul Creek, tributary to the South Fork Eel River in Mendocino and Humboldt Counties (Figure 1), as an initial phase of a South Fork Eel Water Conservation Program (CalTrout et al. 2014). Project partners include Humboldt State University River Institute (HSU-RI), Trout Unlimited (TU), and McBain Associates (MA). The purpose of this program is to establish scientifically defensible, standardized methodologies for determining instream flow criteria for cold-water species in unregulated coastal California watersheds.

This ***Sproul Creek Instream Flow Study Report*** presents results of field investigations and modeling analyses to identify hydraulic habitat thresholds and other flow-ecology relationships important for anadromous salmonids and other aquatic resources in Sproul Creek. Results of this study will provide traditional bypass flow thresholds or *flow criteria* intended to maintain migratory access and high quality freshwater habitat for anadromous salmonids and other aquatic species. The site-specific flow criteria developed from this study may be used by state agencies in subsequent phases for determining instream *flow objectives*, assessing impacts of ongoing water diversions in Sproul Creek, and implementing water conservation actions in Sproul Creek to protect public trust resources. These flow criteria may also be used to evaluate the performance of regional approaches being developed to determine protective instream flow criteria without site-specific studies.

CalTrout received funding from the California State Water Resources Control Board's Nonpoint Source Pollution Control Program and Federal Clean Water Act 319(h) grant program to advance these program goals and implement this *Sproul Creek Instream Flow Study Project*. The Sproul Creek project is administered by the State Water Resources Control Board (SWRCB) with project management provided by staff from the North Coast Regional Water Quality Control Board (RWB).

Gradually diminishing streamflows in the spring, typically beginning in May and lasting through September, is the natural stressful condition salmon and steelhead encounter in the South Fork Eel River annually. However, over the past several decades natural low-flow conditions have become compounded by anthropogenic factors, including climate change, increased rates of forest evapotranspiration and groundwater depletion, and surface water diversion for domestic and agricultural consumption. Low summer streamflows have been identified as a major cause of temperature impairments (NCRWQCB 2013, 2014) and have been linked to the proliferation of water diversions for wine-grape, cannabis, and other agricultural activities. The SF Eel River is on the Federal EPA 303d list for water temperature and sediment impairment. Three native salmonid populations inhabit the SF Eel River, all of which are federally listed as threatened: the Southern Oregon and Northern California Coast (SONCC) coho salmon (*Oncorhynchus kisutch*), North Coast (NC) steelhead (*O. mykiss*), and California Coastal (CC) Chinook salmon (*O. tshawytscha*). The South Fork Eel River is identified as a salmon stronghold (WSC 2012), and sustains one of the largest coho salmon population in the SONCC ESU. Despite this status, adult abundance is at an historical low, currently hovering around 1000 adults annually (CDFW 2014a). Chinook and steelhead populations are also depressed relative to historic abundance, although those two species have shown signs of population stability (CalTrout 2017). The South Fork Eel River and Sproul Creek also provide habitat for Pacific Lamprey (*Entosphenus tridentatus*), considered a species of concern by the US Fish and Wildlife Service (USFWS), and the Foothill Yellow-Legged Frog (*Rana boylii*), which was recently identified as a candidate species under the

California Endangered Species Act (CESA). The South Fork Eel River is one of five priority basins selected as part of the California Water Action Plan for instream flow evaluation.

Figure 1. *Location of Sproul Creek in the South Fork Eel River, CA. Reference watersheds Bull Creek and Elder Creek, and USGS gaging sites are highlighted.*

1.2 Study Objectives

The objectives of this Sproul Creek Instream Flow Study (deliverables with CWA 319h grant funding) are to:
(1) Conduct a site-specific instream flow study in Sproul Creek following the field methods, analytical approaches, and study protocols adopted by CDFW for prescribing instream flow criteria, and prescribe numeric flow criteria for specific Points of Interest (POIs) in the Sproul Creek watershed. This site-specific study implemented the following suite of actions:

- Install streamflow gages across a range of watershed areas to collect streamflow and water temperature data, correlate streamflow data to nearby USGS gages, and assess variation in streamflow unit runoff at different scales and locations in the watershed;
- Select study reaches in strategic locations to assess the potential effects of surface water diversions on salmonids, other aquatic species, and Sproul Creek water quality;
- Conduct habitat inventory surveys identifying meso-habitat units, hydraulic units, and riffle crest thalweg depths, as needed to support the selection of flow study sites and to provide a reasonable basis for extrapolating site-specific findings to broader reaches of the watershed;
- Implement empirical and modeling instream flow methods over a range of flows to assess hydraulic habitat and streamflow-ecology relationships, focusing primarily on fish passage, spawning and rearing hydraulic habitat, the spring recession, and summer low-flow period;
- report streamflow thresholds protective of salmonid life history needs, and prescribe numeric flow criteria;

(2) Estimate unimpaired streamflows and human water demand resulting from rural residential use and cannabis irrigation in the Sproul Creek watershed; compare water demand to water supply and instream flow needs for salmonids.
(3) In a later phase of analysis, CalTrout and our partners will use the Sproul Creek flow criteria as a basis for evaluating the performance of regional methods for developing flow criteria proposed for north coast watersheds where site specific studies are not conducted.

1.3 Watershed Description

The 689 mi^2 South Fork Eel River (Figure 1) is the second largest sub-basin in the Eel River, with 450 tributaries providing approximately 690 miles of perennial stream habitat (CDFW 2014a). The SF Eel River joins the mainstem Eel River at river mile forty (RM 40). The SF Eel River thus provides nearly seven hundred miles of salmonid habitat in tributary watersheds, a 100 mile long South Fork mainstem, then flows into a 40 mile long Eel River mainstem, and through an historically vast delta and estuary before joining the Pacific Ocean.

The South Fork historically sustained the largest populations of salmon and steelhead in the Eel River (CDFW 2014a). A fish ladder operated at Benbow Dam from 1938 to 1975, located just a mile upstream of the Sproul Creek confluence, provided annual salmon and steelhead counts for the Upper (southern) half of the South Fork basin (360 mi^2). The average adult abundance from the 38 year data record was approximately 7,000, 7,500, and 11,200 adult Chinook, coho, and steelhead, respectively. However, the years prior to the 1955 flood had much higher abundance (Figure 2), with counts peaking higher than 20,000 adult spawners for each species.

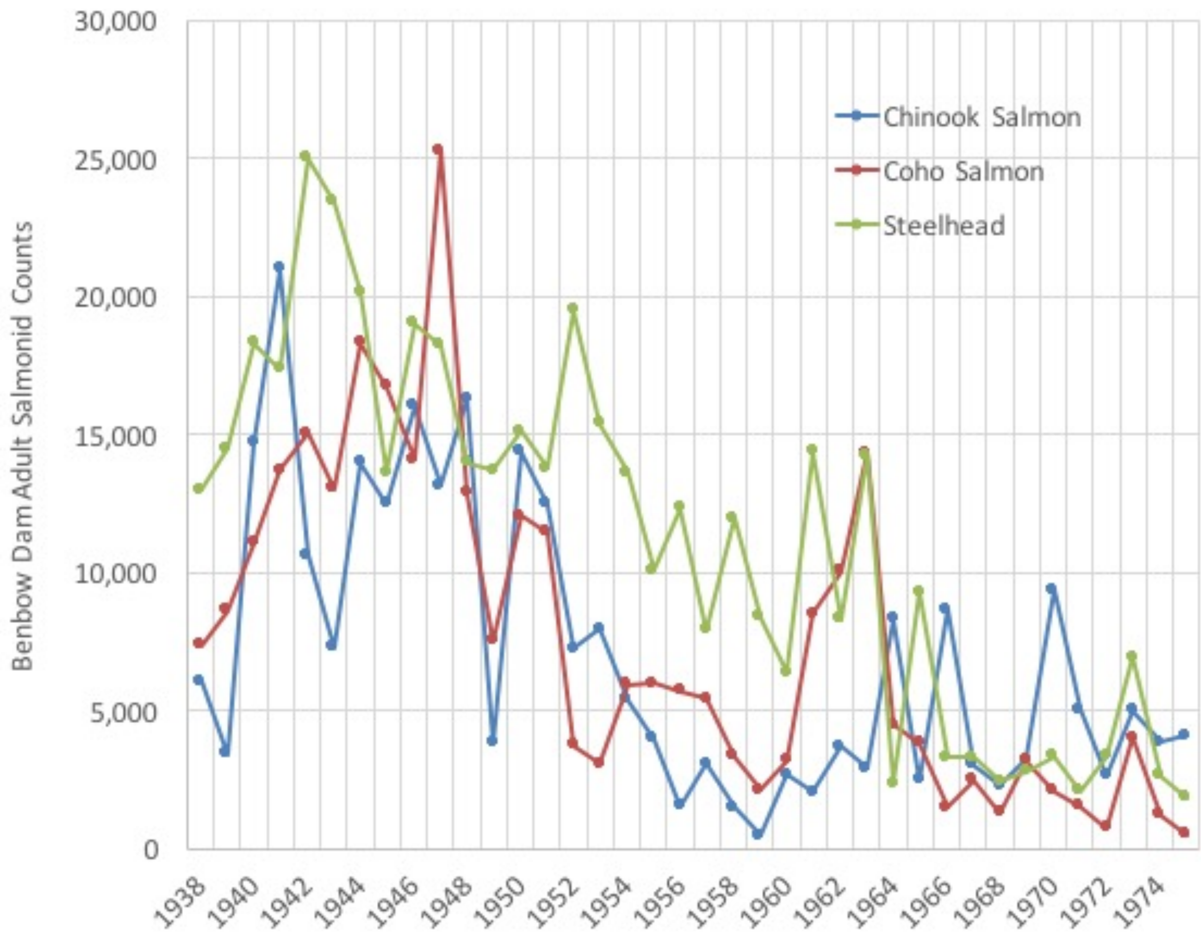

Figure 2. Adult salmon and steelhead counts at the Benbow Dam site, conducted from 1938 to 1975.

Sproul Creek is a tributary to the South Fork Eel River, entering from the western slope near Garberville, CA, approximately 34 miles upstream from the confluence of the SF Eel River with the mainstem Eel River (Figure 1). The Sproul Creek watershed (24.0 mi^2) is dominated by conifer and mixed hardwood forest composed primarily of redwood (*Sequoia sempervirens*), Douglas Fir (*Pseudotsuga menziesii*), tanoak (*Notholithocarpus densiflorus*) and madrone (*Arbutus menziesii*), and with riparian vegetation along stream channels composed of willow (*salix spp*) and red alder (*Alnus rubra*). Elevations range from 310 ft at the confluence with the SF Eel River up to approximately 2,028 ft at Rose Peak along the north-western ridge of the watershed. The watershed is entirely privately owned, with extensive areas of undeveloped working forest lands (Figure 3). Boyle Forests LLP and Wagner Corporation are two large timber landowners. Medium-sized ranches and residential parcels comprise the remaining area. There are approximately 20 rural residential parcels in the Upper South Fork Sproul Creek headwaters (Figure 3), and approximately 7 residential parcels along the mainstem Sproul Creek near the mouth. Sproul Creek has a history of timber harvest and impacts from the 1955 and 1964 floods. Its forest and riparian canopy have recovered from those floods, and now provides among the highest quality salmonid habitat in the South Fork Eel River basin. Sproul Creek has approximately 26 miles of anadromous salmonid habitat (CDFG 2004), and supports recently stable runs of Chinook and coho salmon, and steelhead (Renger 2015 Personal Communication). Monitoring access to most stream reaches is good. The CDFW

Coastal Monitoring Program began conducting adult spawner surveys in Sproul Creek in 2011 (CDFW 2016).

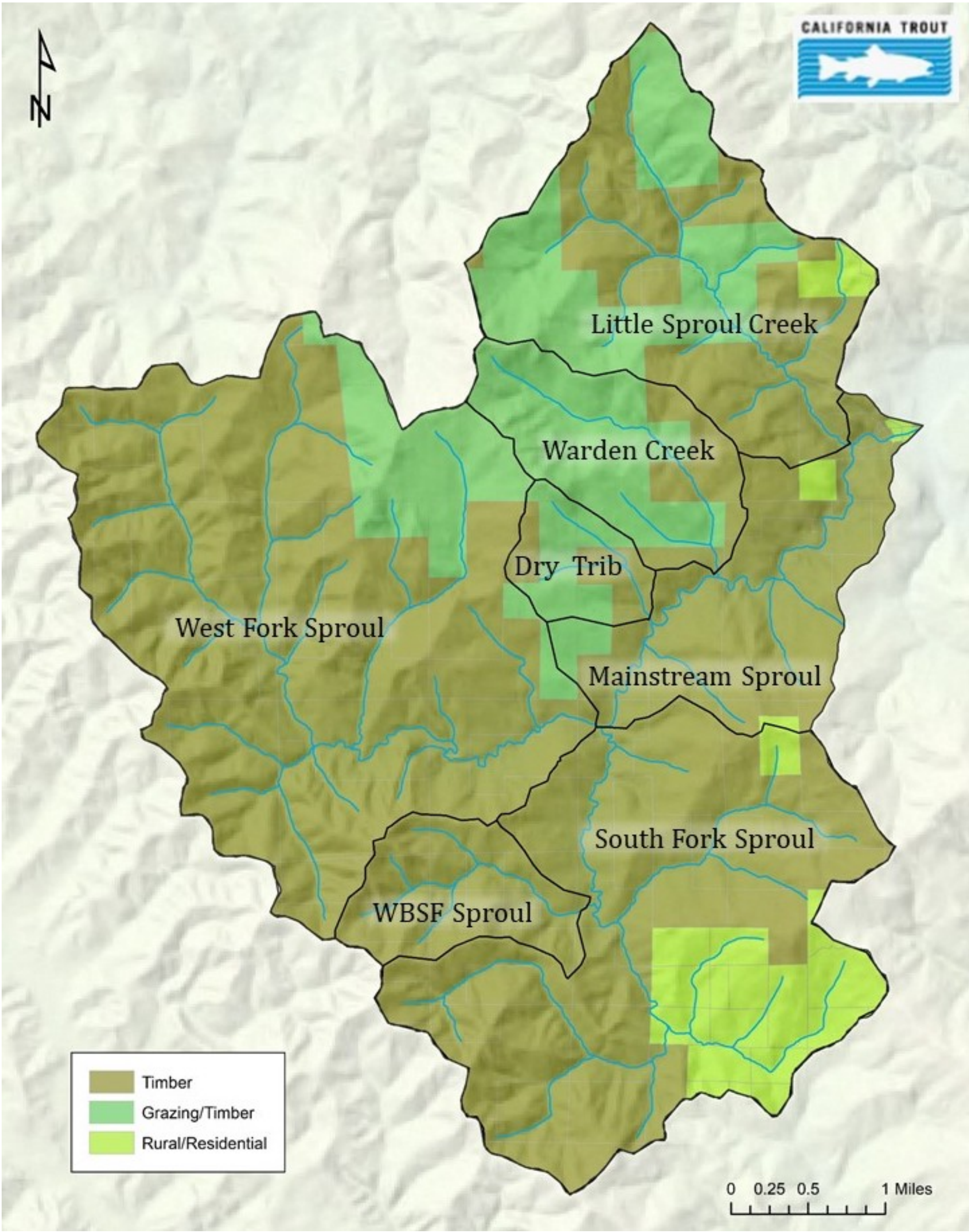

Figure 3. The 24 mi^2 *Sproul Creek watershed, sub-watersheds, and general land ownership.*

Sproul Creek exhibits a Mediterranean climate typical of the South Fork Eel River and the north coastal ranges of California. Precipitation is distinctly seasonal with very little rainfall (less than 3% of the average annual rainfall) occurring from June through September (Table 1). Extended periods of drought, beyond the annual dry season, are not uncommon. During such extended droughts, as in 1977 and 2014, surface streamflow along the Sproul Creek mainstem and its forks have become disconnected.

Table 1. *Monthly and annual mean precipitation data for Sproul Creek, for a 30 year period of record (1981-2010). Data from the PRISM Climate Group.*

Month	Mean Monthly Precipitation (in)	Mean Monthly Runoff (af)
October	3.57	332
November	9.23	3,584
December	14.18	12,014
January	12.96	14,189
February	11.17	11,559
March	9.81	10,763
April	4.74	4,922
May	2.61	1,748
June	0.98	793
July	0.1	283
August	0.25	106
September	0.77	76
Mean Annual Precipitation (in) and Yield (af)	**70.36**	**60,369**

1.4 Why Sproul Creek was Selected for a Site Specific Study

Sproul Creek was selected for this study for several reasons. First, Sproul Creek provides abundant, high quality salmonid habitat representative of desired habitat conditions in the SF Eel River and its tributary watersheds. Unlike other nearby watersheds, Sproul Creek has had very little residential development and has had very low timber harvest rates in recent decades. In addition, CDFW Region-1 staff have collected recent habitat inventory and spawner survey data, and have proposed Sproul Creek as a preferred location for a life-cycle monitoring station and continued salmonid population monitoring. Finally, the primary timber landowner has been very generous and supportive of streamflow and salmonid habitat studies, providing a unique opportunity for long-term monitoring and data collection in a healthy watershed with very little residential development.

In addition to these general reasons, there was a specific reason for Sproul Creek being selected as a location for instream flow study: during the 2014 drought there were credible reports of salmonid-bearing stream reaches in Sproul Creek being disconnected or dried up, likely due in part by surface water diversions. The residential parcels in Sproul are concentrated in a small area of the Upper South Fork, which enables a focused flow study evaluating the potential effects of water diversions on surface flows and salmonid habitat. The Regional Water Board responded by selecting Sproul Creek as a pilot watershed for implementing its cannabis waiver program, and by approving and administering funding for this study with CalTrout.

2 OVERVIEW OF STUDY APPROACH

The Sproul Creek flow study generally followed a four-step process for identifying monthly flow criteria for two study reaches:

1. Describe Chinook salmon, coho salmon, and steelhead habitat requirements and life stage periodicities specific to Sproul Creek, primarily from literature sources;
2. Develop reference data of estimated daily average unimpaired streamflows and measured streamflows for the previously ungaged Sproul Creek watershed;
3. Apply traditional and commonly used empirical and modeling instream flow methods in representative study reaches of Sproul Creek to (a) identify bypass flow thresholds for priority salmonid life stages; and (b) identify a range of spring recession and dry season flow thresholds which may indicate progressively higher risk of habitat impairment from water diversions;
4. Prioritize individual life-stage instream flow needs for each month to prescribe a set of protective bypass flow criteria for a range of water year types.

The Sproul Creek instream flow study data, including streamflow data, empirical hydraulic analyses, and the PHABSIM modeling and time-series analyses, are reported in a series of technical appendices to this report, including the following:

Appendix A – Project Location, Habitat Inventories, and Study Reach Selection
Appendix B – Unimpaired Hydrology for Sproul Creek Watershed
Appendix C – Streamflow Gaging for WY2015 and WY2016
Appendix D – Riffle Crest Thalweg (RCT) Rating Curves from Sproul Creek Study Reaches
Appendix E – 1-Dimensional PHABSIM Modeling in the Upper South Fork (USF) reach
Appendix F – 2-Dimensional PHABSIM Modeling in the Upper Mainstem (UMS) reach
Appendix G – Time-Series Analysis Methods and Results for Monthly Flow-Habitat Thresholds
Appendix H – Critical Riffle Analysis for Juvenile and Adult Fish Passage
Appendix I – Wetted Perimeter Analysis
Appendix J – Benthic Macroinvertebrate Drift
Appendix K – Water Demand Analysis for the Sproul Creek Watershed.
Appendix L – Pool Thalweg Velocity Core from Sproul Creek Study Reaches

Empirical and modeling data were used to identify monthly bypass flow thresholds protective of targeted life stages for each of three salmonid species. These bypass flow thresholds were compiled into a master table of flow thresholds for each of the two study reaches in Sproul Creek. These thresholds were then compared for the three species, and prioritized to develop a set of monthly flow criteria for five equally weighted water year classes: Extremely Wet, Wet, Normal, Dry, and Extremely Dry. We compared the annual unimpaired water supply, the minimum bypass flow requirements, and the current estimated water demand from residential and agricultural uses to determine if any threat of impact from water diversions may be occurring in Sproul Creek. We conclude with recommendations on appropriate study plan components for future site specific instream flow studies in the South Fork Eel River and other similar north coast watersheds.

3 STEP-1: IDENTIFY FOCAL SPECIES AND LIFE STAGE PERIODICITIES

The South Fork Eel River supports three functionally independent populations of *Oncorhynchus*: Chinook salmon, coho salmon, and steelhead trout (Bjorkstedt et al. 2005, Williams et al. 2006) all of which have declined sharply from historical abundances (EPA 1999, NMFS 2014, 2016). The three ESU's: Southern Oregon/Northern California Coasts (SONCC) coho salmon, California Coast (CC) Chinook salmon, and Northern California (NC) Steelhead are all federally listed as threatened (United States Office of the Federal Register 1997, 1999, 2000). There are no hatcheries in the basin, although Chinook salmon genetics may be affected by past transplants (NMFS 2007) and steelhead were planted in the South Fork Eel River as recently as 1995 (SEC 1998). Anadromous Pacific lamprey are not listed, but are a species of concern, with similar population declines and habitat needs as the salmonids.

Salmonids are adapted to the annual hydrograph, and receive environmental cues that trigger their behavioral responses. The life-history patterns and timing of Chinook, coho, and steelhead have been described in detail in many documents and are briefly summarized here. Figure 4 shows each major life-stage at monthly time steps for the three target salmonid species.

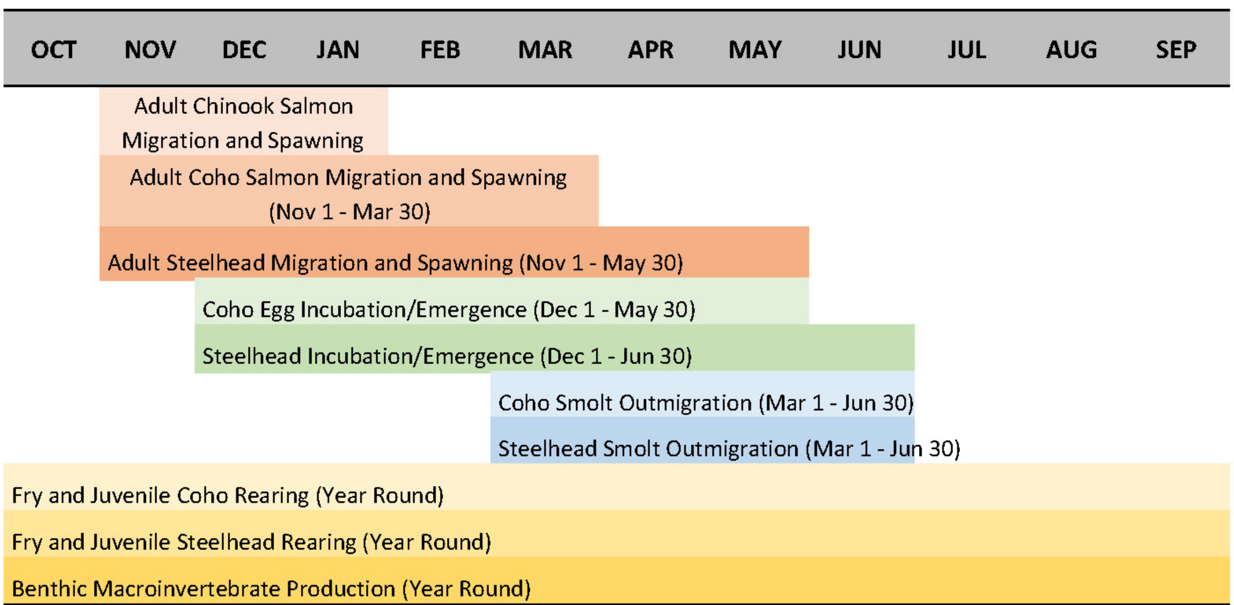

Figure 4. Life stage periodicity for the three native salmonid species inhabiting Sproul Creek. Each of these populations is listed as Threatened under the Federal Endangered Species Act.

3.1 Summary of Anadromous Salmonid Life Histories

Chinook Salmon (*O. tshawytscha*)

Eel River Chinook salmon are a subpopulation of the CA Coastal Chinook Salmon ESU. These fall-run Chinook exhibit the typical "ocean-type" anadromous life cycle: hatching in freshwater, migrating to the ocean in their first year, and returning to freshwater to spawn and die. Adult Eel River Chinook salmon spend 2-5 years in the ocean. They are "fall run" fish, with sexually mature adults entering freshwater as early as August if streamflows allow, to January (Chase et al. 2007 *in* NMFS 2016), and spawning within a few weeks of entering freshwater. Adult migration typically occurs during the peak and recession of fall and winter storm hydrographs, when streamflows enable passage into mainstem and headwater tributary streams. The preferred spawning substrate is clean, loose gravel with minimal fine sediment, typically found on pool-tails and at the crests of riffles (NMFS 2016). Eggs incubate in gravel nests (redds) for 90 to 150 days depending on water temperature (Allen and Hassler 1986 *in* NMFS 2016). Fry emerge from the redds from December until April (Leidy and Leidy 1984 *in* NMFS 2016) immediately seeking out cover in areas behind fallen trees, back eddies, and undercut banks (Everest and Chapman 1972 *in* NMFS 2016). Fall Chinook juveniles migrate to the estuary and ocean as smolts after minimal rearing time in their natal stream, usually within a few weeks to several months. Smolts require adequate streamflows to travel downstream to estuarine areas, where they frequently reside during spring and summer months before entering the ocean.

Coho Salmon (*O. kisutch*)

South Fork Eel River coho salmon, a sub-population of the SONCC Coho Salmon ESU, generally have a 3-year life cycle. Adult coho salmon begin migrating into the Eel River as early as mid-October (Baker and Reynolds 1986), with the peak run during December and January. Coho spawn by mid-winter, and die after eggs are deposited. Eggs incubate in redds for 45-120 days, with peak fry emergence between March and July (Shapovalov and Taft 1954, Koski 1966 *in* NMFS 2014). The hatched juveniles rear in freshwater for approximately 12 to 18 months. Juveniles typically migrate to the ocean in spring as pre-smolts and smolts from March to July (Shapovalov and Taft 1954, Sandercock 1991 *in* NMFS 2014). After leaving freshwater, they spend two growing seasons in the ocean before returning to freshwater as adults to spawn.

Steelhead Trout (*O. mykiss*)

O. mykiss have the most varied life history of the Eel River salmonids, including anadromous and non-anadromous forms. The anadromous form of *O. mykiss*, steelhead, exist as two distinct runs in the Eel River: the more abundant winter run, and the less abundant summer run. Summer steelhead are known to persist in areas of the Middle Fork Eel and Van Duzen rivers, but are assumed extirpated from the South Fork Eel River (CDFG 1992). While there is relatively limited data on Eel River winter run steelhead abundance (Good et al. 2005), they are likely less imperiled than coho salmon and Chinook salmon (Yoshiyama and Moyle 2010, CalTrout 2017). Unlike Chinook and coho salmon, steelhead are capable of returning to the ocean after spawning, and re-entering freshwater to spawn in subsequent years.

Winter run steelhead typically enter the Eel River in a sexually mature state to spawn from December to May. Steelhead typically ascend higher into headwater streams to spawn. After an incubation period of approximately 25-35 days, eggs hatch into alevins (Shapovalov & Taft 1954), which remain in the gravel for two to three more weeks until they emerge as fry. Fry rear in slow-velocity edgewater habitats, gradually moving into deeper and faster water as they grow (Chapman and Bjornn 1969; Everest and Chapman 1972; Vondracek and Longanecker 1993 *in* NMFS 2016). South Fork Eel River juvenile steelhead generally rear in freshwater for one to two years, typically using faster water habitats than Chinook or coho salmon. Steelhead smolt migration to the ocean generally occurs in the spring months.

Pacific lamprey (Entosphenus tridentatus)
Pacific lamprey are the namesake of the Eel River. Lamprey are fast-growing opportunistic parasites in the ocean environment, feeding upon a variety of fish species (Orlov et al. 2009). They stop feeding as they begin their spawning migration into freshwater (Beamish 1980). Adults migrate upstream to holding habitats, where they hibernate for the summer and spawn the following spring (Robinson and Bayer 2005). Juvenile lamprey, called ammocetes, filter feed in sandy deposits along stream margins (Potter 1980) for 5-7 years before they migrate back to the ocean. Goodman et al. (2015) suggest the downstream migration of ammocetes may be a limiting factor for lamprey, as "populations … encounter altered streamflow regimes, diversions, and misleading environmental cues".

Habitat requirements for freshwater life stages of salmon and steelhead

- Adult Migration: Chinook, coho, and steelhead generally return to the Eel River in succession: Chinook begin migrating into the Eel River estuary as early as September, but more typically into October, where they await the arrival of fall rainstorms and decreased water temperatures before ascending into the watershed. As Chinook spawning season wanes, coho salmon begin their migration into the watershed. Steelhead migration overlaps with the latter stages of the Chinook run but peaks later in the winter and continues past the coho run. Steelhead are much stealthier than salmon and are known to migrate during storm hydrographs farther into headwater streams. Adult salmonids require cold water temperatures and streamflows that provide minimum riffle and riffle crest depths. CDFW recommends minimum passage depths of 0.9 ft for adult Chinook, and 0.7 ft for adult coho and steelhead. Adult salmonids use deep pools and undercut banks as holding habitat for staging upstream and finding refugia during storm events.
- Spawning: adult salmonids typically spawn in well-oxygenated gravel and cobble facies with median particles sizes ranging from 12 to 128 mm (cite). Heavily embedded channelbed sediments, with high percentage of fine sediment (<0.85 mm), are known to reduce survival to emergence. Typical spawning sites include the tail-out of pools, the crests of riffles, and low-gradient riffles with sorted gravel patches. Water depths and velocities vary among the three salmonid species, but generally range between 0.7 to 2.0 ft deep and 0.5 to 2.5 ft/s.
- Egg Incubation: Habitat requirements and vulnerabilities at this life-stage for both steelhead and salmon are the same. Incubation of eggs within a redd requires clean, cool stream flow, free of contamination and fine sediments. Damage (scour, desiccation) to a single redd could result in the death of thousands of steelhead or salmon embryos.
- Alevins: After hatching, steelhead and salmon alevin remain within the gravel, and feed from their attached yolk sacs. Here, the alevin remain highly vulnerable to siltation and scour and still require cool well-oxygenated waters for survival.
- Juveniles: In small streams and larger rivers, juvenile salmonids utilize a variety of habitat types, with steelhead associated with faster water habitats and coho associated with slower and deeper habitats. Riparian vegetation helps support some of the insects consumed by juveniles, provides cover from predators, and limits solar radiation to streams keeping water temperatures cool. Tree roots stabilize streambanks and create habitat structure. Fallen logs and other woody debris create cover and refugia during high flows. Pools, wetlands, and seasonally inundated floodplains provide shelter from high flows, opportunities for rapid growth, and facilitate sediment deposition and sorting.
- Smolts: Steelhead and salmon smolts reared in freshwater streams need adequate stream flow to travel downstream to estuaries in spring. During spring, estuary/lagoon habitats provide

productive feeding habitats and brackish water, which help facilitate the transition to life in the ocean.

Critical Threats to Salmonids

Coho salmon were the first salmonid listed as threatened in the Eel River basin (1997), and are the most threatened extant species in the basin (Yoshiyama and Moyle 2010, CDFW 2014a). Their extended freshwater rearing period and cold-water requirements render coho especially susceptible to poor habitat conditions during summer low-flow periods. According to NMFS (2014), the highest threats to Eel River coho salmon are streamflow diversions and consequent high water temperatures, and lack of floodplain and winter refugial habitat. The most impaired life stage for Eel River Chinook salmon is the pre-smolt (NMFS 2016), which reflects a similar set of freshwater habitat impairments facing coho salmon juveniles. As with Chinook and coho salmon, "most steelhead mortality occurs in freshwater, and during the rearing stage when juveniles may be exposed to a lack of suitable summer rearing habitat (*e.g.,* drying of channels or excessive water temperatures), a lack of refuge during high winter and spring floods, and predation (Shapovalov and Taft 1954, Moyle 2002, Quinn 2005)."

Salmonid Distribution in the Sproul Creek Watershed

Sproul Creek is a third order stream with approximately 25.9 miles of blue line stream according to the USS Garberville 7.5 minute quadrangle (from CDFW 2004). The CDFW South Fork Eel Watershed Assessment estimated the current distribution of Chinook, coho, and steelhead throughout the SF Eel River (CDFW 2014a pp. 89-91), including in Sproul Creek (Figure 5). A total of 73,965 ft (13.8 mi) of Chinook and coho salmon habitat and 92,225 ft (17.4 mi) of steelhead habitat are available in Sproul Creek (Table 2). Adults ascend well into the West Fork and South Fork headwaters to spawn. In all but extremely dry drought years summer rearing habitat likely persists throughout this range, with water temperatures maintaining suitable conditions throughout the low-flow season. A natural bedrock cascade near the mouth of LaDoo Creek blocks adult migration into that watershed. The estimated distribution high into Cox Creek in the Upper South Fork sub-watershed is speculative, as stream gradient is steep in this creek just above its confluence with the Upper South Fork reach.

Table 2. *Estimated current salmon and steelhead habitat (in linear feet of stream habitat) in the Sproul Creek watershed (From CDFW 2014a).*

	Chinook and Coho	**Steelhead**
Mainstem Sproul	22,935	22,935
Little Sproul Creek	12,010	12,010
West Fork Sproul	19,660	32,080
South Fork Sproul	18,360	25,200
Total	**72,965 (13.8 mi)**	**92,225 (17.4 mi)**

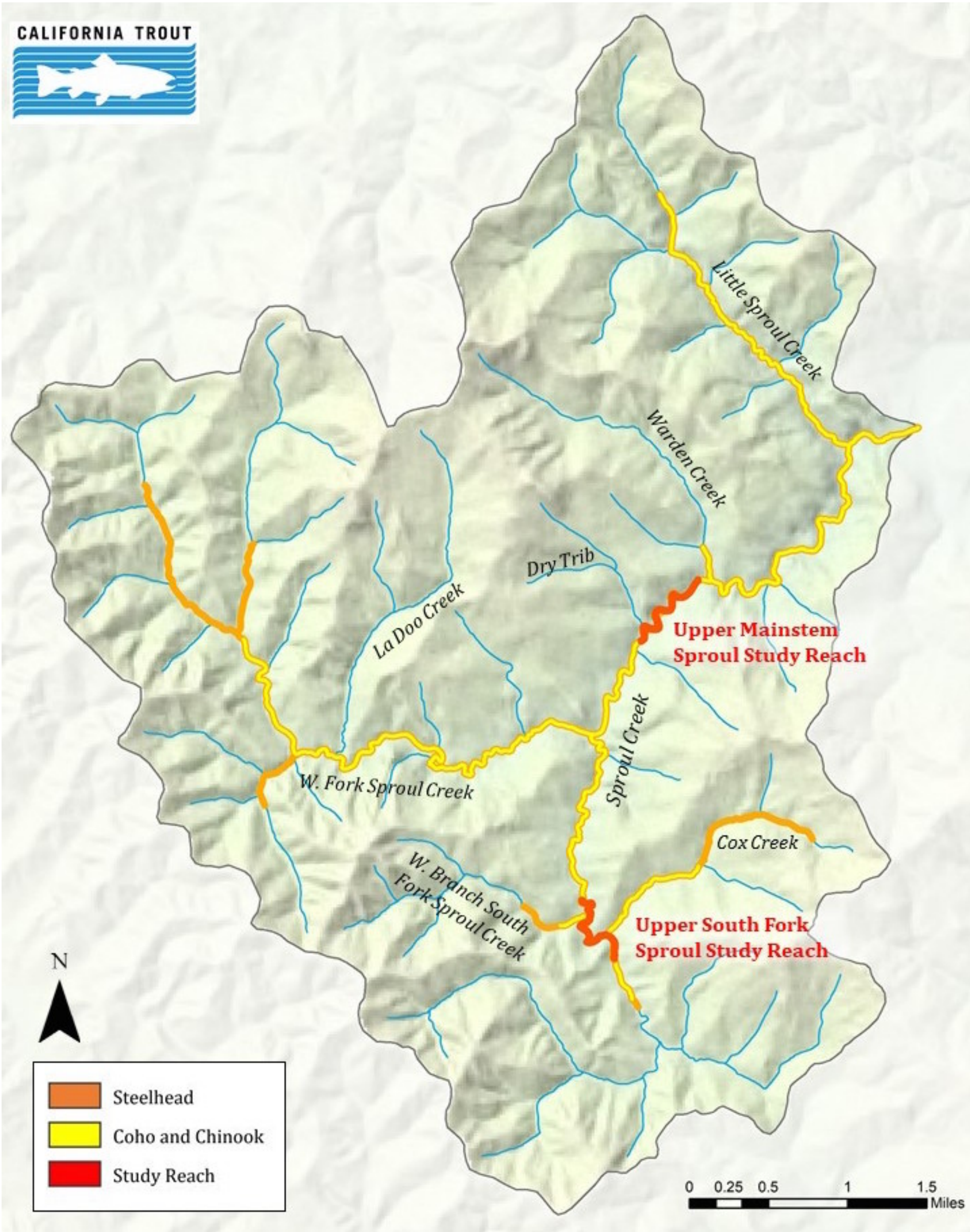

Figure 5. Estimated current range of salmonids in Sproul Creek (modified from CDFW 2015, Figures 47, 48, and 49).

4 STEP-2: DEVELOP SPROUL CREEK HYDROLOGY DATA

A site specific flow study requires a set of unimpaired annual hydrographs of daily average flow to describe intra-annual (within water year) flow variability, and for as many water years as possible to describe inter-annual (across water years) flow variability. In addition to characterizing intra- and inter-annual flow variability, these annual hydrographs provide the basis for quantifying water supply, and for conducting a time-series analysis in the habitat-flow modeling methods.

We developed a set of annual hydrographs for Sproul Creek using the nearby USGS Bull Creek (USGS 11-476600) gaging record for the 49 year period of record 1968 to 2016 (Figure 6). Bull Creek, also a western-draining tributary to the SF Eel River, has similar watershed conditions to Sproul Creek in terms of location, geology, historical land uses, and forest cover type. Bull Creek has slightly higher annual rainfall than Sproul Creek (81.3 inches), and is known to have extremely low summer streamflows. We used the formula recommended by the State Water Board (Mann et al. 2004) to scale Bull Creek daily average flows to Sproul Creek. This formula incorporates a drainage basin area-ratio and a precipitation ratio, as follows:

$$\textbf{Sproul Creek Streamflow} = \textbf{Bull Creek Streamflow} * (DA_{Sproul}/DA_{Bull}) * (MAP_{Sproul}/MAP_{Bull})$$

Bull Creek daily average data were scaled to Sproul Creek using drainage area and precipitation ratios at the whole-watershed scale, and were then adjusted to our Sproul Creek study reaches based only on drainage area. Methods and results used to prepare unimpaired daily average flows representing Sproul Creek are presented in Appendix B.

Generally, Sproul Creek hydrographs (developed from the USGS Bull Creek gage) exhibit an annual pattern of rainfall-runoff typical of north coast California watersheds: fall (Sept-Oct) low streamflows are punctuated by moderate fall rainfall freshets leading to increasingly larger winter peak storm flows (Nov-Mar); as winter storms diminish, winter baseflows transition to a steady spring recession (April-June), occasionally punctuated by spring rains of diminishing magnitude; the spring seasonal recession gradually declines to a summer low-flow period (July-Sept).

Five streamflow gages were established and monitored in Sproul Creek during WY2015 and WY2016 as part of this flow study (Figure 7). Streamflow gaging methods and results, stage-discharge rating curves, and daily average flows for each Sproul Creek gage are presented in Appendix C. Streamflow data collected in Sproul Creek was used to (a) further refine the conversion of Bull Creek data to Sproul Creek using a linear regression for low streamflows less than 2 cfs, (b) for habitat model calibration, and (c) in analyses using empirical flow study methods. Dataloggers deployed at strategic locations in the Sproul Creek watershed were also used to assess potential impacts from ongoing streamflow diversions during the summer low-flow period. Finally, flow measurements made at several different drainage area scales within the Sproul Creek watershed were used to compute and compare unit runoff (cfs/ mi^2) over a range of low-flow conditions to assess water yield variability, which is an important factor when extrapolating flow study results from a study reach to other locations in the watershed.

The modeled Sproul Creek data were used to develop a flow exceedance curve. Exceedance values were used to estimate a provisional range of target flows to support empirical habitat assessments and hydraulic modeling adopted by CDFW. The annual exceedance flows are presented in Figure 8.

5 STEP-3: APPLY EMPIRICAL AND MODELING INSTREAM FLOW METHODS TO IDENTIFY MONTHLY BYPASS FLOW THRESHOLDS

5.1 Overview of Data Collection and Analysis

Between April and November 2016, we collected empirical data and modeled hydraulic habitat using 1-dimensional and 2-dimensional Physical Habitat Simulation (PHABSIM) models, in two primary reaches in Sproul Creek: a 2,626 ft Upper Mainstem reach (at 17 mi^2 watershed area) and a 1,961 ft Upper South Fork reach (at 5.0 mi^2 watershed area). Additional empirical data were collected in several smaller tributaries within the Sproul Creek watershed, including Little Sproul Creek (3.9 mi^2), Warden Creek (1.6 mi^2), Dry Trib (0.6 mi^2), the West Fork (8.5 mi^2), the South Fork (7.1 mi^2) the West Branch South Fork (1.1 mi^2), and Cox Creek (1.5 mi^2) (Figure 3).

To select our primary study reaches (UMS and USF), we performed reconnaissance surveys of several potential study reaches along the Mainstem, the West Fork, and the South Fork during the WY2015 low-flow season, followed by habitat inventory surveys using standard methods (Flosi et al. 2010) in the spring of 2016. Within our project budget constraints, our objective was to demonstrate instream flow methods and collect empirical and modeling data at two reaches that were representative of the salmonid-bearing stream reaches in Sproul.

Following the selection of our two primary study reaches in April 2016, we collected the following field data:

- Meso-habitat and hydraulic units were mapped in each study reach, using standard field methods described in Flosi et al. (2010). A total of 5,721 ft of channel was habitat typed in the Mainstem Sproul Creek in two segments: (a) the 2,626 ft ***Upper Mainstem Sproul (UMS)*** study reach (Figure 9) from Warden Creek to Dry Trib confluences, and (b) 3,095 ft from Dry Trib to the Wet Ford near the confluence of WF Sproul and SF Sproul. A total of 4,154 ft of channel was habitat typed in the South Fork Sproul Creek in two segments: (a) the 1,961 ft ***Upper South Fork Sproul (USF)*** study reach (Figure 10) above the West Branch South Fork to the confluence with Cox Creek, and (b) the 2,193 ft reach below the WBSF. Habitat typing data are reported in Appendix A, including Tables A-1 and A-2.
- Riffle Crest Thalweg (RCT) depths were measured at 13 hydraulic units in each study reach. RCT rating curves were plotted for each hydraulic unit. Reach-representative 50th and 90th percentile RCT rating curves were developed for each study reach. In addition, RCT rating curves were developed for the West Fork Sproul, South Fork Sproul, and the West Branch South Fork Sproul creeks.
- Four wetted perimeter cross sections were established and monitored in each study reach, following the CDFW (2013a) SOP;
- Critical Riffles (CR) for fish passage assessment were identified from meso-habitat mapping; three CR cross sections in the Upper Mainstem study reach, and four CR cross sections in the Upper South Fork study reach were monitored to identify minimum flow thresholds for juvenile and adult salmonid passage following the CDFW (2013b) SOP;
- Velocity Cores, representing the linear distance that thalweg water velocities extended from riffles into pools, was measured in each hydraulic unit, and velocity core rating curves were plotted representing each study reach;

- Spawning and rearing habitat area (expressed as *weighted usable area* or WUA) was quantified using 1D and 2D PHABSIM modeling for five water year types; life-stage specific flow criteria were then computed following CDFW's time-series analysis for estimating monthly median habitat values.

Minimum bypass flows for each salmonid life stage and for each calendar month were summarized in a *Master Table* that presents flow *thresholds* derived from each flow study method for each study reach (Tables 3a and 3b). With three salmonid species and several age-classes inhabiting Sproul Creek in any given month (Figure 4), more than one priority life stage may be present in a given month. Weighing all life-stage needs, the bypass threshold most protective of all the life stages for a given month or season was prioritized as a minimum bypass flow. The resulting synthesized monthly *flow criteria* for each water year type are presented in summary tables presented in Section 6 of this report.

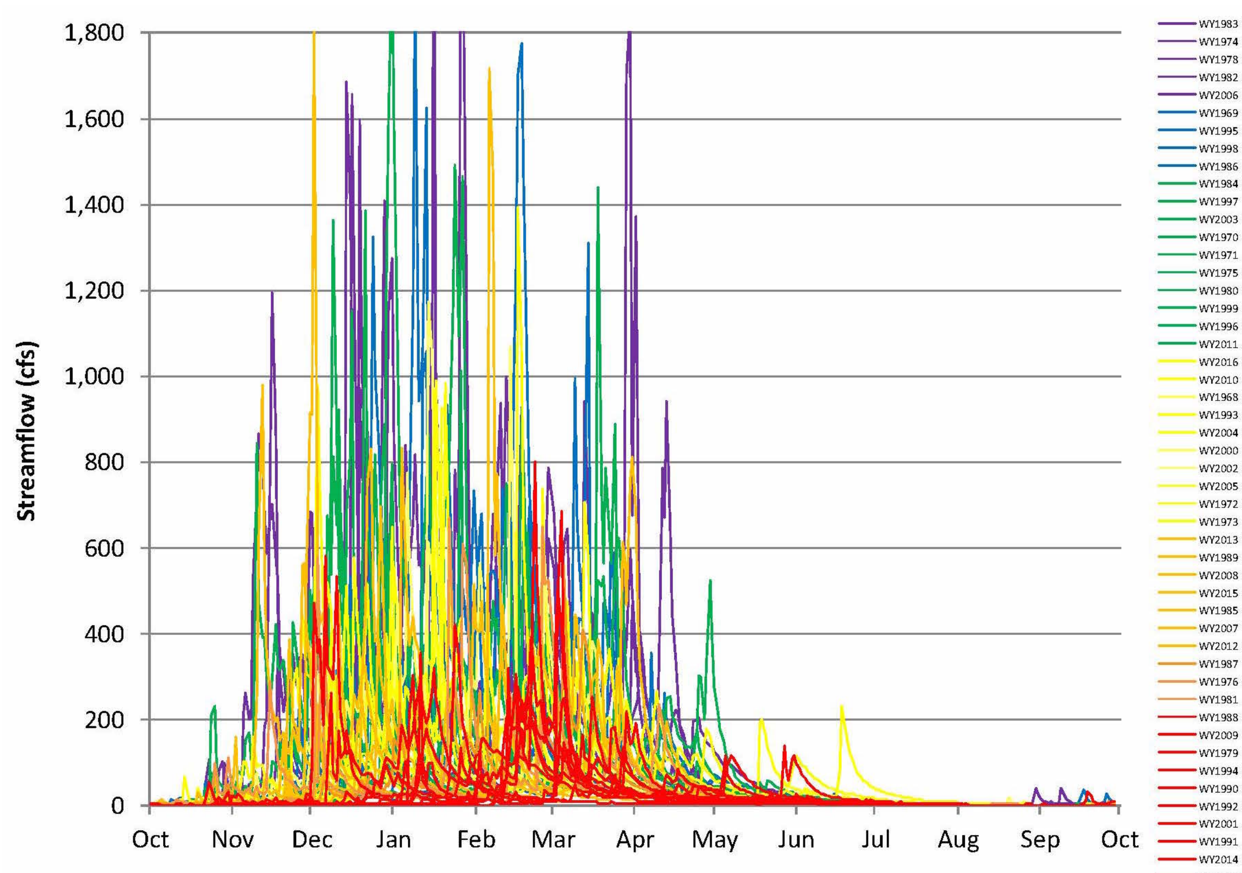

Figure 6. Annual hydrographs of daily average flow, modeled from the USGS Bull Creek near Weott (11-476600) gage for the 1968-2016 period of record, representing daily average streamflows in Sproul Creek.

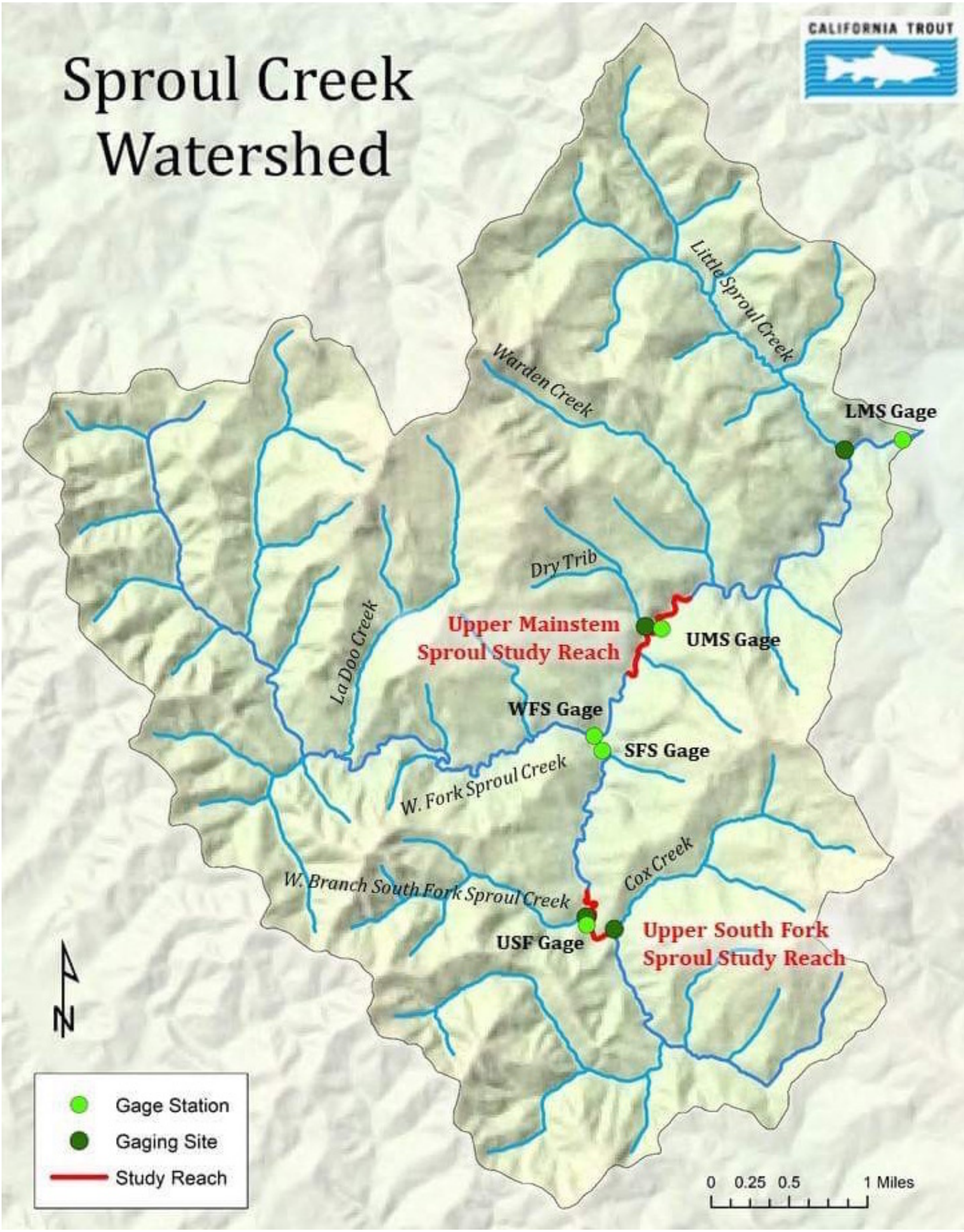

Figure 7. Sproul Creek watershed with location of streamflow gages and instream flow study reaches.

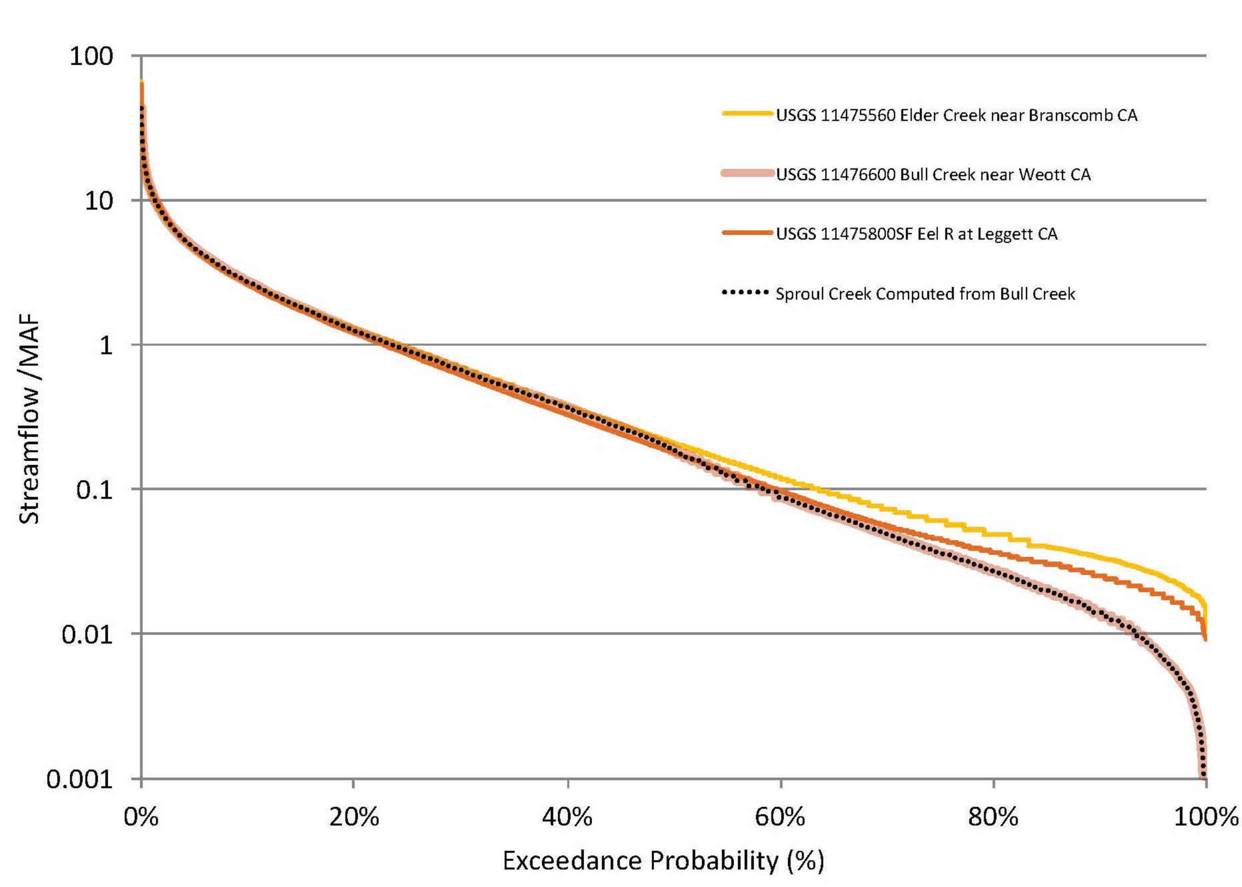

Figure 8. Flow duration curve for Sproul Creek (24.0 mi^2) at the confluence with the South Fork Eel River.

Table 3a. *Habitat thresholds and median habitat values for the Upper Mainstem Sproul Creek study reach, derived for each target species and life stage from instream flow analyses. Values in bold font were selected as flow criteria.*

UMS		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Chinook Migration			**98**	**98**	**98**								
Coho Migration			53	53	53	53	53						
Steelhead Migration			53	53	53	53	53	53	53				
Chinook Spawning	Ex Wet		6.3	140.3	179.7								
	Wet		4.5	116.7	102.1								
	Norm		4.8	93.2	153.5								
	Dry		5.0	10.3	18.0								
	Ex Dry		2.5	3.2	7.3								
Coho Spawning	Ex Wet		6.8	140.3	179.7	159.9	127.2						
	Wet		5.5	121.4	102.1	85.5	112.5						
	Norm		5.5	105.2	153.5	95.0	80.8						
	Dry		5.8	14.9	22.0	17.8	20.9						
	Ex Dry		2.5	3.6	9.4	10.5	19.6						
Steelhead Spawning	Ex Wet		8.3	140.3	179.7	159.9	127.2	78.6	19.4				
	Wet		7.7	129.8	102.1	94.0	112.5	81.7	17.3				
	Norm		5.8	110.7	153.6	95.0	83.2	23.0	12.6				
	Dry		7.7	21.2	23.9	21.8	24.6	21.8	9.9				
	Ex Dry		2.5	3.6	11.7	13.0	25.7	19.4	11.5				
Coho Fry	Ex Wet	3.1	19.9	140.9	179.7	159.9	135.4	61.8	19.9	8.4	3.8	2	0.5
	Wet	0	10.2	116.7	123	85.5	128.8	55.8	17.8	7.9	3.5	1.9	0
	Norm	0	6.8	86.6	153.5	123.8	80.8	34	12.8	5.8	2.7	3.4	0.5
	Dry	0.5	9.4	52.3	37.7	47.6	49	25.6	9.9	4.4	2.1	0.5	0
	Ex Dry	0.5	2.7	3.6	20.4	42.9	48.2	19.9	11.8	6.3	3.1	0	0
Coho Juvenile	Ex Wet	1.6	19.9	140.3	179.7	**160**	**127**	**61.8**	19.9	8.9	3.8	1.6	0.5
	Wet	0	0.9	105.2	102.1	**95**	**113**	**55.7**	17.8	8.9	3.5	1.5	0
	Norm	0	1.6	86.7	153.6	**85.6**	**80.8**	**34**	12.8	3.8	2.3	1	0.5
	Dry	0.8	11.4	52.3	37.7	**47.6**	**48.9**	**25.6**	9.9	4.3	1.8	0.5	0
	Ex Dry	0.5	2.5	2	20.4	**43.7**	**48.2**	**19.9**	11.7	9.9	2.2	0	0
Steelhead Fry	Ex Wet	1.5	19.9	140.3	179.7	159.9	127.2	61.8	19.9	8.4	3.5	1.6	0.5
	Wet	0	0.9	105.2	102.1	85.5	112.5	55.7	17.8	7.9	3.4	1.5	0
	Norm	0	9.4	86.6	153.6	95	80.8	34	12.8	6.8	1.9	1	0.5
	Dry	0.8	9.9	52.3	37.7	47.6	48.9	25.6	9.9	5.9	1.8	0.5	0
	Ex Dry	0.5	2.4	1.9	20.4	43.7	48.2	19.9	11.7	7.3	7.7	0	0
Steelhead 1+	Ex Wet	1.8	8.1	140.3	179.7	159.9	127.2	87.9	19.9	8.4	3.8	1.6	0.5
	Wet	0	6.8	131.9	106.8	106	113.6	85.2	17.3	7.9	3.5	1.5	0
	Norm	0	5.8	117.5	153.6	95	86.4	25.1	12.6	5.8	2.6	1	0.5
	Dry	1.5	6.7	23.6	25.1	24	26.2	22.7	9.9	4.3	1.8	0.5	0
	Ex Dry	0.5	2.5	3.6	13.1	14.1	28.9	19.6	11.7	6.3	#N/A	0	0
Steelhead 2+	Ex Wet	1.8	10.4	146.7	179.7	159.9	127.4	33	19.9	8.4	3.8	1.6	0.5
	Wet	0	8.9	136.6	114.6	115.6	119.9	93.4	17.8	7.9	3.5	1.5	0
	Norm	0	5.8	127.2	156.2	98.3	92	26.7	12.6	5.8	2.6	1	0.5
	Dry	1.5	9.4	25.6	26.3	26.6	28.3	23.5	9.9	4.3	1.8	0.5	0
	Ex Dry	0.5	2.5	3.6	13.8	15.7	30.9	19.9	11.7	6.3	2.2	0	0
Coho Outmigration							18.9	18.9	18.9	18.9			
Steelhead Outmigration							18.9	18.9	**18.9**	**18.9**	18.9		
Benthic Invertebrates								91.7	19.9	8.4	3.8	1.6	
High Recession Threshold								11.5	11.5	11.5	**11.5**		
Medium Recession Threshold		**3.3**								3.3	33	**3.3**	**3.3**
Low Recession Threshold		0.37										0.37	0.37

Table 3b. *Streamflow thresholds and median habitat values for the Upper South Fork Sproul Creek study reach, derived for each target species and life stage from instream flow analyses. Values in bold font were selected as flow criteria.*

USF		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Chinook Migration			43	43	43								
Coho Migration			**36**	**36**	**36**	36	36						
Steelhead Migration			**36**	**36**	**36**	36	36	36	36				
Chinook Spawning	Ex Wet		5.9	21	21								
	Wet		2.6	21	21								
	Norm		1.7	21	21								
	Dry		2.8	15.4	11.1								
	Ex Dry		0.7	1.1	5.4								
Coho Spawning	Ex Wet		5.9	8	8.5	8.3	11.3						
	Wet		2.6	9.5	12.2	10.9	12						
	Norm		1.7	10.6	10.6	14	15.4						
	Dry		2.8	9.8	9.2	9.7	10.5						
	Ex Dry		0.7	1.1	5.4	7.7	11.6						
Steelhead Spawning	Ex Wet		5.9	11.4	11.4	11.4	11.4	14	5.9				
	Wet		2.6	11.5	14.9	14.2	15.6	15.2	5.2				
	Norm		1.7	14.4	14.7	17.2	18.5	10	3.7				
	Dry		2.8	11.4	11.1	11.4	11.7	7.5	2.9				
	Ex Dry		0.7	1.1	5.4	11.4	12.9	5.9	3.4				
Coho Fry	Ex Wet	0.2	5.9	41.3	52.9	47	37.4	18.2	5.9	2.5	1.1	0.5	0.1
	Wet	0.1	2.6	30.9	30	25.1	33.1	16.4	5.2	2.3	0.3	0.3	0.1
	Norm	0.1	1.7	25.5	45.2	28	23.8	10	3.7	1.7	0.3	0.2	0.1
	Dry	0.1	2.8	15.4	11.1	14	14.4	7.5	2.9	1.3	0.5	0.1	0
	Ex Dry	0.1	0.4	1.1	5.4	12.6	14.2	5.9	3.4	1.8	0.3	0.1	0
Coho Juvenile	Ex Wet	2.9	5.9	41.3	52.9	**47**	**37.4**	**18.2**	5.9	2.5	1.5	0.5	0.1
	Wet	0.1	0.3	30.9	30	**35.5**	**33.1**	**16.4**	5.2	2.3	1.5	0.4	0.1
	Norm	0.1	0.4	25.5	45.2	**25.1**	**23.8**	**10**	3.7	0.8	0.6	0.3	0.1
	Dry	0.3	2.9	15.4	11.1	**14**	**14.4**	**7.5**	2.9	1.5	0.5	0.1	0
	Ex Dry	0.1	0.7	0.6	5.4	**12.6**	**12**	**5.9**	3.4	0.7	0.6	0.1	0
Steelhead Fry	Ex Wet	0.5	1	41.2	47.7	46.9	37.4	18.2	5.9	2.3	1.1	0.5	0.1
	Wet	0.1	0.7	30.9	30	25.1	33.1	16.4	5.5	2.2	1	0.4	0.1
	Norm	0.1	1	25.5	45.2	27.9	23.8	10	2.5	1.4	0.8	0.3	0.1
	Dry	0.3	9.2	15.4	11.1	14	14.4	7.5	2.6	1.3	0.5	0.1	0
	Ex Dry	0.1	0.7	0.7	10.2	13.9	14.2	6.8	2	1.7	0.6	0.1	0
Steelhead 1+	Ex Wet	0.5	5.9	13.4	13.4	13.4	15.1	14.7	5.9	2.5	1.1	0.5	0.1
	Wet	0.1	2.6	13.4	15.6	15	16.8	15.4	5.2	2.3	1	0.4	0.1
	Norm	0.1	1.7	15.7	15.8	17.9	18.8	10	3.7	1.7	0.8	0.3	0.1
	Dry	0.4	2.8	13.4	11.1	13.4	13.4	7.5	2.9	1.3	0.5	0.1	0
	Ex Dry	0.1	0.7	1.1	5.4	12.6	13.4	5.9	3.4	1.8	0.6	0.1	0
Steelhead 2+	Ex Wet	0.5	5.9	18.9	18.9	18.9	18.9	18.2	5.9	2.5	1.1	0.5	0.1
	Wet	0.1	2.6	18.9	18.9	18.9	20	16.4	5.2	2.3	1	0.4	0.1
	Norm	0.1	1.7	19	19.2	20.3	20.6	10	3.7	1.7	0.8	0.3	0.1
	Dry	0.4	2.8	15.4	11.1	14	14.4	7.5	2.9	1.3	0.5	0.1	0
	Ex Dry	0.1	0.7	1.1	5.4	12.6	14.2	5.9	3.4	1.8	0.6	0.1	0
Coho Outmigration							5	5	5	5			
Steelhead Outmigration							5	5	5	**5**	**5**		
Benthic Invertebrates								9.7	5.9	2.5	1.1	0.5	
High Recession Threshold								6	**6**	6			
Medium Recession Threshold		**2.0**								2.0	2.0	**2.0**	**2.0**
Low Recession Threshold		0.3										0.3	0.3

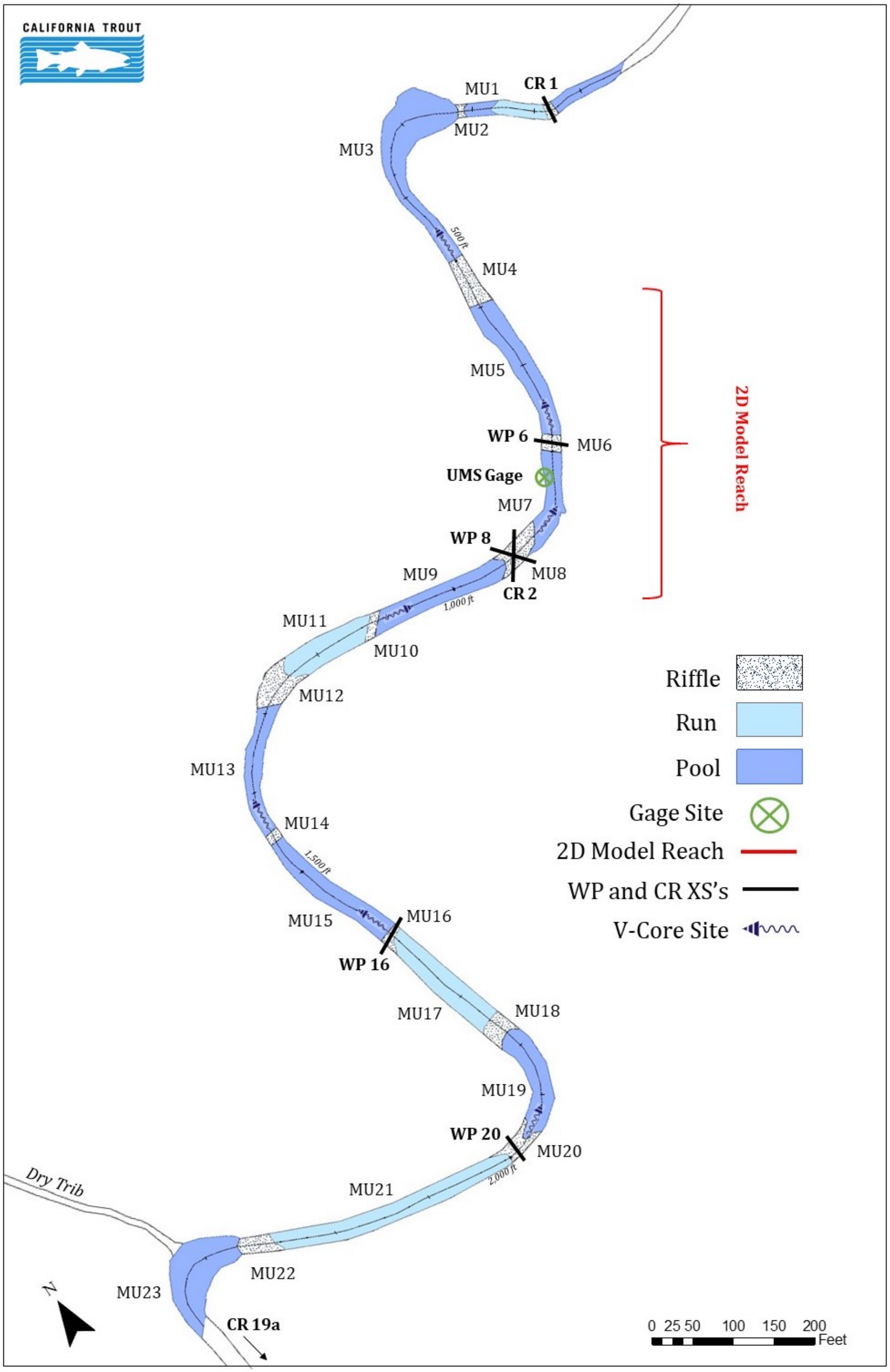

Figure 9. Upper Mainstem Sproul Creek (UMS) study reach map.

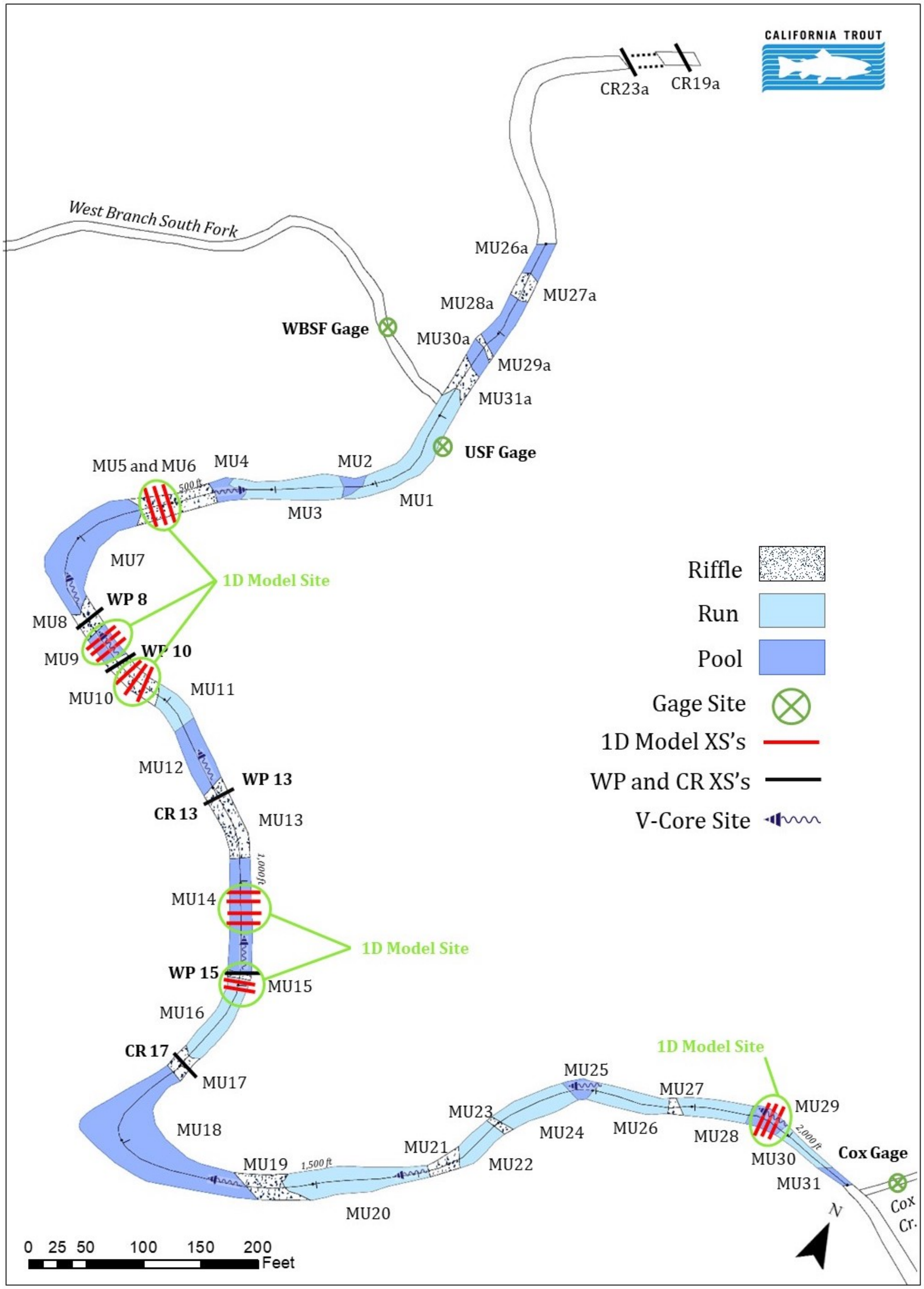

Figure 10. Upper South Fork (USF) study reach map.

5.2 Empirical Water Depth and Velocity Reference Data for Evaluating Flow Thresholds

Two primary stream hydraulic variables – water depth and velocity – dominate the development and evaluation of instream flow thresholds for juvenile and adult salmonid habitat. Each of the independent instream flow methods conducted in Sproul Creek to develop flow criteria, including the wetted perimeter method, the critical riffle method, and the PHABSIM hydraulic modeling, focus on one or both of these hydraulic variables. To aid our evaluation of the output of these methods, we developed baseline empirical relationships between water depth and streamflow, and water velocity and streamflow. These baseline data were the Riffle Crest Thalweg (RCT) data presented in Appendix D and the Velocity Core data presented in Appendix L. In this section we briefly describe these empirical hydraulic relationships and how they were subsequently applied to evaluate the instream flow hydraulic methods.

Riffle Crest Thalweg vs Streamflow Relationship.

As described in detail in Appendix D, we collected water depth measurements at the riffle crest thalweg, defined as the lowest channelbed elevation along the riffle crest cross-section, at 13 hydraulic units in each study reach. Depth measurements were collected over a range of streamflows to produce 13 independent RCT-Q rating curves for each study reach. The "family" of RCT curves is shown in Figures D-7 and D-8. Individual rating curves were synthesized into a reach-wide representative RCT-Q curve by plotting the 50th percentile (median) and 90th percentile RCT depth at each monitored streamflow, resulting in a 50th Percentile or median RCT (RCT50) curve and a 90th Percentile RCT (RCT90) curve (Figures 11 and 12). The RCT50 curve is used as a reference for estimating "how deep is the stream" at a given streamflow. For example, at a given streamflow ***x***, the median riffle crest thalweg depth ***y*** is known, with half the RCT depths shallower and half deeper. The RCT50 rating curve power function can also be used to compute the RCT50 depth with known Q, or vis-versa. The RCT90 curve is primarily used to evaluate critical riffle passage depths in Section 5.3 below. The RCT50 and RCT90 depths are reported along with streamflow thresholds derived from the instream flow analyses primarily to aid in contextualizing the computed threshold values. The RCT50 power function equations are given as:

Upper Mainstem: **RCT50 = 0.3417*Q^0.3129**
Upper South Fork: **RCT50 = 0.3522*Q^0.3008**

Velocity Core vs Streamflow Relationship.

As described in detail in Appendix L, we measured the distance downstream from a fixed riffle-pool boundary that the thalweg water velocity "core" extending into the pool from the upstream riffle exceeded three velocity thresholds: 0.5 ft/s, 1.0 ft/s, and 1.5 ft/s. The velocity core of maximum water velocities is a hydraulically complex feature of pools; the velocity core extends into the pool for a given distance dependent on streamflow magnitude, and creates shear zones with slower water velocities on one or both sides, i.e., the pool margins or eddies. The velocity core length was measured in eight pools in the Upper Mainstem study reach, and ten pools in the Upper South Fork. The velocity core length was normalized as a percent of the total pool length, and the average percent velocity core length was computed for each streamflow. The average percent length of velocity core is plotted vs streamflow for each study reach (Figures 13 and 14). Velocity cores measure the longitudinal extent of pool velocities at a particular streamflow. For example, at a given streamflow 'Q', the velocity core exceeded 0.5 ft/s for ***x*** feet into a pool of ***y*** length, for a total of ***x/y*100*** percent of the total pool length.

In each of the following report sections, we describe the streamflow thresholds computed from each instream flow method for the targeted salmonid life stage. We then express that flow threshold in terms of RCT50 or RCT90 water depth, or in Velocity Core lengths, as appropriate, to evaluate the hydraulic performance of the flow threshold.

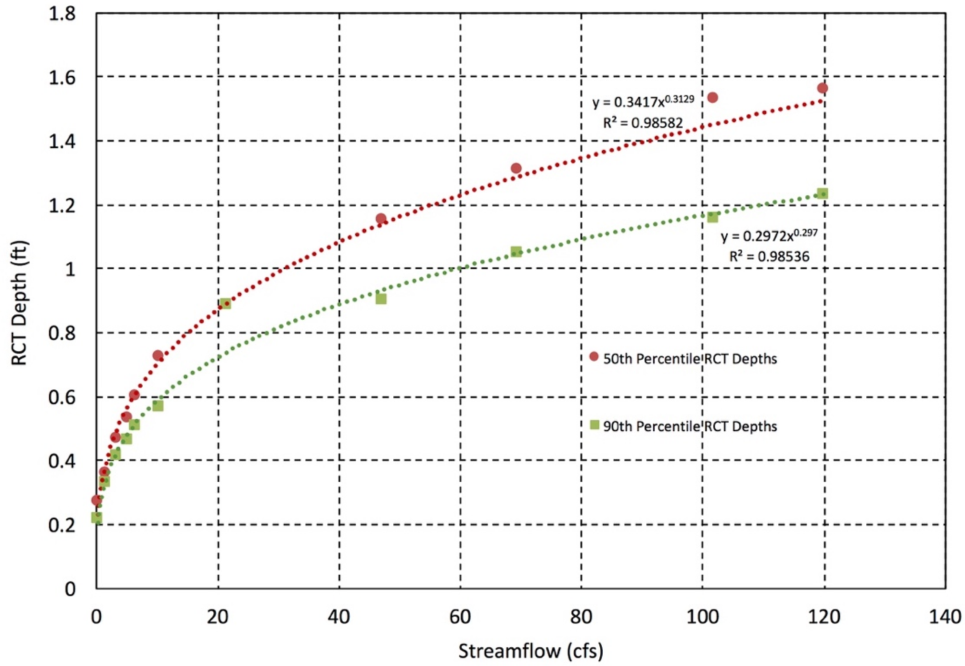

Figure 11. The 50th and 90th percentile riffle crest thalweg rating curves for Upper Mainstem Sproul Creek.

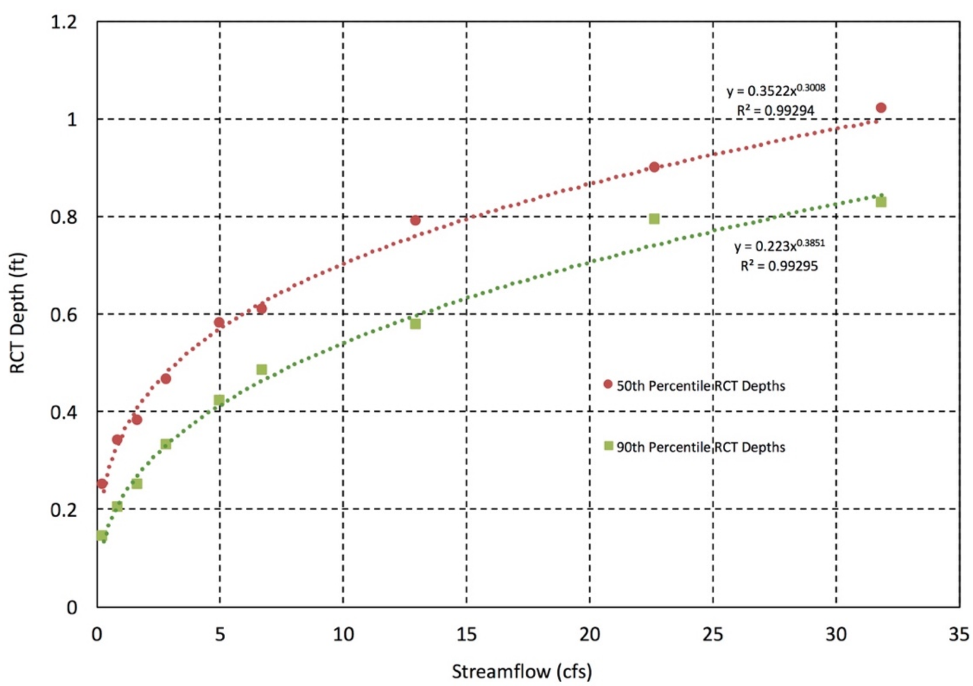

Figure 12. The 50th and 90th percentile riffle crest thalweg rating curves for Upper South Fork Sproul Creek.

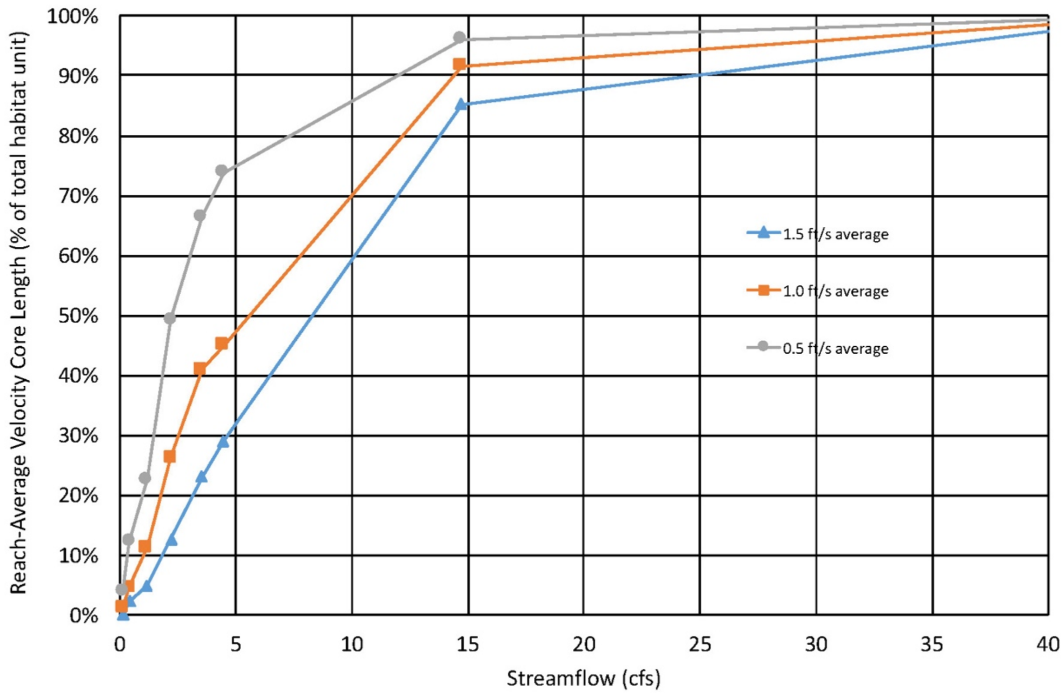

Figure 13. Reach-average velocity core length, as percent of total unit length, for the Upper Mainstem Sproul study reach.

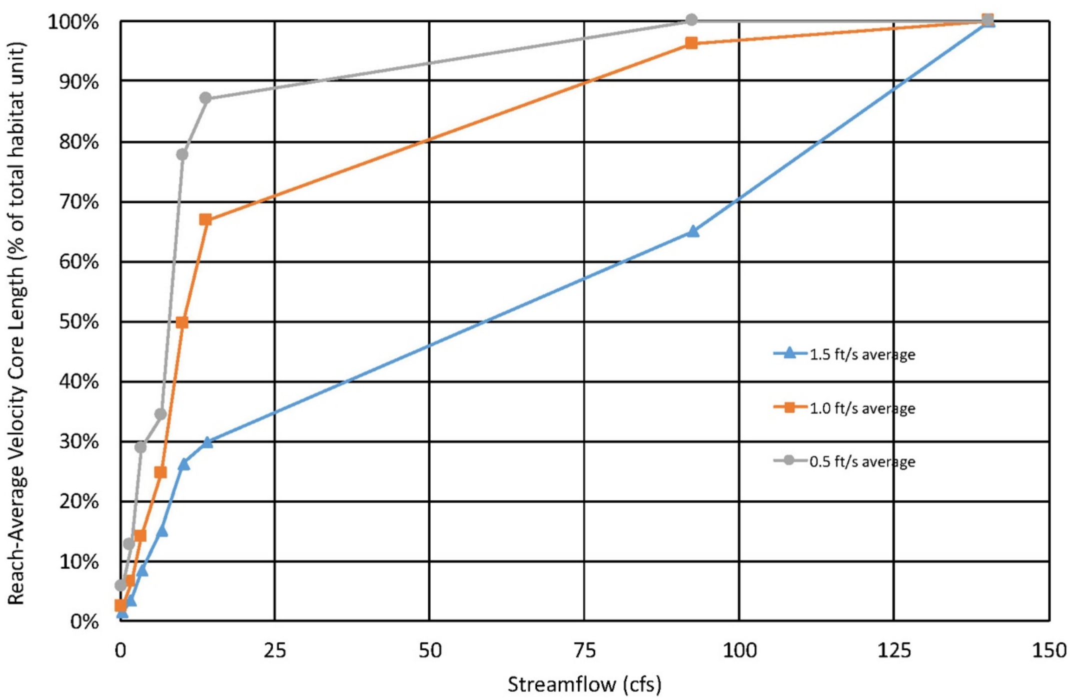

Figure 14. Reach-average velocity core length, as percent of total unit length, for the Upper South Fork Sproul study reach.

5.3 Adult Salmon and Steelhead Passage Thresholds from Critical Riffle Analysis

Critical riffles are individual riffle meso-habitat units that exhibit the shallowest relative depths along a given stream reach, and thus represent the greatest challenge to adult upstream migration as well as downstream juvenile/smolt outmigration. The CDFW *Critical Riffle Analysis* (CRA) approach for assessing fish passage through riffles (CDFW 2013b, Thompson 1972) was applied in the Upper Mainstem and the Upper South Fork study reaches to identify critical passage flow thresholds for juvenile and adult life stages. Appendix A describes field methods for mesohabitat mapping conducted in Sproul Creek in 2016. Habitat unit mapping by CalTrout field crews in April 2016, followed methods described in Flosi et al. (2010). Using the mesohabitat data, those critical riffles with the shallowest minimum 'passage corridor' depths, were identified following CDFW guidelines (CDFW 2013b) along a 5,721 ft reach of the Upper Mainstem and along a 4,154 ft reach of the Upper South Fork Sproul Creek. We identified three critical riffles in the UMS study reach, and four critical riffles in the USF study reach. The CRA method identifies a minimum bypass flow providing adult upstream passage or downstream juvenile passage when the minimum passage depth criterion is exceeded over a continuous 10% of the active channel stream width or 25% of the total wetted width. The CRA method selects the higher of the two threshold (contiguous and total width) as a flow criterion at an individual riffle site, then typically computes a reach-wide average from several critical riffles to derive a reach-wide passage flow criterion. Empirical observations and site conditions may warrant interpretation of the CRA computations. Appendix H describes the full Critical Riffle Analysis conducted at the Upper Mainstem and Upper South Fork study reaches. The CFDW passage thresholds are shown in H-1. A summary of critical riffle minimum flow thresholds is reprinted in Table 4.

In the following section we report the minimum passage flows in the Upper Mainstem Sproul (UMS) and Upper South Fork Sproul (USF) for adult Chinook salmon (using the 0.9 ft depth criterion) and adult coho salmon and steelhead (using the 0.7 ft depth criterion).

<u>Upper Mainstem (UMS) Adult Chinook Passage Bypass Flow (November through January)</u>
The upstream migration of Chinook salmon in the fall is highly dependent on variable and unpredictable fall rainstorms ending the low-flow season and signaling the initiation of adult migration and spawning. Flow thresholds protective of the natural timing and full range of Chinook salmon migration are critically important. Unimpeded passage through the 4.0 mile long mainstem Sproul Creek is a first-tier priority.

During the 2016 field season, field crews collected water depths across the critical riffle cross section at three UMS critical riffles (CR's): CR1, CR2, and CR 19a (Figure 9). In the Upper Mainstem reach, CR2 required the highest passage flow (i.e., was the most critical riffle): 138 cfs to meet the 25% total width criterion. This passage flow was determined from linear extrapolation of two measured data points at 119 cfs and 134 cfs (Figure H-34), because the stream was unwadable above 134 cfs. According to a conservative application of the CRA SOP, the adult Chinook salmon passage flow criterion in the UMS reach would be 138.3 cfs. The maximum passage flows from CR1 and CR19 were 86.8 cfs and 69.6 cfs. **The reach average 25% total width passage flow criterion was 98.2 cfs (rounded to 98 cfs).**

The 2D hydraulic model developed for the UMS Reach included the CR2 critical riffle at the upstream boundary of the modeled reach. The 2D model was thus used to identify the shallowest cross section across the riffle, then to compute water depths at 1.0 ft intervals across the 2D CRA cross section, over a range of modeled streamflows assumed to span adult passage thresholds. Modeled flows were 52, 65, 80, 85, 90, 105, 120, 125, 130, 138, and 145 cfs. The 2D CRA cross section was 79 ft wide, therefore requiring a 8 ft wide corridor to meet the 10% contiguous criterion or 20 ft to meet the 25% total criterion. Based on modeled flows, the 10% contiguous width criterion was met at 85 cfs; the 25% total width criterion was met at 126 cfs (Figure 15). We suggest the 85 cfs threshold providing a 8 ft wide passage corridor width is adequate to meet minimum passage requirements of Chinook salmon at the UMS CR2 riffle. Based on the 2D model and our interpretation, **the 2D CR2 passage flow threshold meeting a 10% contiguous corridor width was 85 cfs.**

Based on our empirical (field) observations, the CR2 25% passage flow of 138 cfs is much higher than a minimum threshold enabling upstream passage. For example, the lowest streamflow in which our field empirical observations determined CR2 was passable, with a minimum corridor width of at least 2 ft along the entire length of the riffle, was 57 cfs. And in November 2016, field crews were unable to safely wade the UMS reach at a streamflow of 134 cfs. The 2D model analysis indicates this passage flow would provide a 24 ft wide passage corridor exceeding 0.9 ft deep at the CR2 riffle crest. A protective adult Chinook passage threshold was identified in the range of streamflows from 85 to 98 cfs, with **98 cfs identified as a minimum protective flow criterion for adult Chinook salmon from November through January**.

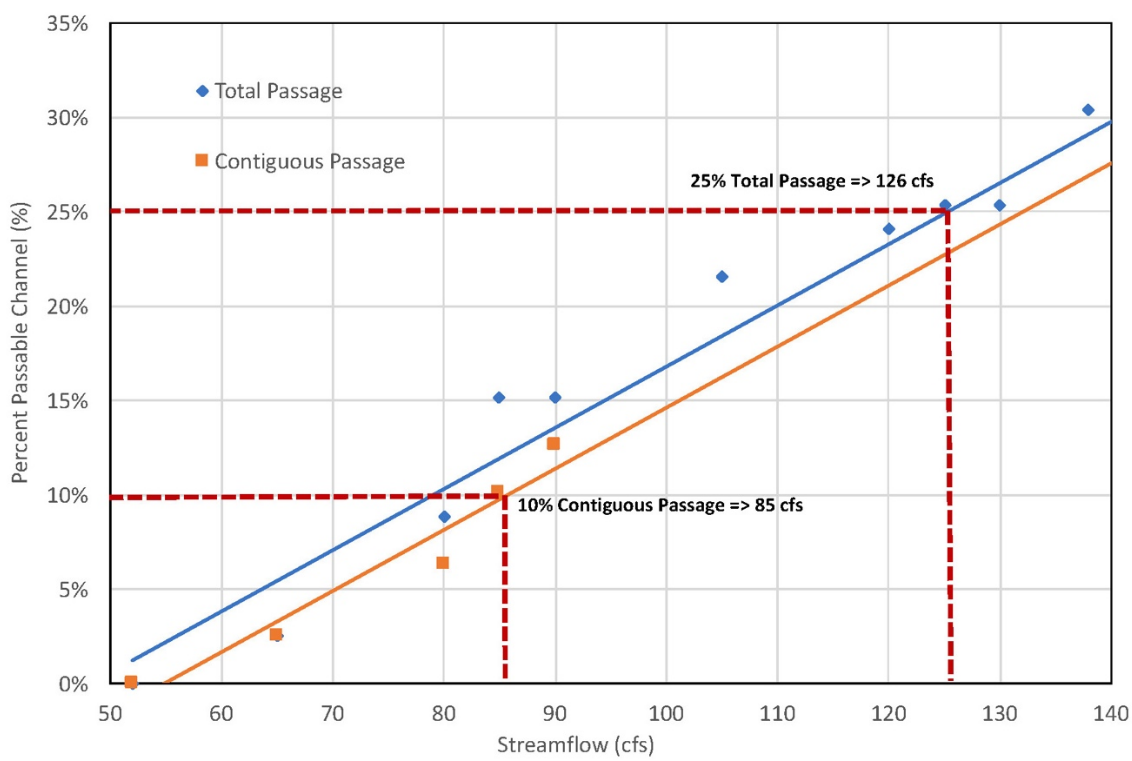

Figure 15. Critical passage threshold for the Upper Mainstem riffle CR2 using the 2D hydraulic model.

This range of passage flows is considered protective of passage along the entire Sproul Creek mainstem (from the SF Eel River confluence 4.0 miles upstream to the WF and SF confluence). We base this assertion on the following three factors: (1) the 85-98 cfs flow range is a conservative passage threshold, given that the two other critical riffles (CR1 and CR19a in Table H-1) met the 10% contiguous width criterion at much lower flows of 34.6 cfs and 41.0 cfs; (2) our habitat inventory identified *the three most critical riffles* along the upper ~5,721 ft of the mainstem Sproul Creek; streamflow accretions below the UMS reach (e.g., Warden Creek , Little Sproul Creek, and several unnamed tributaries) provide additional streamflow below the UMS reach; and (3) the CDFG Sproul Creek Habitat Inventory (CDFG 2004) did not identify any other riffles in the entire mainstem Sproul Creek that were significantly more limiting than those we analyzed in the Upper Mainstem Sproul reach.

We computed the 90th percentile RCT depths (RCT90) from our Upper Mainstem Sproul RCT rating curves for these Chinook bypass flow thresholds. The 85-98 cfs range of streamflows equates to RCT90 depths of approximately 1.10 ft to 1.16 ft (Figure 12). Therefore, 90% of the riffle crests in our Upper Mainstem study reach would be deeper than 1.16 ft at the 98 cfs passage flow criterion.

Table 4. *Summary of Critical Riffle minimum streamflow thresholds for the Upper Mainstem and Upper South Fork Sproul Creek study reaches, measured in 2016.*

			0.9 ft Depth Threshold		**0.7 ft Depth Threshold**		**0.4 ft Depth Threshold**		**0.3 ft Depth Threshold**	
Reach	**Cross Section**	**Site Name**	**Streamflow (cfs) for 25% Total Passage**	**Streamflow (cfs) for 10% Contiguous Passage**	**Streamflow (cfs) for 25% Total Passage**	**Streamflow (cfs) for 10% Contiguous Passage**	**Streamflow (cfs) for 25% Total Passage**	**Streamflow (cfs) for 10% Contiguous Passage**	**Streamflow (cfs) for 25% Total Passage**	**Streamflow (cfs) for 10% Contiguous Passage**
UMS	1+50	CR1	86.8	41.0	51.2	32.5	22.4	4.4	4.2	3.1
UMS	10+10	CR2	138.3	124.4	65.5	78.2	13.0	4.9	5.8	4.1
UMS	35+00	CR19a	69.6	34.6	41.5	26.7	21.2	16.0	15.4	10.8
Reach Average			98.2	66.6	52.7	45.8	18.9	8.4	8.4	6.0
USF	7+50	CR13	28.3	28.4	22.7	19.8	8.6	5.5	6.0	2.6
USF	10+00	CR17	35.2	17.9	13.2	9.1	11.1	1.5	7.6	0.85
USF	-(8+10)'	CR19a	41.9	37.9	22.4	21.1	11.4	5.0	9.3	2.5
USF	-(6+40)'	CR23a	43.1	33.4	35.9	29.4	20.9	9.8	18.4	6.9
Reach Average			37.1	29.4	23.6	19.9	13.0	5.5	10.3	3.2

<u>Upper Mainstem (UMS) Coho and Steelhead Passage Bypass Flow Threshold (November through May)</u>
Coho and steelhead are assessed together because they have the same passage criterion. Several miles of coho and steelhead spawning reaches are available in the Sproul Creek watershed upstream of the UMS reach. In addition to the importance of adult Chinook passage, flow thresholds must also accommodate coho and steelhead passage through the mainstem Sproul Creek and into headwater reaches into the winter months (Feb to May), well beyond the Chinook passage season (Nov to Jan).

The 0.7 ft depth criterion was applied to the three UMS critical riffles; CR2 again had the highest passage flow of 78.2 cfs to meet the 10% contiguous width criterion. **The reach average 25% total width passage flow criterion was 52.7 cfs (rounded to 53 cfs).** This threshold was corroborated by field observations on 11/4/16 in which 50 cfs was considered passable based on our professional judgment in the field. In addition, based on the 2D model analysis at CR2, the lowest modeled flow to exceed the 10% contiguous width criterion was 52 cfs, and provided a 13 ft wide corridor exceeding 0.7 ft water depth. The next-lowest modeled discharge was 40 cfs and only provided 8% contiguous width; we did not interpolate between these flows. The 25% total width criterion was nearly met at the 65 cfs modeled flow (23% of total width). **A streamflow of 53 cfs is considered a protective passage flow for adult coho and steelhead** for the months February through May according to the CRA approach.

We computed the 90th percentile RCT depths (RCT90) from our Upper Mainstem Sproul RCT rating curves for the coho and steelhead bypass flow threshold. The 53 cfs threshold was 1.0 ft on RCT90; 65 cfs was 1.05 ft deep. As a general rule, we suggest RCT90 depths of 1.0 to 1.1 ft are adequate for adult Coho and steelhead passage. This general rule could be applied to other reaches of Sproul Creek in which critical riffle analyses weren't performed, but for which passage flow estimates may be needed.

<u>Upper South Fork (USF) Chinook Passage (November through January)</u>
The Upper South Fork Sproul Creek, at 5.0 mi^2 watershed area, is at the upper end of the range of Chinook salmon migration and spawning. Flow criteria should protect Chinook passage through the South Fork and into the Upper South Fork reach, but adult Chinook passage in this reach is limited in many water years because unimpaired streamflows exceed the 0.9 ft depth criterion for Chinook passage only during winter storm hydrographs of moderate magnitude. During the 2016 field season, field crews collected water depths across the critical riffle cross section at four USF critical riffles (CR's): CR13, CR17, and CR 19a, and CR23a (Figure 10).

In the Upper South Fork study reach, CR23a required the highest passage flow (i.e., was the most critical riffle). According to application of the CRA procedure (CDFW 2013a), **the adult Chinook salmon passage flow criterion in the USF reach is 43.1 cfs (rounded to 43 cfs) based on the 25% total passage width at CR23a** (Table H-1). The passage flows from CR13, CR17, and CR19a were 28.3 cfs, 35.2 cfs, and 41.9 cfs, respectively. **The reach average passage flow criterion meeting the 25% total width criterion was 37.1 cfs.** These are relatively high storm flows in the USF reach. A protective flow threshold of 43.1 cfs would meet Chinook passage criteria in nearly all critical riffles in the Upper South Fork reach. The RCT90 was 0.96 ft for 43.1 cfs in the Upper South Fork study reach. **The 43 cfs passage flow for Chinook salmon is considered very conservative and protective, and is used as a passage threshold (Table 3).**

<u>Upper South Fork (USF) Coho and Steelhead Passage (November through May)</u>
Upstream migration for Coho and Steelhead is a high priority for the USF. The passage window for coho and steelhead comes later in the winter season when high streamflows are more frequent, and often sufficiently high to accommodate fish passage into first- and second-order streams. From the CRA analysis, **the highest passage streamflows meeting the 0.7 ft depth criterion based on the 25% total passage width is 35.9 cfs at CR23a**. **The reach average passage flow was 23.6 cfs. A flow threshold of 35.9 cfs (rounded to 36 cfs) is considered protective for the USF reach for the early (Nov) and late (Apr-May) months of the spawning season, and during the critical winter months (Dec-Mar).** The 36 cfs passage threshold equates to a RCT90 depth of 0.89 ft; a 23.6 cfs passage threshold equates to a RCT90 depth of 0.75 ft. For additional reference, streamflows meeting the 10% contiguous passage

criterion were 19.8, 9.1, 21.1, and 29.4 cfs. Given that most riffles in the upper reaches are relatively short, the passage flow thresholds for coho and steelhead are considered protective.

5.4 Spawning and Rearing Median Habitat Values from PHABSIM Modeling

Spawning and rearing flow thresholds were derived for the Upper Mainstem and Upper South Fork study reaches using PHABSIM modeling and time-series analysis methods and results presented in Appendix E (Upper South Fork 1D Modeling), Appendix F (Upper Mainstem 2D Modeling) and Appendix G (Time-Series Analysis for both study reaches). PHABSIM procedures used in previous CDFW studies (CDFW 2014b) were followed. In general, PHABSIM methods were used to derive habitat-flow relationships and develop *median monthly habitat values* for Chinook, coho, and steelhead spawning, coho fry and juvenile rearing life stages, steelhead fry, 1+, and 2+ rearing life stages, and productive benthic invertebrate habitat. Individual habitat values were developed for these life stages for five equally weighted water year types: Extremely Wet, Wet, Normal, Dry, and Extremely Dry. Median monthly habitat values are reported in Table 3a for the Upper Mainstem study reach and Table 3b for the Upper South Fork study reach.

In the Upper South Fork study reach, 1-dimensional hydraulic modeling methods were chosen to allow characterization of hydraulic variability along the 1,961 ft long study reach, a study reach that could be sensitive to potential flow alterations from upstream water diversions. Six meso-habitat units were selected from among a total of 30 units along the reach, with three cross sections placed within each habitat unit, for a total of 18 hydraulic model cross sections. Study site and habitat unit selection, hydraulic and topographic data collection, selection of habitat suitability criteria from literature values, model calibration, and development of habitat-flow relationships are described in detail in Appendix E. The resultant reach-wide habitat-flow relationships are shown in Figure 16. [Figure E-54]

In the Upper Mainstem study reach, a 2-dimensional hydraulic model was developed for a 495 ft long modeling reach spanning five meso-habitat units (riffle-pool-riffle-pool-riffle units). The 2D modeling approach provides the traditional habitat-flow relationships for the targeted species and life stages, but also allows flexibility to model biological responses under different flow management approaches. These responses include: (1) invertebrate drift sampled at three riffles, above, within, and below the 2D model reach, (2) lamprey ammocete habitat, and (3) food web phenology in relation to juvenile salmonid foraging behavior. Results of these analyses were not used to determine bypass flow criteria and are not presented in this report, but will be used in future water management analyses in Sproul Creek. Study site and habitat unit selection, hydraulic and topographic data collection, selection of habitat suitability criteria from literature values, model calibration, and development of habitat-flow relationships are described in detail in Appendix F. The Upper Mainstem habitat-flow relationships are shown in Figure 17. [Figure F-55]

The modeling and CDFW time-series analytical protocol begins with the habitat suitability indices (HSI) selected for target species and life stages (presented in Appendix E and F), combined with water depth and velocity outputs over a range of streamflows produced by either 1-dimensional (1-D) or 2-dimensional (2-D) hydraulic models. Habitat suitability indices were not developed from site-specific studies, but were derived from literature values, recommendations from CDFW staff, and professional judgment. The end-product of the PHABSIM analysis is a set of habitat-flow relationships ("weighted usable area" [WUA] vs streamflow rating curves) for each species and life stage developed for the USF and UMS reaches (Figures 16 and 17 above). These habitat-flow relationships were then used in conjunction with unimpaired daily average flow data to develop *monthly median habitat values*. The *median habitat value* is the computational product of the time-series analysis, but is not considered a flow criterion until it is weighted against other life stage needs.

Development of flow criteria from the PHABSIM model data is thus a two-step process: Step-1 is meant to identify *median habitat values* for each salmonid species and life stage independently (i.e., spawning, fry, juvenile) throughout the year, based on habitat vs streamflow relationships developed in 1-D and 2-D hydraulic modeling. These results are presented in Table 3, and discussed in this section. In Step-2, *flow criteria* are then selected for each life stage based on the most sensitive species' flow needs, integrated with other hydraulic habitat flow methodologies (e.g., fish passage flows), as well as for the five water year classes. Those results are presented in Section 6 of this report.
An important outcome of CDFW's time-series analysis approach used in this study is that the median habitat values generated from the analysis are not "optimal" nor "minimum" protective flows for a particular species' life stage, as are commonly prescribed from PHABSIM analyses. Instead, the habitat flow relationship (WUA vs streamflow) is integrated with the study reach unimpaired hydrology, by water year type, and the median habitat value is selected, such that the median habitat value is strongly influenced by the unimpaired flow data. The median habitat flows thus have a much wider range for each life stage, driven by the season (intra-annual hydrograph variability) as well as by water year type (inter-annual hydrograph variability). The flow thresholds reported in Table 3 are thus not defensible independent of the month and water year type for which they are computed.

The following sections present the median habitat values (flow thresholds) for each species and life stage. We assess if these flow thresholds would provide suitable habitat for each life stage during each month in which that life stage requires suitable habitat.

<u>Upper Mainstem (UMS) Spawning 2D PHABSIM Modeling (November through March)</u>
The 2D model developed in the Upper Mainstem reach assessed spawning flows in two riffle-pool units within our study reach. Both units had suitable spawning gravels, and typical pool tail hydraulic characteristics. The model predictions for Chinook, coho, and steelhead spawning flows (reported in Table 3) are reasonable habitat index flows in the UMS reach, but should only be applied to the entire Sproul Creek mainstem with caution.

The median spawning habitat values for all three salmonid species are quite low in November, ranging from 2.5 to 8.3 cfs (Table 3). December and January index values are generally higher, ranging in the 100 to 180 cfs range for Chinook in December and January in Norm to Ex Wet years, but ranging from 10 to 20 cfs in Dry years and into single digits in Ex Dry years. Chinook would likely not find abundant or high quality spawning habitat in the UMS reach in the lower range of flows, but that is the normal hydrologic condition in coastal Mediterranean watersheds, i.e., the median habitat value, if prescribed as a flow criterion in some months or water years, may not provide suitable spawning conditions.

Coho and steelhead median spawning habitat flows show a similar trend: highest in December and January of Ex Wet and Wet years, and diminishing by month and water year type. Median coho spawning flows are in the 80 to 180 cfs range in Normal years and above, and from 3.6 to 22 cfs in Dry and Ex Dry years. There is a large gap in index flow magnitude between Dry and Normal years, i.e., there are no median habitat flow values in the 20 to 80 cfs range.

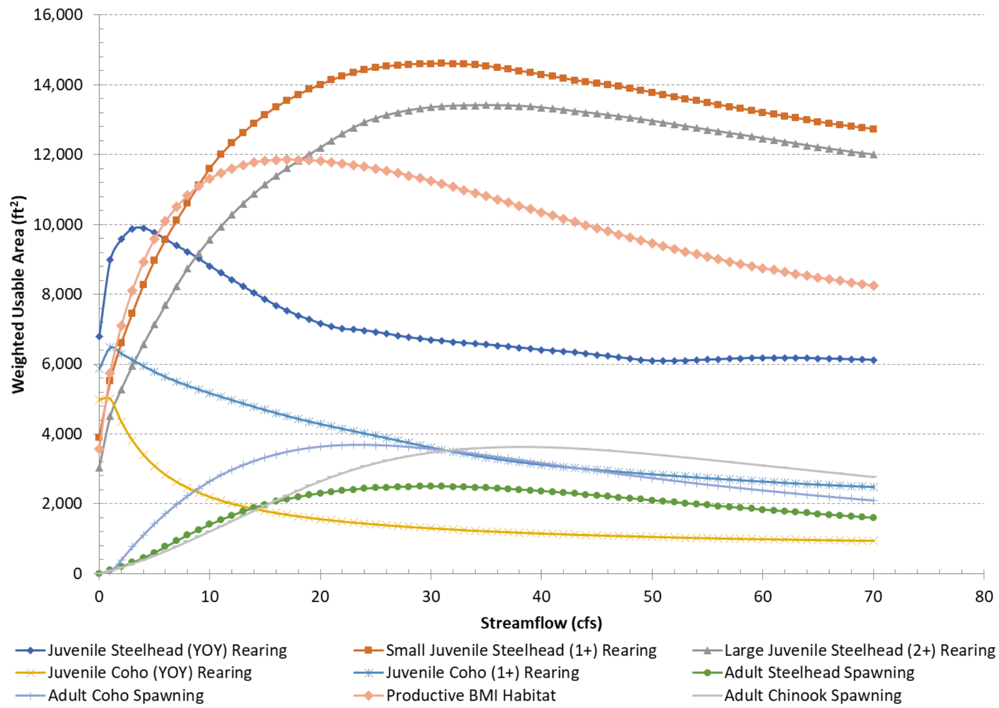

Figure 16. Upper South Fork 1D PHABSIM WUA vs streamflow curves for each targeted life stage (from Appendix E, Figure E-54).

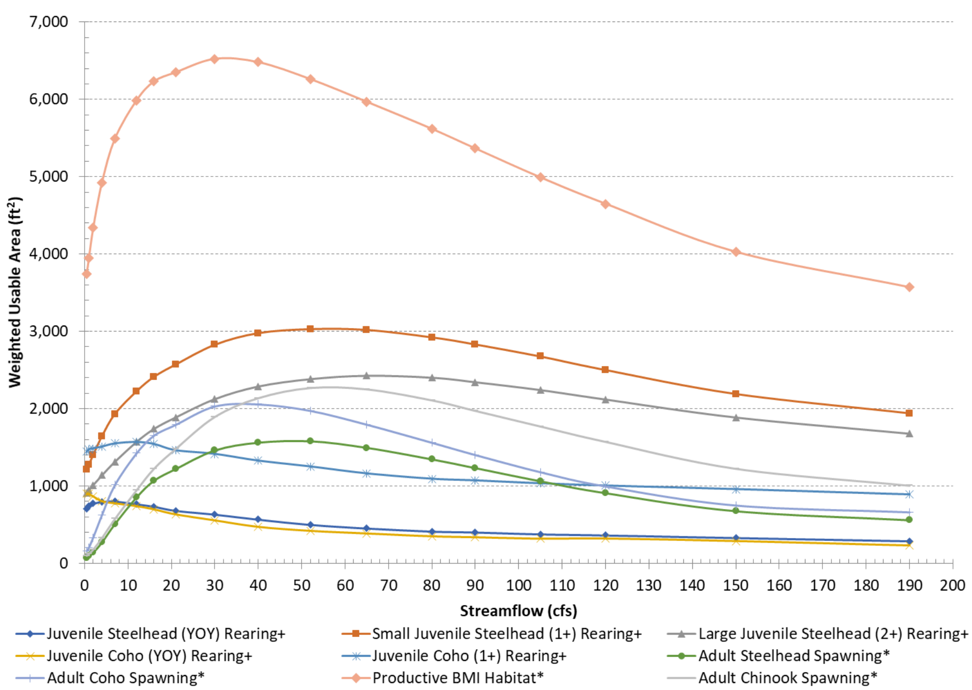

Figure 17. Upper Mainstem 2D PHABSIM WUA vs streamflow curves for each targeted life stage (from Appendix F, Figure F-55).

Upper Mainstem (UMS) Rearing 2D PHABSIM Modeling (October through September)
Streamflows providing suitable rearing habitat were identified by the time-series analysis, with resulting median habitat values reported for each life stage and month for five water year types. Median habitat values were computed for five rearing life stages: coho fry and juveniles, and steelhead fry, 1+, and 2+ age classes (Table 3). Median rearing habitat values are provided for each month of the water year from October through September, by water year type.

For all five rearing life stages assessed, median habitat values for October had a narrow range of flows, from 0.0 to 3.1 cfs. These flows would provide poor habitat conditions for rearing salmonids, with disconnected pools below 0.37 cfs, and only slightly better rearing habitat at 3 cfs. The habitat-flow curves for the Upper Mainstem study reach (Figure G-9) were relatively flat for coho and steelhead parr, and juvenile coho, and increase only slightly for larger steelhead, meaning the rearing habitat index area (WUA) does not increase with increasing streamflow. October flows of 3 cfs would provide "maintenance" salmonid rearing conditions – daily average water temperatures remained below 55°F in October at UMS in all water years observed (2015-17), but 3 cfs provides poor velocity core length, and low invertebrate drift abundance. The RCT50 at 3.1 cfs is 0.49 ft. Median habitat values increase slightly in November, ranging up to 20 cfs. Streamflows in the 10 to 20 cfs range would provide more abundant and higher quality rearing habitat, with the 1.5 ft/s velocity core length extending through approximately 80% of pool lengths, and RCT50 depths ranging from 0.70 to 0.87 ft.

Median habitat values are much higher during the winter months December through March, ranging up to 180 cfs in Ex Wet and Wet years, but with much lower index values in Ex Dry water years, ranging as low as 2 to 3 cfs. The five rearing life stages had very similar median habitat values, with nearly identical trends across seasons and water year types. Given the fact that the unimpaired hydrology has a strong determinant effect on the median flow value, the trend in these values is apparent and similar across the months and water year types. The habitat suitability index values (the depth and velocity "preferences" modeled for each species and life stage) had much less of an effect on the median habitat output, whereas the daily average streamflow strongly determined the median habitat values. During winter months, young-of-year and juvenile salmonid rearing median habitat values are dominated by winter flow conditions, as indicated by the wide range of rearing habitat values in Table 3.

Upper South Fork (USF) Spawning 1D PHABSIM Modeling
The Upper South Fork is an important spawning reach in the Sproul Creek watershed, providing abundant spawning gravel and excellent habitat for all three salmonid species. Median spawning habitat values for Chinook, coho, and steelhead spawning were derived from 1D PHABSIM modeling and the CDFW median habitat time-series approach. Monthly median habitat flow thresholds are presented in Tables 3a and 3b.

Median spawning habitat values for November were the same for each species in the five water year types (Table 3), ranging from 5.9 cfs in Ex Wet years to 0.7 cfs in Ex Dry years. As would be expected early in the spawning season, these flow values are at the low end of spawner suitability, and November streamflows would typically not provide high quality spawning habitat in this flow range. The RCT50 depth for the USF at 6 cfs was 0.6 ft, which is the low end of spawning suitability depths.

For the December to March coho and steelhead spawning season, the median spawning habitat values ranged between 9.2 and 21 cfs except for a few monthly index values in Ex Dry water years. This flow range would provide excellent spawning conditions for salmonid spawning in the USF reach. The peak spawning values from the habitat rating curves (Figure 16) were 36 cfs for Chinook, 24 cfs for coho, and 30 cfs for steelhead. The median spawning habitat values thus favor coho and steelhead spawning. Spawning habitat values for Ex Dry water years are similar to early season (November) flows, and are less suitable than wetter months or years. The RCT50 depths for 9.2 and 21 cfs were 0.7 ft and 0.9 ft, respectively.

<u>Upper South Fork (USF) Rearing using 1D PHABSIM Modeling</u>
Streamflows providing suitable rearing habitat were identified by the median time-series analysis approach, with resulting median habitat values reported for each life stage and for each month for five water year types. Median habitat values were computed for coho fry and juveniles, and for steelhead fry, 1+, and 2+ age classes of fish (Table 3). Median rearing habitat values are provided for each month of the water year October through September.

The median habitat values for Oct and Nov are relatively low streamflows for all of the rearing life stages, ranging from 0.1 to 5.9 cfs. These are common streamflows for this period of the water year, and rearing habitat quality is typically not optimal in the fall season, especially in drier water year types. As was described above for the Upper Mainstem reach, the median habitat values for fry and juvenile rearing in the USF are strongly influenced by the unimpaired hydrology, with a resulting trend of higher index values in the wetter winter months and in wetter water year types, and diminishing through the late-winter and spring months and during drier water year types. Index values for coho fry and juveniles were very similar (nearly identical), ranging in the 40 to 50 cfs range in December through February in wetter water year types. These flows represent low habitat values from the habitat-flow curves (Figure 16) for coho rearing. Median habitat values for steelhead fry had a similar range in winter months. Rearing flow values diminish in drier water years and progressively later in the winter and spring season, as streamflows recede (Table 3).

To provide more quantitative context for assessing the median monthly values derived from the time-series analysis, we computed the peak WUA values for each modeled life-stage, the streamflow associated with the peak of the WUA curves, and the RCT50 depths at those flows (Table 5).

Table 5. *Peak WUA values (ft^2) and streamflow associated with peak WUA from the Upper Mainstem 2D model reach, and the Upper South Fork 1D model reach.*

	Upper Mainstem		Upper South Fork	
Life-Stage Modeled	**Q (cfs) at Peak WUA**	**RCT50 (ft) at Peak WUA**	**Q (cfs) at Peak WUA**	**RCT50 (ft) at Peak WUA**
Adult Chinook Spawning	52	1.18	38	1.02
Adult Coho Spawning	40	1.08	23	0.90
Adult Steelhead Spawning	52	1.18	30	1.0
Juvenile Coho (YOY) Rearing+	0.5	0.28	1	0.35
Juvenile Coho (1+) Rearing+	12	0.74	1	0.35
Juvenile Steelhead (YOY) Rearing+	7	0.78	4	0.53
Small Juvenile Steelhead (1+) Rearing+	52	1.18	31	0.99
Large Juvenile Steelhead (2+) Rearing+	65	1.26	35	1.03
Productive BMI Habitat	30	0.99	17	0.81

5.5 Spring Recession Thresholds from Critical Riffle and Wetted Perimeter Analysis

A seasonal streamflow recession occurs each year on Sproul Creek and is an important hydrograph component for juvenile salmonid life stages. The seasonal recession generally occurs during the spring months of April, May, and June, with the onset of the recession dependent on water year type: dry water years generally have an earlier recession than wet water years. During the spring recession, hydraulic complexity diminishes. Water depths at riffle crests recede from ~1.0 ft RCT50 depths, to less than ~0.5 ft RCT50 depths. Velocity cores retract from the full length of pools in early spring to extending only a small distance below the heads of pools by late spring. Benthic algal growth accelerates in late-April and into May, stimulating aquatic invertebrate productivity. Benthic invertebrate drift rates increase, stimulating growth rates of juvenile salmonids.

<u>Juvenile Passage Flow Analysis</u>

During the spring recession, chinook fry, juvenile coho, and 1+ and 2+ steelhead begin their downstream migration. Over-summering life stages (coho and steelhead YOY) also frequently redistribute in spring, searching upstream or downstream for better habitat. Streamflows meeting CDFW passage criteria of 0.4 ft and 0.3 ft are prescribed for juvenile and fry salmonids, respectively, to protect downstream and upstream movement. The CRA approach for assessing fish passage through riffles (CDFW 2013b, Thompson 1972) was applied in the USF and UMS study reaches. The CRA method identifies a minimum bypass flow providing upstream or downstream juvenile passage when the minimum passage depth criterion is exceeded over a continuous 10% of the active channel stream width or 25% of the total wetted width. The CFDW passage criteria are shown in H-1. A summary of critical riffle minimum streamflows is in Table 4.

Acknowledging upstream passage is more difficult than downstream passage, we selected the daily average streamflow from the critical riffles meeting a 0.4 ft passage depth as a juvenile passage flow criterion. Streamflows in spring should also enable downstream migrants to "rear their way out" of headwaters streams, i.e., migrate downstream while facing upstream to feed. In the Upper South Fork (USF) study reach, the streamflow meeting these conditions was 5.0 cfs. This streamflow has a RCT50 depth of 0.57 ft, and provided velocity core velocities extending from 30 to 75% of pool unit lengths, for water velocities exceeding 1.5 ft/s and 0.5 ft/s, respectively. This streamflow provides moderately robust hydraulic conditions and should be protected throughout the spring recession (April-June) of all water year types. In the Upper Mainstem (UMS) study reach, the streamflow meeting these conditions was 18.9 cfs. This streamflow has a RCT50 depth of 0.86 ft, providing core velocities extending from 30 to 75% of pool unit lengths when water velocities exceed 1.5 ft/s and 0.5 ft/s, respectively. This streamflow provides diverse hydraulic conditions and should be protected throughout the spring recession (April-June) of all water year types, i.e., a single criterion applied to all water year types. The passage criterion of 0.3 ft was not used in the analysis to determine juvenile passage flows.

<u>Wetted Perimeter Incipient Threshold Analysis</u>

Wetted perimeter curves were developed for Sproul Creek using CDFW's Wetted Perimeter method (CDFW 2013a) (Appendix I). The wetted perimeter vs streamflow curve was used to identify the curve's first point of maximum curvature (breakpoint) and a second inflection point (incipient asymptote). Eight riffles within the two study reaches were selected during field reconnaissance in early spring of 2016 for wetted perimeter analysis, with four cross sections per study reach. All riffles were well defined, low gradient (<4%) units, with gravel to cobble-dominated substrates and roughly rectangular in cross section. The wetted perimeter riffle sites generally represented the riffle structure and shape of the overall reach.

The wetted perimeter incipient asymptote generally provides good hydraulic conditions typically encountered in late-spring and early summer during the spring recession. Streamflows at the wetted perimeter incipient asymptote were similar in magnitude to juvenile passage flows. CDFW assumes the incipient asymptote provides hydraulic conditions that will sustain benthic invertebrate productivity during the spring recession in April, May, and June.

Streamflows at the incipient asymptote for the Upper South Fork (USF) were 6.0 cfs for the two cross sections with identifiable inflections (Table 6). This flow provides RCT50 depths of 0.60 ft. The velocity cores in Upper South Fork pool units extended through approximately 35% of pool units at this flow providing velocities up to 1.5 ft/s. We computed an **incipient asymptote of 6 cfs** from the wetted perimeter method. This flow criterion was labeled a "high recession threshold" and was applied from April through June (Table 3).

Streamflows at the incipient asymptote for the Upper Mainstem ranged from 6.6 to 14.0 cfs (mean=11.5) (Table 6). This flow range provides RCT50 depths of 0.62 to 0.78 ft. The velocity cores in Upper Mainstem pool units extended through approximately 15 to 30% of pool units at this range of flows for velocities up to 1.5 ft/s, and up to 87% of pool lengths for velocities up to 0.5 ft/s. We computed the **reach average incipient asymptote of 11.5 cfs** as a practical way to derive a flow criterion from the wetted perimeter method. This flow criterion was labeled a "high recession threshold" and was applied from April through June (Table 3).

Table 6. *Streamflows where Breakpoints and Incipient Asymptotes occur on wetted perimeter curves, along with reach averages. An "N/A" indicates that the asymptote could not be identified from the wetted perimeter curve.*

Reach		Cross Section	Breakpoint (cfs)	Incipient Asymptote (cfs)
UMS	WP6	7+70	2.5	
UMS	WP8	10+10	3.3	14.0
UMS	WP16	15+90	3.3	14.0
UMS	WP20	21+50	2.0	6.6
UMS			3.3 (Max)	11.5 (Avg)
USF	WP8	4+00	1.4	6.0
USF	WP10	5+00	2.0	
USF	WP13	7+50	1.4	
USF	WP15	10+00	1.4	6.0
USF			2.0 (Max)	6.0 (Avg)

Benthic Macroinvertebrates and Riffle Productivity

The drift of benthic macroinvertebrates (BMI) plays a key role in lotic food webs, providing food resource for juvenile salmonids (Nielsen 1992; Grossman 2014). The availability of invertebrate drift as well as the magnitude of drift flux directly impacts growth and survival of drift-feeding fish (Rosenfeld et al. 2005; Weber et al. 2014). Benthic invertebrate productivity and drift rates vary with streamflow magnitude. Svendsen et al. (2004) note that most studies they reviewed showed "a positive correlation between streamflow and stream drift", and a "positive correlation between biomass production and drift rates". Invertebrate drift is thus a useful indicator of benthic invertebrate productivity in riffles.

Invertebrate drift was sampled during the spring recession in Sproul Creek in 2016 to quantify drift abundance and biomass, and to identify the taxonomy of drifting organisms. Three riffles were sampled in the Upper Mainstem 2D modeling reach in April, May, June, and July 2016. A drift net with a 30 cm x 60 cm opening was placed at the downstream end of each riffle, in the thalweg, with the net positioned along the stream bottom and the top of the net extending above the water surface. Nets were placed in mid-afternoon and left for 24h. A total of twelve 24-hr drift samples were collected, subsampled, and measured, and macroinvertebrates were identified to family. Summary data from BMI sampling is presented in Table 7. A detailed description of BMI sampling and analysis is reported in Appendix J, and summarized here:

- April, May, and June appeared to maintain similar invertebrate biomass and abundance, despite the sharp decline in streamflows, with only minor shifts in percent aquatic vs terrestrial bugs;
- Invertebrate biomass and abundance appear to be positively correlated with flow later in the season, with both biomass and abundance declining sharply along with streamflow between June and July 2016;
- July drift samples had significantly lower overall abundance and biomass than other months (at α=0.05), primarily resulting from a steep drop in the presence of drifting aquatic invertebrates;
- Aquatic taxonomic groups that have been previously found in the diet of salmonids were compared to the total taxa found in the drift; May 2016 had the highest percentage of prey species in the drift (93%) while July had the lowest (78%);
- A conservative estimate of aquatic energy content available to drift-feeding fish suggests June 2016 had the greatest energy content while July had the lowest (Table 7). Therefore prey availability does not appear to correlate with overall abundance, but rather depends on total biomass as well as diversity.

Table 7. *Benthic Macroinvertebrate sampling data collected in the Upper Mainstem study reach in 2016.*

Sample Date (2016)	Daily Average Flow (cfs)	Average Biomass (mg) Aquatic + Terrestrial	% Biomass Terrestrial	Average Abundance	% Abundance Terrestrial
April	23.9	287.6	17.2%	1219	10.6%
May	7.55	256.7	14.3%	1434	3.72%
June	3.23	288.2	28.2%	1089	6.61%
July	0.32	95.9	17.5%	264	7.84%

As described above, the wetted perimeter incipient asymptote from four cross sections sampled in the Upper Mainstem ranged from 6.6 to 14.0 cfs, with a mean of 11.5 cfs. The wetted perimeter breakpoint ranged from 2.0 to 3.3 cfs, with a mean of 2.8 cfs. BMI samples collected in May (7.55 cfs) and June (3.23 cfs) fell below the incipient asymptote but above the breakpoint. Streamflows above the breakpoint, at least during the spring season 2016, appear to have maintained abundant benthic invertebrates. If there is a correlation between streamflow and BMI abundance and biomass, the July flow of 0.32 cfs would not maintain high BMI drift rates.

The 2D hydraulic model in the Upper Mainstem reach was used to model productive benthic invertebrate habitat in riffles. *The generic EPT* habitat suitability indices from Gore et al. (2001) were used to model BMI habitat suitability. Table 3 reports median habitat values for BMI. The WUA vs streamflow rating curve (Figure F-56) shows peak BMI habitat values at 20 to 55 cfs, with steep declines in habitat below 20 cfs. This habitat vs flow relationship does not conflict with the Sproul Creek drift sampling results.

5.6 Summer Low Flow Thresholds from Wetted Perimeter and Velocity Core Analysis

Summer Low-Flow Threshold

The wetted perimeter breakpoints were readily identifiable for all cross sections in the Upper South Fork and Upper Mainstem study reaches. Streamflows at the **wetted perimeter breakpoints for the Upper South Fork (USF) reach ranged from 1.4 to 2.0 cfs (mean=1.6 cfs)**. This flow range corresponded to RCT50 depths of 0.39 to 0.43 ft, with RCT50 depth of 0.41 ft at the wetted perimeter mean flow of 1.6 cfs. At 2.0 cfs, velocity core lengths ranged from 11-43% of the total pool unit lengths exceeding the 1.5 ft/s and 0.5 ft/s velocity thresholds, respectively. We observed an inflection in the Upper South Fork velocity core data at approximately 3.5 to 4.0 cfs (Figure 14) at an approximate RCT50 depth of 0.50 ft. Below this threshold the velocity core length in pool units began to retract rapidly. Velocity cores were measured on the USF on 6/15/16 at 1.1 cfs; at this flow barely any water velocity above 0.5 ft/s was observed at the heads of pools.

Based on the low-flow hydraulic inflections identified in the wetted perimeter and velocity core data, we identified a critical low-flow threshold of 2.0 cfs (RCT50 = 0.43 ft) in the Upper South Fork Sproul study reach, maintaining the wetted perimeter breakpoint flow at all sampled cross sections. Below this streamflow, hydraulic diversity of riffles and pools declines and the stream becomes unproductive for rearing salmonids.

The **wetted perimeter breakpoint for the Upper Mainstem (UMS) reach ranged from 2.0 to 3.3 cfs (mean=2.8 cfs)**. This flow range corresponded to RCT50 depths of 0.42-0.50 ft, with a RCT50 depth of 0.47 ft at the wetted perimeter average breakpoint flow of 3.3 cfs. At 3.3 cfs, velocity core lengths ranged from 8 to 30% of the total pool unit lengths exceeding the 0.5 ft/s and 1.5 ft/s velocity thresholds, respectively. An inflection was observed in the Upper Mainstem study reach velocity core data, at approximately 14 cfs (Figure 13), with a RCT50 of 0.78 ft depth. This occurred much earlier in the season at the Upper Mainstem study reach: the 14 cfs velocity core was measured on 4/28/16.

Based on the low-flow hydraulic inflections identified in the wetted perimeter and velocity core data, and the invertebrate drift data collected at the Upper Mainstem reach, we identified a critical low-flow threshold of 3.3 cfs (RCT50 = 0.5 ft) in the Upper Mainstem study reach, which maintains the wetted perimeter breakpoint flow at all sampled cross sections. Below this streamflow, hydraulic diversity of riffles and pools declines, invertebrate drift decreases significantly, and the stream becomes unproductive for rearing salmonids.

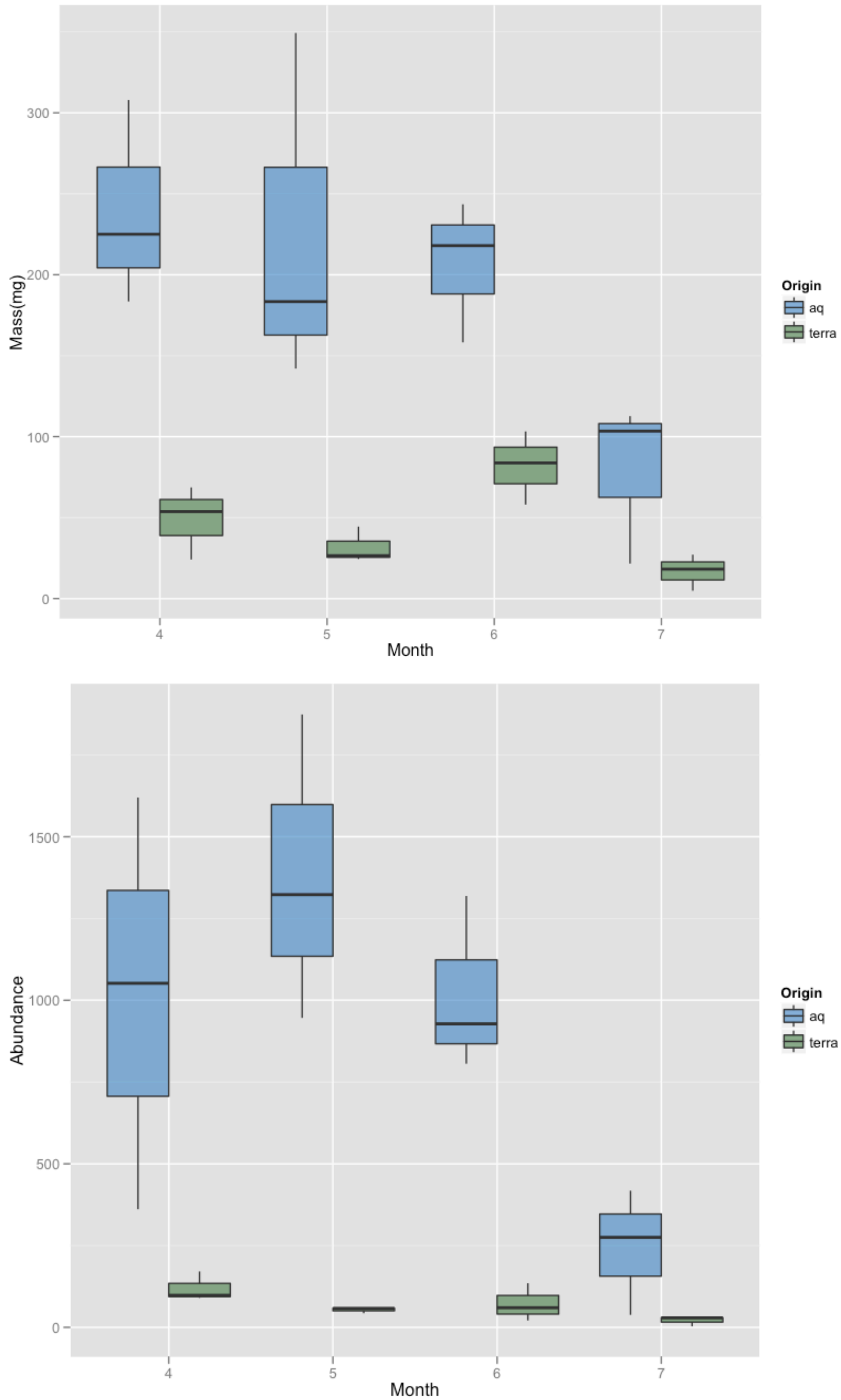

Figure 18. The distribution of macroinvertebrate biomass in milligrams (top) and drift abundance (bottom) by month and by origin-aquatic (aq) or terrestrial (terra) in Sproul Creek.

Threshold for Streamflow Disconnection
During the 2015 field season in which the north coast region was experiencing a prolonged drought, we observed several Sproul Creek reaches disconnect during a 6 to 8 week period between mid-July and mid-September, and included the entire mainstem Sproul Creek, the WF Sproul, SF Sproul, Little Sproul, Warden Creek, Dry Trib, and LaDoo Creek. South Fork Sproul Creek became disconnected approximately 2 weeks prior to West Fork Sproul and mainstem Sproul Creek, and had approximately half the measured unit runoff during two low-flow measurements made prior to and after stream disconnection.

Streamflow is difficult to measure accurately as flows approach disconnection stage. However, stream depth at the riffle crest is more readily measureable. Our observations suggest that a RCT depth of 0.25 ft is an approximate RCT depth below which riffles become disconnected. Our RCT rating curves were used to predict the streamflow at this depth. However, use of the actual RCT depth measurement is considered more accurate.

In both study reaches, the RCT50 depth of 0.25 ft corresponded with streamflow of approximately 0.3 cfs. Similarly, a RCT50 depth of 0.2 ft equated to a streamflow of approximately 0.2 cfs.

- USF RCT50 of 0.25 ft = 0.3 cfs (=194,000 gal/day); USF RCT50 of 0.15 ft = 0.2 cfs
- UMS RCT50 of 0.25 ft = 0.37 cfs; UMS RCT50 of 0.15 ft = 0.2 cfs

6 STEP-4: SUMMARY OF MINIMUM BYPASS FLOW CRITERIA

The threshold values presented in Table 3, derived independently from each instream flow method and analysis, were not considered final flow criteria for each associated salmonid life stage, month and water year type. To derive flow criteria, specific life stages were prioritized for each Sproul Creek study reach. The rationale for selection of priority life stages is described below. Flow criteria for each study reach and water year type are summarized in Tables 8a-b. Criteria are plotted with unimpaired annual hydrographs in Figures 19a and 20.

6.1 Fall and Winter Adult Migration (Nov – Jan)

Chinook upstream passage is dependent on unpredictable fall freshets and fall/winter storm hydrographs; delays in upstream passage may significantly impact the annual life cycle of this species. In the Upper Mainstem study reach, streamflows of 98 cfs providing unimpeded upstream passage for adult Chinook salmon were prioritized as flow criteria for November through January. The median habitat values derived from the PHABSIM time-series analysis for spawning and rearing were higher than the Chinook passage threshold in Norm through Ex Wet water year types, but those median values are computed in part from the unimpaired flow hydrology, and exceed streamflows needed to provide abundant Chinook spawning and rearing habitat. The fall Chinook passage criteria was thus considered protective of other life stage needs.

In the Upper South Fork study reach, streamflows of 36 cfs providing unimpeded upstream passage for coho and steelhead were prioritized. The flow threshold for Chinook passage was slightly higher (43 cfs) but Chinook passage is naturally constrained in smaller sub-watersheds at the upper end of their range in the USF reach. Similar to the Upper Mainstem reach, spawning and rearing flows from PHABSIM time-series analysis were higher than flow thresholds for coho and steelhead passage in wetter water year types, but 36 cfs is higher than the peak of the WUA curves in Figure 16, and provides abundant habitat for these species.

6.2 Spawning and Fry/Juvenile Rearing (Feb – Apr)

The juvenile coho life stage is known to be particularly vulnerable to winter rearing habitat alteration, flow reduction, and reduced growth rates in the critical winter/spring months of February through April, and is often considered a limiting life stage or population “bottleneck”. The median habitat flows for coho juvenile rearing were prioritized as flow criteria for February through April in both the Upper Mainstem and Upper South Fork study reaches. These flows ranged from 160 cfs to 20 cfs in the Upper Mainstem, and 47 cfs to 6 cfs in the Upper South Fork. These flows were nearly identical to median WUA values for coho and steelhead fry rearing and were higher than the median WUAH threshold values for the larger steelhead life stages (1+ and 2+). Flow criteria in February through April vary by water year type.

Steelhead migration extends through April and May, and had higher flow thresholds during April of drier water year types. However the natural (unimpaired) hydrographs typically do not exceed the steelhead passage criteria during these water year types, except during infrequent spring rainstorm events. Excessive water management during spring of dry water years may impact the ability of steelhead to migrate to upper headwater reaches.

6.3 Juvenile Rearing and Smolt Outmigration (May – Jul)

The spring streamflow recession is a critical period among freshwater life stages of salmonids. Fry and juvenile abundance and density are highest in these months, leading to heightened competition for available rearing habitat. Growth during this period is imperative for survival in subsequent life stages.

The CDFW protocol for maintaining abundant benthic invertebrate productivity as a food base for juvenile rearing relies on the wetted perimeter incipient asymptote (WP-IA). This flow criterion is termed “high recession threshold” in Table 3). The WP-IA flow criterion was slightly higher than the benthic invertebrate median habitat values from the time-series analysis. The WP-IA and the coho/steelhead passage thresholds were similar in magnitude for both study reaches: 11.5 cfs and 18.9 cfs in the Upper Mainstem; 6 cfs and 5 cfs in the Upper South Fork, respectively. To identify flow criteria for May through July, the higher of the two values was prioritized for May and June when the spring recession is steeply declining, and the lower of the two values was used for July.

6.4 Summer Juvenile Rearing and Low Flow Threshold (Aug – Oct)

The summer low flow period is a naturally stressful condition to juvenile salmonids rearing in Sproul Creek. As streamflows diminish, hydraulic complexity retracts to a few localized areas of the stream channel, typically at the heads of pools and in riffles in pockets of faster water channeled between cobbles/boulders. Connectivity between hydraulic units is gradually lost, rendering pools isolated from one-another and stagnating until fall freshets return.

The CDFW protocol for identifying flow criteria protective of summer low flow conditions relies on the Wetted Perimeter breakpoint (WB-BP), identified in the CDFW WP SOP (CDFW 2013a). Flow criteria for the Upper Mainstem and Upper South Fork study reaches for August through October were based on the WP-BP, with flows of 3.3 cfs and 2.0 cfs, respectively. These streamflows correspond with the highest breakpoint streamflow value for the wetted perimeter cross sections (as opposed to an arbitrary average of all breakpoint flows)

Water quality conditions (water temperature, dissolved oxygen concentration) influenced by surface streamflow as well as hyporheic flows are likely more dominant factors than hydraulic habitat (depth and velocity) during the summer low flow period.

Table 8a. *Summary of flow criteria for five different water year types, for the Upper Mainstem study reach. WPBP=Wetted Perimeter Breakpoint; WPIA=Wetted Perimeter Incipient Asymptote.*

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
	WPBP	**Chinook Passage**			**Coho Juv Rearing**			**Coho Juv Mig**		**WPIA**	**WPBP**	
Ex Wet	3.3	98	98	98	159.9	127.2	61.8	18.9	18.9	11.5	3.3	3.3
Wet	3.3	98	98	98	95	112.5	55.7	18.9	18.9	11.5	3.3	3.3
Norm	3.3	98	98	98	85.6	80.8	34	18.9	18.9	11.5	3.3	3.3
Dry	3.3	98	98	98	47.6	48.9	25.6	18.9	18.9	11.5	3.3	3.3
Ex Dry	3.3	98	98	98	43.7	48.2	19.9	18.9	18.9	11.5	3.3	3.3

Table 8b. *Summary of flow criteria for five different water year types, for the Upper South Fork study reach. WPBP=Wetted Perimeter Breakpoint; WPIA=Wetted Perimeter Incipient Asymptote.*

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
	WPBP	**Chinook Passage**			**Coho Juv Rearing**			**WPIA**		**Steel-head Juv Mig**	**WPBP**	
Ex Wet	2	36	36	36	47	37.4	18.2	6	6	5	2	2
Wet	2	36	36	36	35.5	33.1	16.4	6	6	5	2	2
Norm	2	36	36	36	25.1	23.8	10	6	6	5	2	2
Dry	2	36	36	36	14	14.4	7.5	6	6	5	2	2
Ex Dry	2	36	36	36	12.6	12	5.9	6	6	5	2	2

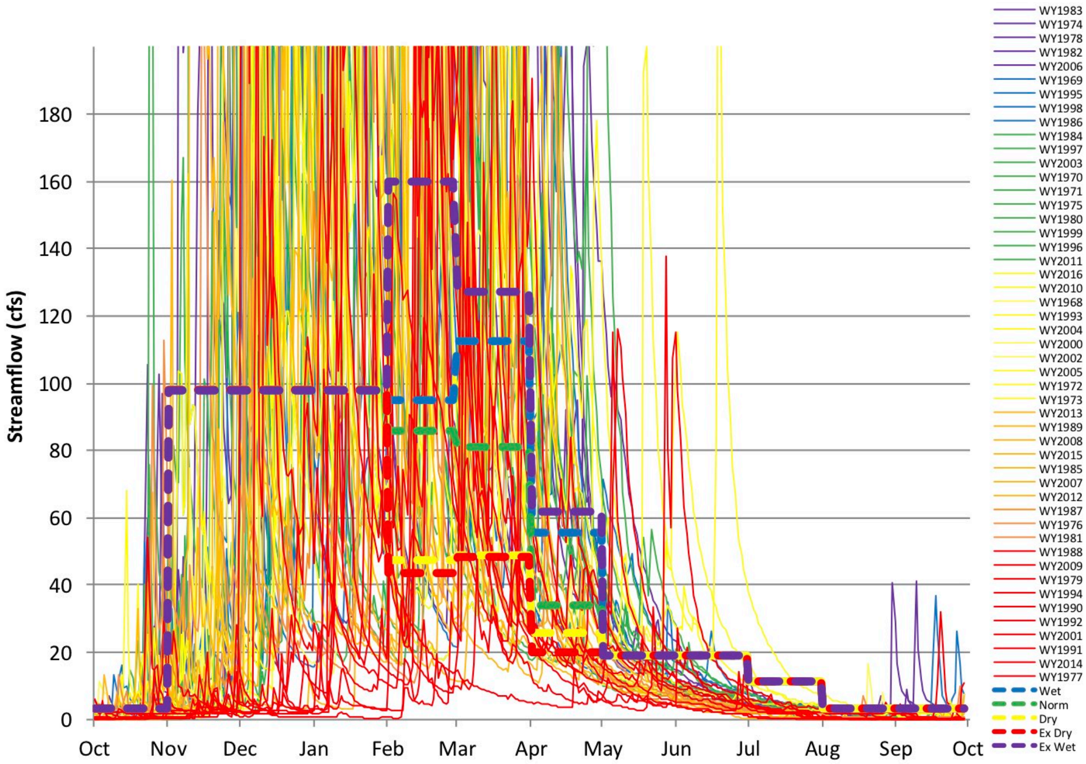

Figure 19. Upper Mainstem Sproul Creek monthly flow criteria plotted with annual unimpaired hydrographs.

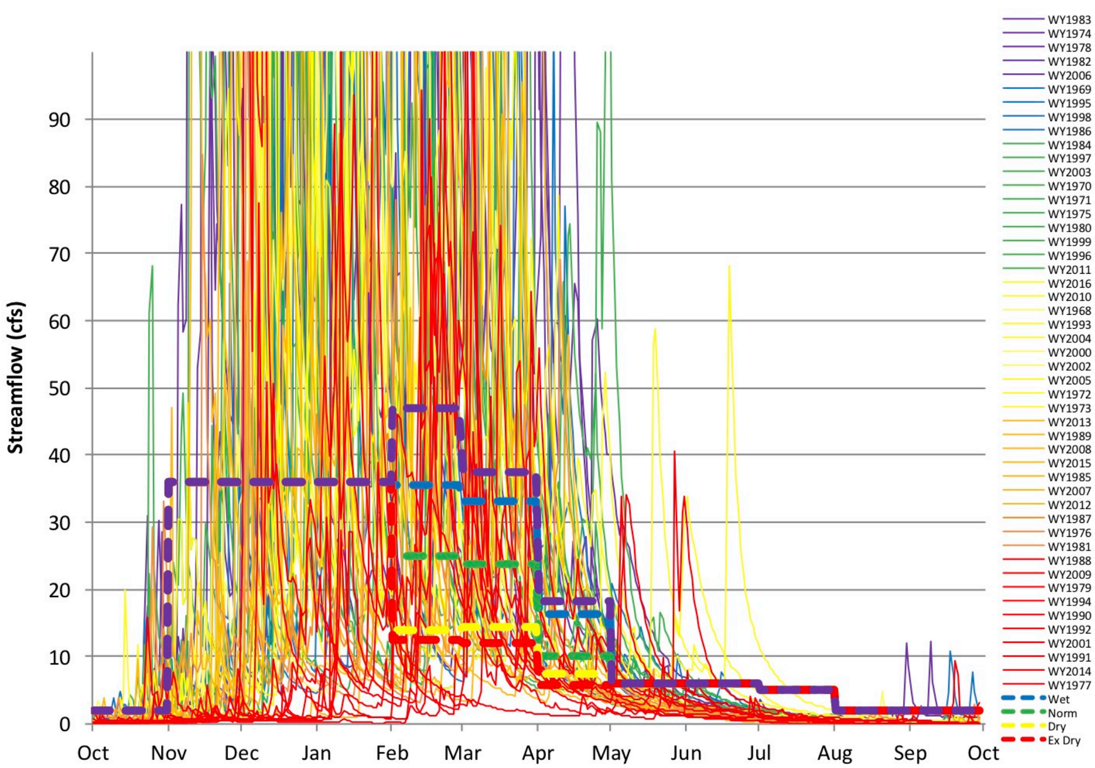

Figure 20. Upper South Fork Sproul Creek monthly flow criteria plotted with annual unimpaired hydrographs.

7 HUMAN WATER DEMAND IN SPROUL CREEK

Like many watersheds in the region, Sproul Creek supports residential and cannabis farm land uses, both of which rely on water obtained from surface water diversions (springs or creeks). As part of the Sproul Creek instream flow study, we assessed the distribution of water use, overall seasonal water demand, and the potential for water diversions to influence instream flows in the Sproul Creek watershed (Appendix K). We used aerial imagery in ArcMap to digitize human infrastructure, including building structures, cannabis operations, and reservoirs. Residences and other structures were mapped as points. Marijuana cultivation areas and reservoirs were mapped as polygons to enable an estimate of area in square feet. Water demand was estimated using the following rules:

Residential. All building structures were identified as either residential (homes) or residential storage (e.g., garage or shed). Residential structures were assigned a standard water use value of 355 gallons per day per structure for a five-month summer period (153 days), and 155 gallons per day for a seven-month winter period (212 days). These summer and winter values are based on regional water use estimates (citation).

Cannabis. The spatial data of cannabis farms was used to estimate total water demand, as well as to distinguish demand from indoor and outdoor cannabis grow operations. Water use for irrigated cannabis was based on six gallons per plant per day from June through October (Bauer et al., 2015). We then calculated the water demand associated with each of the above water uses, in addition to the annual and dry-season water needs.

Water demand was estimated for sub-watersheds within Sproul Creek, including: Little Sproul Creek, West Fork Sproul Creek, South Fork Sproul Creek, and the Mainstem Sproul Creek.

Disclaimers. More accurate estimates of the actual water consumption in the Sproul Creek watershed could be made if individual water use data were available. Our study requested this information, but we were unable to obtain adequate information for this purpose.

Total Sproul Creek Watershed Water Need

Our analysis identified 27 independent residential structures and approximately 3.5 acres of cannabis grow area in the Sproul Creek watershed (Table 9). Not all rural residential areas mapped in Sproul Creek had cannabis farms evident in the imagery. Based on these estimates and the average consumer demand described above, the total annual water demand for residential and cannabis irrigation was estimated at approximately 20.15 af per year; the total water demand during the dry season was estimated at approximately 17.41 af.

The Upper South Fork Sproul Creek sub-watershed, with drainage area of 5.0 mi^2, had the highest concentration of cannabis cultivation and estimated water demand, with 20 rural residents, 2.3 acres of outdoor cannabis grows, and 0.9 acres of indoor grows.

Table 9. *Residential and cannabis cultivation area, and estimated water demand for residential use and cannabis irrigation in four sub-watersheds and the entire Sproul Creek watershed.*

Sub-Watershed	Residential Structures	Total Cannabis (acres)	Annual Water Use				Summer Water Use		
			Cannabis Water Demand (6 gpd/plant)	Annual Cannabis Water Use (af/yr)	Annual Residential Water Use (af/yr)	Total Water Demand (af/yr)	Summer Residential Water Demand (af/yr)	Summer Cannabis Water Demand (af/yr)	Total Summer Water Demand (af/yr)
Little Sproul Creek	0	0.16	243,900	0.75	0	0.75	0	0.75	0.75
West Fork Sproul Creek	0	0	0	0	0	0	0	0	0
Upper South Fork Sproul Creek	20	3.13	3,665,700	11.25	5.34	16.59	3.31	11.25	14.56
Mainstem Sproul Creek	7	0.19	307,800	0.94	51.87	2.81	1.16	0.94	2.1
Sproul Creek Watershed	**27**	**3.48**	**4,217,400**	**12.94**	**7.21**	**20.15**	**4.47**	**12.94**	**17.41**

Water Supply vs Demand

The annual and summer water supply (average yield in acre-feet) in Sproul Creek was estimated from the unimpaired streamflow data reported in Section 4 above. Recall that estimates of unimpaired streamflow for Sproul Creek were derived from converting the USGS Bull Creek gaging record to Sproul Creek based on ratios of drainage area and precipitation. Focusing on the portion of the watershed with highest total water demand, the Upper South Fork Sproul (5.0 mi^2), the estimated annual water supply was 12,577 af, with a wide range in annual yield from 1,058 af to 31,932 af (Table 10). On an annual basis and during the dry season, the Upper South Fork Sproul Creek sub-watershed has enough water supply to meet current water demand in the watershed. Annual water demand in Sproul Creek is approximately 0.14% of the total average annual yield (water supply); summer water demand takes up approximately 1.35% of the average summer supply. As an estimate of worst-case scenario, the total summer demand (12.9 af) is only 5.9% of the minimum summer water supply (76 af) for the 49 year period of record.

Table 10. *Comparison of estimated water supply from Sproul Creek's modeled unimpaired streamflow record to the estimated water demand from rural residential uses and cannabis farming operations.*

	Mean (af)	Min (af)	Max (af)
Annual Water Supply	12,577	1,058	31,932
Winter (Nov-May)	12,246	916	31,235
Summer (Jun-Oct)	331	76	1,554
Summer Supply Percent of Total	3%	0.7%	13.8%
Summer Residential Water Demand	4.47		
Summer Cannabis Water Demand	12.94		
Summer Total Water Demand	17.41		
Annual Water Demand	20.15		
Annual Demand Percent of Total	0.16%		
Summer Demand Percent of Supply	5.25%		

8 LITERATURE CITED

Baker, P. and Reynolds, F. 1986. Life history, habitat requirements, and status of coho salmon in California. Report to California Fish and Game Commission, Calif. Dept. of Fish and Game.

Beamish, R.J. 1980. Adult biology of the river lamprey (Lampetra ayresi) and the Pacific lamprey (Lampetra tridentata) from the Pacific coast of Canada. Can. J. Fish. Aquat. Sci. 37: 1906-1923.

Bjorkstedt, E. P., B. C. Spence, J. C. Garza, D. G. Hankin, D. Fuller, W. E. Jones, J. J. Smith, and R. Macedo. 2005. An analysis of historical population structure for evolutionarily significant units of Chinook salmon, coho salmon, and steelhead in the south-central California coast recovery domain. National Marine Fisheries Service, Santa Rosa, CA. 231 pp. U.S. Department of Commerce, NOAA Technical Memorandum NMFSSWFSC-382

CDFG (California Department of Fish and Game). 1992. Historical Distribution and Recent Trends of Summer Steelhead, Oncorhynchus mykiss in the Eel River, California. Report by Weldon E. Jones

CDFG (California Department of Fish and Game). 2004. Stream Inventory Report for Sproul Creek.

CDFW (California Department of Fish and Wildlife). 2013a. Standard Operating Procedure for the Wetted Perimeter Method in California – Instream Flow Program Standard Operating Procedure. Instream Flow Program, Sacramento CA. [Online]: http://www.dfg.ca.gov/water/instream_flow.html

CDFW (California Department of Fish and Wildlife). 2013b. Critical Riffle Analysis for Fish Passage in California. California Department of Fish and Wildlife – Instream Flow Program Standard Operating Procedure. Instream Flow Program, Sacramento CA. [Online]: http://www.dfg.ca.gov/water/instream_flow.html

CDFW (California Department of Fish and Wildlife). 2014a. South Fork Eel River Watershed Assessment. Coastal Watershed Planning and Assessment Program. California Department of Fish and Wildlife

CDFW (California Department of Fish and Wildlife). 2014b. Instream Flow Evaluation: Steelhead Spawning and Rearing, Big Sur River, Monterey County, CA. Stream Evaluation Report 14-2, July 2014.

CDFW (California Department of Fish and Wildlife). 2016. Results of regional spawning ground surveys and estimates of total salmonid redd construction in the South Fork Eel River, Humboldt County, California. California Coastal Salmonid Monitoring Program Annual Report prepared in partnership with Pacific States Marine Fisheries Commission.

Chapman, D.W. and Bjornn, T.C., 1969. Distribution of salmonids in streams. In Symposium on Salmon and Trout in Streams. Edited by TG Northcote. HR MacMillan Lectures in Fisheries. Institute of Fisheries, University of British Columbia, Vancouver, BC (pp. 1302-1310).

Everest, F.H. and Chapman, D.W., 1972. Habitat selection and spatial interaction by juvenile chinook salmon and steelhead trout in two Idaho streams. Journal of the Fisheries Board of Canada, 29(1), pp.91-100.

Flosi, G., S. Downie, J. Hopelain, M. Bird, R. Coey, and B. Collins. 2010. California Salmonid Stream Habitat Restoration Manual, 4th edition. California Department of Fish and Wildlife. Available online at: http://www.dfg.ca.gov/fish/Resources/HabitatManual.asp

Good, T.P., R.S. Waples and P.B. Adams. 2005. Updated status of federally listed ESUs of west coast salmon and steelhead. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, NMFS-NWFSC-66. 598 pp.

Goodman, D.H., Reid, S.B., Som, N.A. and Poytress, W.R., 2015. The punctuated seaward migration of Pacific lamprey (Entosphenus tridentatus): environmental cues and implications for streamflow management. Canadian Journal of Fisheries and Aquatic Sciences, 72(12), pp.1817-1828.

Gore J.A, J.B. Layzer, and J. Mead. 2001. Macroinvertebrate Instream flow Studies After 20 Years: A Role in Stream Management and Restoration. *Regulated Rivers: Research & Management*. Vol. 17. Pages 527–542.

Grossman, G.D. 2014. Not all drift feeders are trout: a short review of fitness-based habitat selection models for fishes. Environmental biology of fishes, 97(5), pp.465-473.

Mann, M. P., Rizzardo, J., & Satkowski, R. 2004. Evaluation of methods used for estimating selected streamflow statistics, and flood frequency and magnitude, for small basins in north coastal California: U.S. Geological Survey Scientific Investigations Report, 2004–5068, 92 p.

Moyle. P.B. 2002. Inland fishes of California (second edition). University of California Press. Berkeley, California. 502 pp.

Moyle, P.B., R.A. Lusardi, P.J. Samuel, and J.V.E. Katz. 2017. State of the Salmonids: Status of California's Emblematic Fishes. A Report Prepared by Center for Watershed Sciences, University of California, Davis, CA.

Nielsen, P. 1992. Coastal bottom boundary layers and sediment transport (Vol. 4). World Scientific Publishing Co Inc.

NMFS (National Marine Fisheries Service). 2007. Federal recovery outline for the evolutionarily significant unit of California coastal Chinook salmon. National Marine Fisheries Service, Southwest Regional Office, Santa Rosa, CA. 22 pp.

NMFS (National Marine Fisheries Service). 2014. Final recovery plan for the southern Oregon/northern California coast evolutionarily significant unit of Coho salmon (Oncorhynchus kisutch). National Marine Fisheries Service. Arcata, CA. 1841 pp.

NMFS (National Marine Fisheries Service). 2016. Coastal Multispecies Recovery Plan. National Marine Fisheries Service, West Coast Region, Santa Rosa, California.

Orlov, A.M., Beamish, R.J., Vinnikov, A.V., Pelenev, D. 2009. Feeding and prey of Pacific Lamprey in coastal waters of the western North Pacific. In: Challenges for diadromous fishes in a dynamic global environment. Edited by A. Haro, K.L. Smith, R.A. Rulifson, C.M. Moffitt, R.J. Klauda, M.J. Dadswell, R.A. Cunjak, J.E. Cooper, K.L. Beal, and T.S. Avery, American Fisheries Society, Symposium 69, Bethesda, Maryland, pp 875‑877.

SEC (Steiner Environmental Consulting). 1998. Potter Valley project monitoring program (FERC No. 77, Article 39). Effects of operations on upper Eel River anadromous salmonids. 1996-97 progress report. Potter Valley, CA. March 1998. 313 pp. + app.

Potter, I.C., 1980. Ecology of larval and metamorphosing lampreys. Canadian Journal of Fisheries and Aquatic Sciences, 37(11), pp.1641-1657.

Quinn, T.P. 2005. The behavior and ecology of Pacific salmon & trout. American Fisheries Society, Bethesda Maryland.

Renger. 2015. Allan Renger, CDFW Fisheries Biologist Personal Communication.

Robinson, T.C. and Bayer, J.M. 2005. Upstream migration of Pacific lampreys in the John Day River, Oregon: behavior, timing, and habitat use. Northwest Science, 79(2), pp.106-119.

Rosenfeld, J.S., Leiter, T., Lindner, G. and Rothman, L. 2005. Food abundance and fish density alters habitat selection, growth, and habitat suitability curves for juvenile coho salmon (Oncorhynchus kisutch). Canadian Journal of Fisheries and Aquatic Sciences, 62(8), pp.1691-1701.

Shapovalov, L. and Taft, A.C. 1954. The life histories of the steelhead rainbow trout (Salmo gairdneri gairdneri) and silver salmon (Oncorhynchus kisutch): with special reference to Waddell Creek, California, and recommendations regarding their management (p. 575). California Department of Fish and Game.

Svendsen, C.R., T Quinn, and D. Kolbe. 2004. Review of Macroinvertebrate drift in lotic ecosystems: Final Report. Prepared for Wildlife Research Program Environmental and Safety Division, Seattle City Light, Seattle WA.

Thompson, K. 1972. Determining stream flows for fish life, in Proceedings, instream flow requirements workshop, Pacific Northwest River Basin Commission, Vancouver, Washington. P. 31-50.

USEPA (U.S. Environmental Protection Agency). 1999b. South Fork Eel River total maximum daily loads for sediment and temperature. San Francisco, CA. December 1999.

United States Office of the Federal Register. 1997. Endangered and threatened species; threatened status for southern Oregon / northern California coast evolutionarily significant unit (ESU) of coho salmon. Federal Register 62(117): 33038-33039.

Weber, S. and Traunspurger, W., 2014. Consumption and prey size selection of the nematode Caenorhabditis elegans by different juvenile stages of freshwater fish. Nematology, 16(6), pp.631-641.

Williams, T. H., Bjorkstedt, E. P., Duffy, W. D., Hillemeier, D., Kautsky, G., Lisle, T. E., McCain, M., Rode, M., Szerlong, R. G., Schick, R. S., Goslin, M. N., and Agrawal, A. 2006. Historical population structure of coho salmon in the southern Oregon / northern California coasts evolutionarily significant unit. National Marine Fisheries Service, Santa Rosa, CA. 85 pp. U.S. Department of Commerce, NOAA Technical Memorandum SWFSC-390.

WSC (Wild Salmon Center). 2012. The California Salmon Stronghold Initiative. Prepared for California Department of Fish and Game by Wild Salmon Center on behalf of the California Stronghold Team. March 2012. Available online:
http://www.wildsalmoncenter.org/pdf/CA%20Stronghold%20Initiative%20-%20Final%20Report.pdf

Yoshiyama, R.M. and P.B. Moyle. 2010. Historical review of Eel River anadromous salmonids, with emphasis on Chinook salmon, coho salmon and steelhead. University of California at Davis. Center for Watershed Sciences working paper. Davis, CA.