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SITE-SPECIFIC INSTREAM FLOW STUDY ON INDIAN CREEK IN THE NAVARRO RIVER BASIN

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1 INTRODUCTION

Historically, the Navarro River watershed supported the most anadromous salmonid habitat in Mendocino County (NCRWQCB 2010) and was famous for its runs of Coho Salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*). Harvest and cannery operations, periods of large-scale timber harvests, and land conversion for sheep grazing and residential development (Cal Trout et al. 2014), coupled with increases in water use for agriculture and viticulture over the last 30 years, have contributed to a substantial decrease in salmonid populations. After nearly a century of declines to California salmonid populations, the National Marine Fisheries Service (NMFS) listed Central California Coastal (CCC) Coho Salmon as threatened in 1996 and endangered in 2005, and listed the Northern California Steelhead Distinct Population Segment as threatened in 2005 under the Federal Endangered Species Act (NMFS 2012).

Anadromous salmonids are dependent on freshwater habitat for adult spawning and juvenile rearing. Coho Salmon and steelhead in the Navarro River Watershed are adapted to the hydrologic and hydraulic regime typical of California streams in Mediterranean climates. They time their migration and spawning to the high rain events in the winter, then depend on the spring recession to provide habitat and abundant food resources to survive the low-flow conditions in the summer. Over the past several decades, increases in legal and illegal water diversions have affected the timing, rate, and shape of the annual hydrograph of many streams (Cal Trout et al. 2014), particularly in the late spring, summer, and fall prior to the first freshets. These altered hydrographs can have an adverse effect on freshwater life history strategies of Coho Salmon and steelhead in the watershed, along with other biotic and abiotic processes, by changing the occurrence and intensity of low-flow periods.

Resource agencies, non-governmental organizations, and landowners throughout the North Coast have been working to manage the timing and reduce the cumulative rate of water diversions, particularly during the seasonal recession and summer low-flow period. Water diversion practices to support agriculture and viticulture have been identified as a primary constraint (along with the legacy effects of logging and grazing) to the recovery of salmonids (SWRCB 2010, Cal Trout et al. 2014).

The Nature Conservancy (TNC) is working with a local vineyard, Roederer Estate, to retire its existing summer diversion and replace it with a water right permit that will allow the vineyard to divert during higher periods of flow instead. They are using the Policy for Maintaining Instream Flows in Northern California Coastal Streams (hereafter "Policy;" SWRCB 2010) as a guideline for acquiring the water right permit. The purpose of this report is to provide minimum bypass flows, according to guidelines set for the Policy, as part of this new water right permit.

The Policy provides two different methods to determine minimum bypass flows. The applicant can (1) calculate a regionally protective minimum bypass flow using a provided formula, or (2) perform a site-specific study to develop site-specific criteria that better reflect instream flow needs of fisheries resources in the study area. Before a site-specific study was considered for the study reach in Indian Creek, a regionally protective minimum bypass flow was calculated (Section 3). The resulting regionally protective minimum bypass flow of 113 cfs was too conservative to be used for the study reach (more detail in Section 4). Therefore, we chose to perform a site-specific study to obtain more applicable, site-specific minimum bypass flows. Specific elements required under the Policy for site-specific studies are identified in Table 1 and their locations in the report identified.

1.1 Focal Species and Life Stages

Three anadromous salmonid species can potentially inhabit Indian Creek: Chinook Salmon, Coho Salmon, and steelhead (Holloway et al. 2016). Coho Salmon and steelhead typically spawn and over-summer in the Navarro River and its tributaries and were identified as the target species for this study. Chinook Salmon are not currently common in the Navarro River and its tributaries (Holloway et al. 2016), and therefore were not identified as target species.

The freshwater life stages of Coho Salmon and steelhead are intimately linked to the hydraulic characteristics and morphology of small gravel and cobble bed streams, particularly the hydraulics of the riffle–pool sequence, which provides spawning habitat for adult salmonids, as well as food production and rearing habitat for juveniles. Water diversions affect each freshwater life history stage for Coho Salmon and steelhead. Since the ratio of diversion rate to streamflow increases during the spring runoff period and especially during the summer low-flow period, the over-summering juvenile life stages are often disproportionally affected by cumulative water diversions.

1.2 Study Goals

The objective of this study was to determine ecological flow thresholds that are protective of key steelhead and Coho Salmon life history needs during their freshwater residence in the study reach, and to use these thresholds to develop site-specific minimum bypass flows for specific flow periods for one or more water right permits under the Policy. This study identifies seasonal site-specific flow thresholds for four primary life history needs of Coho Salmon and steelhead: (1) adult and juvenile passage and migration, (2) adult spawning habitat, (3) juvenile rearing and foraging habitat, and (4) salmonid food production, specifically benthic macroinvertebrate (BMI) habitat. We used empirical methods (California Department of Fish and Wildlife's (CDFW) Critical Riffle Analysis (CRA; CDFW 2013b), and CDFW's Wetted Perimeter Method (CDFW 2013c), along with 2-dimensional (2-D) hydraulic modeling to develop the ecological flow thresholds. Riffle Crest Thalweg (RCT) Method (M&T 2012) and R2Cross (Espegren 1996) calculations were included as points of comparison but were not used to establish ecological flow thresholds. The flow threshold and periodicity information developed in this report is intended to support TNC in their effort to develop different diversion strategies for water right permit holders in lower Indian Creek that will mimic natural flow regimes for salmonids and existing ecological processes while meeting viticulture production needs.

Table 1. Policy reporting requirements and where they can be found in this report.

Policy Reporting Requirements (C.1.2.1)	Location in This Report
1. A description of the study results and the analysis supporting the conclusions; including, but not limited to:	
the purpose for any field surveys that were performed, i.e., reasons why the field surveys were undertaken, what habitats and life stages were evaluated and why;	Section 1– Introduction
the method(s) used to analyze the field data, including the assumptions used and how the field data were used in the analysis;	Section 5 – Methods for Quantifying Ecological Flow Thresholds Appendix B – 2-D Hydraulic Model Preparation, Calibration, And Validation Appendix C – Preparation of Weighted Usable Area Rating Curves
the biological or physical criteria used as the threshold for determining protective streamflows; if alternative depth criteria or favorable stream velocity criteria were used, the report shall describe why these alternative thresholds were appropriate, including the literature citations used; and	Criteria used for WUA curve development: Appendix C Criteria used for each empirical method can be found in Section 5 – Methods for Quantifying Ecological Flow Thresholds
a discussion of the protective minimum streamflows needed for each habitat type analyzed, including how the flows were determined.	Section 6 – Ecological Flow Threshold Results for Each Flow Period Section 7 – Synthesis of Recommended Minimum Bypass Flows
2. Field study methods and data obtained, including:	
a description of the field sampling design used, including the field methods and equipment used to obtain data; upon notice, the applicant may be required to provide literature citations; and	Section 5 – Methods for Quantifying Ecological Flow Thresholds Appendix B – 2-D Hydraulic Model Preparation, Calibration, And Validation
descriptions of the locations at which data were collected, including the rationale used to select the locations, the measurements taken at each location, purpose of the selected locations, map(s) depicting the proposed diversion, senior water rights and sampling locations, and sampling equipment used at each location.	Section 2 – Study Reach Appendix D – Site Selection Methodology for The Indian Creek Study Reach
Upon request, the applicant may be required to provide an inventory of the collected raw data including, but not limited to, dates of collection, photographs of cross section locations, water depth and velocity measurements obtained for each channel cross section evaluated, temperature, GPS coordinates and maps of data collection locations, and purpose of each location.	Electronic Appendices J through O

2 STUDY REACH

The Navarro River drains approximately 315 square miles of the central California Coast Range in southern Mendocino County (Figure 1). Indian Creek is a third order stream, draining 39.6 square miles of the upper Navarro River basin. The study reach on Indian Creek was chosen to accommodate points of interest (POI) that are situated downstream relative to identified points of diversion (POD) following the guidelines from SWRCB (2010). A POI is a location in the stream that is well suited to evaluate the effect of upstream diversions on the life history needs of focal species. In addition, the study reach was chosen because it provides habitat for all freshwater phases of Coho Salmon and steelhead life history (adult migration and spawning, incubation, young of the year (YOY) and juvenile (1+, 2+) rearing, and smolt outmigration), and provides suitable study sites for standard empirical instream flow assessment methods, as well as hydraulic modeling. The study reach begins at the downstream end of Indian Creek County Park and extends 2,635 ft upstream (Figure 2).

In the study reach, mesohabitat types (e.g., pools, riffles, and runs) were delineated to quantify the variability of different mesohabitat types and aid in the selection of study sites for empirical habitat methods and 2-D hydraulic modeling (Figure 2). Final study sites for empirical habitat methods and 2-D hydraulic modeling were determined using site selection criteria for each method. For more information on mesohabitat mapping methods and results, and a more detailed description of how study sites were selected, please refer to Appendix D.

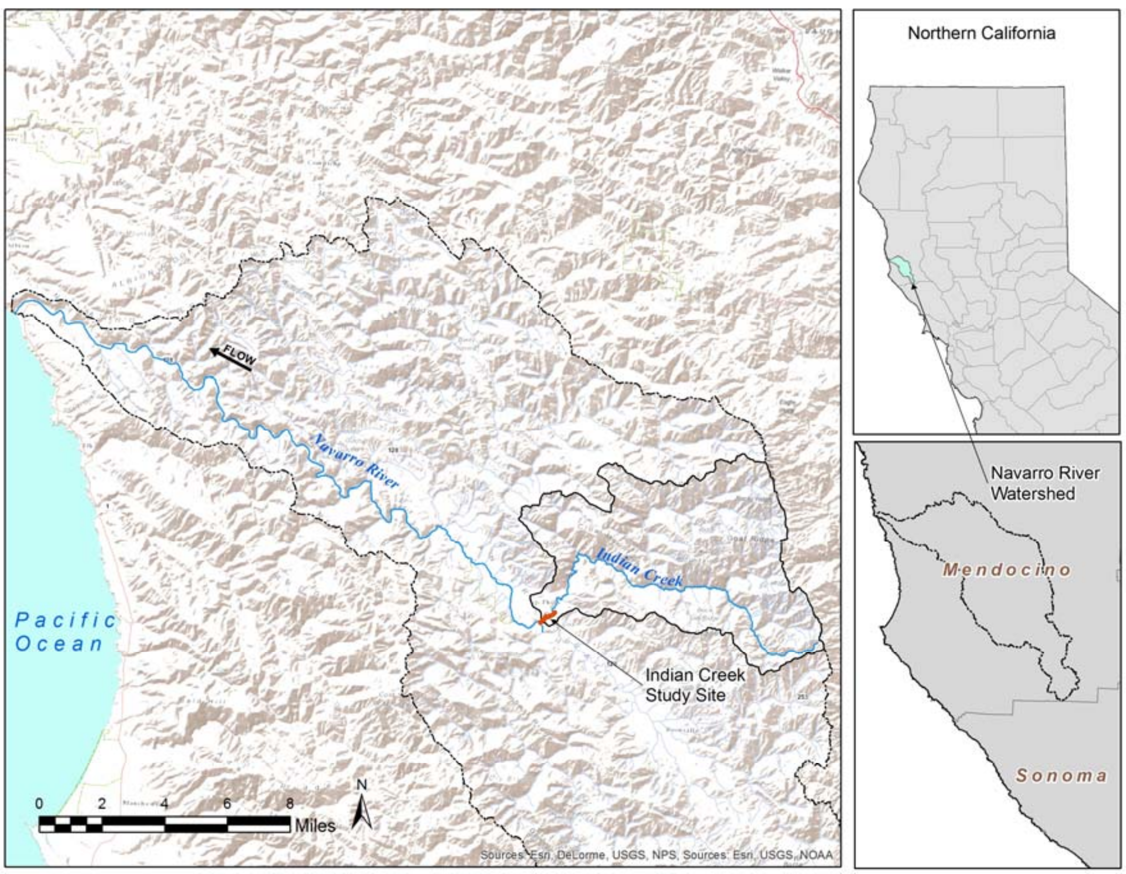


Figure 1. Indian Creek study site in the Navarro River Watershed.

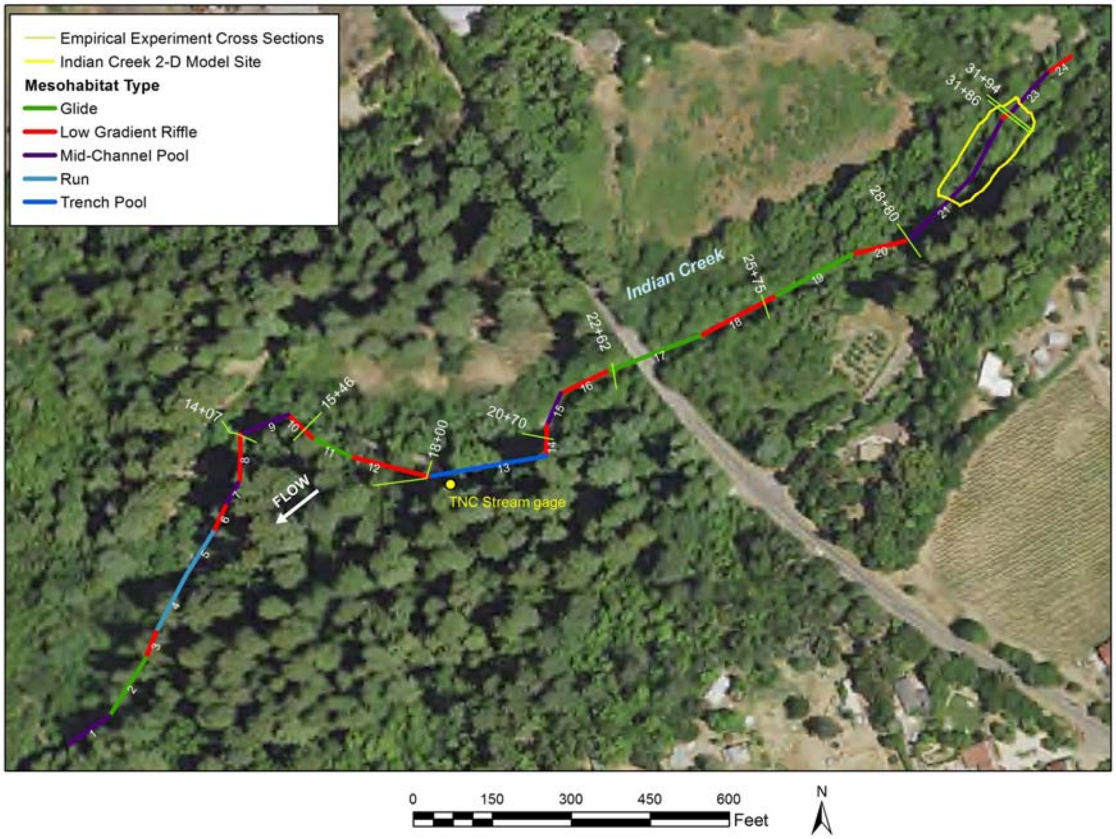


Figure 2. Map of Indian Creek study site showing location of empirical hydraulic habitat assessment cross sections, 2-D hydraulic modeling site, and mesohabitat types.

3 REGIONALLY PROTECTIVE MINIMUM BYPASS FLOW

Regionally protective minimum bypass flow criteria are set forth in the Policy using a minimum bypass flow formula, based on drainage area, that estimates streamflows protective of fisheries resources throughout the policy area. Calculation of a regionally protective minimum bypass flow provides the applicant a cost-effective way to show that operation of their project will not adversely affect fisheries resources in the region, and as a way to expedite the application process. The regionally protective criteria in the Policy intentionally produce a conservative result that may not always be reasonable for a given study area due to natural flow conditions and/or other beneficial uses. Therefore, an alternative site-specific study option is provided in the Policy to determine minimum bypass flows that better reflect instream flow needs of fisheries resources in the study area. In this report, we present our site-specific study on Indian Creek and include the regionally protective minimum bypass flow for context. We present methods and results for the regionally protective minimum bypass flows in this section; however, the result was not used in development of final flow thresholds.

3.1 Calculating Regionally Protective Minimum Bypass Flow

A regionally protective minimum bypass flow for the study area was calculated using methods described in Appendix B of the Policy (SWRCB 2010). The Policy requires the use of one of three equations to calculate the minimum bypass flow based on the drainage area at the POI (Table 2). The drainage area (DA) was defined as the portion of the watershed above the POI that encompasses the total area that drains to the POI and was calculated using the following equation:

$$Q_{MFB} = 8.8\times Q_m \times (DA)^{-0.47} \qquad (1)$$

where:

Q_{MFB} = minimum bypass flows (cfs);

Q_m = mean annual unimpaired flow (cfs);

DA = the watershed drainage area at POI (mi^2).

The Indian Creek drainage area was 39.49 mi^2 according to Policy methods and was used to calculate the regional criteria for the minimum bypass flows (Table 2).

Table 2. Calculations based on drainage area at POI, for calculating regionally protective minimum bypass flow. Table adapted from the Policy (SWRCB 2010).

Drainage Area at POI	Minimum Bypass Flow Formula
1 mi^2 or smaller	$Q_{MFB} = 9\times Q_m$
Between 1 and 321 mi^2	$Q_{MFB} = 8.8\times Q_m \times (DA)^{-0.47}$
321 mi^2 or larger	$Q_{MFB} = 0.6\times Q_m$

Two methods can be used to calculate Q_m according to the Policy: (1) adjustment of streamflow records, or (2) using a precipitation-based streamflow model. We chose to use the adjustment of streamflow records using methods described in Appendix B of the Policy. To calculate Q_m, also denoted as Q_{POI} in the Policy, we used the following equation:

$$Q_{POI} = Q_{gage}\times \left(\frac{DA_{POI}}{DA_{gage}}\right) \times \left(\frac{P_{POI}}{P_{gage}}\right) \qquad (2)$$

where:

Q_{POI} = mean annual unimpaired flow rate estimated at the POI (cfs); = Q_m in Equation 1

Q_{gage} = mean annual unimpaired flow rate recorded at the gage (cfs);

DA_{POI} = drainage area at the POI (mi^2);

DA_{gage} = drainage area at the gage, representative of study area (mi^2);

P_{POI} = average annual precipitation at the POI (in); and

P_{gage} = average annual precipitation at the gage (in).

Data sources are provided in (Table 3). To calculate Q_{gage}, we adjusted the daily average streamflow data from USGS 1146800 Navarro River near Navarro, CA for water years (WY) 1950 to 2015 from impaired to unimpaired by using month-specific adjustment factors developed by the Center for Ecosystem Management and Restoration (CEMAR; Table 4). See Appendix A for methods on how the adjustment factors were developed. Q_{gage} was calculated using the following equation:

$$Q_{gage} = Q_{impaired} \times AF \quad (3)$$

where:

$Q_{impaired}$ = impaired daily average streamflow data;

AF = month specific adjustment factor (Table 4).

Table 3. Data source and results for variables used to calculate Q_{POI} (=Q_m) and Q_{MFB} for the Indian Creek study area. USGS 1146800 Navarro River near Navarro, CA streamflow data were adjusted for impairments to estimate Q_{gage}.

Variable	Data Source	Results
Q_{gage}	Adjusted unimpaired daily streamflow data from USGS 1146800. Water years 1950 to 2015.	492 cfs
DA_{POI}	NHDPlus for Indian Creek (MyWATERS Google Earth layer provided by the U.S. Environmental Protection Agency)	39 mi^2
DA_{gage}	USGS website	303 mi^2
P_{POI}	NHDPlus for Indian Creek (MyWATERS Google Earth layer provided by the U.S. Environmental Protection Agency)	49 in
P_{gage}	NHDPlus for Navarro River at USGS 1146800 (MyWATERS Google Earth layer provided by the U.S. Environmental Protection Agency)	44 in
Q_{POI}	Calculated unimpaired at Indian Creek site using equation: $Q_{POI} = Q_{gage} \times \left(\frac{DA_{POI}}{DA_{gage}}\right) \times \left(\frac{P_{POI}}{P_{gage}}\right)$	72 cfs
Q_{MFB}	**Calculated using equation: $\mathbf{Q_{MFB} = 8.8 \times Q_m \times (DA)^{-0.47}}$**	**113 cfs**

Table 4. Month-specific daily adjustment factors for the Navarro River watershed at USGS 1146800. Adjustment factors were developed by CEMAR and used to adjust daily average streamflow data at the gage from impaired to unimpaired using Equation 3.

Month	Daily Adjustment Factor (cfs)
October–April	0.3
May	4.3
June	4.5
July	4.4
August	4.4
September	4.5

3.2 Results

The regionally protective minimum bypass flow for the study reach was calculated as 113 cfs (Table 3). According to the flow exceedance probability chart calculated for Indian Creek using the unimpaired streamflow data from the Navarro River USGS gage (adjusted to Indian Creek), 113 cfs has been exceeded 13% of the 24,090 days during the period of record analyzed (WY 1950–2015; Figure 3). In addition, when comparing the regionally protective minimum bypass flows to the ecological flow thresholds identified during this site-specific study (discussed in Section 6), none of the methods produced a streamflow value near or above 113 cfs. Therefore, we determined that 113 cfs is too conservative to be used for a minimum bypass flow for the study reach and TNC's objective of developing different diversion strategies for water right permit holders in Indian Creek that mimic natural flow regimes while supporting viticulture production needs.

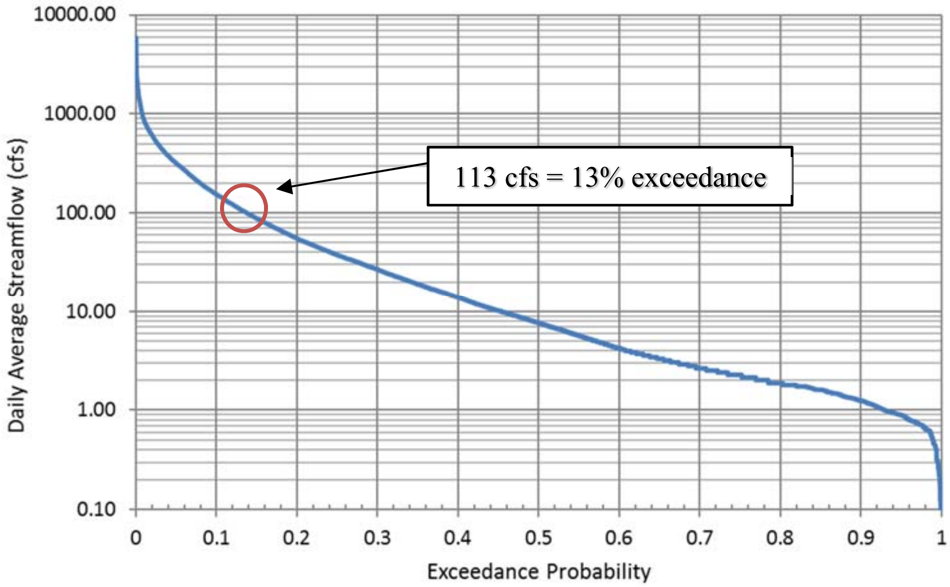


Figure 3. Exceedance probability chart for Indian Creek unimpaired flows using unimpaired streamflow data from USGS 1146800 on the Navarro River for entire year. Streamflow data were adjusted to the Indian Creek watershed as described in Appendix A.

4 IDENTIFYING SITE-SPECIFIC MINIMUM BYPASS FLOWS

Site-specific minimum bypass flows were identified for the study reach using various elements, including periodicity of Coho Salmon and steelhead freshwater life stages, and ecological flow thresholds for life stage needs determined from empirical and hydraulic methods, and applying them to defined flow periods. This process can be described in six analytical steps:

Step 1. Define Flow Periods

Flow periods were defined for this study based on the three proposed diversion periods developed by TNC for the water right permit application.

The four flow periods were defined as follows:

- November 1 through March 31
- April 1 through April 30
- May 1 through May 31

Step 2. Identify Coho Salmon and Steelhead Periodicity

Periodicity of Coho Salmon and steelhead freshwater life history stages are defined below for the study area to understand which life history stages would be most affected during the flow threshold periods. Timing of freshwater life stages can differ among watersheds, and various environmental factors can affect the within-watershed timing from year to year. Timing was determined based on published literature for Coho Salmon and steelhead in California (McEwan et al. 1996 and CDFW 2004) and refined for the Navarro River watershed based on observations made during salmonid life cycle monitoring efforts in Navarro River (J. Carah, D. Ulrich pers. comm; Figure 4). Steelhead and Coho Salmon use the watershed year-round for all freshwater life stages, including juvenile rearing, spawning, egg incubation, and adult and juvenile migration.

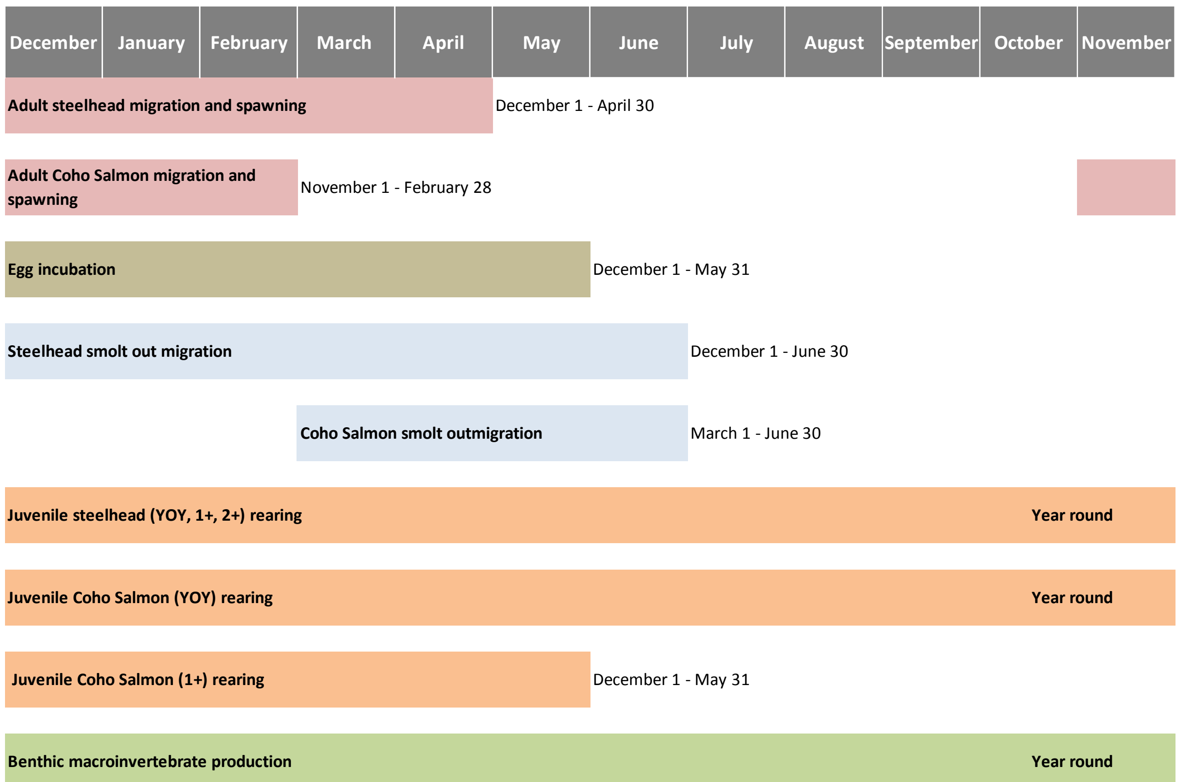


Figure 4. Timing and duration of target salmonid species and life stages in the Navarro River watershed.

Step 3. Identify Priority Life Histories during Flow Threshold Periods

Timing of freshwater life stages of Coho Salmon and steelhead can overlap in Indian Creek, and more than one species and life stage can be present during each flow period defined in Step 1. For example, the November 1 through March 31 flow period coincides with all species and life stages. Some life stages are affected more than others by the timing of reduced instream flows, primarily because they require higher instream flows to maintain function. For this step, we took results from Step 1 and Step 2 and identified which species and life stage would be present during each flow period based on their timing and duration in the Navarro River (Figure 4). We then determined priority life stages for each flow period from which final minimum bypass flows recommendations would be based on. Priority life stages were selected by determining which life stage would be most affected during each flow period and/or which ecological flow threshold would be protective of the other life stages present during the same time period (Table 5). Rational for selection of priority life stages for each period were identified below, and final synthesis of recommended minimum bypass flows based on priority life stages are presented in Section 7.

- <u>Adult Steelhead and Adult Coho Salmon Migration (November 1 through March 31)</u> Adult steelhead and Coho Salmon migration occurs during this time period and flows that allow for upstream passage are necessary to reach all available spawning habitat in the watershed. In addition, flows that allow for good adult upstream passage typically meet the minimum flow needs for all other life stages present for the same time period (eg., spawning and juvenile 1+ and 2+ rearing).
- <u>Adult Steelhead Late Spawning and Juvenile (1+, 2+) Rearing (April 1 through April 30)</u> Ecological flow thresholds that provide adequate spawning area for late spawning adult steelhead, 1+ and 2+ juvenile salmonids rearing need, and abundant habitat for BMI production are protective of other species and life stages present, including egg incubation and smolt outmigration.
- <u>Juvenile Steelhead and Coho Salmon Foraging, and Smolt Outmigration (May 1 through May 31)</u> Streamflow that provides maximum BMI production and downstream passage for outmigrating smolts also provides adequate passage between mesohabitat units and ensures optimal foraging opportunities for juvenile steelhead and Coho Salmon. Ecological flow thresholds for priority life histories identified for this period are protective of egg incubation because they provide water velocities adequate to continuously replenish dissolved oxygen in the remaining redds (Bjornn and Reiser 1991).
- <u>Late Steelhead Smolt Outmigration and YOY Steelhead and Coho Salmon Summer Rearing and Foraging (June 1 through October 31)</u> This flow period for the summer/ fall time period was added to the report to provide information about what streamflow ensures the maintenance of ecological functions in the study reach during a period typically known to be stressful for rearing juvenile salmonids. This period is typically characterized by low flows in streams that occur in Mediterranean climates, such as in Indian Creek. Rearing steelhead and Coho Salmon juveniles can experience low or negative growth rates during this time due to low food availability. Flow thresholds derived for this period are based on maintaining BMI production that will target food production for juvenile salmonid survival through this stressful time period. In addition, late steelhead smolt outmigration can occur through the end of June during wetter water years; therefore, streamflows that allow downstream juvenile passage are considered when determining a minimum bypass flow for the month of June. Results for this summer/ fall time period are presented in Section 6.4, however, no diversions are proposed for this time period and therefore a recommended ecological flow threshold is not included in Table 12.

Table 5. Freshwater life stages of Coho Salmon and steelhead present in Indian Creek during flow periods. Grey boxes indicate which life stages were identified as priority life stages for each flow period. CRA= critical riffle analysis, WUA= weighted usable area.

Life Stage	Analytical Method	Priority Life Stages for Each Flow Period		
		November 1–March 31	April 1–April 30	May 1–May 31
Adult steelhead migration	CRA (25% total passage ≥ 0.7 ft deep)	X	X	
Adult Coho Salmon migration	CRA (25% total passage ≥ 0.7 ft deep)	X		
Adult steelhead spawning	Inflections on adult steelhead spawning WUA curve	X	X	
Adult Coho Salmon spawning	Inflections on adult Coho Salmon spawning WUA curve	X		
Egg Incubation	Not evaluated (See Section 5)	X	X	X
Steelhead smolt outmigration	CRA (25% total passage ≥ 0.4 ft deep)	X	X	X
Coho Salmon smolt outmigration	CRA (25% total passage ≥ 0.4 ft deep)	X	X	X
Juvenile steelhead (YOY) rearing	Inflections on juvenile steelhead (YOY) WUA curves	X	X	X
Juvenile steelhead (1+, 2+) rearing	Inflections on small juvenile steelhead (1+) WUA curve	X	X	X
	Inflections on large juvenile steelhead (2+) WUA curve	X	X	X
Juvenile Coho Salmon (YOY) rearing	Inflections on juvenile Coho Salmon (YOY) WUA curve	X	X	X
Juvenile Coho Salmon (1+) rearing	Inflections on juvenile Coho Salmon (1+) WUA curve	X	X	X
BMI production	Inflections on BMI WUA curve	X	X	X
	Wetted Perimeter curves	X	X	X

Step 4. Evaluate Ecological Flow Thresholds

Empirical and hydraulic modeling results were used as ecological flow thresholds, which are defined as the minimum flows needed to maintain healthy function for target species and life stages in the study reach. These ecological flow thresholds apply to the study reach regardless of within-year environmental factors and water year types. They are used to determine the final site-specific minimum bypass flows for each flow period. More information regarding methods used to evaluate ecological flow thresholds and results can be found it Sections 5.2 and 5.3.

Step 5. Define a Low-Flow Ecological Threshold

A low-flow ecological threshold is a protective flow at which ecological function can be maintained. It is a baseline that protects fisheries resources and the processes that support them. No minimum bypass flows were recommended below the low-flow ecological threshold. Low-flow ecological threshold results can be found in Section 6.5.

Step 6. Synthesize Recommended Minimum Bypass Flow for Each Flow Period

Minimum bypass flows for each flow period were synthesized by comparing ecological flow thresholds for the priority species and life stages identified for each flow period. If more than one priority life stage was identified for a flow period, the ecological threshold most protective or most applicable to environmental conditions was chosen as the minimum bypass flow for that flow period Final minimum bypass flow recommendations and their rationales are presented in Section 7.

The minimum bypass flows developed for each flow period constitute part of the information necessary for developing a diversion management strategy that addresses cumulative effects and protects fisheries resources. Seasonal (and inter-annual) diversion rates and cumulative effects analysis are also key components to any flow management strategy. The cumulative diversion analysis required under the Policy evaluates whether the new proposed diversion would cause streamflows to fall below ecologically significant flow thresholds identified in this site-specific study at the point of diversion, and whether the cumulative diversions from the Indian Creek drainage network, plus this new diversion, would have the potential to impair flows at downstream points of interest. The cumulative diversion analysis is included as Attachment 3c to the Roederer Estate permit application.

5 METHODS FOR QUANTIFYING ECOLOGICAL FLOW THRESHOLDS

To determine site-specific minimum bypass flows for the flow periods, ecological flow thresholds for all freshwater life stages of Coho Salmon and steelhead were determined in the study area using both empirical habitat assessment and hydraulic modeling methods. We used a suite of methods in this study to be as thorough as possible when assessing flow needs for species and life stages in the study reach. For simplicity, only results for priority life stages from each flow period are provided in the main body of this report. For a description of how sites were selected for each method and the mesohabitat effort to characterize the study reach, please refer to Appendix D. Methods to evaluate an ecological flow threshold for egg incubation were not included in this study because the minimum bypass flows developed for other life stages were protective of egg incubation during the time periods when egg incubation occurred (Figure 4).

5.1 Streamflow

Streamflow data were used for empirical habitat assessment methods and for 2-D hydraulic modeling. Empirical habitat assessment methods primarily used streamflow gaging for synoptic flow data during each sampling event. Streamflow gaging was conducted by TNC with support from the Center for Ecosystem Management and Restoration (CEMAR). TNC is currently operating three gages in mainstem Indian Creek (Nancy Smith pers. comm). The TNC gage used for this study was located at Station 18+50 at the downstream end of mesohabitat unit MHU 13 in the study reach (Figure 2).

In addition, streamflow data were collected by McBain Associates staff in the Indian Creek study reach to provide additional data points for TNC's development of the stage–streamflow rating curve for their gage, and to obtain synoptic streamflow data when streamflow data from TNC's gage were not available. Streamflow measurements were completed following standard U.S. Geological Survey (USGS) procedures (Turnipseed and Sauer 2010) and in conformation with the CDFW's Standard Operating Procedure for Discharge Measurements in Wadeable Streams in California (CDFW 2013a).

5.1.1 Developing Rating Curve for 2-D Hydraulic Model

A stage–streamflow rating curve was developed by McBain Associates for the 2-D hydraulic modeling site using the Excel-based computer program Brian's Aid for Rating Creating (BARC), developed by Brian J. Loving of the USGS (Loving 2002). The software follows standard USGS techniques (i.e., Kennedy 1984) to plot and evaluate the stage–streamflow relationship based on data collected for individual streamflow measurements (Figure 5). Stage data used to develop the rating curve were collected from the staff plate at the downstream end of the 2-D hydraulic modeling site. Stage readings from the 2-D modeling site were paired with streamflow measurements made by MA staff during model calibration and validation data collection events or based on streamflows from the TNC gage located at Station 18+50 (Figure 6). For each a staff plate measurement, not associated with a measured streamflow, a date and time were taken and used to determine the streamflow from the TNC gage at the time the 2-D modeling site staff plate was read. Comparisons between the measured streamflows made at the 2-D modeling site and the TNC gage showed no gains or losses in streamflow in the approximately 1,200 ft between the two sites (2-D modeling site and TNC gage, Figure 2).

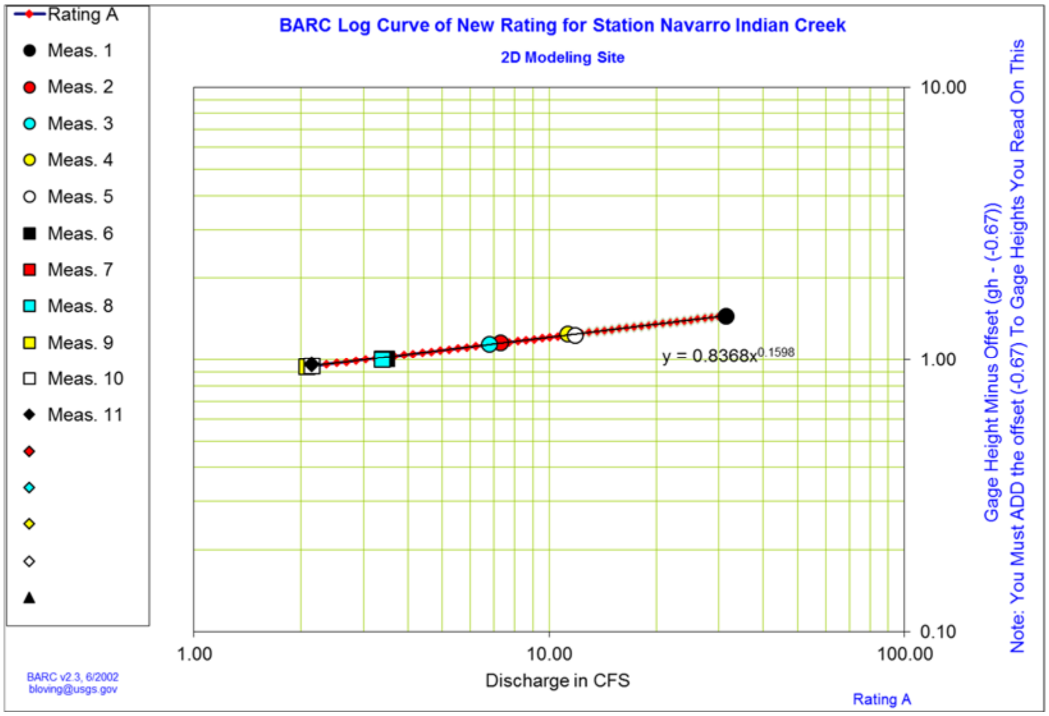
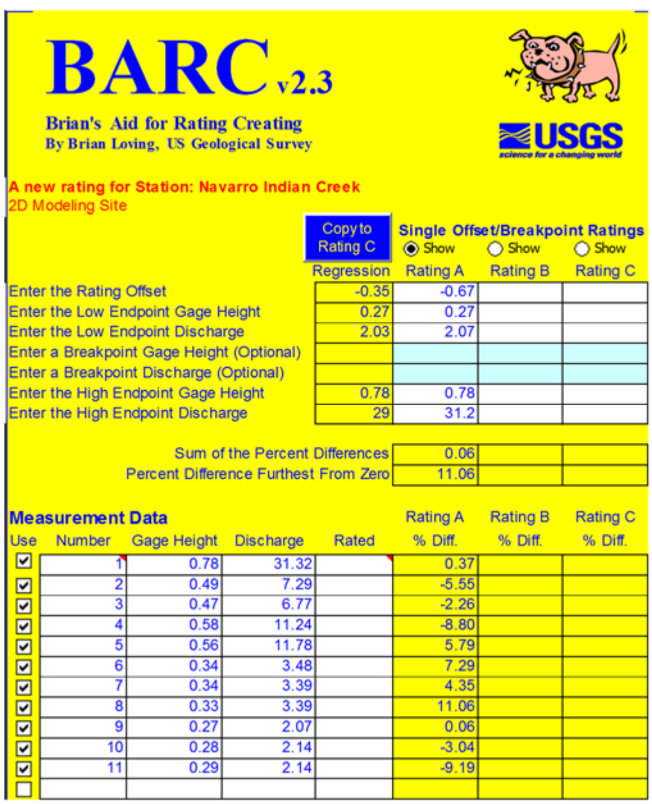


Figure 5. Stage–streamflow rating curve developed for the 2-D hydraulic modeling site in the Indian Creek study reach using BARC, developed by Brian J. Loving of the U.S. Geological Survey (Loving 2002).


BARC v2.3
Brian's Aid for Rating Creating
By Brian Loving, US Geological Survey
USGS
A new rating for Station: Navarro Indian Creek
2D Modeling Site

Copy to Rating C — Single Offset/Breakpoint Ratings

	Regression	Rating A (Show)	Rating B (Show)	Rating C (Show)
Enter the Rating Offset	-0.35	-0.67		
Enter the Low Endpoint Gage Height	0.27	0.27		
Enter the Low Endpoint Discharge	2.03	2.07		
Enter a Breakpoint Gage Height (Optional)				
Enter a Breakpoint Discharge (Optional)				
Enter the High Endpoint Gage Height	0.78	0.78		
Enter the High Endpoint Discharge	29	31.2		
Sum of the Percent Differences		0.06		
Percent Difference Furthest From Zero		11.06		

Measurement Data

Use	Number	Gage Height	Discharge	Rated	Rating A % Diff.	Rating B % Diff.	Rating C % Diff.
☑	1	0.78	31.32		0.37		
☑	2	0.49	7.29		-5.55		
☑	3	0.47	6.77		-2.26		
☑	4	0.58	11.24		-8.80		
☑	5	0.56	11.78		5.79		
☑	6	0.34	3.48		7.29		
☑	7	0.34	3.39		4.35		
☑	8	0.33	3.39		11.06		
☑	9	0.27	2.07		0.06		
☑	10	0.28	2.14		-3.04		
☑	11	0.29	2.14		-9.19		
☐							

Figure 6. Screenshot from BARC (Loving 2002) spreadsheet showing the stage and streamflow data used to develop the rating curve for the 2-D hydraulic modeling site.

5.2 Empirical Methods

A riffle is the shallowest part of a gravel-bed stream where a decrease in depth causes an increase in velocity. Riffles can act as a hydraulic control, and if conditions (depth, velocity) remain favorable in the riffle for aquatic organisms, then instream flows will be sufficient to maintain habitat for fish in nearby pools and runs and provide drift foraging opportunities. Empirical instream flow methods generally focus on riffle habitats because of their importance to fish and BMI (i.e., fish migration and BMI production) and their effect on hydraulic condition in adjacent mesohabitat types.

The CDFW Water Branch's Instream Flow Program has established standard operating procedures (SOP) for several empirical habitat assessment methods. These include the CRA and the wetted perimeter analysis. The Instream Flow Program encourages use of their SOPs to promote data comparability among projects by standardizing procedures. For this study, we included the use of two additional empirical habitat assessment methods, the R2Cross method, and riffle crest thalweg (RCT) depth analysis. In addition, a longitudinal passage analysis of thalweg depths through the 2-D modeling site was used to improve the passage assessment. While, RCT depths associated with fish passage suitability criteria are included in the main body of this report (Sections 6.1.2 and 6.3.2), results were not used in synthesis of final minimum bypass flow recommendations. In addition, when results from the R2Cross method were assessed (Section 6.2.2), it became apparent that the results were not applicable to the Mediterranean-type Indian Creek watershed. For that reason, they were not used to develop minimum bypass flow requirements, but results are in included in the report as a point of information.

5.2.1 Critical Riffle Analysis (CRA)

Critical riffles are shallow riffles in which water depth is particularly sensitive to changes in streamflow due to their wide, oblique morphology. Critical riffles represent potential impediments to upstream and downstream adult and juvenile salmonid passage. The Thompson Method, often used to evaluate potential riffle migration barriers, employs the criterion that passage is not impeded if the depth/velocity requirements are met over 25% of the wetted stream width or a contiguous 10% of the wetted stream width (Thompson 1972). The Thompson Method was incorporated into the CDFW SOP for assessing fish passage through riffles (CDFW 2013b). The SOP depth criterion is 0.7 ft for adult steelhead and Coho Salmon passage, 0.4 ft for 1+, 2+ juvenile salmonid (including downstream smolt passage), and 0.3 ft for salmonid YOY passage.

A critical riffle inventory was conducted during the mesohabitat mapping effort, and riffles with the shallowest pool tail depths (also known as riffle crest thalweg depth) were selected for the critical riffles analysis sites. Depth was measured over six streamflows at five critical riffle transects installed at Stations 14+07, 18+00, 22+62, 28+80, and 31+94 in the Indian Creek study area (Figure 2). During the initial sampling event, pins were installed on the left bank and right bank of each transect to ensure repeatability between sampling events. A tape was strung along the shallowest course of the riffle and depth was measured with a stadia rod in at least 1-ft increments along the tape. In the case of Indian Creek, most of the riffle crests sampled occurred at essentially straight, transverse bars. When a riffle crest did not follow a straight line, we used temporary pins installed in the active channel to ensure the tape followed the shallowest course (Figure *7*).

Figure 7. Photo looking downstream at critical riffle transect 18+00 with tape strung from left bank to right bank. A temporary pin was installed to ensure that the tape followed the shallowest course of the transect.

After the data were gathered, streamflow was plotted against percent passable wetted width. Protective streamflows that met the SOP criteria of at least 25% of the total transect length and 10% contiguous section of the transect length at the appropriate depth for each life stage were identified. The CRA method uses the higher of the two (contiguous and total passage criteria) as a flow recommendation, typically averaged over all CRA cross sections (Thompson 1972). As a conservative approach, we took the average of the two highest streamflows for either total or contiguous passage at the most critical riffles (i.e., riffles where streamflow for passage is relatively high compared to other riffles within the study reach) as the ecological flow threshold results for 1+, 2+ juvenile salmonid passage (0.4 ft), and for salmonid YOY passage (0.3 ft).

5.2.1.1 *Adult Critical Riffle Passage Assessment Using the 2-D Hydraulic Model*

Due to the WY 2015 drought that took place during critical riffle data collection efforts, streamflows high enough to evaluate adult passage thresholds rarely occurred. Therefore, adult passage thresholds could not be assessed from empirically collected data alone. During the initial critical riffle inventory, riffle MHU 22 was identified as the most depth sensitive of all the riffles evaluated in the study reach (See Appendix D), which fell within the 2-D hydraulic modeling site. Using methods described in Holmes et al. (2014) and CDFW (2017), we conducted a critical riffle analysis to determine adult passage thresholds using local depth data generated from the 2-D hydraulic model.

The most depth sensitive passage transect located at station 31+94 in MHU 22, was identified in the 2-D model site from the digital terrain model (DTM) of existing topography, and modeled depths using ARC GIS software. Modeled depths were extracted from the 2-D model output and displayed as a triangulated irregular network (TIN) in ARC GIS, and the shallowest course from left bank to right bank was identified for transect 31+94 based on minimum depth values (Figure 8). Depth data was extracted at, at least 1 ft increments along transect 31+94 from modeled streamflows between 0.5 cfs and 60 cfs, and exported to Microsoft Excel for further analysis. For a complete description of the 2-D hydraulic model used for this analysis, including model calibration and how bed topography was collected and the DTM developed, please refer to Appendix B.

Once depth data was exported from the 2-D hydraulic model to Microsoft Excel, percent total and contiguous passage along with the corresponding length (ft) of total and contiguous passable channel was calculated for each modeled streamflow. The modeled streamflow that provided at least 25% total passable channel was identified as the adult passage threshold for the study site.

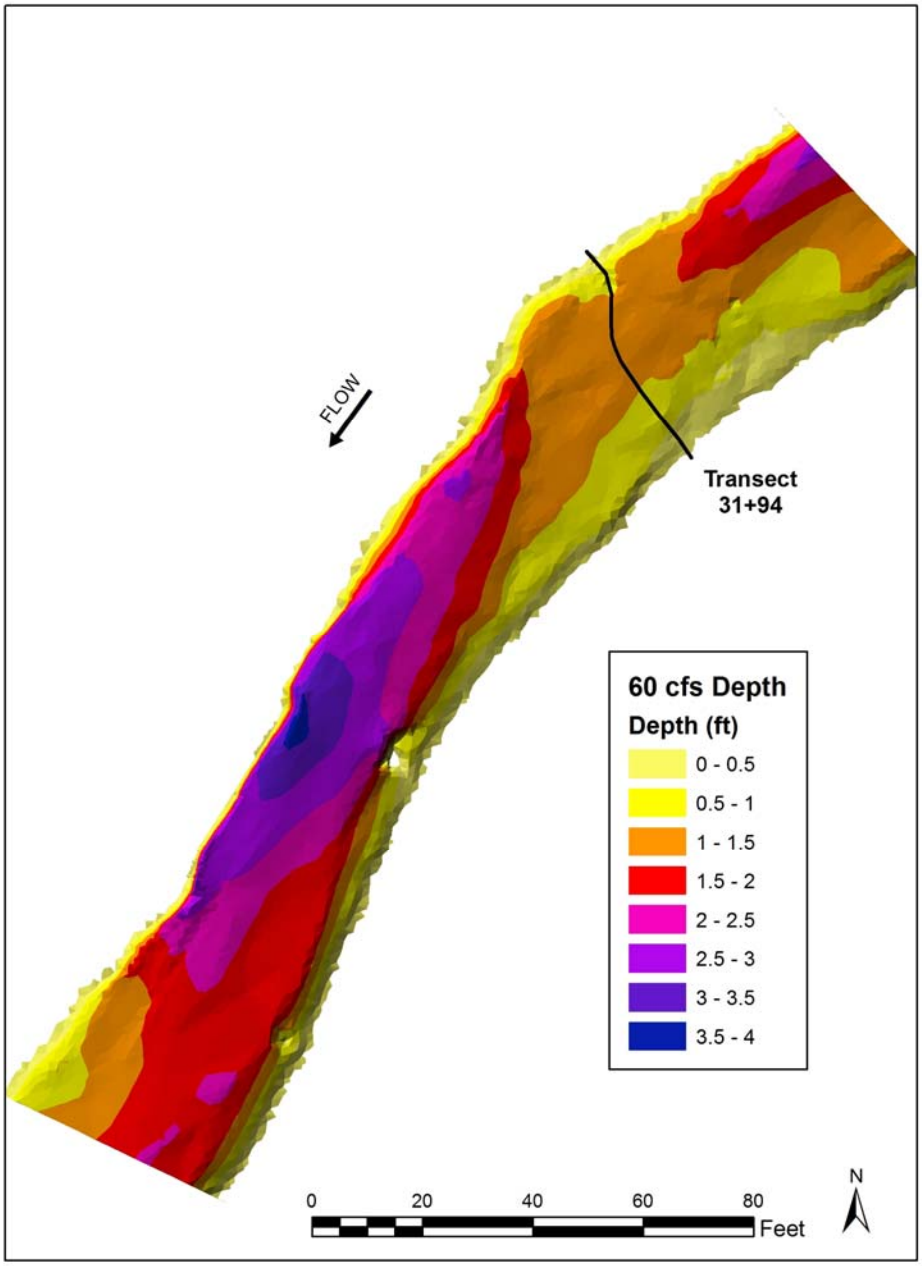


Figure 8. Planform map of 2-D hydraulic modeling site with shallowest course from bank to bank delineated for critical riffle transect 31+94.

5.2.2 Riffle Crest Thalweg Analysis

The riffle crest thalweg is one of the few repeating topographic features that can be reproducibly located and sampled in gravel bed streams. Riffle crest thalweg depths are surveyed during mesohabitat mapping to identify potential critical riffles for the critical riffle analysis (Section 5.2.1). In addition, as a single point measurement, depth (and velocity) at the riffle crest thalweg can be sampled at multiple streamflows to create hydraulic relationships between RCT depths and streamflow. For the purpose of this study, depth criteria, defined in the CDFW fish passage SOP as outlined in Section 5.2.1, are applied to these hydraulic relationships to estimate ecological flow thresholds for fish passage. The RCT depth analysis was included in the study as a point of comparison, and as an illustrative analysis to describe the effects of flow diversion, but was not used to establish flow thresholds. At each riffle crest, only one depth measurement at the thalweg was taken using a stadia rod. Because the RCT will vary between riffles for a given streamflow, data for many riffle crests were collected in the Indian Creek study reach. Surveyed RCT depths for a given streamflow were ranked to estimate the exceedance probability of shallower values (M&T 2012). During each flow event, we calculated the riffle crest depth at which 90% of values are deeper (RCT90) to evaluate adult and juvenile salmonid passage potential in shallower riffles. We also calculated the riffle crest depth at which 50% and 99% of values were deeper (RCT50 and RCT99, respectively) for comparison to RCT90 results.

5.2.3 Wetted Perimeter Analysis

Wetted perimeter is the width of wetted channel bed between left and right bank edges of the water surface. The wetted perimeter method (Annear and Condor 1984, CDFW 2013c) is used to identify ecological flow thresholds for maintaining productive riffle habitats, specifically during the low-flow period. It assumes a direct relationship between the wetted perimeter in riffles and aquatic habitat for favorable BMI food production (Annear et al. 2004, Bell 1986, Swift 1976). For each cross section, wetted perimeter values are plotted versus streamflow to identify the maximum curvature (or breakpoint) and the incipient asymptote in the wetted perimeter curve (Figure 9). The incipient asymptote is the point on the curve associated with streamflow that is most protective of BMI production, while the breakpoint represents the lower ecological flow threshold for critically important food production (CDFW 2013c).

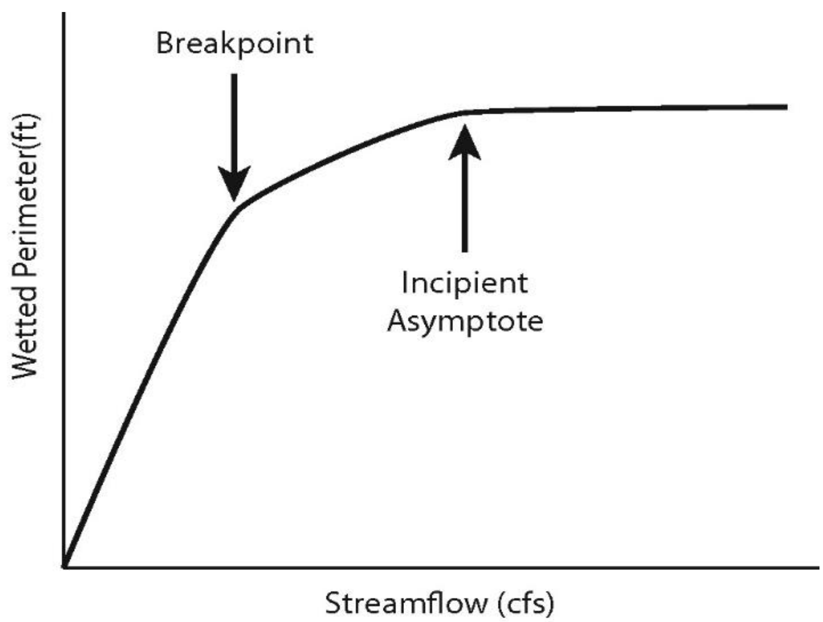


Figure 9. CDFW (2013c) wetted perimeter breakpoint and incipient asymptote streamflow thresholds.

Five cross sections selected for wetted perimeter analysis were installed in riffles throughout the study area at Stations 15+46, 20+70, 22+62, 25+75 and 31+86 (Figure 2). The hydraulic geometry of each cross section was modeled at a minimum of 10 streamflows as recommended in CDFW’s Wetted Perimeter SOP (CDFW 2013c) to develop a robust wetted perimeter–streamflow relationship. Originally, a one-dimensional (1-D), steady/unsteady flow model, the U.S. Army Corps of Engineers Hydrologic Engineering Center’s River Analysis System (HEC-RAS), was used to simulate the water surface profile for cross sections 20+70, 22+62, 25+75, and extended from Station 19+67 to 25+75 in the study area. A Total Station was used to survey the 1-D hydraulic model reach from Station 19+67 to Station 22+62 on February 22, 2015, and calibration data were collected on the same day. The 1-D study site was later extended upstream to 25+75 and the additional section was surveyed June 2, 2015. Additional calibration data were collected on June 2, 2015, as well. For a description of 1-D hydraulic modeling methods, please refer to Section 5.3.1.

To increase the number of wetted perimeter cross sections included in the analysis, cross sections 15+46 and 31+86 were modeled using cross section survey data and water surface elevations for 10 streamflows estimated using the stage–streamflow rating curve developed for each cross section (Section 5.1).

Once all cross sections were modeled, wetted perimeter curves were plotted using the streamflow vs. wetted perimeter data. The breakpoint and incipient asymptote streamflows were identified by eye from the wetted perimeter rating curves when either inflection was found. Some cross sections had no identifiable incipient asymptote inflections, in which case they were not included. Once the breakpoint and incipient asymptotes were identified, associated streamflows were identified from the wetted perimeter curves.

5.2.4 R2Cross Method

The R2Cross method is a standard setting method that is commonly applied in many Rocky Mountain states to provide reconnaissance-level estimates of instream flow needs (Nehring 1979, Espegren 1996). The method assumes that if hydraulic habitat in riffles is maintained, then instream flows will be sufficient to maintain habitat for fish in nearby pools and runs (Espegren 1996). Average velocity, average depth, and percent wetted perimeter were measured at four cross sections over five stream flows in the Indian Creek study area. R2Cross cross sections were located at Stations 15+46, 22+62, 25+75 and 31+86 (Figure 2). Following Espegren (1996), an ecological flow threshold was determined at each cross section when minimum levels of two or more hydraulic criteria (Table 6) were reached for fall and winter and when all three criteria were met for spring and summer thresholds. Hydraulic criteria were determined based on stream top width at bankfull discharge. Stream top width at bankfull discharge was estimated in the field by measuring the distance between bankfull indicators on either side of the cross section. Bankfull indicators are identified by a break in the slope of the channel bank and/or changes in vegetation type and density. The average results from the four cross sections were used to determine the ecological flow thresholds required to maintain rearing habitat for steelhead and Coho Salmon in Indian Creek for both winter/fall and spring/summer time periods from the R2Cross method. As noted above and in Sections 5.2 and 6.2.2, R2Cross flow thresholds were not used to establish flow thresholds for Indian Creek, and are only presented here as a point of information.

Table 6. Hydraulic criteria for determining instream flows using the R2Cross single cross section method (adapted from Espegren 1996). Bold values indicate the criteria used for this study based on a stream top width between 21 and 40 ft.

Stream Top Width (ft)*	Average Depth (ft)	Percent Wetted Perimeter (%)*	Average Velocity (ft/sec)
1–20	0.2	50	1.0
21–40	**0.2–0.4**	**50**	**1.0**
41–60	0.4–0.6	50–60	1.0
61–100	0.6–1.0	≥ 70	1.0

**= at bankfull streamflow.*

5.3 Hydraulic Modeling

Hydraulic modeling was used for two purposes: 1-D modeling was used for the wetted perimeter method, and 2-D modeling was used to assess flow–habitat relationships. It also allowed examination/simulation of hydraulic conditions within pools, which was not possible using the empirical methods (i.e., only riffles were evaluated using empirical methods).

5.3.1 1-D Hydraulic Modeling

The 1-D HEC-RAS model used a steady-state flow, standard step backwater calculation to estimate hydraulic characteristics along the upstream portion of the study site. HEC-RAS calculates the slope of the water surface as a function of channel geometry, Manning's *n* (roughness), and streamflow, as described in the HEC-RAS Manual (Brunner 2001). Channel geometry was surveyed using a total station in June 2015 and cross section geometry was created from horizontal and vertical positioning data collected using a Total Station. Horizontal coordinates are referenced to North American Datum of 1983 using the California State Plane Zone II coordinate system. Elevations were referenced to an arbitrary datum of 100 ft. The model domain extended from Station 19+67 to Station 25+75, approximately 300 ft upstream and downstream of the Highway 128 Bridge over Indian Creek. The bridge itself was not explicitly represented in the hydraulic model using the bridge geometry module because the structure is not hydraulically significant during low flows. At these flows, there is no flow contraction or expansion at the bridge, and there were no obstructions, piers, or abutments within the bankfull channel under the bridge.

Water surface elevations were surveyed using a Total Station during two events (2 cfs and 26 cfs) at multiple locations along the Indian Creek study site section (Station 19+67 through 25+75). Manning's *n* coefficients for each cross section were estimated in the field and then calibrated to the measured 2 cfs and 26 cfs water surface elevations, such that the deviation between the predicted backwater profile and the measured water surface was minimized. Roughness was observed to vary inversely with streamflow; therefore, flow roughness factors were applied in the calibration process. Manning's *n* coefficients were applied along the channel to simulate the variability in roughness as a function of streamflow, as variability has been shown to occur in gravel bed streams by other researchers (Jarrett 1985). Manning's *n* values ranged from 0.035 for the 26 cfs flow to 0.27 for the 2 cfs flow. The HEC-RAS model was run at 1 cfs increments, and the wetted perimeter from each flow computed and added to the wetted perimeter curves. This approach added much more detail to the wetted perimeter curves, aiding our interpretation of breakpoints and incipient asymptotes.

5.3.2 2-D Hydraulic Modeling and Weighted Usable Area Curve Development

2-D hydraulic modeling was used to predict depth and velocity for 10 streamflows and the predicted depths and velocities were used with habitat suitability indices (HSI) data to assess flow–habitat relationships for target species and life stages, specifically adult Coho Salmon and steelhead spawning, juvenile Coho Salmon and steelhead rearing habitat, and BMI production. It also allowed for examination and simulation of hydraulic conditions within pools to assess instream flow needs of life stages that utilize pool habitat, which was not possible using the empirical methods (i.e., only riffles were evaluated using empirical methods).

Weighted usable area (WUA) curves were used to assess habitat area as a function of streamflow for targeted species and life stages. WUA curves were generated by applying habitat suitability indices (HSI), for targeted salmonid life stages and BMI production, to cover and substrate data mapped in the field and depth and velocity data predicted by a 2-D hydraulic model. Habitat suitability indices curves were determined for each target species and life stage based on a review of relevant literature, including several Technical Review Teams for North Coast instream flow studies, recommendations from CDFW, and our professional experience. A comprehensive description of the method used to generate WUA curves and their interpretation along with HSI depth, velocity, substrate and cover curves for the target species and life stages can be found in Appendix C (Figure C-3 through Figure C-21).

The 2-D hydraulic modeling site selected was 228 ft long, representing 9% of the overall Indian Creek study reach length (Appendix D, Table D-9). The System for Transport and River Modeling (SToRM), a 2-D hydraulic model within the International River Interface Cooperative (iRIC) framework, was used to predict depth and velocity for 10 streamflows ranging from 0.5 cfs to 80 cfs. The 2-D hydraulic model was set up using topography, substrate and cover data collected in the field on February 21 and 22, 2015. In addition, water surface elevation, depth, and velocity points were collected for three streamflows (1.74 cfs, 8.15 cfs, and 25.9 cfs) to calibrate and validate the 2-D hydraulic model. Meeting 2-D model setup, calibration, and validation criteria established by USFWS (2011) and modified to be applicable to SToRM, ensured reasonable depth and velocity predictions by SToRM for all flows modeled. Depth and velocity results for the 10 modeled flows were exported from SToRM/iRIC for use in preparation of the WUA curves. A complete description of model preparation, calibration and validation is provided in Appendix B.

6 ECOLOGICAL FLOW THRESHOLD RESULTS FOR EACH FLOW PERIOD

The ecological flow thresholds results are presented in this section and discussed for each flow period separately. Only selected minimum bypass thresholds for priority life stages are included in the rationale for threshold selection, Section 7. All results, analysis, figures, tables, and raw data are provided for each method in Appendices A through O.

6.1 November 1 through March 31: Adult Steelhead and Adult Coho Salmon Migration

6.1.1 Adult Critical Riffle Passage Assessment Using the 2-D Hydraulic Model

The adult passage threshold for the study reach was determined using 2-D hydraulic model depth output as described in Section 3. Percent total and contiguous passage along with the corresponding length (ft) of total and contiguous passable channel was calculated for each modeled streamflow (Table 7). The modeled streamflows that provided at least 25% total and 10% contiguous passable channel were identified. The passage threshold that met at least 25% total passage was 33 cfs providing 26% total passage or 11 ft of the 43 ft of maximum wetted width. At least 10% contiguous passage criteria were met at 28 cfs and provided 10% contiguous passage or 4 ft of the 43 ft of maximum wetted width.

Table 7. Percent total and contiguous passage and associated length (ft) of total and contiguous passable channel for each modeled streamflow. The modeled streamflow that provided at least 25% total passable channel was identified as the adult passage threshold for the study site.

Adult Coho and Steelhead (minimum depth criteria = 0.7 ft)				
Maximum Wetted Width = 43 ft				
Flow (cfs)	**Total Width (ft)**	**Percent Total Width**	**Contiguous Width (ft)**	**Percent Contiguous Width**
60	28	65%	28	65%
40	15	35%	15	35%
35	13	31%	13	31%
33	**11**	**26%**	11	26%
31	9	20%	9	20%
28	4	10%	**4**	**10%**
26	0	0%	0	0%
20	0	0%	0	0%
16	0	0%	0	0%
8	0	0%	0	0%
4	0	0%	0	0%
1.8	0	0%	0	0%
0.5	0	0%	0	0%

6.1.2 Riffle Crest Thalweg Analysis

RCTs were measured at all riffles throughout the study area during six streamflow events ranging from 2.2 to 72 cfs. The 50th, 90th, and 99th percentile shallowest RCT depths were computed at each surveyed streamflow, and the 90th percentile result was compared to the ecological flow threshold result from CRA method that allowed upstream adult passage. At the highest streamflow event (72 cfs), the 90th percentile RCT depth was 1 ft. The minimum ecological flow threshold that provides adult steelhead and Coho Salmon passage (0.7 ft) at the RCT90 depth is 35 cfs (Figure 10). When comparing RCT90 depths to the results from adult steelhead and Coho Salmon passage CRA using the 2-D hydraulic model, RCT90 depth for adult steelhead and Coho Salmon passage (35 cfs) was comparable to the CRA result of 33 cfs. As noted in Section 5.2.2, the RCT depth analysis was not used to establish flow thresholds for the permit, but results are included for informational purposes.

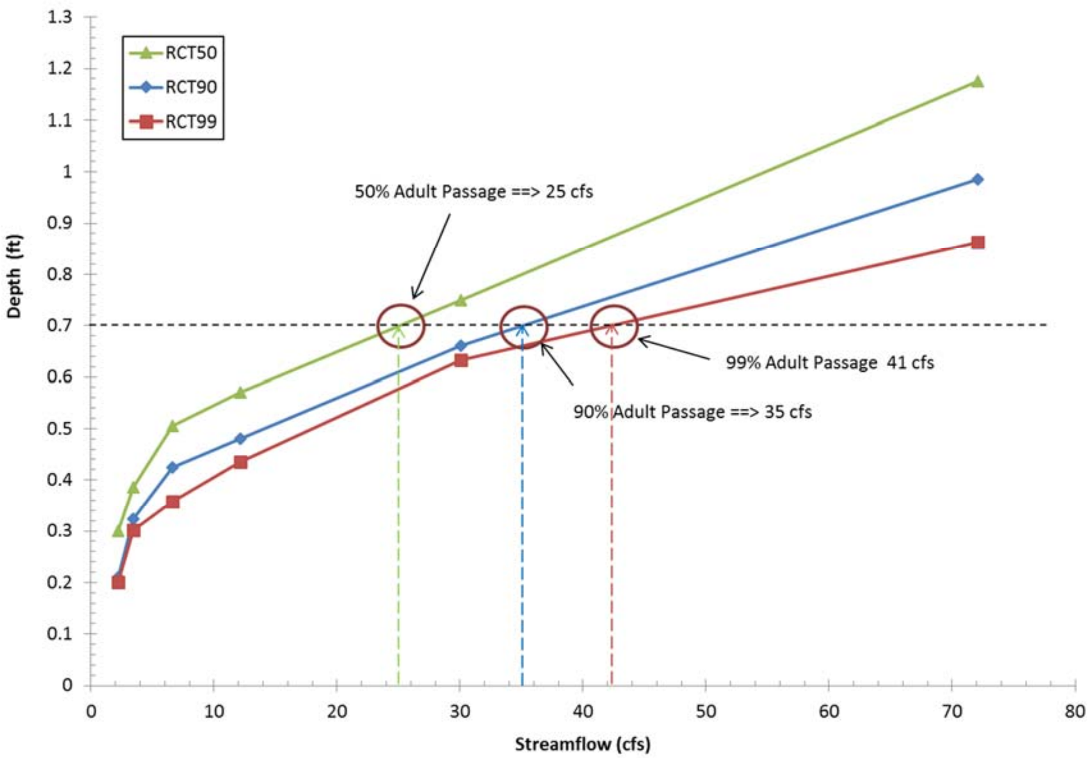


Figure 10. Shallowest RCT depths (50th, 90th, and 99th percentile) plotted against streamflow, showing streamflows that meet 0.7 ft. passage criteria (black dashed line) for adult Coho Salmon and steelhead upstream migration.

6.1.3 Longitudinal Passage Analysis at 2-D Hydraulic Modeling Site

Using the topographic data from the 2-D hydraulic modeling site, the longitudinal thalweg depth was computed for eight modeled streamflows to determine the range of streamflows that allowed for longitudinal passage through the most depth sensitive riffle, which was present in the 2-D model Figure 11). From the critical riffle inventory, MHU 22 was identified as the most depth sensitive of all the riffles in the study reach. From the modeled longitudinal analysis, the streamflow that met adult steelhead and Coho Salmon passage requirements longitudinally throughout riffle MHU 22 was between 25 and 40 cfs. The adult steelhead and Coho Salmon passage threshold results from the critical riffle analysis at transect 31+94 using the 2-D hydraulic model (33 cfs) and the results from the RCT depth (35 cfs) both fall within this range and most likely provide longitudinal passage at this riffle.

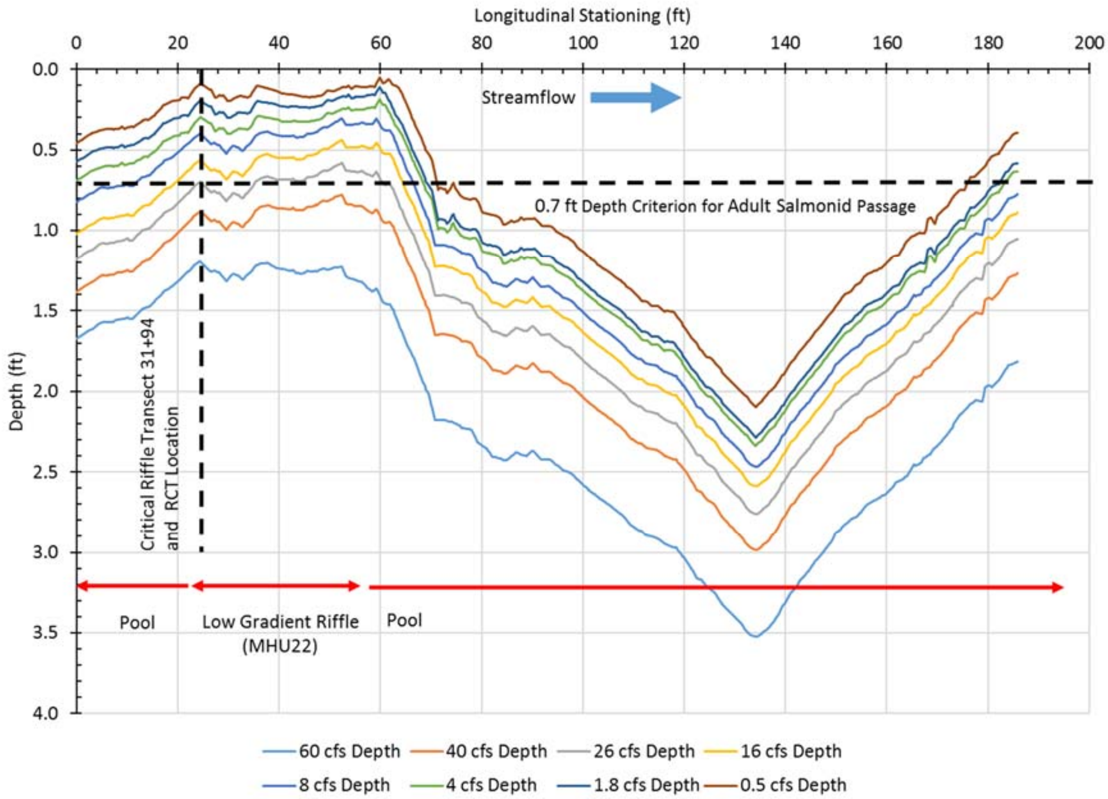


Figure 11. Modeled longitudinal thalweg depths for the Indian Creek 2-D hydraulic modeling site for eight streamflows.

6.2 April 1 through April 30: Adult Steelhead Late Spawning and 1+, 2+ Juvenile Salmonid Rearing

6.2.1 2-D Hydraulic Modeling and WUA Curves

WUA curves based on the 2-D hydraulic modeling results show habitat availability for adult spawning area, juvenile salmonid rearing, and BMI habitat at streamflows between 0.5 cfs and 80 cfs (Figure 12 and Figure 13). Ecologically important streamflows were observed at 3 cfs, 26 cfs, and 40 cfs for both small (1+) and large (2+) juvenile steelhead rearing; 16 cfs, 26 cfs and 60 cfs for adult steelhead spawning; and 2 cfs and 8 cfs for juvenile Coho Salmon rearing (Figure 12). In addition, 3 cfs, 16 cfs, 26 cfs were identified as important ecological flow thresholds for productive BMI habitat (Figure 13). The ecological flow threshold result from 2-D hydraulic modeling that provides habitat for adult steelhead spawning and 1+, 2+ juvenile salmonid rearing is 26 cfs.

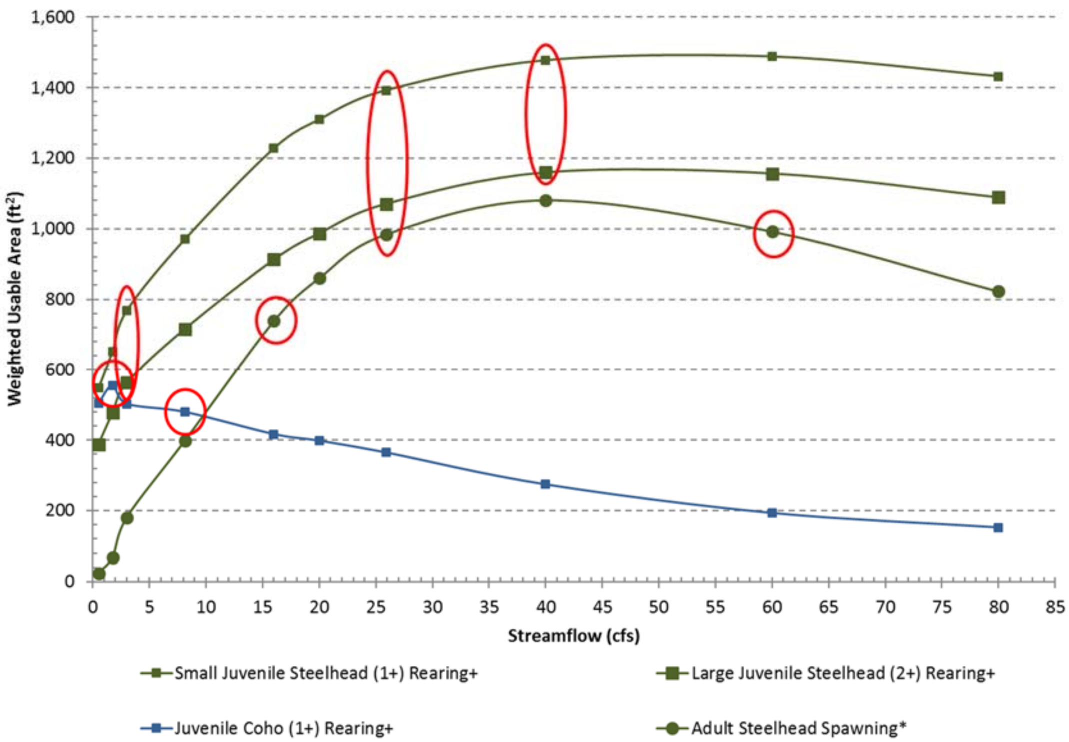


Figure 12. WUA curves derived from Indian Creek 2-D hydraulic modeling results for steelhead 1+ and 2+ juvenile rearing, Coho Salmon 1+ rearing, and steelhead spawning derived from HSI for modeled depth and velocity results and either substrate (*) or distance to cover data (+). Red circles indicate inflections in the curves where ecologically important flows occur.

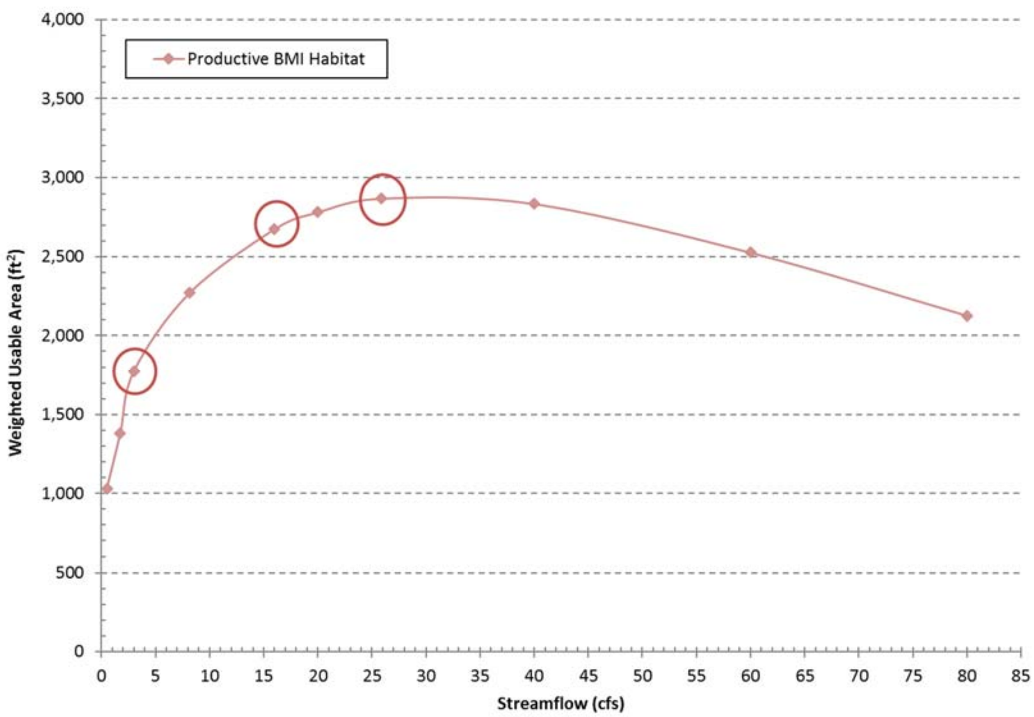


Figure 13. WUA curves derived from Indian Creek 2-D hydraulic model results for BMI productive habitat. Red circles indicate inflections in the curves where ecologically important flows occur.

6.2.2 R2Cross Analysis

R2Cross cross sections were surveyed at streamflows between 2.1 and 30 cfs. Initially, ecological flow threshold results for the April 1–April 30 flow period were to be based on the spring/summer results (streamflow that meet two or more criteria). However, when results were assessed, it became apparent that results from the R2Cross method (Espegren 1996) were not applicable to the Indian Creek watershed (Table 8). When comparing the R2Cross results for both time periods (spring/summer and fall/winter) to the normal hydrograph for Indian Creek, ecological flow threshold values did not correspond well to the Mediterranean type hydrograph of Indian Creek. We concluded that this was because the R2Cross method was developed in Colorado for snowmelt systems, where streamflows in the spring and summer are elevated because of snowmelt inputs, compared to Mediterranean stream types. Therefore, we determined that results from the R2Cross method were not appropriate for the Indian Creek watershed, and we did not use them to develop minimum bypass flow recommendations.

Table 8. Ecological flow thresholds were determined for each cross section when minimum levels of two or more criteria were reached for fall and winter and when all three criteria were met for spring and summer.

Cross section	Spring /Summer Flow Recommendations (cfs)	Fall /Winter Flow Recommendations (cfs)
15+46	18	18
22+62	18	18
25+75	23	8
31+86	25	13
Average	21	14

6.3 May 1 through May 31: Juvenile Steelhead and Coho Salmon Foraging, and Smolt Outmigration

6.3.1 Wetted Perimeter Analysis: Incipient Asymptote

The average incipient asymptote streamflow was used as the ecological flow threshold result for the wetted perimeter method during the May 1–May 31 flow period because it is the streamflow that is most protective of BMI production. Five of the six of cross sections had observable incipient asymptotes (Table 9). The average incipient asymptote streamflow for the remaining five cross sections resulted in an ecological flow threshold result of 10 cfs for optimal BMI production.

Table 9. Streamflows associated with breakpoints and incipient asymptotes observed on wetted perimeter charts.

Cross section	Streamflows	
	Breakpoint (cfs)	Incipient Asymptote (cfs)
15+46	6	10
20+70	2	12
22+62	4	9
25+75	3	None Apparent
31+86	1	9
Average	3	10

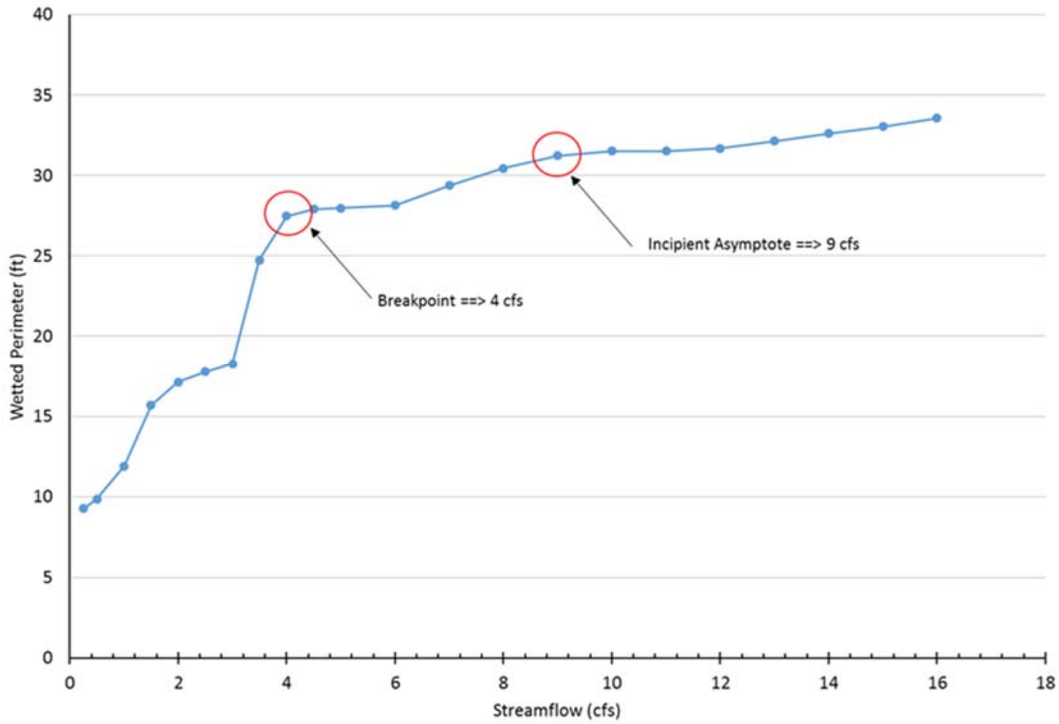


Figure 14. Example wetted perimeter curves of cross section 22+62 in Indian Creek used for determining breakpoint and incipient asymptote at each surveyed cross section.

6.3.2 Critical Riffle Analysis

Empirical critical riffle data was used to determine 1+, 2+ juvenile and YOY salmonid passage using the CRA method. Critical riffle transects were surveyed at streamflows between 0.86 cfs and 74 cfs. The CRA method uses the higher of the two (contiguous and total passage criteria) as a flow recommendation, typically averaged over all CRA transects (Thompson 1972). Results for 1+, 2+ juvenile salmonid passage are presented in this section. YOY passage was not identified as a priority life stages for this flow period but results were considered as part of the low-flow ecological threshold determination, and are presented in Section 6.5. Average flow for 1+, 2+ juvenile salmonids passage at all the transects was 7 cfs for total passage and 5 cfs for contiguous passage (Table 10). The average for the two highest streamflows (10 and 8 cfs) for total passage at the most critical riffles (14+07 and 22+62) was 9 cfs and was used as the ecological flow threshold result for 1+, 2+ juvenile salmonids passage (Table 10, Figure 15).

When comparing CRA results to RCT90 and longitudinal passage results for 1+, 2+ juvenile salmonid passage (0.4 ft depth passage criteria), the results from the CRA method were more conservative than the 6 cfs result from the RCT90 analysis (Figure 16) and less conservative then the 8 to 16 cfs range from the 2-D modeling longitudinal passage results (Figure 17).

Table 10. Streamflows that met the 25% total passage and 10% contiguous passage criteria at 0.4 ft depth for 1+, 2+ juvenile salmonids at each transect on Indian Creek. Ecological flow threshold results were based on the average streamflow that met the passage criteria for all transects surveyed.

Transect	Streamflow for Total Passage (cfs)	Streamflow for Contiguous Passage (cfs)
14+07	10*	6
18+00	6	6
22+62	8*	3
28+80	7	5
31+94	5	3
Average:	7	5
Average of two highest streamflows:	9	

*Two highest streamflows at the most critical riffles.

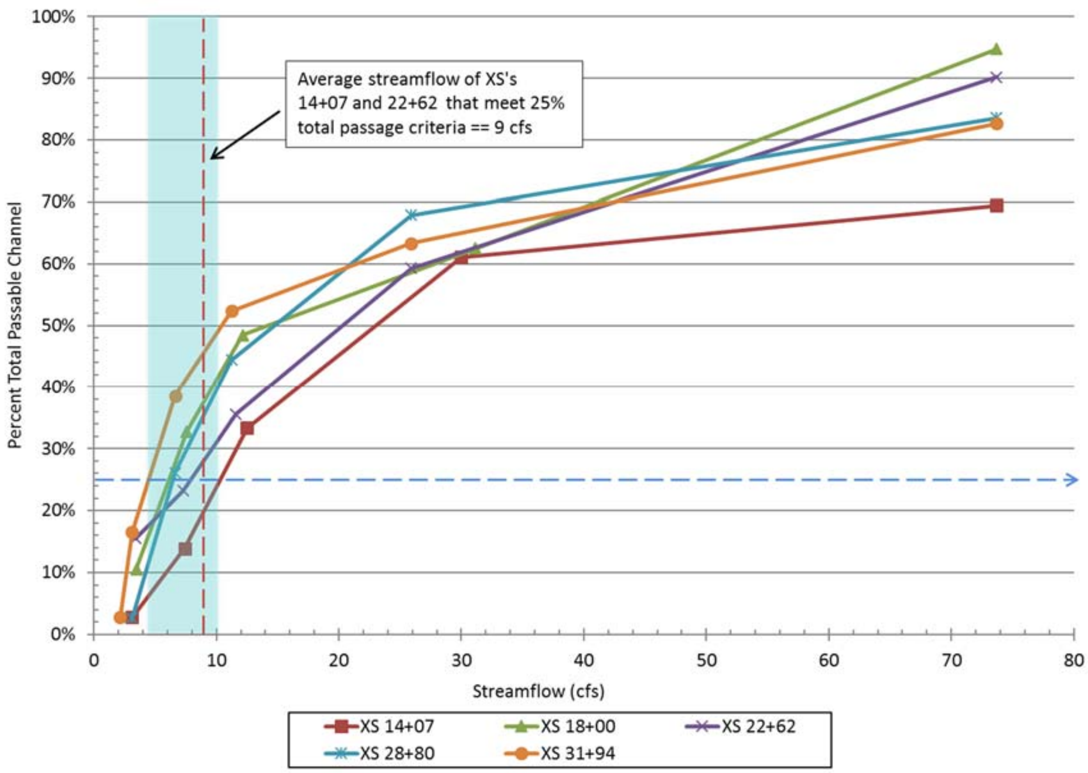


Figure 15. Streamflows that meet 25% total passage criterion for 1+, 2+ salmonid upstream passage. Blue shaded area represents range of streamflows for 25% total passage from all critical riffles analyzed, and the red dashed line is the average of the two highest streamflows.

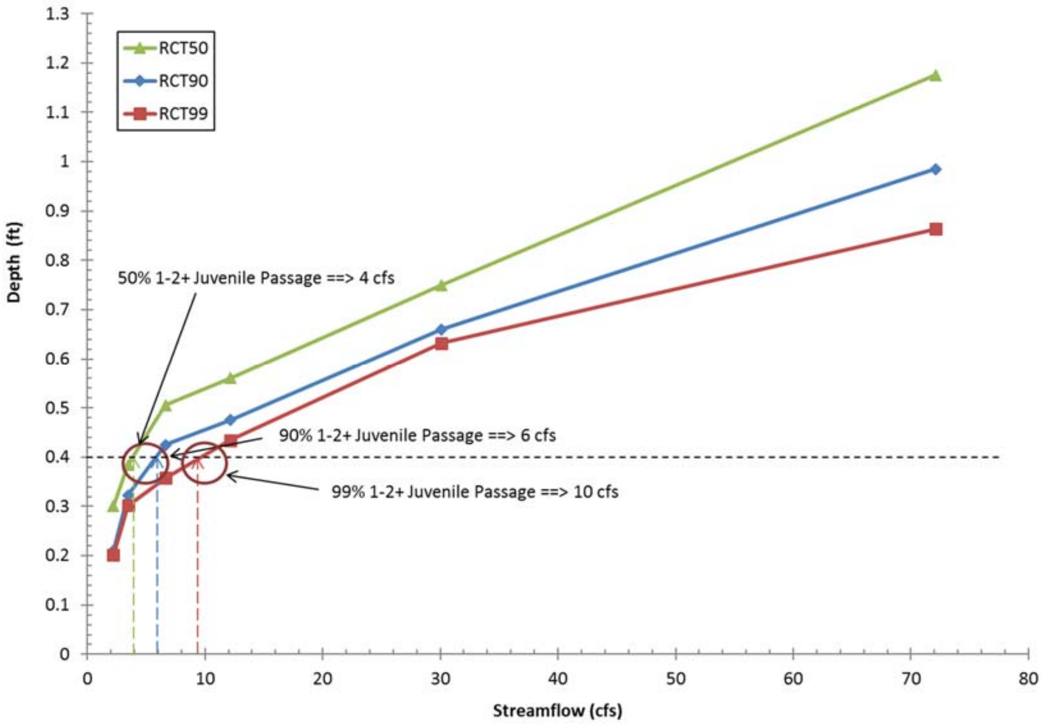


Figure 16. Shallowest RCT depths (50th, 90th, and 99th percentile) plotted against streamflow, showing streamflows that meet 0.4 ft. passage criteria (black dashed line) for 1+, 2+ juvenile Coho Salmon and steelhead passage.

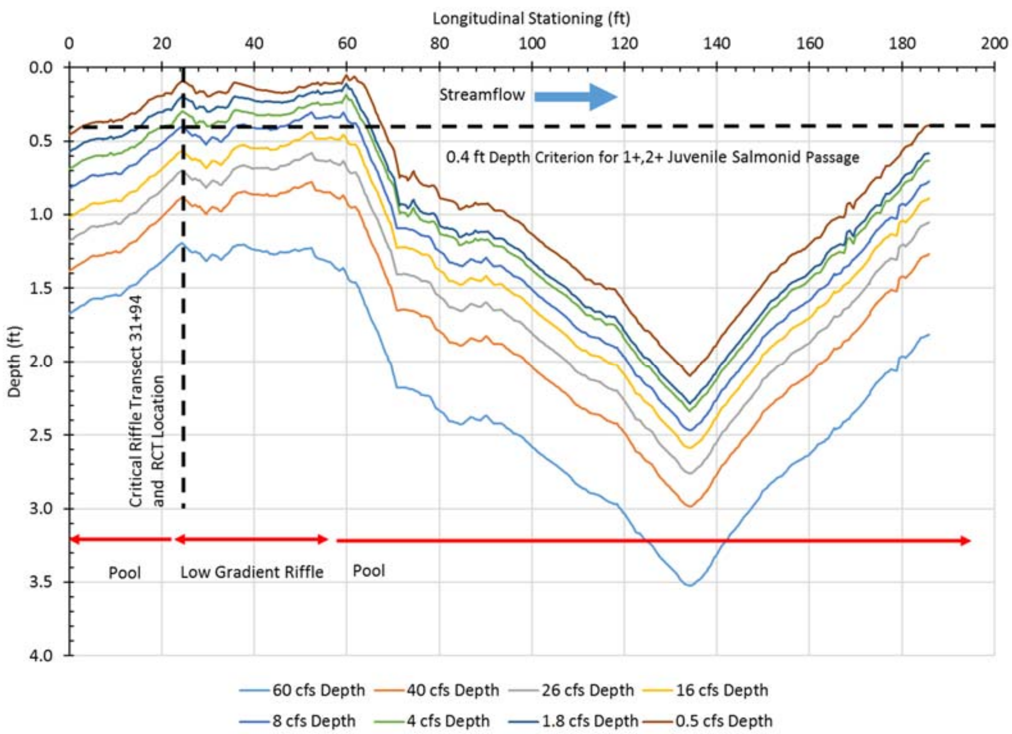


Figure 17. Modeled longitudinal thalweg depths for the Indian Creek 2-D hydraulic modeling site for eight streamflows.

6.4 June 1 through October 31: Late Steelhead Smolt Outmigration and YOY Steelhead and Coho Salmon Summer Rearing and Foraging

As previously noted, diversion is not proposed in this time period in the Roederer Estate permit application, but the data are included here for informational purposes.

6.4.1 Critical Riffle Analysis

The ecological flow threshold result of 9 cfs for 1+, 2+ juvenile salmonids passage from Section 6.3.2, was also used as the ecological flow threshold result for late steelhead smolt outmigration (through June). As was done in Section 6.3.2, the two highest streamflows (10 and 8 cfs) for total passage at the most critical riffles (14+07 and 22+62) were averaged to provide the most protective ecological flow threshold result for smolt outmigration (Figure 15). The ecological flow threshold for smolt outmigration applies through the end of June for the June 1–October 31 flow period.

6.4.2 Wetted Perimeter Analysis – Breakpoint

The average wetted perimeter breakpoint streamflow represents the point where critically important food production occurs and will decrease rapidly once streamflow drops below this point (CDFW 2013c). Streamflows below this ecological flow threshold could have a detrimental effect on salmonids and other organisms that rely on invertebrate production either directly as a food source or as part of a food chain. The ecological flow threshold from this method based on average breakpoint for all wetted perimeter cross sections is 3 cfs (Table 9).

6.4.3 2-D Hydraulic Model and WUA Curves

Ecologically important streamflows were observed at ≤ 0.5 and 2 cfs for YOY steelhead rearing, and ≤ 0.5 and 3 cfs for YOY Coho Salmon rearing (Figure 18). Less than 0.5 cfs provided maximum WUA for both YOY steelhead and Coho Salmon; however, 0.5 cfs was below the low-flow ecological flow threshold identified for the study area (Section 6.5). Since maintenance of productive BMI habitat was identified along with YOY rearing as an important life history need for this time period, recommended ecological flow thresholds are based on the ecological flow threshold identified from the productive BMI habitat curve at 3 cfs (Figure 13).

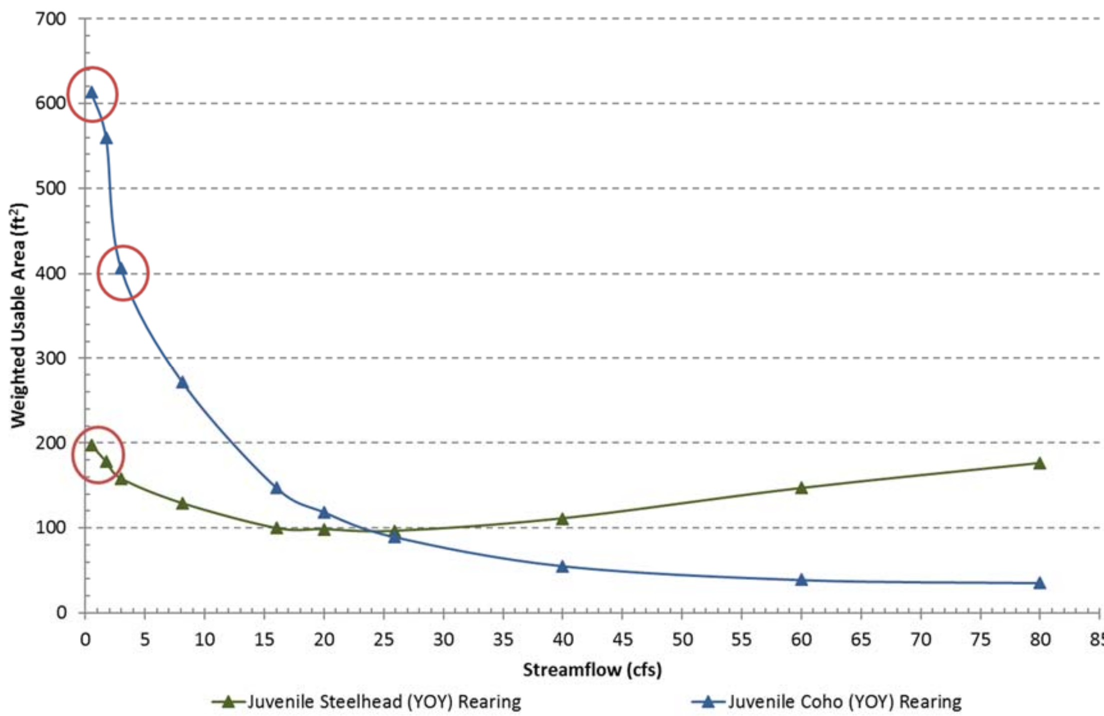


Figure 18. WUA curves derived from Indian Creek 2-D hydraulic modeling results for steelhead YOY rearing and Coho Salmon YOY rearing, derived from HSI for modeled depth and velocity, and distance to cover data. Red circles indicate inflections where ecologically important flows occur.

6.5 Low-flow Ecological Threshold

Low-flow ecological thresholds protect fisheries resources, and can preserve ecosystem structure and function in riverine ecosystems that support fisheries (DFO 2013; Holmes and Cowan 2014). A low-flow ecological threshold is a protective flow at which ecological function can be maintained year round and is especially important to maintain in the summer and fall time periods in streams that occur in Mediterranean climates, such as Indian Creek. For the purpose of this study, we used the average streamflow at which the breakpoint on the wetted perimeter curves occurred for all wetted perimeter cross sections. The average wetted perimeter breakpoint streamflow represents the point where the wetted area of riffles starts to reduce rapidly and indicate a change in ecological processes, including a rapid decrease in production of aquatic invertebrates. Based on our analysis, the low-flow ecological threshold established for the study reach is 3 cfs (Table 9).

The 3 cfs low-flow ecological threshold also corresponds with the ecological flow threshold results from other methods used in this study. The first inflection points from WUA curves for juvenile Coho Salmon (1+), juvenile steelhead (1+, 2+), and BMI production were all at 3 cfs (Figure 12, Figure 13). In addition, the ecological flow threshold result averaged from all transects for YOY salmonid passage was 4 cfs from the CRA method (25% total passage criterion, Table 11) and 3 cfs from the RCT depth analysis (RCT 90, Figure 19). Results for 1+, 2+ salmonid passage were 4 cfs from the RCT depth analysis (RCT50, Figure 16).

We chose to use the 3 cfs from the wetted perimeter method over the higher flow of 4 cfs from the CRA method for YOY passage for several reasons: (1) an agreement among methods and results throughout the study reach allows for confidence that the 3 cfs recommendation for the low-flow ecological threshold will maintain ecological function in the study reach and protect fisheries resources and the processes upon which they depend; (2) 3 cfs provides more WUA than 4 cfs for rearing YOY Coho (Figure 18), who are present in Indian Creek during the summer and fall low-flow period; and (3) we chose to follow precedent and use the wetted perimeter breakpoint value as was done in Holmes and Cowan (2014).

Table 11. Streamflows that met the 25% total passage and 10% contiguous passage criteria at 0.3 ft for YOY salmonids at each cross section on Indian Creek. Instream flow threshold results were based on the average streamflow that met the passage criteria for all cross sections surveyed.

Transect	Streamflow for Total Passage (cfs)	Streamflow for Contiguous Passage (cfs)
14+07	6	3
18+00	3	<2
22+62	5	2
28+80	3	<2
31+94	2	< 1
Average:	4	3

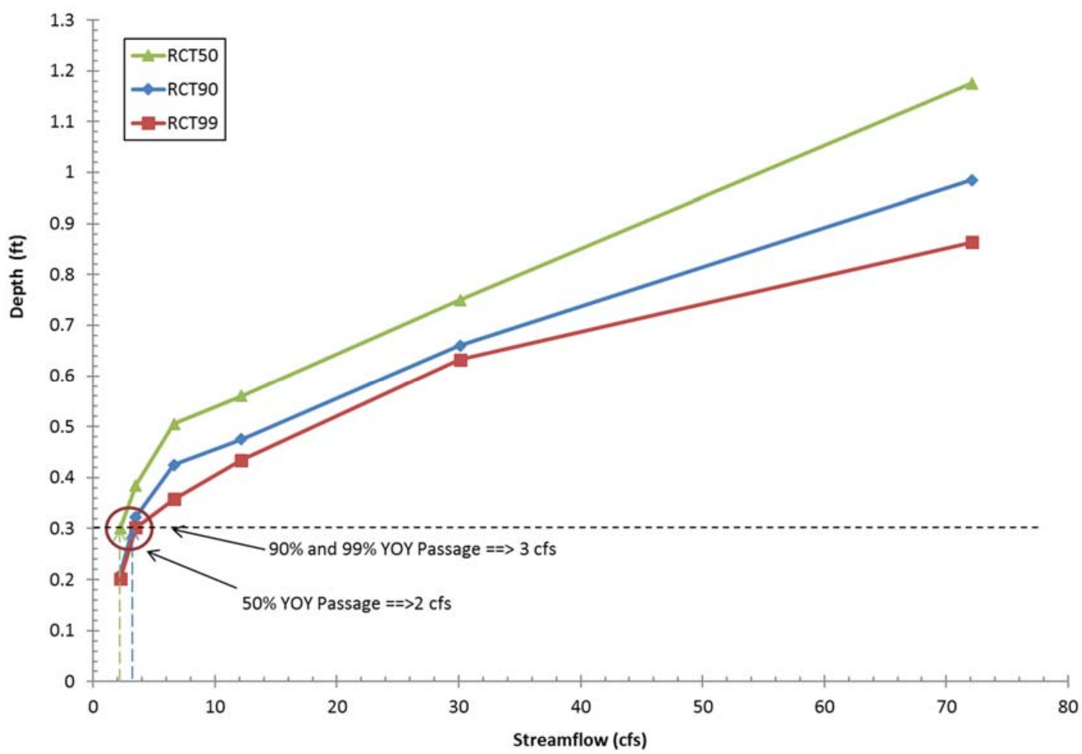


Figure 19. Shallowest RCT depths (50th, 90th, and 99th percentile) plotted against streamflow, showing streamflows that met the 0.3 ft. passage criteria (black dashed line) for YOY salmonid passage.

7 SYNTHESIS OF RECOMMENDED MINIMUM BYPASS FLOWS

The site-specific minimum bypass flows for the study reach are based on needs of Coho Salmon and steelhead life histories in Indian Creek, identified as having the highest importance during the flow periods (Section 4). It is recommended to be conservative when determining diversion rates, as any decrease in streamflow below recommend minimum bypass flows can potentially have a large effect on the ecology of the system, especially during dry years when the ecosystem is already under stress. The most protective minimum bypass flows recommended in this report should not be exceeded or only minimally exceeded naturally during all years, especially during dryer water year types. The effect of diversion at flows above (or below) these flows is largely a function of diversion rates and should be considered in the context of a cumulative effects analysis.

Rationale for site-specific minimum bypass flows in the Indian Creek study area for each flow period is provided in this section and results are summarized in Table 12. The “Analytical Method” column in Table 12, is provided to help the reader cross-walk which method was used for each life stage and which method’s ecological flow threshold results are used for each flow period in Sections 6.1, 6.2, 6.3, and 6.4. Ecological flow threshold results from each analytical method used for the final minimum bypass flow recommendation are highlighted in bold. In addition, recommended minimum bypass flows for the four time periods were overlaid on unimpaired hydrographs for Indian Creek for three water year types (Figure 20, Figure 21, and Figure 22) to observe how recommended flows can affect water diversions during the flow periods. Unimpaired annual streamflow data for Indian Creek used to develop the hydrographs were calculated by CEMAR. CEMAR’s methods for developing unimpaired streamflow data for Indian Creek are attached in Appendix A.

7.1 November 1 through March 31: Adult Steelhead and Adult Coho Salmon Migration

Spawning is the first and most critical stage of the salmonid life cycle. If adult salmonids cannot reach ideal spawning habitat in the watershed because flows necessary to pass over the most depth–sensitive riffles are not available, then spawning will occur in less favorable habitats and subsequent life stages (egg incubation, rearing, smolt outmigration etc.) can be negatively affected. Therefore, passage for adult steelhead and Coho Salmon upstream migration was identified as the life history where maintaining adequate instream flow was the most critical for this time period. The 33 cfs ecological flow threshold for adult salmonid passage from the CRA method (using 2-D hydraulic modeled input data) was used as the recommended bypass flow for this period because it was protective of adult passage. In addition, 33 cfs was protective of the minimum ecological flow thresholds for all other freshwater life stages of Coho Salmon and steelhead present in Indian Creek during this time period (Table 12). This minimum bypass flow recommendation was compared against available water for dry (Figure 20), normal (Figure 21), and wet (Figure 22) water years. This comparison suggests that the recommended minimum bypass flow could be met during this time period in dry, normal, and wet years, though with less frequency during dryer water years.

7.2 April 1 through April 30: Adult Steelhead Late Spawning and Juvenile (1+, 2+) Rearing

Maximum spawning habitat for late spawning adult steelhead, maximum rearing habitat for 1+ juvenile Coho Salmon and 1+, 2+ juvenile steelhead, and abundant habitat for BMI production were identified as priority life stages for this flow period where instream flows needs were most critical. WUA curves derived from the 2-D hydraulic modeling results for all priority life stages had an inflection point at 26 cfs, with the exception of 1+ juvenile Coho Salmon. However, 26 cfs only decreased WUA for 1+ juvenile Coho Salmon by 200 ft^2 and still provided adequate rearing habitat. Therefore, a 26 cfs minimum bypass flow is recommended for this flow period (Table 12).

While adult steelhead migration, coupled with steelhead spawning, is identified as occurring during this time period in Figure 4, April is the tail end of the steelhead spawning season in the Navarro River watershed and there are less individuals spawning during April than in previous months. Therefore, 33 cfs for adult steelhead migration was not identified as the threshold for this flow period since most adult steelhead have reached their spawning grounds by April.

Maximum ecologically important streamflows from 1+, 2+ juvenile steelhead rearing and adult steelhead spawning WUA curves were identified at 40 cfs and 60 cfs, respectively (Section 6.2.1). When comparing a 40 or 60 cfs streamflow to the unimpaired hydrographs for dry, normal, and wet water years (Figure 20 through Figure 22), 40 cfs and 60 cfs are attainable during this flow period. However, we chose not to make 40 cfs or 60 cfs the minimum bypass flow for several reasons: (1) 26 cfs meets the flow objectives of protecting late spawning adult steelhead, rearing for 1+ juvenile Coho Salmon and 1+, 2+ Juvenile steelhead, and BMI production as stated in the Water Permit Application for Anderson Vineyards Inc./DA Ranch); (2) flows exceed 40 and 60 cfs episodically during this flow period following storm events, maintaining flow complexity and diversity; and (3) 40 and 60 cfs for this flow period are storm runoff flows and do not represent a realistic base flow.

7.3 May 1 through May 31: Juvenile (YOY, 1+, 2+) Steelhead and Coho Salmon Foraging, and Smolt Outmigration

Passage for Coho Salmon and steelhead smolt outmigration, and maximum BMI production to provide optimal foraging opportunities for juvenile Coho Salmon (YOY, 1+) and juvenile steelhead (YOY, 1+, 2+) were identified as priority life stages for this flow period where instream flows needs were most critical. During this flow period, maximizing feeding opportunity for soon-to-be over-summering steelhead and Coho Salmon is a priority to ensure high growth rates needed to survive the upcoming low-flow summer/fall period. Summer streamflows in northwestern California streams (Indian Creek included) can significantly lower growth rates of juvenile steelhead and can be attributed to the corresponding decrease in invertebrate drift rates (Harvey et al. 2006). In addition, flows that prioritize smolt outmigration ensure connectivity between habitat units for BMI drift and movement of foraging juvenile salmonids between habitat units to maximize foraging opportunities. The ecological flow threshold result for maximum BMI production identified from the incipient asymptote on the wetted perimeter curves was 10 cfs. The ecological flow threshold results for smolt outmigration passage was identified as 9 cfs from the CRA method. However, 10 cfs is recommended as the minimum bypass flow for this flow period because it is protective of both priority life stages.

While habitat for BMI production are important during this flow period, we did not use the 26 cfs streamflow seen on the WUA curves for productive BMI habitat (Table 12) as the recommended minimum bypass flow because a 26 cfs streamflow does not naturally occur during this flow period during dry and some normal water years (Figure 20 through Figure 22). In addition, YOY Coho Salmon and steelhead are emerging during this flow period and maintaining habitat for them is important to ensure their survival. A 10 cfs minimum bypass flow would provide more WUA for rearing YOY Coho Salmon and steelhead than a 26 cfs minimum bypass flow as evident from WUA curves (Figure 18).

7.4 June 1 through October 31: Late Steelhead Smolt Outmigration, and YOY Steelhead and Coho Salmon Summer Rearing and Foraging

For this last time period, late steelhead smolt outmigration only occurs during June, and streamflows that allow smolt passage are not as necessary from July 1 – October 31 when YOY steelhead and Coho Salmon summer rearing and foraging are a priority. Therefore, this section is separated into two subsections to discuss the ecological flow thresholds needed for smolt outmigration in June, and for YOY steelhead and Coho Salmon summer rearing and foraging from

July 1 – October 31. As stated in Section 4, the June 1 through October 31 flow period was added to the report simply for information purposes and to ensure the maintenance of ecological functions and protection of fisheries resources during a time period typically know to be stressful for rearing juvenile salmonids in that occur in Mediterranean climates. Since diversions are not proposed for this flow period, we did not include a recommended minimum bypass flow in Table 12 . Ecological flows discussed in the section can be found in Section 6.4 and 6.5.

7.4.1 June 1 through June 30: Late Steelhead Smolt Outmigration

The hydrologic regime of streams that occur in Mediterranean climates are typically dependent on rainfall, with most rain occurring in the late fall, winter, and early spring. Therefore, the frequency and intensity of rainfall can greatly affect the hydrologic regime of a stream from year to year depending on water year types (dry, normal, wet). The June 1 through October 31 time period occurs during the drying season when rainfall is rare and is typically characterized by decreasing baseflows. Low rainfall during a dry water year type will cause low baseflows early in the season (June), while a wet year type can shorten the low baseflow period (Gasith and Resh 1999).

A 9 cfs ecological flow threshold was considered for this flow period to allow for adequate steelhead smolt outmigration through June; however, 9 cfs only occurs for a portion of June for wet and normal years and not at all during dry years. Therefore, a 9 cfs minimum bypass flow is appropriate for June 1 – June 30th under normal and wet year types to ensure steelhead smolt outmigration.

7.4.2 July 1 through October 31: YOY Steelhead and Coho Salmon Summer Rearing and Foraging

Maintaining streamflows at or above recommended ecological flow thresholds that provide adequate rearing habitat and feeding opportunities for over-summering YOY steelhead and Coho Salmon during the dry period is critical to decrease mortality rates. A 3 cfs ecological flow threshold was identified from the breakpoint from the wetted perimeter method, WUA curves for BMI production, and WUA curves for YOY Coho Salmon and steelhead rearing. The 3 cfs is based on the first inflection for the BMI habitat WUA curve and the breakpoint threshold from the wetted perimeter method. Three cfs is present in Indian Creek for all water year types analyzed (Figure 20 through Figure 22) and therefore, was identified as a minimum bypass flow for the July 1–October 31 flow period to protect food resources and provides adequate rearing habitat for YOY Coho Salmon and steelhead.

Table 12. Summary of ecological flow thresholds for each flow period and corresponding recommended minimum bypass flows in the Indian Creek Study reach. Results from analytical methods used to synthesize recommended minimum bypass flows are shaded in grey and the ecological flow thresholds used for the final recommendations are highlighted in bold.

Life Stage	Analytical Method	Ecological Flow Thresholds During Proposed Periods (cfs)		
		November 1–March 31	April 1–April 30	May 1–May 31
Adult steelhead migration	CRA (25% total passage ≥ 0.7 ft deep)	**33**	33	
Adult Coho Salmon migration	CRA (25% total passage ≥ 0.7 ft deep)	**33**		
Adult steelhead spawning	Inflections on adult steelhead spawning WUA curve	26	**26**	
Adult Coho Salmon spawning	Inflections on adult Coho Salmon spawning WUA curve	26		
Steelhead smolt outmigration	CRA (25% total passage ≥ 0.4 ft deep)	9	9	9
Coho Salmon smolt outmigration	CRA (25% total passage ≥ 0.4 ft deep)	9	9	9
Juvenile steelhead (YOY) rearing	Inflections on juvenile steelhead (YOY) WUA curves	3	3	3
Juvenile steelhead (1, 2+) rearing	Inflections on small juvenile steelhead (1+) WUA curves	26	**26**	26
	Inflections on large juvenile steelhead (2+) WUA curves	26	**26**	26
Juvenile Coho Salmon (YOY) rearing	Inflections on juvenile Coho Salmon (YOY) WUA curves	2	2	2
Juvenile Coho Salmon (1+) rearing	Inflections on juvenile Coho Salmon (1+) WUA curves	2	2	2
Habitat for BMI production	Inflections on BMI WUA curve	26	**26**	26
	Wetted Perimeter curves- incipient asymptote	10	10	**10**
Low-flow ecological threshold	Wetted Perimeter curves- breakpoint	3	3	3
Minimum Bypass Flows		**33**	**26**	**10**

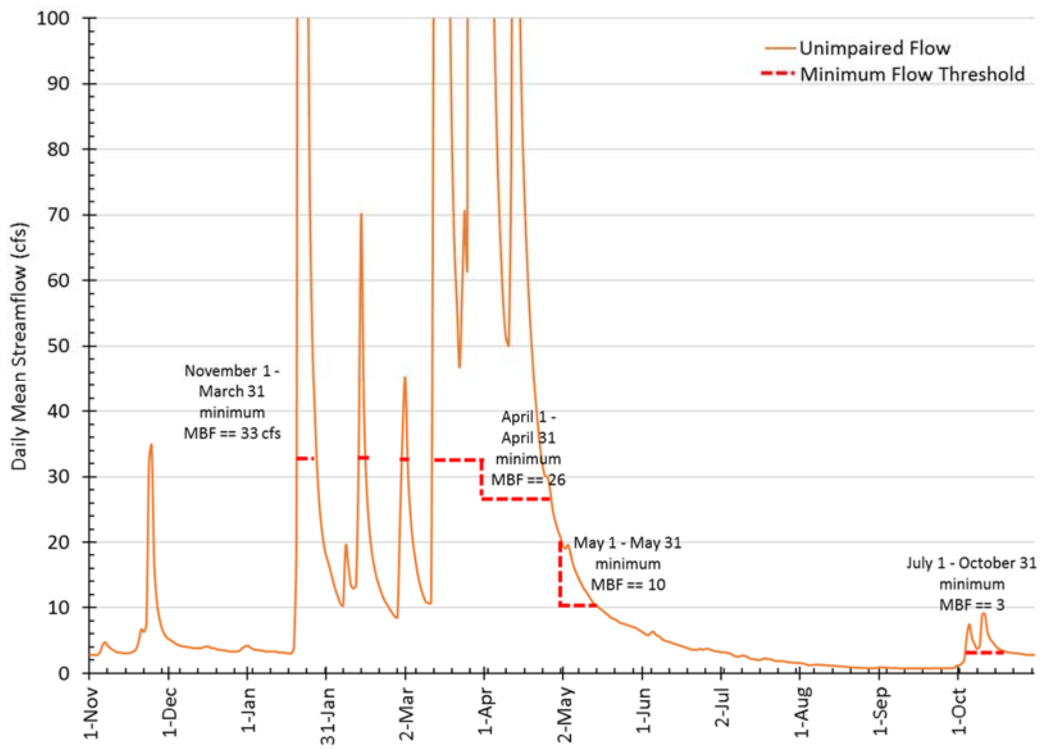


Figure 20. Comparison of recommended minimum bypass flows to the unimpaired dry water year (2012) hydrograph for Indian Creek.

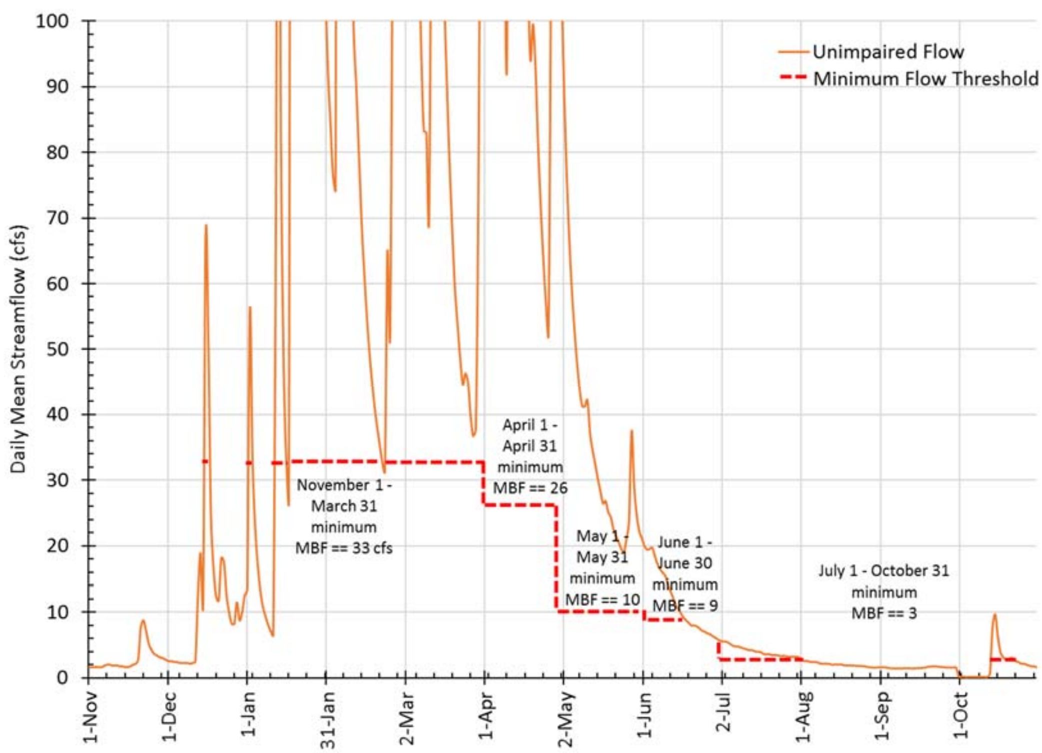


Figure 21. Comparison of recommended minimum bypass flows to the unimpaired normal water year (2010) hydrograph for Indian Creek.

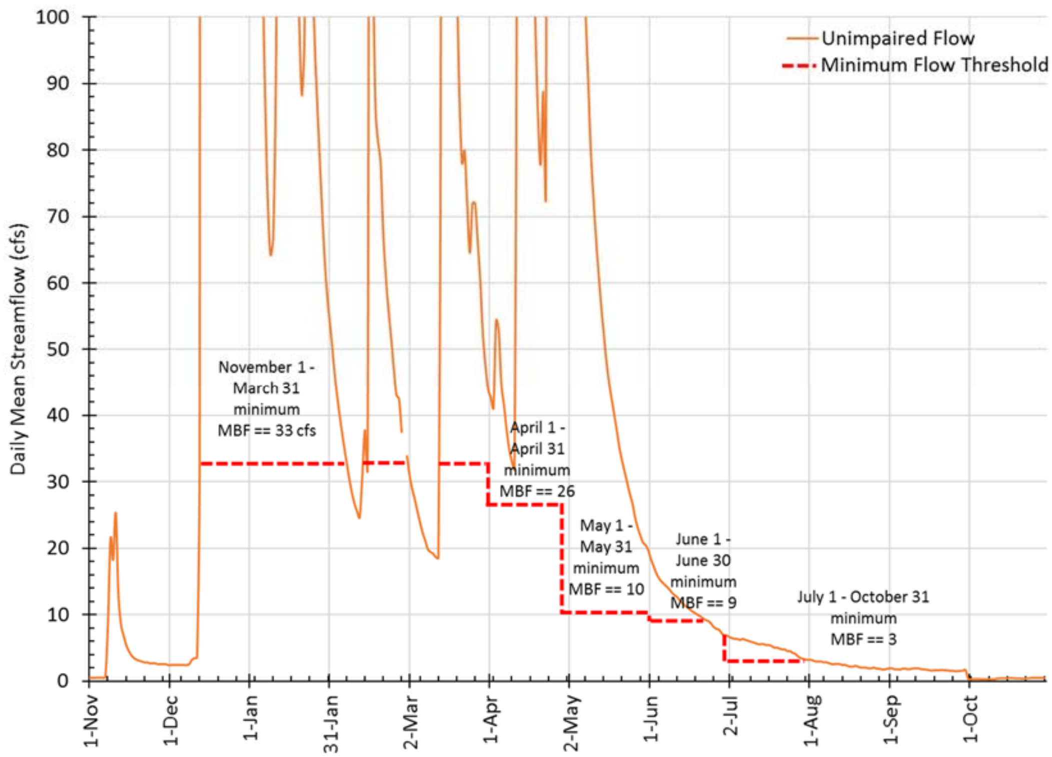


Figure 22. Comparison of recommended minimum bypass flows to the unimpaired wet water year (2003) hydrograph for Indian Creek.

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