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

INSTREAM FLOW EVALUATION: SOUTHERN CALIFORNIA STEELHEAD PASSAGE THROUGH THE INTERMITTENT REACH OF THE VENTURA RIVER, VENTURA COUNTY

STREAM EVALUATION REPORT 2021-01

April 2021

Cover photo: Ventura River intermittent reach near Santa Ana Bridge, downstream view. Photo taken 03/25/2019.

California Department of Fish and Wildlife
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California Department of Fish and Wildlife
Water Branch
Instream Flow Program
Stream Evaluation Report 2021-01

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PREFACE

The Ventura River is an essential watershed for the recovery and perpetuation of native Southern California anadromous rainbow trout (*Oncorhynchus mykiss*), commonly known as steelhead. The Southern California steelhead recovery plan (NMFS 2012) classified the Ventura River basin as a high priority Core 1 watershed, because of its potential to support independent viable populations of the Southern California steelhead distinct population segment (DPS). The Ventura River was also identified as a priority stream to support the California Water Action Plan (CWAP), which outlines actions to address challenges and promote reliability, restoration, and resilience in the management of California's water (CNRA et al. 2014; CNRA et al. 2016). Under Action 4 of the CWAP, the California Department of Fish and Wildlife (Department) and State Water Resources Control Board (State Water Board) were directed to implement actions to enhance instream flows within five priority stream systems that support critical habitat for anadromous fish. The Ventura River was selected as one of these five streams because of its high biological resource value and potential for species recovery.

The Department holds fish and wildlife resources in California in trust for the people of the State and has jurisdiction over the conservation, protection, and management of those resources (Fish and Game Code §711.7 (a); Fish and Game Code §1802). The Department seeks to manage California's diverse fish, wildlife, plant species, and natural communities for their intrinsic and ecological value and their use and enjoyment by the public. The Department's Instream Flow Program develops scientific information to determine flows needed to maintain healthy conditions for fish, wildlife, and the habitats on which they depend. The Department recommends using the Instream Flow Incremental Methodology (IFIM) to evaluate and develop instream flow criteria for actions that may affect California's aquatic resources. The IFIM process and instream flow evaluations, in general, should include broad consideration of the structure and function of riverine systems, and examination of five core riverine components (i.e., hydrology, biology, geomorphology, water quality, and connectivity).

To address the CWAP in the Ventura River watershed, the Department has conducted two instream flow studies and produced a watershed-wide flow criteria report. The studies evaluate flows for maintaining ecological condition, adult steelhead passage through the intermittent reach of mainstem Ventura River, and adult steelhead spawning and juvenile rearing within San Antonio Creek. To fulfill its obligations under the CWAP, the State Water Board is developing a groundwater-surface water model. The groundwater-surface water model will quantify the relationship between surface and subsurface flow, providing a better understanding of water supply, water demand, and instream flows in the watershed. Integration of the Department's study results with the State Water Board's groundwater-surface water model will be essential to enhancing instream flows and informing water management within the Ventura River watershed.

This technical report summarizes results of the instream flow study conducted along 1.3 miles (mi) of braided stream channel within a segment of the intermittently flowing mainstem Ventura River. The study design was outlined in the Department's *Study Plan: Habitat and Instream Flow Evaluation for Steelhead in the Ventura River, Ventura County* (CDFW 2017b). This report describes the methods employed to develop predictive hydraulic models and resulting relationships between flow and passage conditions in the Ventura River. Details on the hydraulic models are presented in the Appendices. The results of this study, along with other supporting information and data, are intended to be used to identify instream flow needs for adult steelhead passage in the intermittent reach of the mainstem Ventura River.

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ABBREVIATIONS AND ACRONYMS

1D	one-dimensional (hydraulic model)
2D	two-dimensional (hydraulic model)
cfs	cubic feet per second
CMWD	Casitas Municipal Water District
CRA	critical riffle analysis
CWAP	California Water Action Plan
Department	California Department of Fish and Wildlife
DPS	distinct population segment
DTM	digital terrain model
ft	foot (feet)
GPS	Global Positioning System
HEC-RAS	Hydrologic Engineering Center's River Analysis System
IFIM	Instream Flow Incremental Methodology
LIDAR	Light Detection and Ranging
m	meter
m^2	square meter(s)
mi	mile(s)
NMFS	National Marine Fisheries Service
PT	pressure transducer
RTK	Real Time Kinematic
SC	side channel
SOP	standard operating procedure
USGS	United States Geological Survey
XS	cross section
WSEL	water surface elevation

CONVERSIONS

1 cubic foot per second ≈ 2.83×10^{-2} cubic meters per second
1 inch = 2.54 centimeters
1 foot = 30.48 centimeters
1 foot ≈ 0.31 meters
1 mile ≈ 1.61 kilometers
1 square mile ≈ 2.59 square kilometers

1.0 INTRODUCTION

Stream flow is the dominant driver of connectivity between aquatic organisms and their riverine habitats (Wiens 2002). Loss of connectivity can affect the flow of nutrients, energy, and materials, as well as the movement and viability of biota in the aquatic ecosystem (Freeman et al. 2007). Naturally occurring low stream flows combined with water withdrawal for anthropogenic uses can interrupt riverine connectivity and movement opportunities for anadromous salmonids (Spina et al. 2006). When these low stream flow conditions occur, water depth becomes a meaningful variable for evaluating fish passage opportunities and riverine habitat connectivity in low-gradient alluvial river channels (Mosley 1982; Thompson 1972).

The Ventura River, located in Ventura and Santa Barbara counties, was historically known for its large runs of native Southern California anadromous rainbow trout (*Oncorhynchus mykiss*), commonly known as steelhead (NMFS 2012). Southern California steelhead run sizes have plummeted from historic levels, declining from estimated annual returns of 32,000-46,000 adults to less than 500 adults (Busby et al. 1996). The Southern California steelhead DPS was listed as endangered under the federal Endangered Species Act in 1997 (62 Federal Register 43937) and reaffirmed in 2006 (79 Federal Register 20802; NMFS 2012). As a requirement to the Endangered Species Act listing, the National Marine Fisheries Service (NMFS) designated the Ventura River watershed as a critical Southern California steelhead habitat in 2005 (70 Federal Register 52488; NMFS 2012). Southern California steelhead are also listed as a Species of Special Concern (Moyle et al. 2008). The Ventura River is considered a priority watershed for Southern California steelhead conservation and recovery.

Dams and surface water diversions are the primary challenges for struggling populations of Southern California steelhead within the Ventura River watershed (NMFS 2012). These factors, in addition to urbanization, loss of habitat, flood control, and poor ocean conditions have all contributed to a decrease in the number of viable steelhead populations as well as limited their distribution (Moyle et al. 2008; NMFS 2012; VCFGC 1973). Wildfires, invasive *Arundo donax* (a perennial cane), and extensive algal growth have also impacted the watershed by changing the hydrology and sediment transport patterns of the Ventura River (Giessow et al. 2011; Lai 2012; Tetra Tech 2009).

Although there is no single factor responsible for the decline of Southern California steelhead, the destruction and modification of habitat has been identified as one of the primary causes for the deterioration of the Southern California steelhead DPS (NMFS 2012). Over 90% of the highest quality spawning habitat within the Ventura River watershed has been rendered inaccessible by Matilija and Casitas dams since 1959 (NMFS 2012). Due to the degradation and loss of most high-quality habitat, suitable instream flows must be identified to improve access to remaining upstream spawning and rearing habitat.

Previous studies on the Ventura River mainstem identified an intermittently dry reach that restricts adult steelhead migration to spawning grounds in upstream perennial headwaters (Entrix Inc 1999; Lewis and Gibson 2009). This study identifies the flows required to support adult steelhead passage through the intermittent reach of the mainstem Ventura River (Figure 1) using two-dimensional (2D) modeling. A large channel-forming flow event occurred in winter of 2017, resulting in evaluation of pre- and post-storm passage flows.

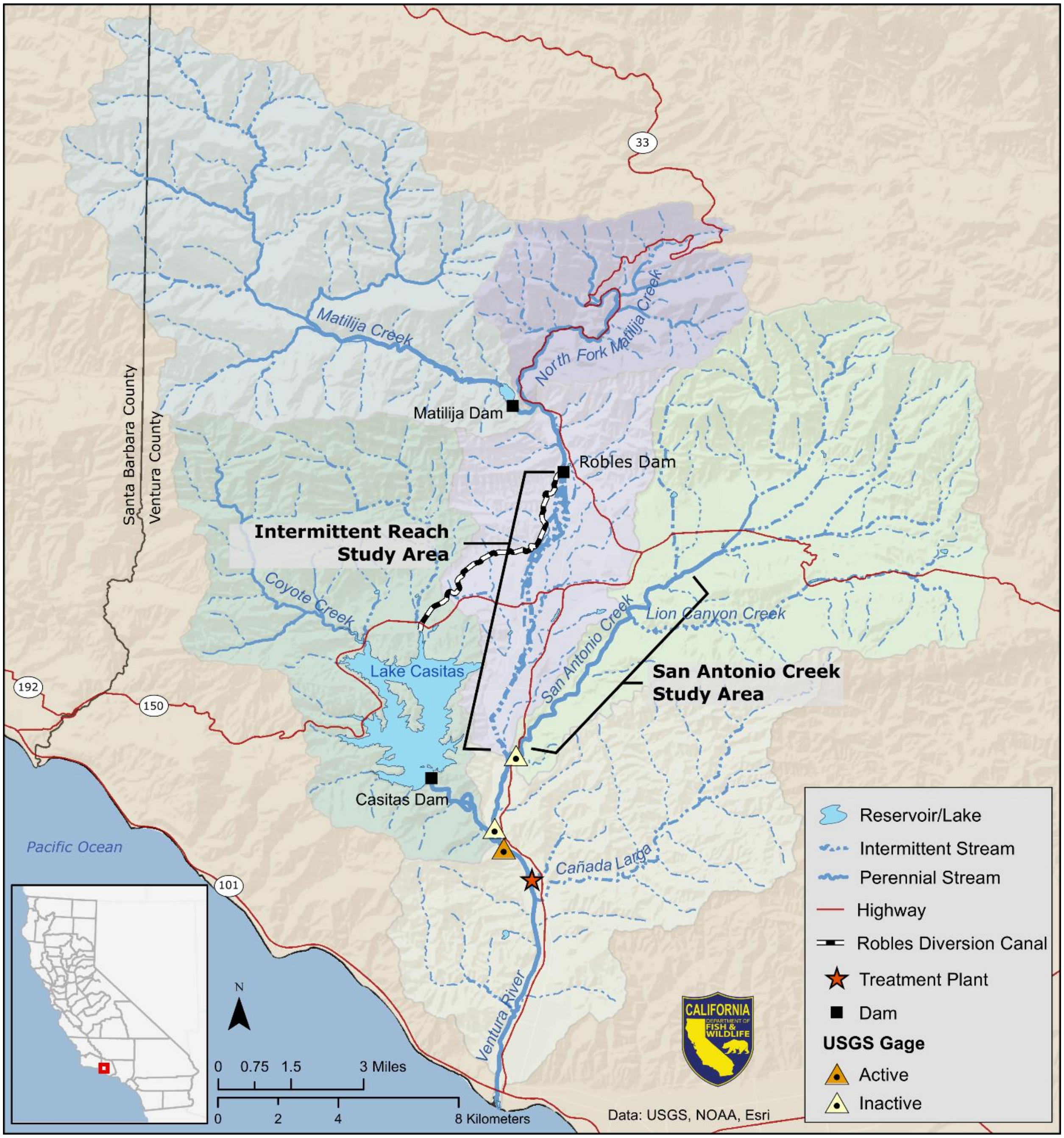


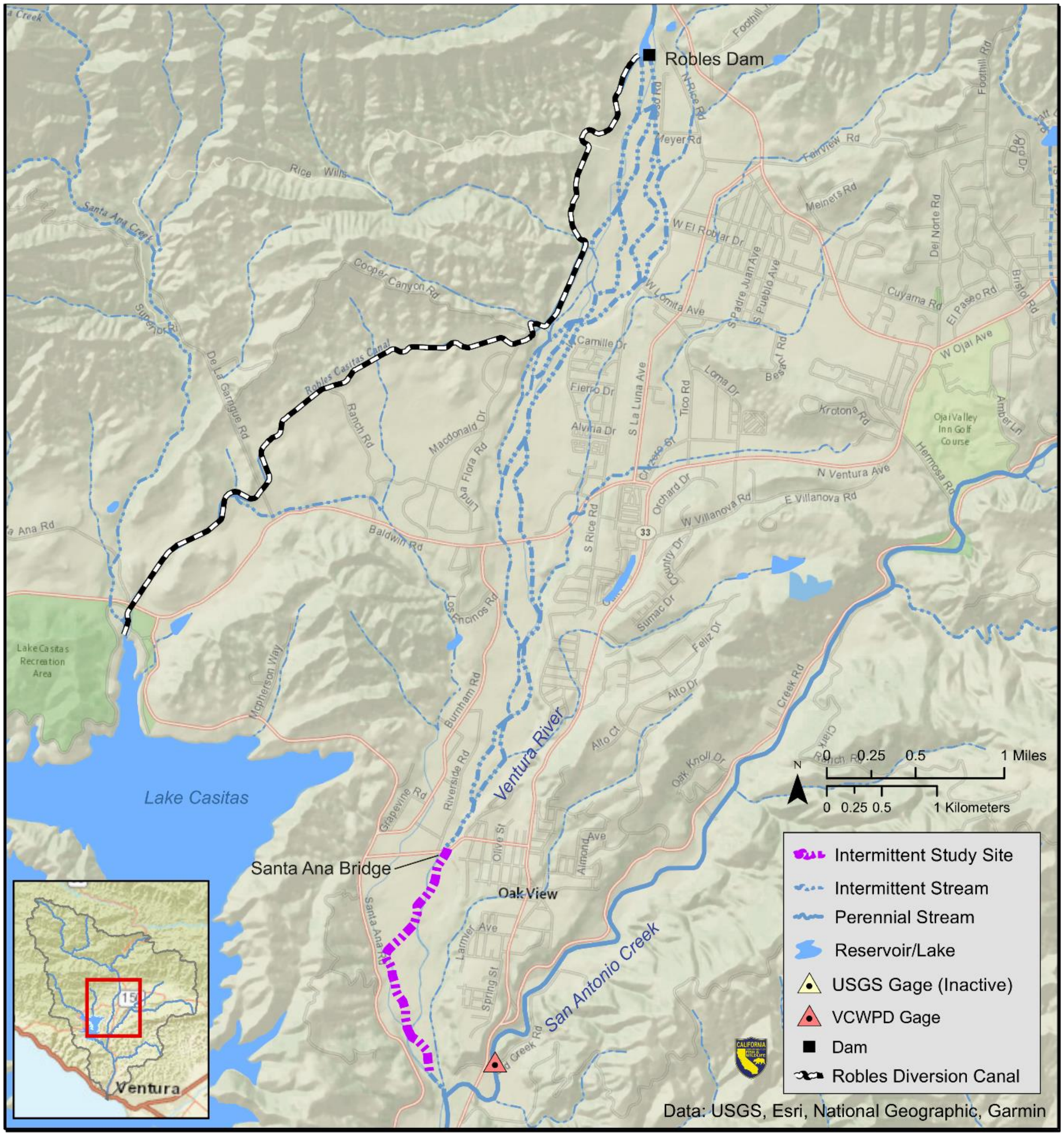
Figure 1. Map of study areas within the Ventura River watershed. In addition to the two study areas shown, a third report assesses instream flow needs at locations throughout the watershed (CDFW 2020). The active gage is USGS 11118500. Additional USGS gages not used in the intermittent reach or San Antonio Creek reports are not shown. Note: intermittent and perennial streams shown here were classified by the USGS (USEPA and USGS 2012).

1.1 Study Goals and Objectives

The goal of this study was to identify flows that support unimpeded adult steelhead migration through the Ventura River mainstem to upstream spawning and rearing habitat. This study identified stream flows needed to ensure adequate water depths for adult steelhead passing through the intermittent reach. The intermittent reach is located between the San Antonio Creek confluence and the Robles Diversion Facility, with the study site in the lower 1.3 mi (Figure 2). Objectives of this study include the following:

- development and calibration of predictive hydraulic models for a representative section of the intermittent reach of the Ventura River mainstem;
- evaluation and comparison of passage conditions limiting to steelhead at critical riffles before and after the February 2017 storm event in the intermittent reach of the Ventura River mainstem; and
- identification of flows necessary to protect adult steelhead passage through the intermittent reach of the Ventura River mainstem.

This technical report is one component of a set of interrelated reports (Figure 1) derived from the Department’s *Study Plan: Habitat and Instream Flow Evaluation for Steelhead in the Ventura River, Ventura County* (CDFW 2017b). Flow-habitat relationships for steelhead spawning and rearing developed based on one-dimensional (1D) hydraulic modeling in San Antonio Creek are presented in *Instream Flow Evaluation: Southern California Steelhead Adult Spawning and Juvenile Rearing in San Antonio Creek, Ventura County* (Maher et al. 2021). Ecological flows throughout the Ventura River watershed are presented in the report *Instream Flow Regime Criteria on a Watershed Scale: Ventura River* (CDFW 2020).



Data: USGS, Esri, National Geographic, Garmin

Figure 2. Study site (indicated in purple) within the intermittent reach in the Ventura River mainstem.

1.2 Description of Watershed

The Ventura River watershed covers 226 square miles with a total stream length of 409 mi. The Ventura River mainstem flows southwest into the Pacific Ocean in southern Ventura County. Headwaters flow from a high coastal terrace, which ranges from 5,700 to 8,600 feet (ft) in elevation (CDFW 2017b; Walter 2015). Land use comprises 87% open space (vacant or water) and 13% developed land use. About 5% of developed land use is agricultural, excluding grazing lands; inclusion of grazing increases agricultural use to 18.5% of the land area (Walter 2015).

The Ventura River watershed has a Mediterranean climate which is heavily dependent on an unpredictable rainy season (Walter 2015). Rainfall occurs almost exclusively between November and April with an average rainfall of 35.17 inches in the upper watershed, 21.31 inches in the middle watershed, and 15.46 inches in the lower watershed (Walter 2015). The region usually follows a pattern of wet and cool winters and warm, dry summers (LARWQCB 2012). El Niño and La Niña cycles may dramatically increase or decrease winter rainfall, causing highly variable flows (NMFS 2012). Mean annual flow can vary by two orders of magnitude, and cycles of dry and wet periods frequently span decades (Beller et al. 2011; Walter 2015). Discharge is often characterized by short-duration, high-intensity peak storm events in the winter (Keller and Capelli 1992) and low to absent summer flows which may be enhanced by overnight coastal fog (CRWQCB 2002). The unconfined aquifer beneath the streambed can rapidly recharge after large storm events (Walter 2015), which also influences flow duration in the intermittent reach.

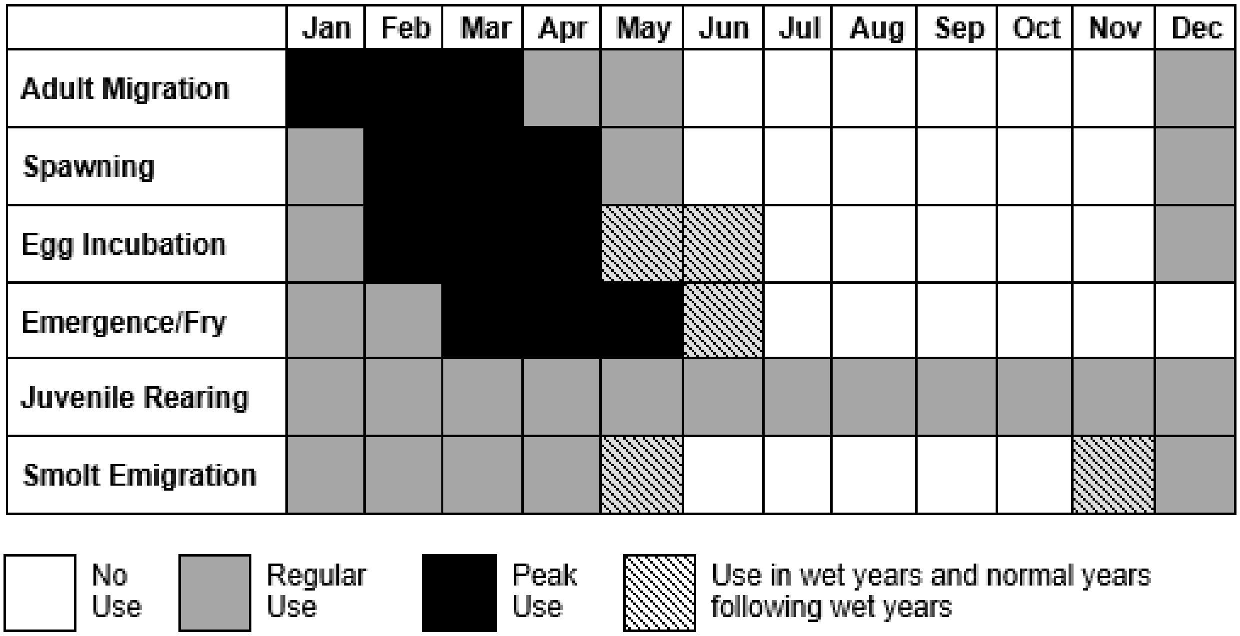
This study focuses on the intermittent mainstem within the Ventura River watershed. Sections of the Ventura River watershed, including some of the minor tributaries and a six-mile reach in the mainstem, are typically dry during summer and fall. Sometimes referred to as the “Robles Reach”, the intermittent reach within the Ventura River mainstem does not have stationary boundaries since flow varies with month, rainfall, and groundwater storage (Beller et al. 2011; Walter 2015). The intermittent reach is wide and alluvial with a high infiltration rate (Figure 3). Stream flow patterns are typically flashy and intermittent in response to rainfall events (Figure 3; Walter 2015). The Department has identified the intermittent reach as a major impediment for adult steelhead passage to spawning and rearing habitat in upstream perennial reaches (Entrix Inc 1999; Lewis and Gibson 2009).

Figure 3. View of the intermittent reach on the Ventura River mainstem upstream of the Santa Ana Bridge.

Perennial reaches providing important year-round habitat for fish can be found both upstream and downstream of the intermittent reach. In the upper portion of the watershed, Matilija Creek and North Fork Matilija Creek support flow year-round down to the Robles Diversion Dam (Figure 1). Groundwater inputs and flow through broken rocks along fault lines maintain perennial flow in Matilija Creek and North Fork Matilija Creek (Walter 2015). Flow is also perennial in the mainstem from the confluence with San Antonio Creek down to the mouth of the Ventura River (Beller et al. 2011). Perennial flow in this reach is supported by springs, rising groundwater, inputs from San Antonio Creek and Live Oak Acres Creek, and discharges from the Oak View Sanitary District sewage treatment facility (Figure 1; Moore 1980).

1.3 Steelhead

Steelhead are anadromous, moving to the ocean as smolts and returning to freshwater to spawn. Juveniles rear in freshwater for one to three years until they transition to smolts and migrate to the ocean to mature (NMFS 2012). They remain in the ocean for one to four years before returning to freshwater to spawn. Steelhead are iteroparous, meaning they may spawn multiple times in their lives, potentially returning to the same watershed for years and migrating back to the ocean between spawning seasons. Figure 4 shows the general periodicity for Southern California steelhead within the Ventura River watershed throughout a given year.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adult Migration	■	■	■	▒	▒	□	□	□	□	□	□	▒
Spawning	▒	■	■	■	▒	□	□	□	□	□	□	▒
Egg Incubation	▒	■	■	■	▨	▨	□	□	□	□	□	▒
Emergence/Fry	▒	▒	■	■	■	▨	□	□	□	□	□	□
Juvenile Rearing	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
Smolt Emigration	▒	▒	▒	▒	▨	□	□	□	□	□	▨	▒

□ No Use ▒ Regular Use ■ Peak Use ▨ Use in wet years and normal years following wet years

Figure 4. Life stage periodicity for Southern California steelhead in the Ventura River watershed.[a]

Southern California steelhead have adapted to a wide range of habitats and may have a broader physical tolerance for poor conditions than other steelhead populations (Moyle et al. 2008). Southern California steelhead are dependent on winter rains for seasonal passage up estuaries and rivers. Their continued persistence is largely due to their ability to divide their populations between inland rivers and the ocean. This strategy has been beneficial as their range is characterized by highly variable winter flows. Southern California steelhead are distributed from the Santa Maria River to the Tijuana River,

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[a] Larson, M. CDFW South Coast Region Fisheries Supervisor, personal communication August 14, 2018.

which makes them the southernmost anadromous salmonid in the United States (NMFS 2012). The Ventura River is one of four major watersheds still supporting steelhead within the Monte Arido Highlands biogeographic population group.

The National Marine Fisheries Service (NMFS) identified Ventura River steelhead as a Core 1 population for the recovery effort of the Southern California steelhead DPS. Core 1 populations are considered to have the greatest potential to support independent viable populations (NMFS 2012). Critical recovery actions for the Ventura River Core 1 populations include “implementing operating criteria to ensure the pattern and magnitude of groundwater extractions and water releases, including bypass flows around diversions from Casitas, Matilija, and Robles Diversion dams provide the essential habitat functions to support the life history and habitat requirements of adult and juvenile steelhead” (NMFS 2012).

1.4 Ventura River Hydrology and Water Supply

Flows and adult steelhead passage in the mainstem Ventura River are affected by the presence of Matilija Dam and Robles Diversion Dam. Matilija Dam currently obstructs fish access to 10 mi of historic steelhead spawning and rearing habitat in the Ventura River watershed (Figure 1; CDFG 1996). Abundance estimates for the Ventura River watershed place the highest population of coastal rainbow trout/steelhead in the perennial reaches upstream of the Robles Diversion Dam and below Matilija Dam (Allen 2015; Thomas R. Payne and Associates 2003). Additional fry and juvenile *O. mykiss* are also commonly found in North Fork Matilija Creek, which feeds into the Ventura River above the Robles Diversion Dam (Figure 1).

The Robles Diversion Dam is a facility operated by the Casitas Municipal Water District (CMWD). The facility diverts up to 500 cubic feet per second (cfs) from the Ventura River (NMFS 2003). Water flows through the Robles Diversion Canal to Lake Casitas, a reservoir built by the U.S. Bureau of Reclamation that provides water for municipal use (Figure 2). During the fish passage augmentation season (January 1–June 30), bypass flows of at least 30 cfs are required at the dam. This minimum bypass flow increases to 50 cfs for 10 days following a storm event (see NMFS 2003 for details). When the facility experiences flow greater than 500 cfs, non-diverted flows are passed downstream into the Ventura River mainstem (NMFS 2003). The Robles Diversion Dam blocks fish passage, so a vertical slot weir fishway was constructed in 2005 to facilitate steelhead access to the upper watershed.

1.4.1 Flow Duration Analysis

Flow duration analysis estimates the probability that a given stream discharge will be equaled or exceeded, based on the period of record (CDFW 2013b). This probability is expressed as a percent exceedance probability, and the discharge associated with that probability is referred to as an exceedance flow. Exceedance flows were calculated using the *Standard Operating Procedure for Flow Duration Analysis in California* (CDFW 2013b).

In the absence of a permanent flow gage in the intermittent reach, USGS gages 11118500 and 11118501 were used to calculate impaired and least-impaired annual exceedance flows for the Ventura River (Figure 5). USGS 11118500 (Ventura River near Ventura) is an active gage located in Foster Park. USGS 11118501 (Ventura River and Ventura City Diversion near Ventura) is the combined discharge of USGS 11118500 and a gage recording Ventura City surface water diversions, representing the synthetic least-impaired hydrology. Although these gages are located downstream of the confluence with San Antonio Creek and experience higher flows than the intermittent reach, the exceedance values are provided to illustrate flow dynamics within the mainstem Ventura River (Figure 5). The distribution of mean daily flows by month were also calculated using USGS 11118501 to describe flow patterns throughout the year (Figure 6).

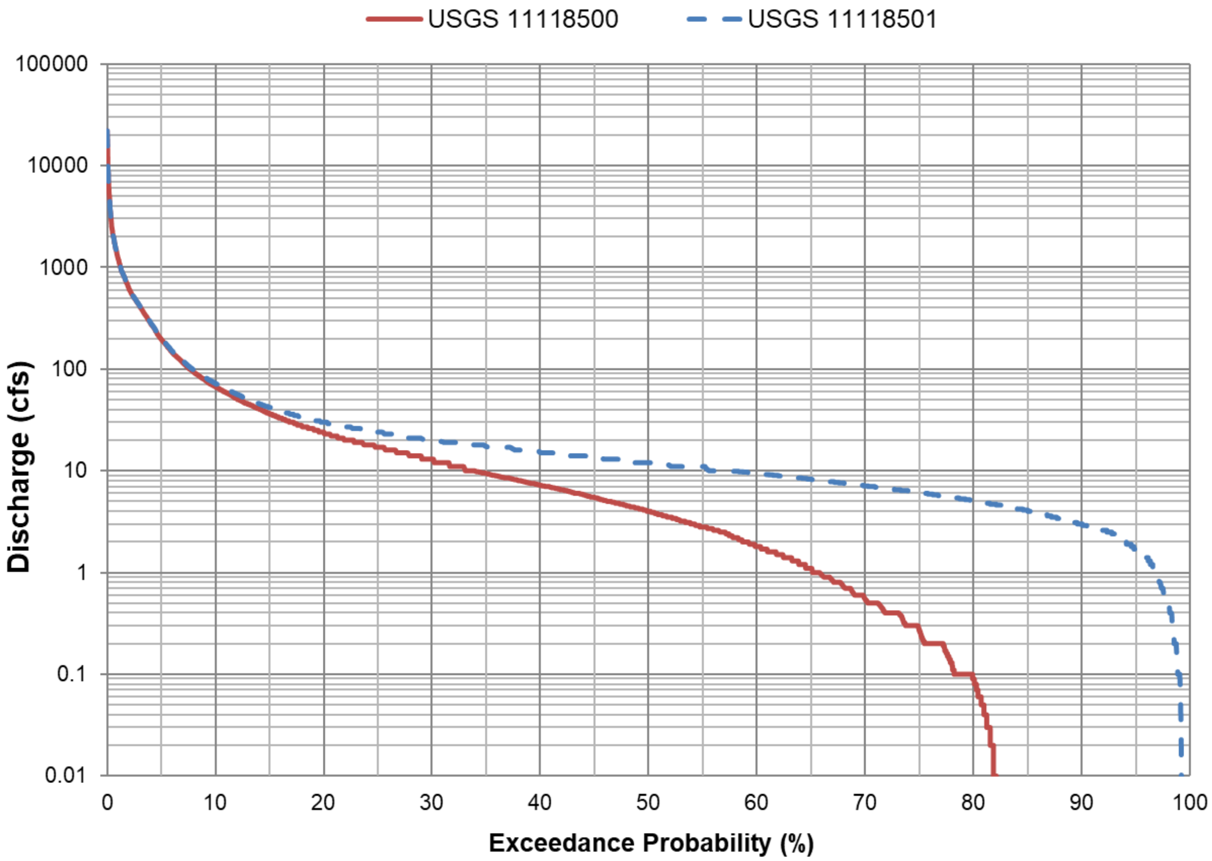

Figure 5. Percent exceedance of Ventura River flows based on average daily flows at USGS 11118500 and 11118501 for period of record water years 1933-2007 (excludes 1933, 1934, and 1936 due to missing data).

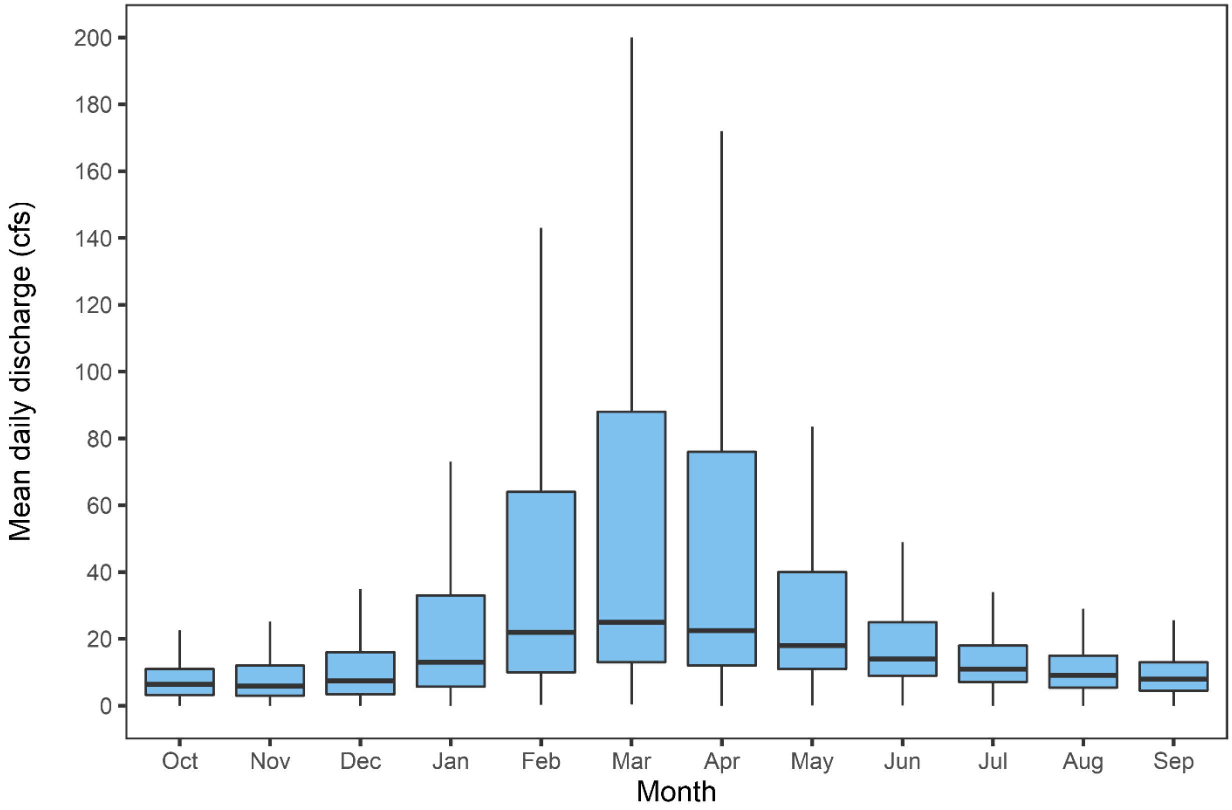

Figure 6. Boxplot of the distribution of mean daily discharge by month based on USGS 11118501 period of record water years 1933-2007 (excludes 1933, 1934, and 1936 due to missing data). Colored bars represent 25th-75th percentile values, whiskers extend to 1.5x the interquartile range, and horizontal lines are median values. Outliers are not shown.

1.4.2 Channel-forming Flows

Although evaluating the distribution of flows over the period of record can provide useful information about general patterns, these numbers can mask the highly variable hydrology within the watershed. Channel-forming, maintenance, and flushing stream flows are valuable components for developing and/or maintaining a stream's diverse morphological and hydraulic characteristics. These flows, which are generally associated with peak runoff during the winter and spring, are required to maintain the quality of the substrate and channel conditions for steelhead. Periodic storm events also cue adult steelhead migration, providing narrow windows of opportunity for passage.

The USGS 11118500 stream flow gage at Foster Park records and reports the instantaneous peak flow values for each storm event. Figure 7 illustrates the variation in timing and magnitude of instantaneous peak flows within the mainstem Ventura River during the 2017 and 2018 water years. In February 2017, a large storm event occurred with an instantaneous peak flow of 18,500 cfs recorded at USGS 11118500.

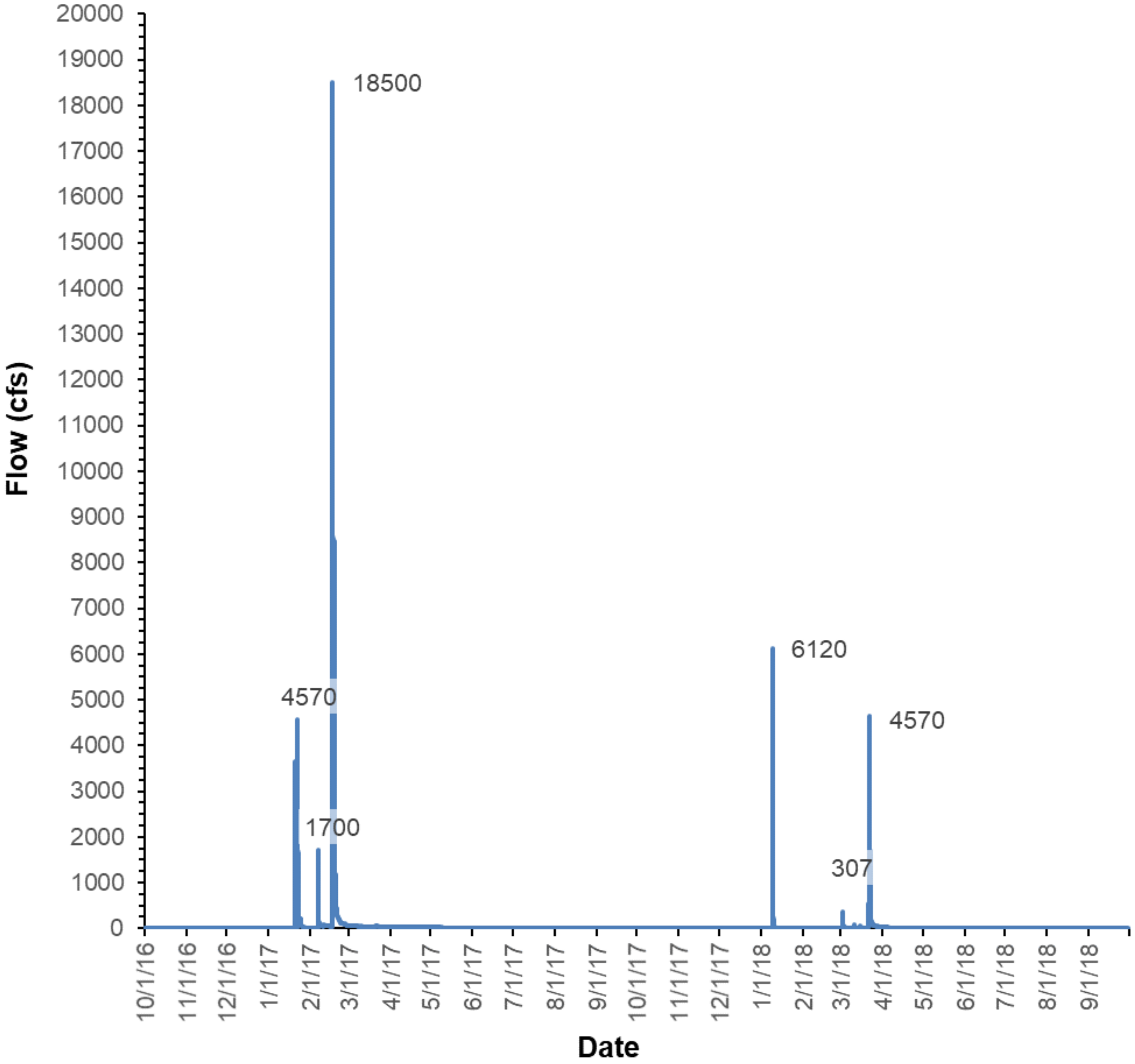

Figure 7. Flows recorded at USGS 11118500 during water years 2017-2018.

Leopold (1994) estimated that the bankfull discharge has an average recurrence interval of 1.5 years. The 1.5-year recurrence flood was determined to be 1,876 cfs using the flood frequency analysis computer program PeakFQ (Flynn et al. 2006; Veilleux et al. 2014) based on Bulletin 17C (England et al. 2019). In water years 2017-2018, the four peaks that exceeded the 1.5-year recurrence flood event threshold were assumed to be channel-forming flows (Figure 7). The February 2017 storm was the largest flow event within this two-year period (with an estimated 6.5-year recurrence interval) and likely had the greatest effect on channel topography of this series of storms. In response, the Department generated two separate models to evaluate passage conditions: Pre-storm and Post-storm. These models were designed to examine passage flows within the watershed, and to evaluate whether riffles limiting adult steelhead passage before the storm remained critical after these flood flows had altered the main channel.

2.0 OVERVIEW OF CRITICAL RIFFLE ANALYSIS

Selection of appropriate methods for an instream flow assessment is a fundamental component of the IFIM process (Bovee et al. 1998). While the most commonly applied components of the IFIM process are the hydrology and the biology components (Dunbar et al. 1998), aquatic habitat connectivity is an equally important and often overlooked element (Fullerton et al. 2010). Adult steelhead need unimpeded passage over barriers and adequate aquatic habitat connectivity to migrate to upstream perennial reaches of the watershed to spawn. Methods were selected to assess connectivity and the needs of adult steelhead moving through passage impediments.

To assess passage in this study, potential passage impediments within the Ventura River intermittent reach were identified. The impediments surveyed within the study site were all low-gradient alluvial riffles and did not present jumping barriers. Next, 2D hydraulic models were developed and combined with the Critical Riffle Analysis (CRA) method to evaluate hydraulics at riffles in the Ventura River intermittent reach. The passage assessment considered steelhead depth criteria and channel width criteria used in CRA (CDFW 2017a).

2.1 Critical Riffle Analysis

Passage assessments in alluvial river systems typically focus on riffles. Critical riffles are defined as the shallowest riffles in a stream channel and are particularly sensitive to changes in stream flow level. As flows diminish in a stream channel, the critical riffles contain the shallowest water depths, potentially reducing the channel’s overall hydraulic connectivity and/or restricting the movement of aquatic species such as adult steelhead.

Several standard methods have been developed to estimate the amount of flow needed to consider a riffle passable to salmonids (e.g., Habitat Retention, CRA, 1D Modeling, 2D Modeling). Thompson (1972) described a field-based procedure developed to identify passage flows needed for salmonids migrating through passage-limiting, flow-sensitive critical riffles. The Department developed a CRA standard operating procedure (SOP; CDFW 2017a) that is based on the Thompson methodology and applies species and life-stage-specific criteria relevant to California salmonids. The CRA SOP can be used in wadeable streams in California with low-gradient riffles (less than 4% gradient) and substrates dominated by gravel and cobble (CDFW 2017a).

The purpose of the CRA method is to identify flow conditions that support movement of salmonids through critical riffle locations. Water depths are measured in the field along the shallowest course across each riffle from bank to bank at a range of representative flow levels. Three to six field sampling events are required to generate a relationship between depth and flow, which can then be used to predict depths over a range of flows. At least one depth measurement meeting the minimum depth criterion must be recorded at each flow event for the flow event to be used in the analysis. The length of the shallowest course and depth data collected at each flow are used to create relationships between flow and the percent total or contiguous width available to migrating fish (CDFW 2017a). These relationships are used to determine the flows necessary for salmonid passage.

Minimum depth criteria used in CRA are based on the water depth needed for a salmonid to navigate over a critical riffle with enough clearance to minimize abrasion and contact with the streambed (R2 Resource Consultants Inc. 2008). The minimum depth passage criterion for adult steelhead is 0.7 ft (CDFW 2017a; R2 Resource Consultants Inc. 2008). Based on Thompson (1972) criteria, a stream channel is deemed passable when the water depth meets or exceeds the minimum required by adult steelhead as follows:

1) at least 25% of the total channel width along the shallowest course meets the 0.7-ft depth criterion; and

2) at least 10% of the longest contiguous portion of the channel width along the shallowest course meets the 0.7-ft depth criterion.

Modifications to the Thompson (1972) percent criteria have been applied in several Southern California passage studies. Entrix Inc (1999) performed an evaluation of potential passage impediments in the Ventura River that required 8 ft of channel width to meet depth criteria, in addition to 25% total and 10% contiguous width. Casitas Municipal Water District (CMWD 2017) evaluated 5-ft, 8-ft, and 10-ft contiguous length requirements in addition to the Thompson percent criteria in the Ventura River. Adaptations used in other studies within the same Monte Arido Highlands biogeographic population group include an 8-ft section applied to the Santa Ynez River (SYRTAC 1999), and 10-ft sections used in the Lower Santa Clara River (Harrison et al. 2006) and Santa Maria River (Stillwater Sciences and Kear Groundwater 2012). All of these passage studies applied shallower depth criteria (0.5 ft or 0.6 ft) which are no longer considered protective for adult steelhead (R2 Resource Consultants Inc. 2008). Using the passage depth criterion of 0.7 ft for adult steelhead, the Department calculated the flows required to meet the Thompson criteria as well as the flows required to provide 5 ft and 10 ft of contiguous width to align with modifications made by others in this region.

2.2 Critical Riffle Analysis Using Hydraulic Models

In this study, 2D hydraulic models were prepared to simulate the hydraulics at critical riffles and predict depths and widths over a range of flows because they offer multiple advantages over traditional field-intensive CRA methods. The 2D models provide an estimate of water depth over the entire river channel surveyed for the model (Gard 2009). Because the transects may be anywhere within the model, placement of the shallowest course can be optimized based on predicted water depths. The 2D models are also designed to simulate complex hydraulics that are typical of low-gradient riffles (Crowder and Diplas 2000; Ghanem et al. 1996). Finally, 2D models can estimate depths over a broad range of flow conditions that cannot be sampled directly because of timing or unsafe wading conditions.

Several studies have employed 2D models to assess passage flow needs for salmonids and other migratory fish species (Cowan et al. 2016; Grantham 2013; Reinfelds et al. 2010). The Department previously applied 2D modeling to evaluate hydraulic regimes at potential passage barriers in the Big Sur River. Holmes et al. (2015) compared fish passage flows derived from River2D modeling with flows derived from the field-based CRA method (Thompson 1972). Flows predicted using 2D modeling correlated highly with flows derived from the CRA method using only field data ($r^2=0.93$). The full overview of 2D hydraulic model development for the Ventura River study site can be found in Appendix A.

Two 2D models were built to assess depth for fish passage. The Pre-storm 2D model was constructed using the software River2D. River2D is a 2D depth-averaged finite element hydrodynamic model that is well suited for fish habitat analyses (Steffler and Blackburn 2002). The flow in defined stream segments like critical riffles can be simulated over a range of flows using 2D depth averaging models like River2D. Details on the Pre-storm River2D model construction and calibration can be found in Appendix B.

The Post-storm 2D model was constructed using the 2D unsteady flow simulation component in Hydrologic Engineering Center's River Analysis System (HEC-RAS; HEC-RAS 2018). HEC-RAS software was developed through the Hydrologic Engineering Center and available through the US Army Core of Engineers. HEC-RAS was used for the Post-storm 2D hydraulic model because the RAS-Mapper utility in HEC-RAS is raster-based and accommodates the high-resolution Light Detection and Ranging (LIDAR) data that became available after the storm. The RAS-Mapper utility allows multiple rasters to be layered together and combined into a single digital terrain model (DTM). This functionality was necessary to improve the LIDAR data with field surveys collected in the study site. Details on the Post-storm HEC-RAS model construction and calibration can be found in Appendix C.

2.3 Defining Critical Riffles in Hydraulic Models

Consistent with traditional CRA methods, flow-sensitive, passage-limiting critical riffles were identified in the field during the critical riffle survey. Staff walked upstream from the downstream boundary of the site to the upstream boundary to locate and inventory each riffle unit. Staff used topographic survey methods to record the location of the shallowest course from bank to bank across the riffle crest. The surveys were performed at lower flow levels when shallow, passage-limiting areas were most apparent. This technique helps separate out the critical riffles from riffles that appear critical at higher flows but remain passable at lower flow levels.

Riffles are characterized by the grade break that forms along the riffle crest (Leopold 1994). The CRA method functions best in alluvial systems where gravel- and cobble-sized substrates tend to concentrate along the riffle crest forming the shallowest course from bank to bank. The most passage-limiting riffle units in the study occurred where the channel was the widest, containing an irregular mixture of gravel, cobble, and boulder substrates. Figure 8 shows an example of the characteristics of the shallowest (and most passage-limiting) areas in the study site. Critical riffles were verified in the office by calculating contiguous channel widths providing adequate depth (i.e., 0.7 ft) at multiple modeled flows.

Figure 8. Riffle number 20 upstream view at approximately 17 cfs.

After the critical riffles were identified, one of two different methods was used to determine the shallowest portion of each riffle. If the riffle had a clearly defined riffle crest, the traditional CRA shallowest-course method was used. This method follows the shallowest path across the riffle and does not need to follow a straight line. This method is described in the CRA SOP and is designed for riffles dominated by gravel and cobble substrate (CDFW 2017a).

A second method was used where large cobble and boulder-sized substrate obscured the shallowest course, which was particularly common at riffles in the upper portion of the study site (see Figure 25). Where a clearly defined riffle crest was not present, one or a series of straight transects were placed perpendicular to flow in the shallowest portion of each critical riffle (Figure 9). The number of straight transects used per riffle was dependent on the complexity of the channel and difficulty in determining the shallowest location. This straight-transect approach has been adopted by other studies in the region when no obvious riffle crest was present (CMWD 2010; Entrix Inc 1999; Stillwater Sciences and Kear Groundwater 2012).

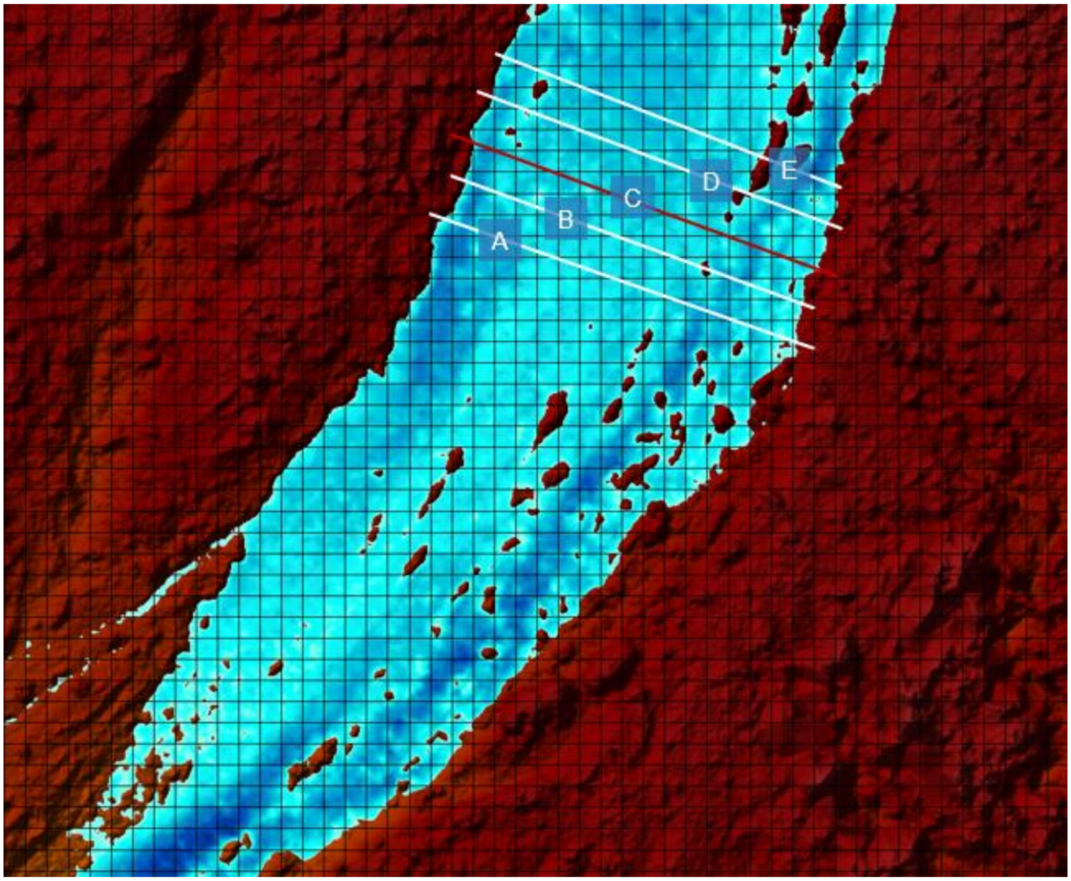

Figure 9. HEC-RAS 2D imagery of Post-storm riffle 20 modeled at 200 cfs with a series of straight transects. The most passage-limiting transect line is indicated in red. Gridlines indicate two-meter spacing. Depth display scale of 0 ft to 1 ft (light and dark blue, respectively).

3.0 SITE SELECTION

The Department selected a representative study site within the intermittent reach (Figure 2) that was consistent with earlier critical riffle study locations and allowed for evaluation of critical riffle passage impediments previously monitored by CMWD[b] (CMWD 2010; CMWD 2017). One of these riffles (i.e., CMWD Site 5) was originally located just downstream of the Santa Ana Bridge. CMWD (2010) surveyed riffles in two channels at CMWD Site 5 (i.e., Site 5-1 and Site 5-2), in addition to six other impediment sites. Results from CMWD (2010) indicated that at seven of the eight survey riffles, all four fish passage criteria assessed by CMWD were met with a flow of 138 cfs or lower[c]. The highest required flow of 138 cfs came from Site 5-2. By comparison, at riffle CMWD Site 5-1, flows of 431 to 3,289 cfs were required to meet passage criteria (as determined through standard and origin-forced regression). The site for the Department's study was selected to allow for evaluation of CMWD Site 5.

The upstream and downstream limits of the site were determined by requirements of 2D modeling as follows: 1) the length of the site must be equal to 4% or more of the length of the study reach (i.e., the intermittent reach); and 2) the downstream and upstream boundaries of the site must be in locations where the river forms one single-thread channel (USFWS 2011). The upstream model boundary, referred to here as cross section 2 (i.e., XS-2), was placed upstream of CMWD Site 5, but downstream of the Santa Ana bridge, where the river was a single-thread channel. The channel became multi-thread immediately downstream of CMWD Site 5, so the downstream model boundary was placed approximately 1.3 mi downstream of the upstream boundary (approximately 385 meters (m) upstream of the confluence with San Antonio Creek; Figure 10). The February 2017 storm did not affect the location of the upstream boundary of the Post-storm 2D model, but the downstream model boundary, cross section 1 (i.e., XS-1), was moved downstream of its original location. The downstream end of the braided portion of the channel migrated approximately 80 m downstream, so the location of the downstream boundary was adjusted to allow XS-1 to be placed in a single-thread channel (see Section 4.1, Figure 11). The study site represents approximately 22% of the study reach by length which exceeds the 4% minimum requirement.

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[b] CMWD implemented an upstream fish migration impediment evaluation study as outlined in the NMFS (2003) Biological Opinion of the Robles Fish Passage Facility. Potential critical riffles were chosen by CMWD based on impediment metrics; passage impediments have been evaluated since 2009 (CMWD 2010; CMWD 2017), and include riffles previously assessed by Entrix Inc (1999).

[c] The criteria used by CMWD to evaluate the amounts of depth and width needed for fish passage are not the same as those used by the Department in this report.

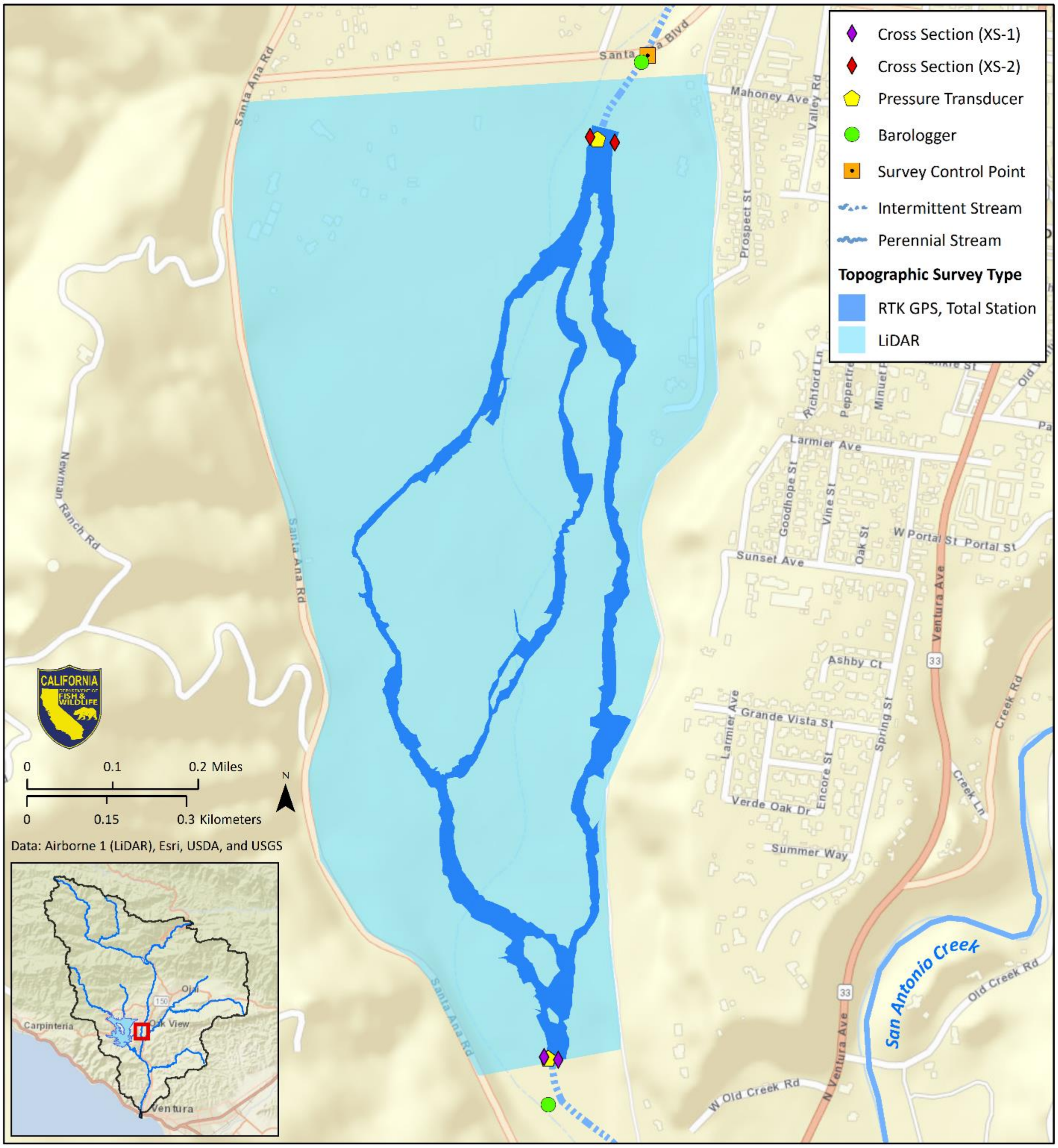

Figure 10. Pre-storm model survey boundaries in the intermittent reach study site. The dark blue and light blue colors indicate areas surveyed using RTK GPS/total station or LIDAR, respectively. Pressure transducers, barologgers, survey control point, and model boundary cross section locations are indicated.

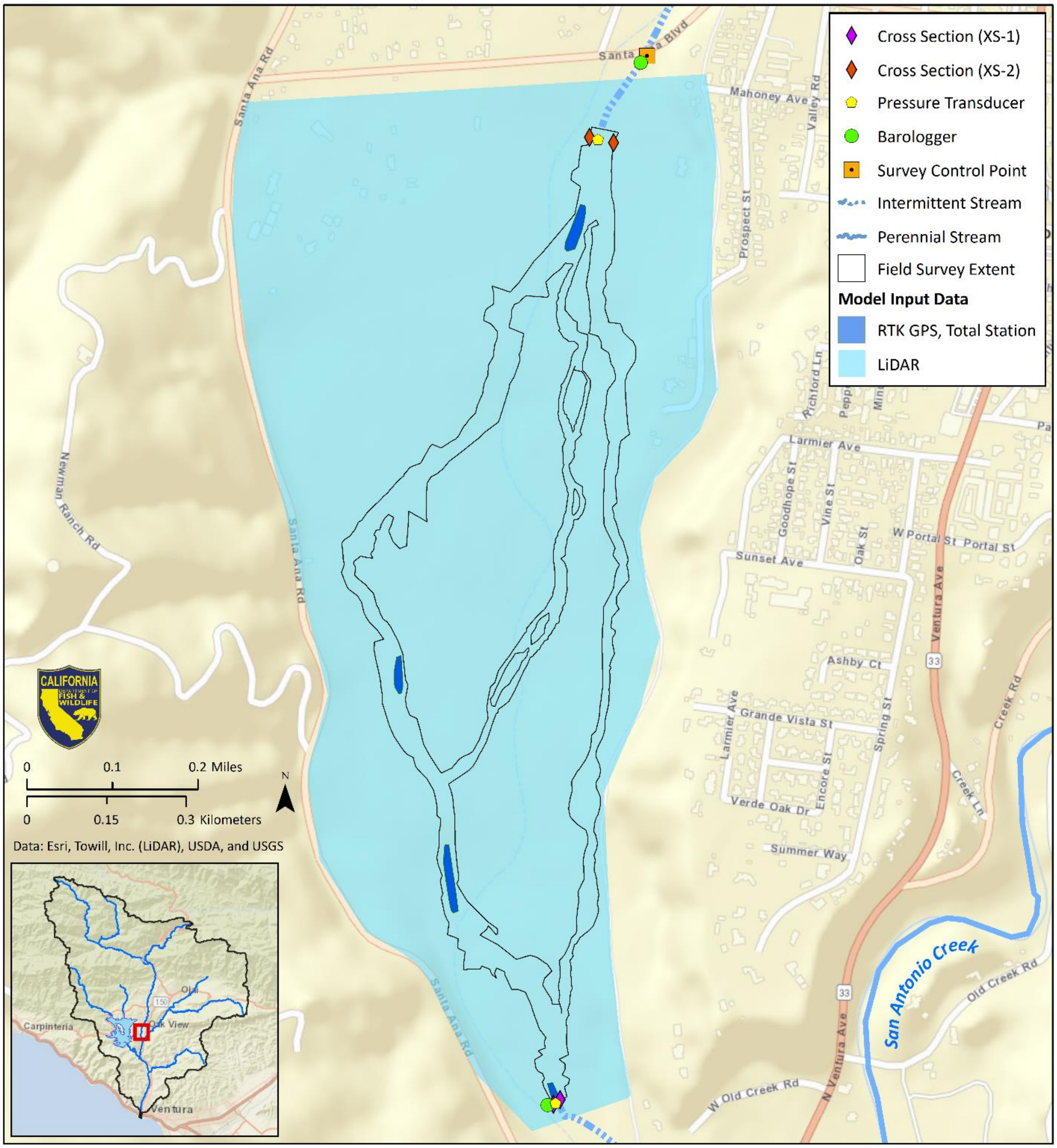

Figure 11. Post-storm model survey boundaries in the intermittent reach study site. The dark blue and light blue colors indicate areas of RTK GPS/total station or LIDAR model input data, respectively. Pressure transducers, barologgers, survey control point, and model boundary cross section locations are indicated.

4.0 DATA COLLECTION

This section describes the methods and protocols used to collect all the data required for the Pre-storm and Post-storm 2D models. 2D model inputs include bed topography, estimates of discharge, and water surface elevations (WSELs). The method-specific data collection standards and protocols are described in further detail in the following sub-sections. Details of 2D model construction and calibration are found in Appendices A, B, and C.

4.1 Topographic Data Collection

The foundation for 2D model simulations are topographic survey points, which are used to create a DTM that characterizes the bed topography of the study site. Topographic data are collected with a stratified sampling scheme, with higher intensity sampling in areas with complex, varying microhabitat features, and lower intensity sampling in areas with uniform bed topography, substrate, and cover. Bed topography, substrate, and cover mapping data were collected at low flows when most of the riverbed was dry. Bed topographic data were collected between the upstream and downstream model boundary cross sections by obtaining the bed elevation and horizontal location of individual points.

To collect topographic survey points for the 2D digital terrain models, survey-grade RTK GPS, total station topographic survey, and LIDAR were used in combination (Figure 10; Figure 11). The Pre-storm model used RTK GPS and total station data instream, and relatively coarse, 10-ft (3-m) resolution LIDAR data flown in 2005 in the overbank areas (Figure 10). The Post-storm model used quarter-meter resolution LIDAR data flown in 2018 for the entire study area. RTK, GPS, and total station data surveyed after the February 2017 storm were used to fill in large, inundated pool areas where the LIDAR resolution proved less accurate than the topographic survey data collected by staff (Figure 11). The only data needed at higher flows were WSELs on the site’s upstream and downstream boundary cross sections. As the Ventura River could not be safely waded at flows above approximately 100 cfs, WSELs at these higher flows were estimated using pressure transducers (PTs) installed in the riverbed along the boundary cross sections.

Bed topography data were collected between the upstream and downstream model boundary cross sections within the main channel using RTK GPS survey instruments (Figure 12) and a total station (Figure 13). The topographic survey data points consisted of bed elevation and horizontal location. Higher densities of bed topography data points were collected within the channel bed, particularly around hydraulically complex portions of the stream channel and areas of varied bed elevations. The total number and density of data points collected for each model are presented in Table 1.

Figure 12. Collecting terrain model data in the study site using RTK GPS.

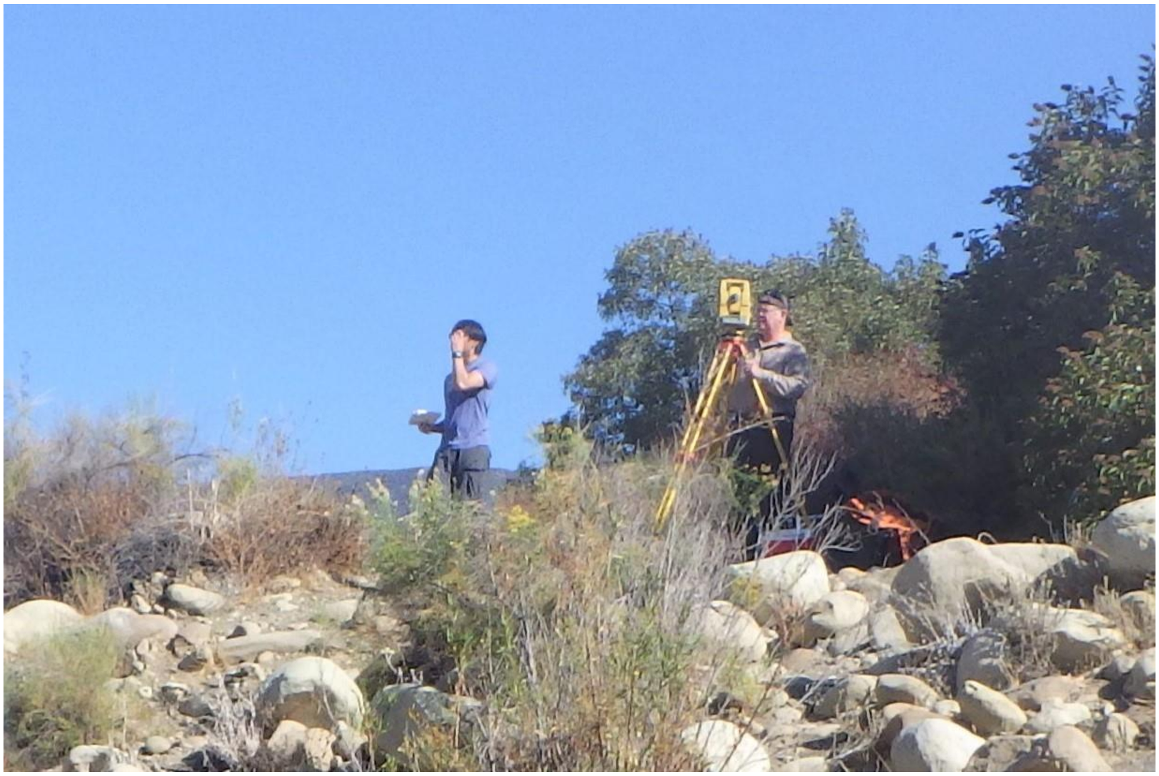

Figure 13. Collecting terrain model data in the study site using a total station.

Table 1. RTK GPS/total station point density.

Model	Surveyed Area (m^2)	Points	Points/m^2	m^2/Point
Pre-storm	124,137	11,786	0.1	10.5
Post-storm	162,298	26,379	0.2	6.2

Quality assurance practices were implemented throughout data collection to ensure an accurate 2D model of the study site. Staff met at the RTK GPS base station during each collection event to ensure each RTK GPS roving unit (RTK rover) was properly set up before collecting data. Staff established benchmarks for the total station with RTK rovers to ensure an accurate azimuth angle. The RTK rovers were set at a consistent height of two meters, and each RTK rover was leveled using a rod mounted bubble before each point was collected. The precision of the fixed signal was preset on each RTK rover (Figure 14) to less than 0.03 m (0.1 ft) in the vertical and 0.015 m (0.05 ft) in the horizontal. To ensure quality control, staff members independently measured the height of the instrument during set up. The total station was leveled during each set up and backsight checks were performed hourly to ensure radial and vertical control.

Point 13604
Elev 109.804
2.000

Figure 14. RTK GPS rover handheld data collector showing bed topography data points.

Each data point collected through RTK GPS or total station was assigned a cover and substrate code (see Appendix B). Substrate and cover coding were used to characterize bed roughness within the 2D models.

4.2 LIDAR

The field topographic survey concentrated on the main channel and two extensive side channels (Figure 10; Figure 11). The field survey data were supplemented with LIDAR data available from the Ventura County Flood Authority. The LIDAR data were used to populate multiple areas, including overbank areas, floodplains, areas overrun by *Arundo donax*, locations too steep to safely survey with RTK GPS or total station, and private property within the study site. Two different LIDAR flights are available through Ventura County's web portal. The 2005 LIDAR flight covered the entire site and had a resolution of one point every 3 m^2. The LIDAR dataset flown in January-February 2018 was collected in response to the Thomas Fire with a much finer resolution of one point every 0.25 m^2. The 2018 LIDAR was flown at a low flow of approximately 3 cfs.

The 2005 LIDAR dataset was used to supplement the Pre-storm model. The 2018 LIDAR dataset was used for the Post-storm model, which was supplemented with RTK GPS and total station data in inundated areas. For the Pre-storm model, substrate and cover codes were assigned to the LIDAR data in ArcGIS using Theissen polygons derived from the total station and RTK GPS points. For the Post-storm model, the LIDAR points were assigned a default substrate code of nine and cover code of zero. Further information on the LIDAR datasets and metadata are available in Appendix A.

4.3 Pressure Transducers and Barometric Pressure Loggers

The relationship between water level and flow magnitude is the key component in calibrating 2D models. A WSEL is a water level referenced to a ground elevation. Normally, WSELs are measured directly in the field at distinct flows targeted for analysis, referred to as calibration flows. If expected calibration flows are too high for staff to safely measure directly, flows must be estimated using data from nearby stream gages. Water stage can be measured by installing PTs, which continuously measure water level when the river is flowing above safe data collection levels. These PTs are installed along the boundary cross sections of a study site. The PTs are used in conjunction with a nearby barologger, which measures absolute pressure. Pressure data is compensated by subtracting the barometric pressure and converting the remaining water pressure to water level. A WSEL is then computed by adding the water level to the surveyed elevation of the PT probe.

Pressure transducers were installed at the upstream and downstream model boundary cross sections of the study site to record water level (Figure 10; Figure 11). Solinst

Levelogger® Edge Model 3001 PTs were installed to monitor the flow pattern and recession in the Ventura River intermittent reach and between 2016 and 2018 (Table 2). Four PTs were originally installed in October 2016, with two PTs installed along each boundary cross section for redundancy in the case of loss or disturbance of one of the PTs. The PTs were non-vented sensors that read absolute pressure and measured water depth and temperature at 15-minute intervals. The PTs were installed in pools where the water surface directly above the PT probe was still, and where the riverbed appeared to be stable. Installation in pools ensured that PTs remained submerged for as long as possible during periods of low flow. The location and elevation of each PT was surveyed using the RTK GPS.

In addition, two Solinst barometric pressure loggers (barologgers) were installed in October 2016. Each barologger was installed to compensate the PT data for atmospheric pressure. Barologgers were installed near the PTs at the upstream and downstream boundaries. Data were periodically downloaded from the loggers through the study period.

Table 2. PTs and Barologgers used in 2D modeling.

Name	Boundary Cross Section	Date Installed	Date Recovered
Pre-storm PT6	Upstream	10/26/2016	3/7/2017
Pre-storm PT7	Upstream	10/26/2016	Missing
Pre-storm PT10	Downstream	10/26/2016	11/14/2017
Pre-storm PT11	Downstream	10/26/2016	11/14/2017
Post-storm PT6b	Upstream	4/4/2017	Missing
Post-storm PT14	Downstream	4/4/2017	5/21/2018
Post-storm PT15	Downstream	4/4/2017	5/21/2018
Barologger B-1	Upstream	10/25/2016	1/12/2018
Barologger B-2	Downstream	10/25/2016	1/12/2018

Each PT was inserted into a length of PVC pipe to act as a stilling well. The PT was then lashed to a 1.5-inch male cleanout plug and fit into the PVC through a 1.5-inch female adapter. A cap was attached to the opposing end of the PVC. Steel rebar were driven into the substrate to secure the stilling wells, which were lashed to the rebar using stainless steel hose clamps. The stilling wells were perforated to allow the water surface level inside the stilling well to match the outside stream level (Figure 15; Figure 16), while also protecting the PTs from the wave action of flowing water and from damage. Stilling well construction and deployment of PTs were adapted from the traditional vault technique found in the State of Utah Division of Water Quality SOP (DWQ 2014). Adaptations were essential for the PTs to withstand high flows and heavy debris seasonally occurring in the Ventura River mainstem. The PTs must remain stationary to collect consistent data (DWQ 2014).

Figure 15. Pre-storm PT7 installation near the upstream boundary.

Figure 16. Post-storm PT6b installation near the upstream boundary.

The 2017 storm event and subsequent flooding deposited enough alluvial substrate in the study site to move the stream channel and bury some of the PTs. Three of the four Pre-storm PTs were recovered and downloaded (Table 2). One PT at the upstream boundary (PT7) was not retrievable as the flooding event either washed away the PT or buried it.

In April 2017 two new PTs were installed at the downstream boundary, and a recovered PT was reinstalled at the upstream boundary. Both PTs installed at the downstream boundary were recovered on May 21, 2018. The PT reinstalled at the upstream boundary (PT 6b) could not be retrieved. An RTK GPS was used to locate the exact spot where the PT had been installed and a metal detector (Schonstedt GA-52Cx Magnetic Locator) was used to search the area. The search indicated that the PT was dislodged and not recoverable.

4.4 Critical Riffle Survey

Among the three channels in the braided study site, the most westward channel stayed hydraulically connected the longest after storm events and was the focus of the passage assessment (see Figure 10; Figure 11). Because the main channel is more likely to support steelhead migration, low-gradient riffles were identified along this channel and were evaluated as potential barriers to adult steelhead passage. As flows increase in the study site, water diverted into side channels. As a result, depth in the main channel did not consistently increase with rising flow.

Prior to the February 2017 storm, staff had not yet had the opportunity to walk up the river under low flow conditions to identify the locations of passage-limiting critical riffles. The absence of the critical riffle survey was overcome using the Pre-storm model results for water depth in conjunction with locations of riffles identified during a Post-storm survey. Staff conducted a riffle survey during April 4-6, 2017, hiking from the downstream boundary to the upstream boundary of the study site. Staff identified 22 potentially critical riffles within the study site (Figure 17). Transects were established across each riffle, and the RTK GPS units were used to survey the shallowest course from bank to bank, which was typically not a straight line (Figure 18). The flow in the main channel was measured each day at the downstream boundary cross section, XS-1, consistent with the Department’s SOP for collecting discharge measurements (CDFW 2013a). The flow was approximately 19 cfs on April 4, and approximately 17 cfs on April 5 and 6.

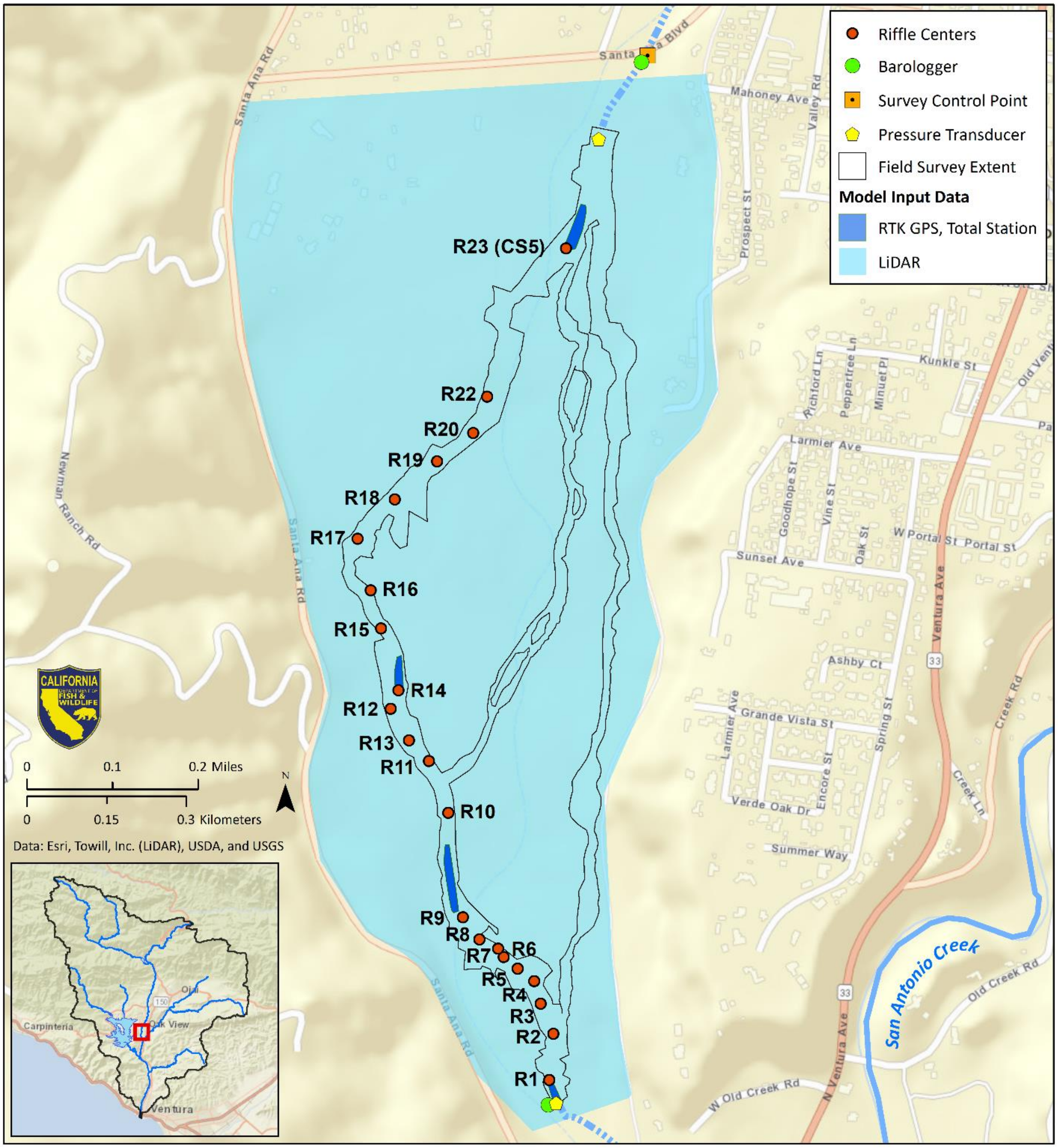

Figure 17. Map of riffles surveyed during April 2017 (Post-storm). Riffle 23 is at the same approximate location of CMWD Site 5 (CS5) identified in the CMWD Robles Monitoring and Evaluation Study (CMWD 2010).

Figure 18. Surveying points across a riffle in the Ventura River intermittent reach study site. Riffle R15, downstream view at approximately 17 cfs.

Figure 17 shows the location of surveyed riffles, with riffle R23 at the same approximate coordinates as CMWD Site 5 (CMWD 2010). CMWD Site 4 was not identified within the main channel during the Post-storm survey and is not shown in Figure 17. The February 2017 storm rearranged the stream channel braids in the lower portion of the site, placing the CMWD Site 4 coordinates in an abandoned portion of the stream channel outside the main channel survey area.

5.0 RESULTS

This section presents the results of the 2D hydraulic habitat modeling to evaluate water depths for adult steelhead passage through shallow critical riffles within the study site. Two different 2D models were prepared to estimate adult steelhead passage depths before and after a large channel-forming flow event that occurred in February 2017. The Pre-storm model was prepared using River2D and the Post-storm model was prepared using HEC-RAS 2D. Model construction and calibration is described in Appendix B for the River2D model and Appendix C for the HEC-RAS model. Channel alterations due to high flows impacted the flow-water surface calibration of the 2D models. Model calibration is discussed further in Appendices A, B, and C.

5.1 Critical Riffle Identification in 2D Models

The results of the critical riffle survey in April 2017 (see Section 4.4) and visualization of water depths in the channel at different flows from both 2D models were used to identify the most passage-limiting areas in the study site before and after the February 2017 storm event. The critical riffle survey locations were verified by visually identifying shallow locations in the Post-storm model throughout the reach at a series of modeled flows; 200 cfs is depicted in Figure 19.

In the Post-storm model, the initial assessment of each of the 22 potential critical riffles was conducted using the field-assigned shallowest course (see Section 4.4). Riffles were evaluated by computing the longest contiguous segment in each riffle meeting the 0.7-ft depth criterion at modeled flows of 50 and 100 cfs (Table 3). All riffles bolded in Table 3 were considered potentially passage-limiting riffles and are further evaluated in Section 5.3.

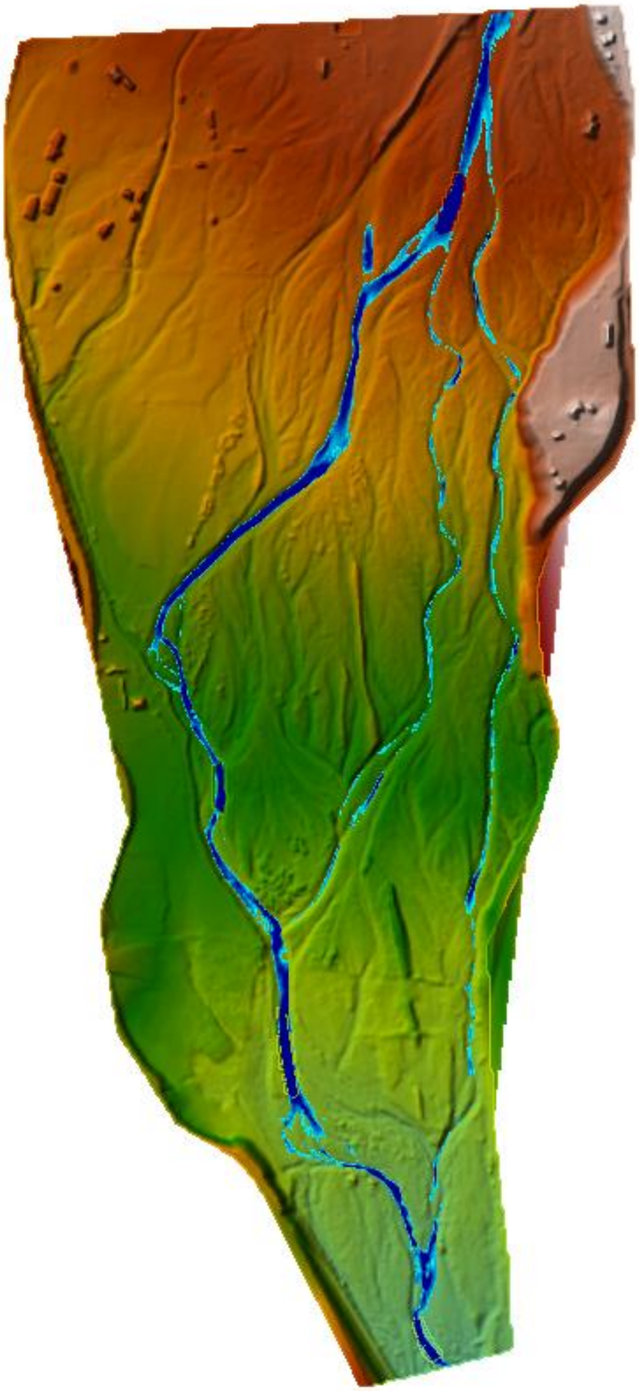

Figure 19. Post-storm 2D HEC-RAS model of the Ventura River study site at 200 cfs with depth scale set to 0 ft to 1 ft (light and dark blue, respectively).

Table 3. Riffles identified during the Post-storm field survey in April 2017[d]. Feet of contiguous width meeting the 0.7-ft depth criterion along the CRA shallowest course at 50 and 100 cfs. Riffles identified for further evaluation are noted with a dagger (†). The abbreviation SC signifies a riffle located in a side channel. Riffles in side channels were not evaluated further.

Riffle	Contiguous Width (ft) at 50 cfs	Contiguous Width (ft) at 100 cfs
R23†	**0.8**	**1.9**
R22	SC	SC
R20†	**1.0**	**1.7**
R19	38.8	39.6
R18	2.5	14.4
R17	34.3	36.0
R16†	**2.5**	**13.9**
R15	47.5	51.6
R14	5.9	21.2
R13	19.7	20.1
R12†	**2.3**	**10.8**
R11	47.4	51.1
R10	5.5	18.7
R9	24.0	30.5
R8†	**0.2**	**2.6**
R7	SC	SC
R6	SC	SC
R5	31.8	34.7
R4	47.0	51.3
R3	24.6	26.1
R2†	**5.6**	**13.8**
R1	32.4	41.7

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[d] Riffle 23 is at the same approximate location of CMWD Site 5 identified in the CMWD Robles Monitoring and Evaluation Study (CMWD 2010).

The following figures present examples that illustrate some of the differences between riffles assessed for this study. Riffle R20 was identified as one of the most passage-limiting areas in the Post-storm model, and shallow depths cover much of the channel at 200 cfs (Figure 20). Riffles R18 (Figure 21) and R12 (Figure 22) were examples of less critical riffles, where channel width meeting the 0.7 ft-depth criterion increased rapidly as flow increased.

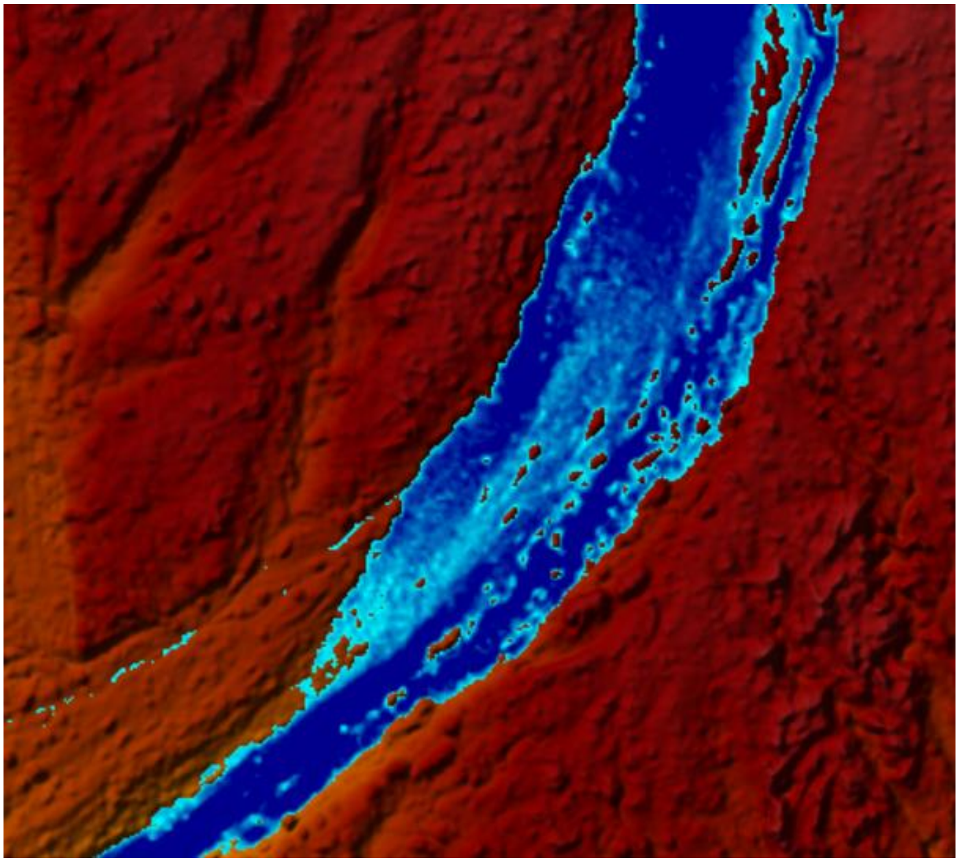

Figure 20. Post-storm critical riffle R20 at 200 cfs with depth display scale set to 0 ft to 1 ft (light and dark blue, respectively).

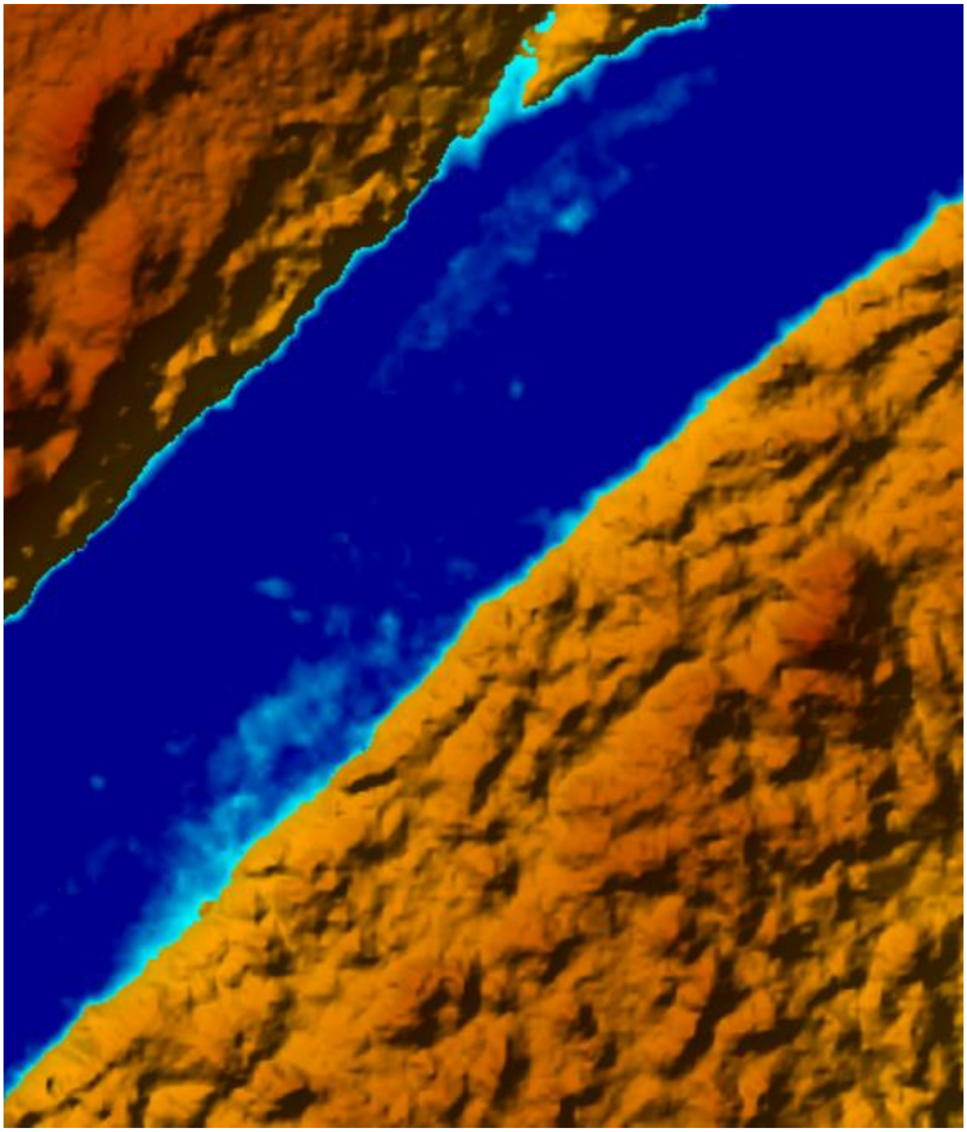

Figure 21. Riffle survey site R18 in the Post-storm model at 200 cfs with a depth display scale of 0 ft to 1 ft (light and dark blue, respectively).

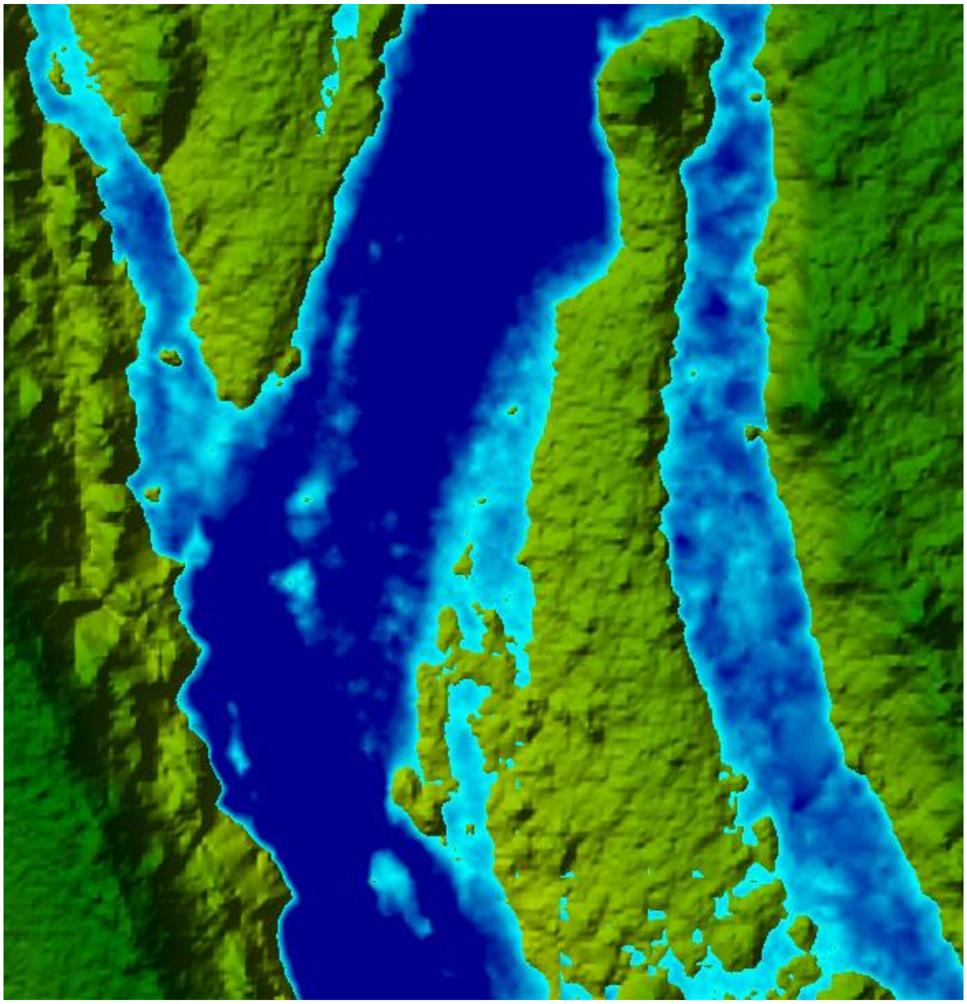

Figure 22. Riffle survey site R12 in the Post-storm model at 200 cfs with a depth display scale of 0 ft to 1 ft (light and dark blue, respectively).

Potentially passage-limiting riffles were not identified in the field for the Pre-storm model, so the process for evaluating potential critical riffles was slightly different. The most passage-limiting areas in the Pre-storm model were identified by searching the Pre-storm model water depth visualization at a variety of flows near the Post-storm critical riffle survey locations. The Pre-storm River2D model depths at 200 cfs are shown in Figure 23. After the passage-limiting sites were selected in the Pre-storm model using the general locations derived from the Post-storm critical riffle field survey, the rest of the main channel Pre-storm model was reviewed to ensure there were no other potentially passage-limiting critical riffles remaining that had not been previously identified.

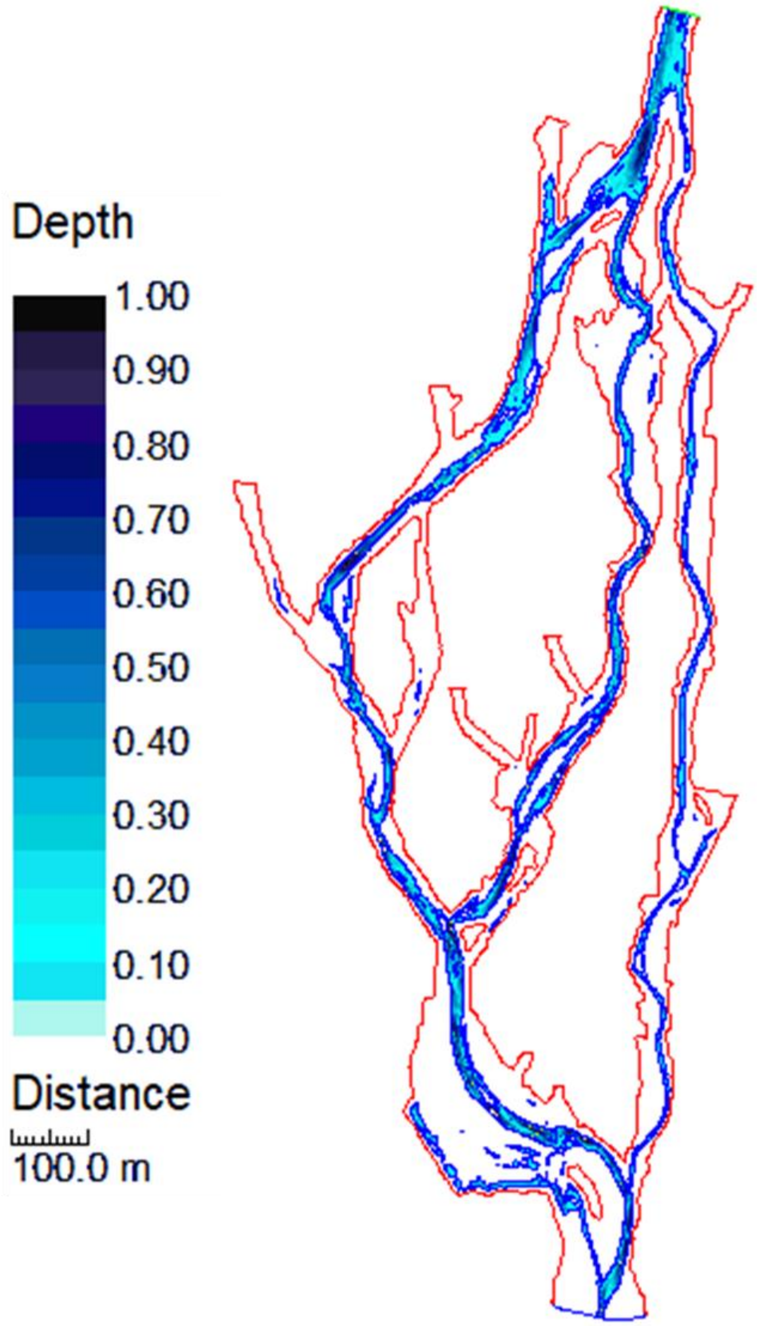

Figure 23. River2D Pre-storm model of the Ventura River study site indicating water depth at 200 cfs. Red border indicates the spatial extent of the model. Downstream boundary (XS-1) indicated by blue line at the downstream extent, and upstream boundary (XS-2) indicated by green line at upstream extent.

A total of 11 flow-sensitive riffles were selected in the Pre-storm model as potentially limiting adult steelhead passage (Table 4; Figure 24). Ten riffles were initially identified in the Pre-storm model using the process outlined above (Table 4), including riffle R23, representing CMWD Site 5 (Figure 17). An eleventh riffle, CS4, was included to represent CMWD Site 4[e]. Riffles in the Pre-storm model that were closest to Post-storm riffle coordinates were given the same riffle name but were not necessarily considered to be identical to the previously identified riffle.

After the 11 riffles had been identified, the CRA shallowest course was identified across each riffle to determine which riffles were likely to limit steelhead passage the most. Contiguous widths along each shallowest course were calculated at 50, 100, and 150 cfs, similar to the process used for the Post-storm model. The set of riffles with the lowest contiguous width meeting the 0.7-ft depth criterion at 150 cfs were selected for further analysis (bolded in Table 4).

Table 4. Potential critical riffles identified using the River2D Pre-storm model[f]. Feet of contiguous length along the CRA shallowest course meeting 0.7-ft depth criterion at 50, 100, and 150 cfs. Riffles identified for further evaluation are noted with a dagger (†).

Riffle	Contiguous Width (ft) at 50 cfs	Contiguous Width (ft) at 100 cfs	Contiguous Width (ft) at 150 cfs
R23†	**0.0**	**0.0**	**0.0**
R22†	**0.0**	**0.0**	**0.0**
R20†	**0.0**	**0.0**	**2.0**
R18†	**2.5**	**4.0**	**4.0**
R15	0.0	10.6	14.1
R14†	**1.5**	**2.0**	**4.0**
R11†	**0.0**	**0.0**	**5.0**
R9	5.0	10.0	16.0
R8	11.0	20.0	23.0
CS4†	**1.5**	**7.0**	**9.0**
R1	1.4	4.4	11.3

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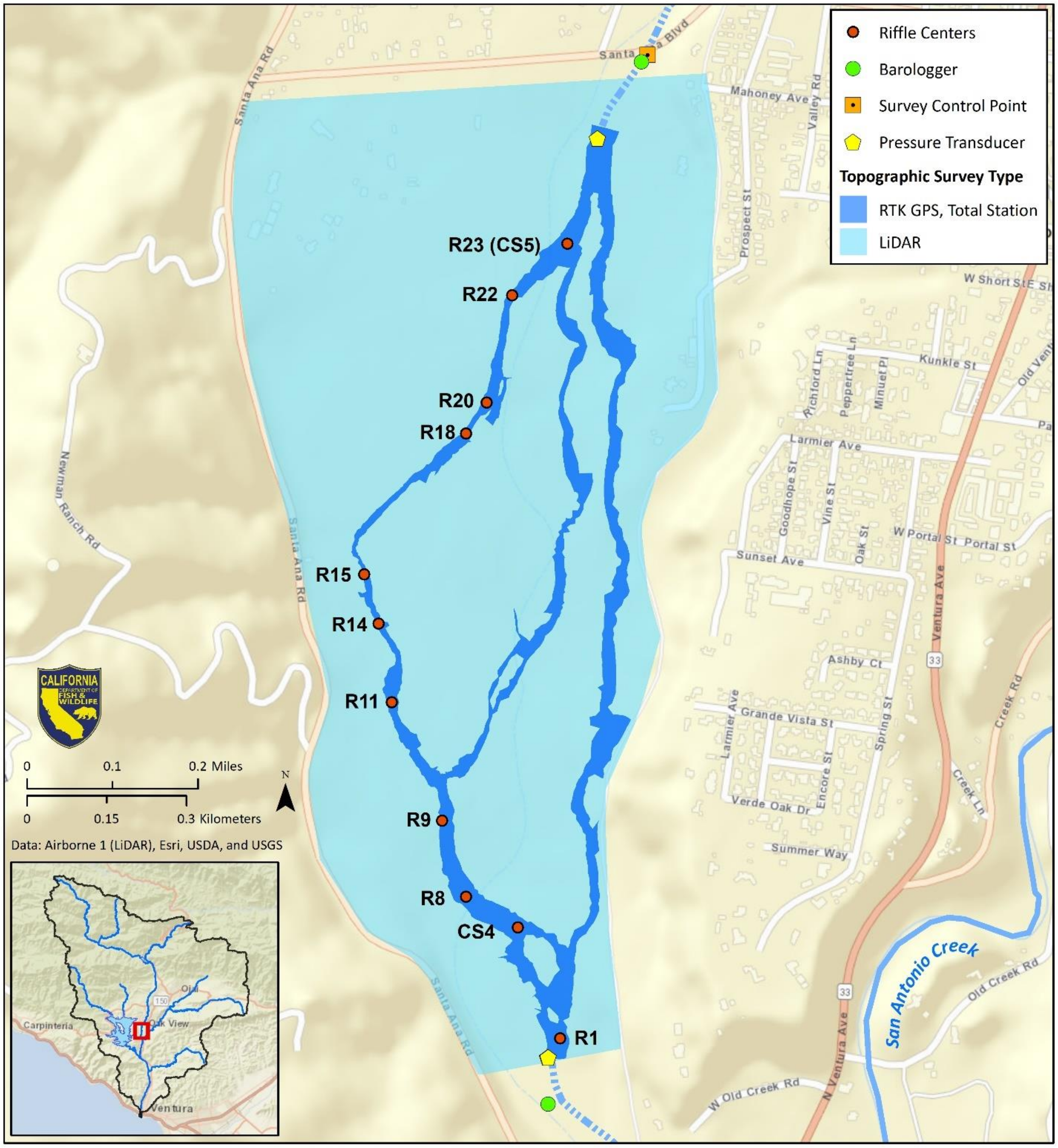
[e] CS4 was not apparent in the Post-storm survey because the portion of the river containing riffle CS4 became an abandoned side channel during the February 2017 storm.

[f] R23 and CS4 are at the same approximate locations as CMWD Site 5 and CMWD Site 4, respectively, in the CMWD *Robles Monitoring and Evaluation Study* (CMWD 2010).



Data: Airborne 1 (LiDAR), Esri, USDA, and USGS

Figure 24. Map of Pre-storm riffles identified using Post-storm coordinates.

Following this initial assessment, a detailed analysis was conducted on 13 riffles, including seven from the Pre-storm model and six from the Post-storm model. Where large boulders covered the shallowest portion of the transect and a clearly defined riffle crest was not present, the initial CRA shallowest-course transects were replaced with one or several straight transects (Figure 25; see more discussion in Section 2.3). Final transect locations are shown using River2D imagery for the Pre-storm riffles (Figures 26 through 30) and HEC-RAS 2D imagery for the Post-storm riffles (Figures 9, 31, and 32).

Flow simulations were run in both models from 50 cfs up to 500 cfs in the Pre-storm model and 400 cfs in the Post-storm model in increments of 5 to 100 cfs (Appendices D and E). The model calibration information for those flow simulations is provided in Appendix B for the Pre-storm River2D model and in Appendix C for the Post-storm HEC-RAS model. Results are presented in section 5.2 (Pre-storm model) and 5.3 (Post-storm model).

Figure 25. R23 partial upstream view at approximately 17 cfs.

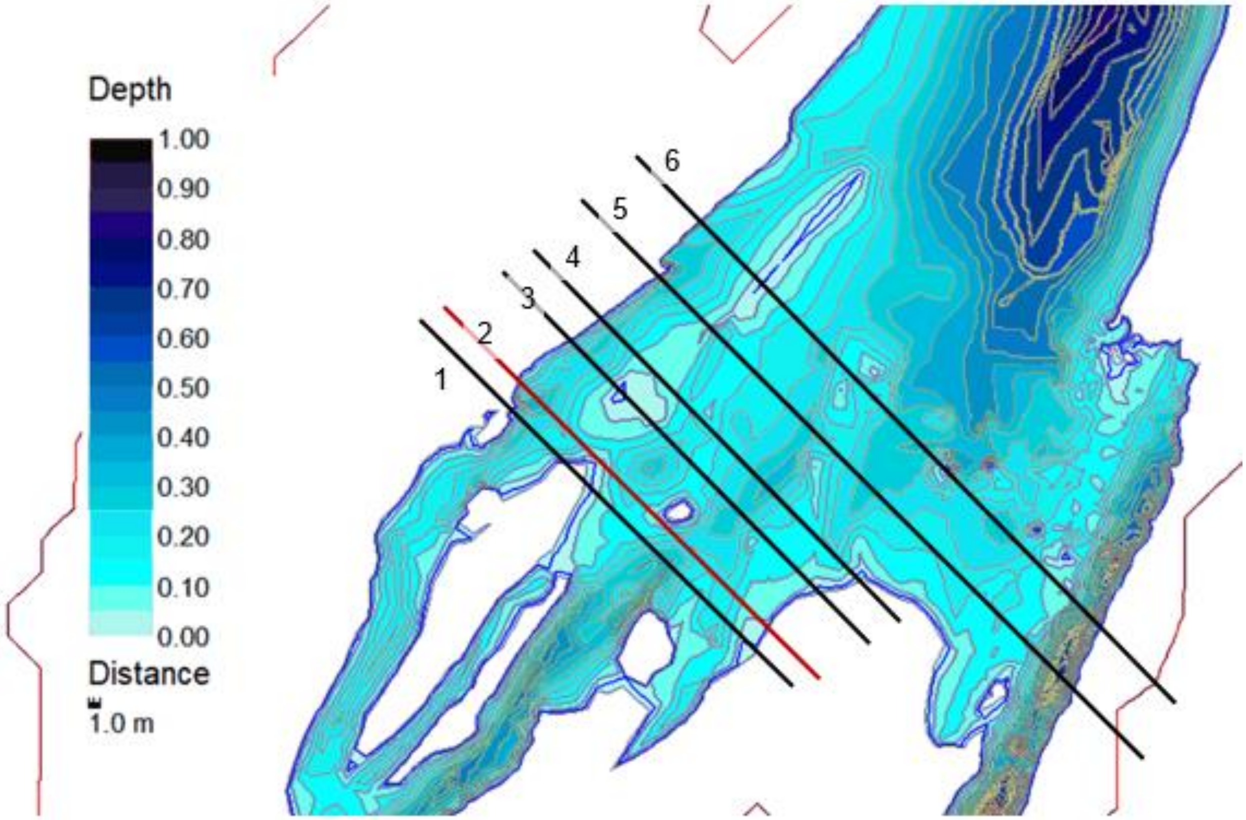


Figure 26. River2D imagery of Pre-storm R23 modeled at 200 cfs with six straight transects. The most passage-limiting transect line is indicated in red. Contour intervals at 0.03 m. White areas within the boundaries indicate out of water.

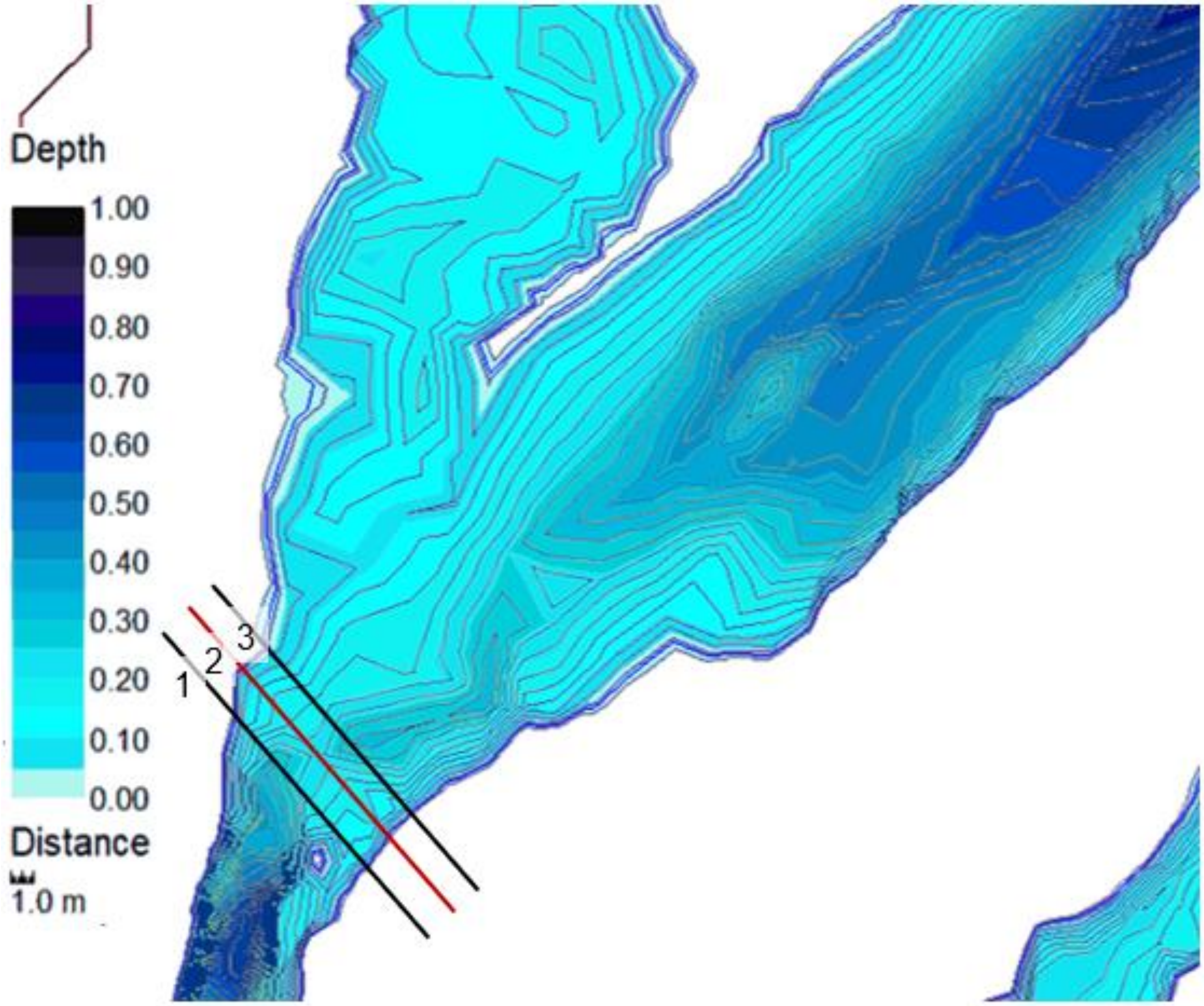


Figure 27. River2D imagery of Pre-storm R22 modeled at 200 cfs with three straight transects. The most passage-limiting transect line is indicated in red. Contour intervals at 0.03 m. White areas within the boundaries indicate out of water.

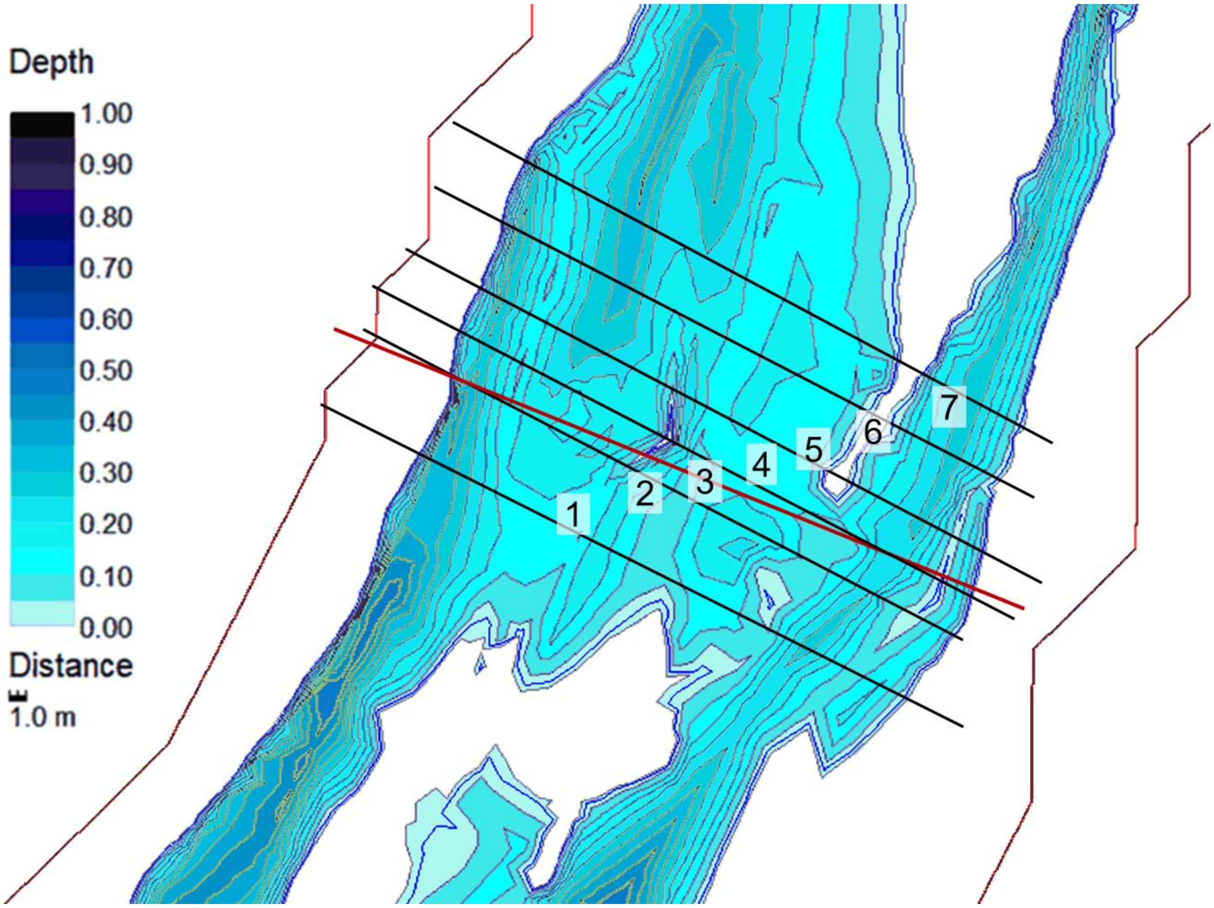


Figure 28. River2D imagery of Pre-storm R20 modeled at 200 cfs with seven straight transects. The most passage-limiting transect line is indicated in red. Contour intervals at 0.03 m. White areas within the boundaries indicate out of water.

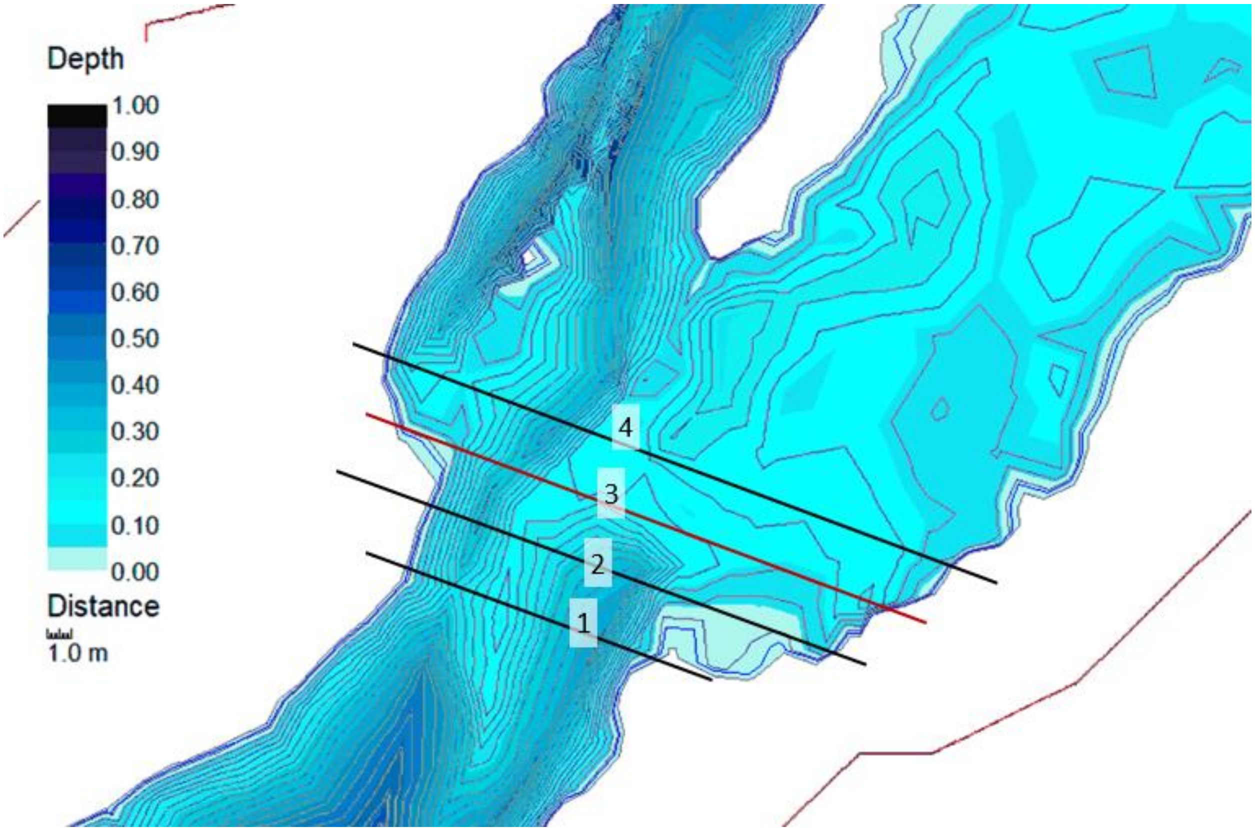


Figure 29. River2D imagery of Pre-storm R18 modeled at 200 cfs with four straight transects. The most passage-limiting transect line is indicated in red. Contour intervals at 0.03 m. White areas within the boundaries indicate out of water.

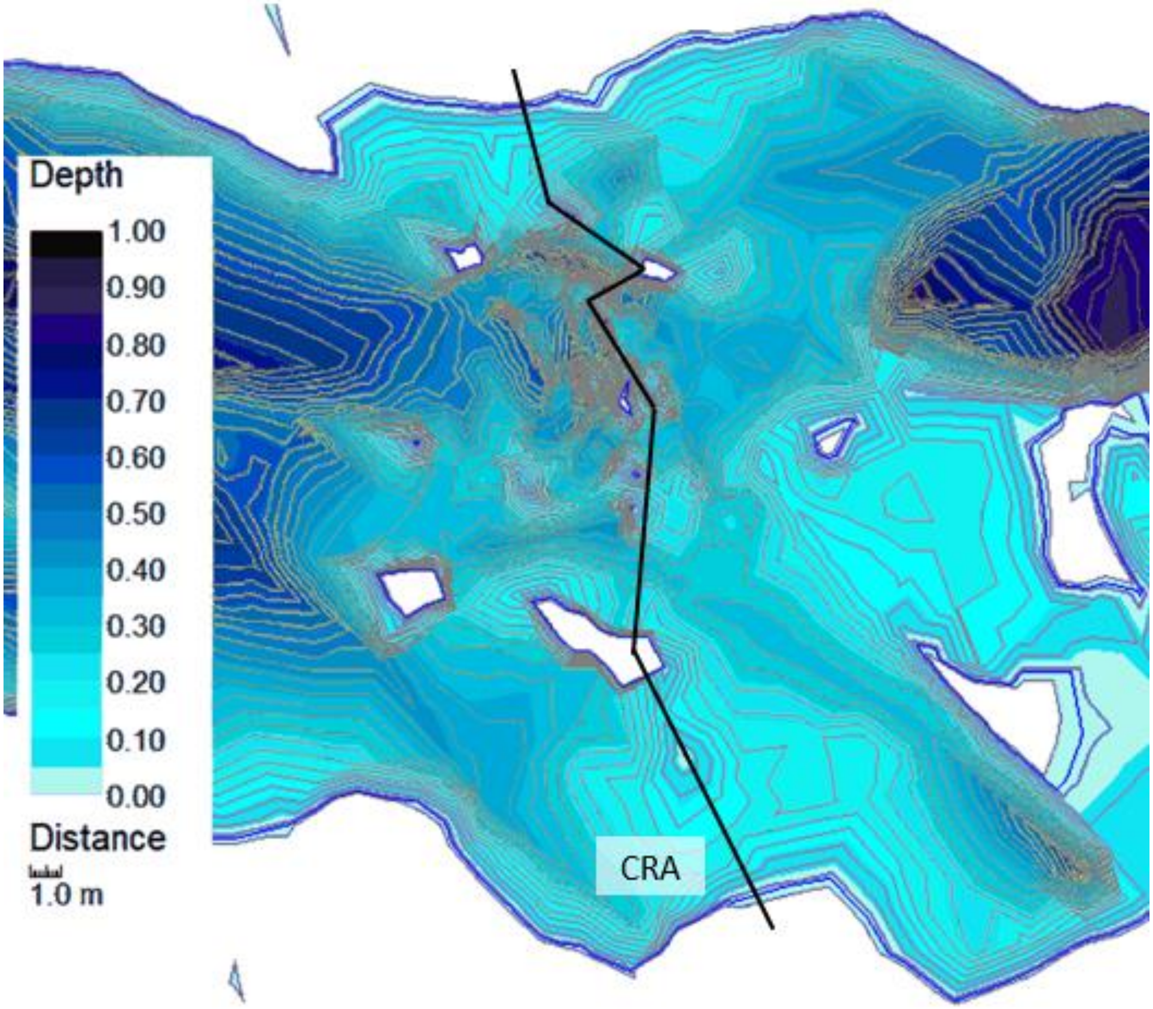


Figure 30. River2D imagery of Pre-storm CS4 modeled at 200 cfs with a traditional CRA shallowest course indicated by the black line. Contour intervals at 0.03 m. White areas within the boundaries indicate out of water.

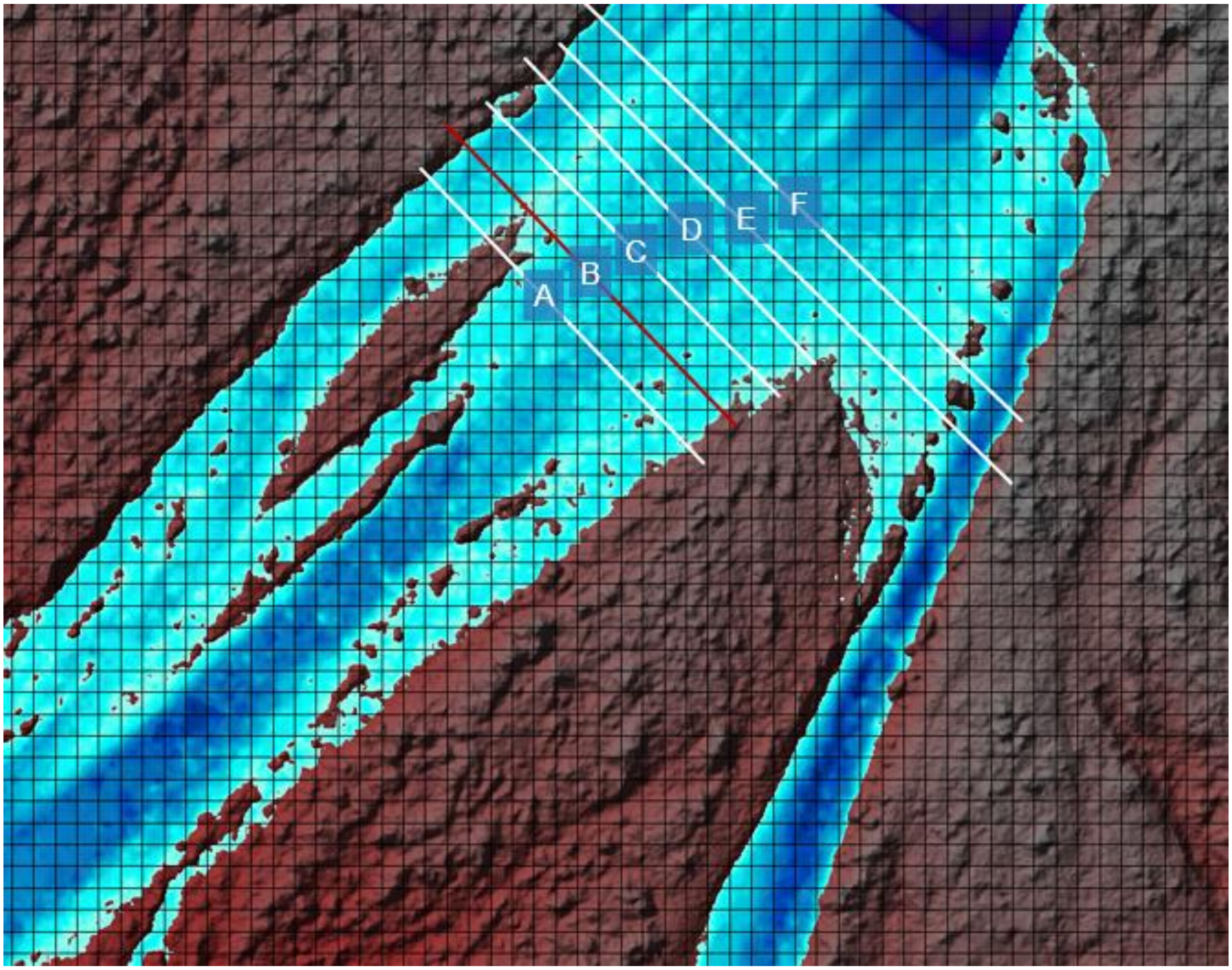


Figure 31. HEC-RAS 2D imagery of Post-storm R23 modeled at 200 cfs with six straight transects. The most passage-limiting transect line is indicated in red. Gridlines indicate 2 m spacing.

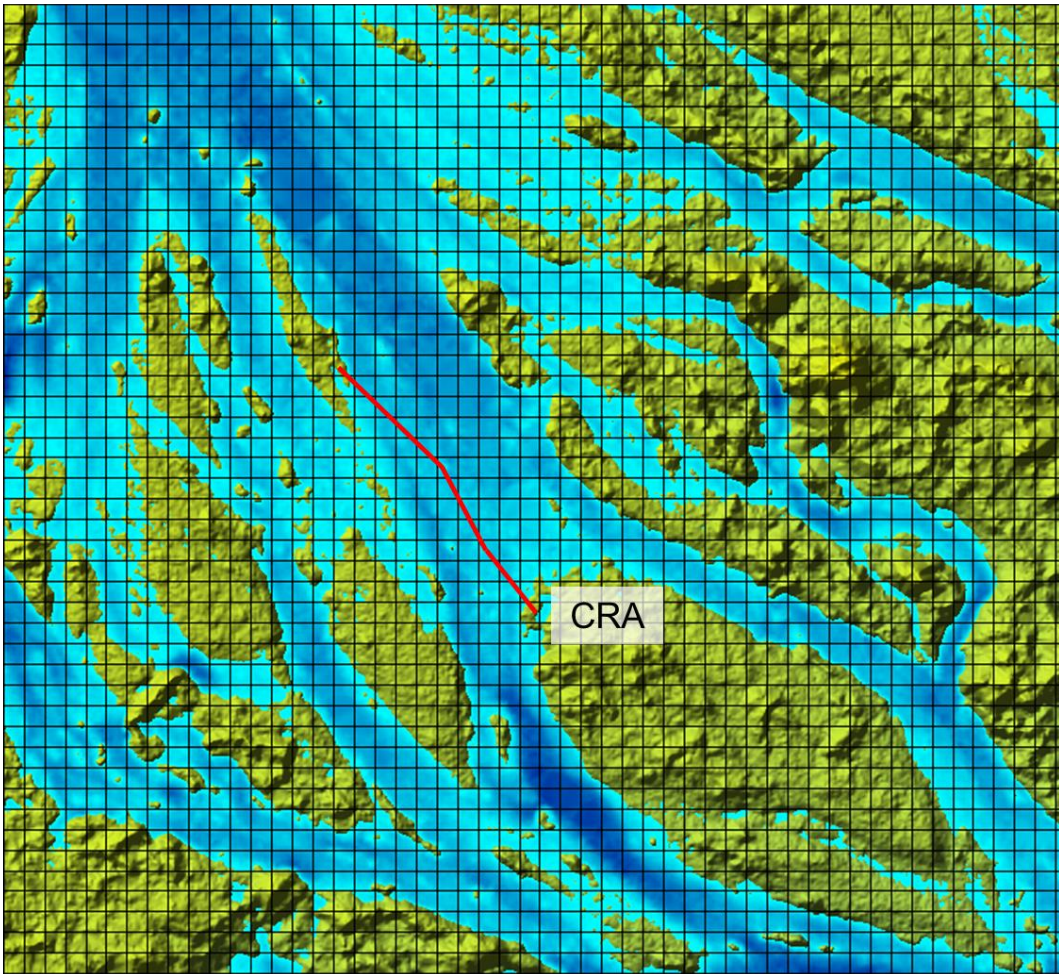


Figure 32. HEC-RAS 2D imagery of Post-storm R8 modeled at 200 cfs with a traditional CRA shallowest course indicated by the red line. Gridlines indicate 2 m spacing.

5.2 Pre-storm Results

The results for the seven most passage-limiting Pre-storm critical riffles are presented below in Table 5. For riffles assessed using the straight transect method, multiple straight transects were used if a single shallowest straight transect was not obvious. The discharges required to meet the depth criterion of 0.7 ft for the four width metrics (i.e., 25% total width, 10% contiguous width, 10-ft contiguous width, 5-ft contiguous width) were calculated using best-fit regression techniques at each riffle. The contiguous width providing 0.7 ft of passage depth at 100 cfs and 50 cfs were added to the summary results to quantify the widths available at lower flows. These results may differ from Table 4 where further analysis required CRA shallowest-course transects to be replaced with straight transects. Additional results from Pre-storm riffles are available in Appendix D.

Table 5. Pre-storm model critical riffle transect summary. Transects with a dagger (†) indicates the most passage-limiting course. Abbreviations: ST=straight transect; CRA=critical riffle analysis shallowest course method.

Riffle	Method	Discharge (cfs) at 25% Total Width ≥0.7-ft Depth	Discharge (cfs) at 10% Contiguous Width ≥0.7-ft Depth	Discharge (cfs) at 10 ft Contiguous Width ≥0.7-ft Depth	Discharge (cfs) at 5 ft Contiguous Width ≥0.7-ft Depth	Contiguous (ft) ≥0.7-ft Depth at 100 cfs	Contiguous (ft) ≥0.7-ft Depth at 50 cfs
R23-1	ST	283	193	199	112	4.0	0.0
R23-2†	**ST**	**386**	**225**	**217**	**148**	**0.0**	**0.0**
R23-3	ST	243	177	191	126	3.0	0.0
R23-4	ST	260	134	117	77	8.5	0.0
R23-5	ST	227	466	83	16	11.0	8.0
R23-6	ST	143	92	45	28	20.0	10.5
R22-1	ST	172	81	200	132	7.0	0.0
R22-2†	**ST**	**223**	**192**	**232**	**200**	**0.0**	**0.0**
R22-3	ST	163	95	175	112	0.0	0.0
R20-1	ST	821	350	299	94	5.0	2.5
R20-2	ST	270	286	246	152	0.0	0.0
R20-3†	**ST**	**328**	**411**	**346**	**195**	**0.0**	**0.0**
R20-4	ST	215	204	198	128	4.0	0.0
R20-5	ST	161	82	79	45	11.5	2.0
R20-6	ST	181	87	81	52	11.0	5.5
R20-7	ST	128	102	105	47	10.5	5.0
R18-1	ST	97	13	138	12	8.5	6.5
R18-2	ST	127	87	163	95	5.5	3.0
R18-3†	**ST**	**357**	**274**	**340**	**146**	**4.5**	**2.5**
R18-4	ST	320	212	260	124	3.5	0.0
R14-1	ST	189	162	208	156	2.0	1.5
R11-1	ST	164	148	172	150	0.0	0.0
CS4-CRA	CRA	109	139	180	83	7.0	1.5

Additional results are provided for riffles R23-2, R22-2, R20-3, R18-3 and CS4 in Tables 6 through 10, respectively. Wetted width represents the inundated channel width at each flow. Total and contiguous widths are the portion of the wetted width meeting the 0.7-ft depth criterion at each flow. The best-fit regression relationships for flow versus contiguous width meeting the 0.7-ft criterion are provided in Figures 33 through 37, in the same order. Flows were modeled in 50- to 100- cfs increments to identify the flow required to provide 10 ft of contiguous width at 0.7-ft depth. Flows that did not meet the depth criterion for any width (0 ft of contiguous width) were excluded from the plot and regression.

Table 6. R23-2 River2D model results for widths meeting 0.7-ft depth criterion.

Flow (cfs)	Wetted Width (ft)	Total Width (ft) ≥0.7-ft Depth	Contiguous Width (ft) ≥0.7-ft Depth	Total Width (%) ≥0.7-ft Depth	Contiguous Width (%) ≥0.7-ft Depth
50	26.5	0.0	0.0	0%	0%
100	51.5	0.0	0.0	0%	0%
150	88.5	5.0	5.0	5%	5%
200	102.5	9.5	9.5	9%	9%
250	105.0	14.0	11.5	13%	11%

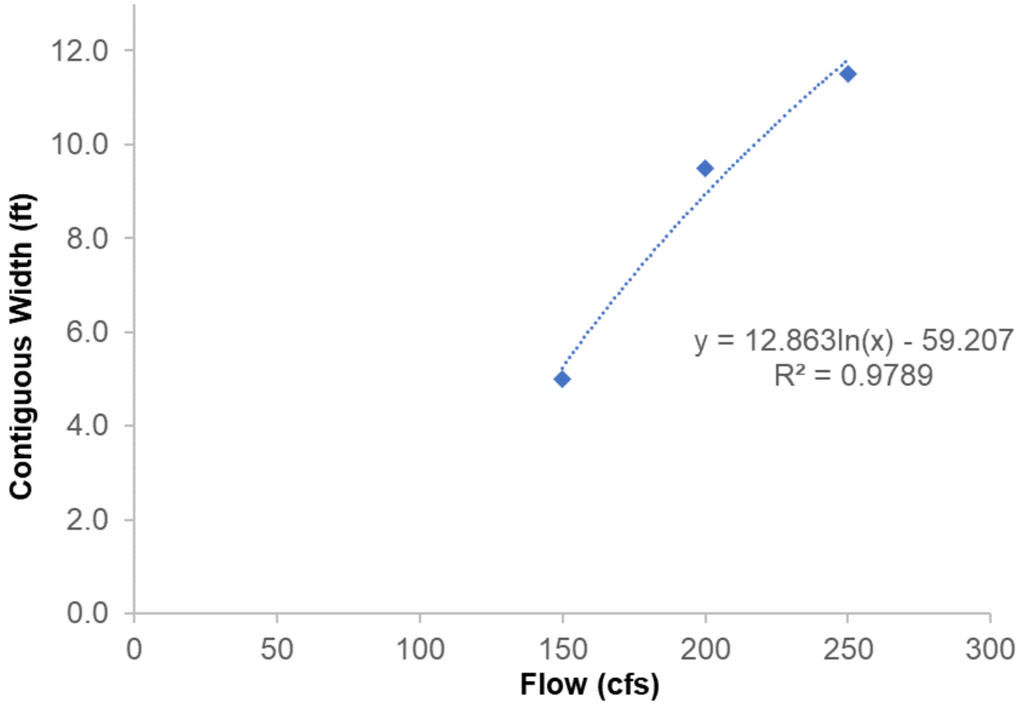


Figure 33. R23-2 River2D results for changes in contiguous width meeting 0.7-ft depth criterion with flow.

Table 7. R22-2 River 2D model results for adult steelhead meeting 0.7-ft depth criterion.

Flow (cfs)	Wetted Width (ft)	Total Width (ft) ≥0.7-ft Depth	Contiguous Width (ft) ≥0.7-ft Depth	Total Width (%) ≥0.7-ft Depth	Contiguous Width (%) ≥0.7-ft Depth
50	15.5	0.0	0	0%	0%
100	20.5	0.0	0	0%	0%
150	29.0	0.0	0	0%	0%
200	31.5	4.5	4.5	13%	13%
250	33.0	14.5	14.5	42%	42%
300	34.5	17.5	17.5	51%	51%

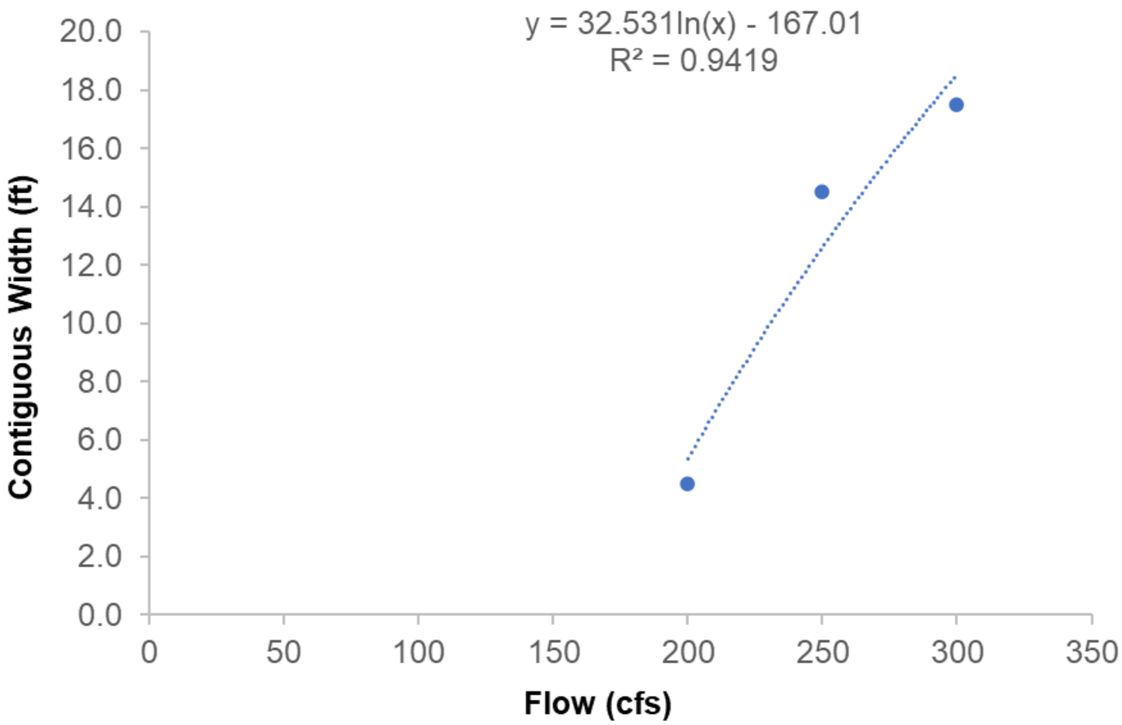


Figure 34. R22-2 River2D results based on adult steelhead meeting 0.7-ft depth criterion.

Table 8. R20-3 River 2D model results for adult steelhead meeting 0.7-ft depth criterion.

Flow (cfs)	Wetted Width (ft)	Total Width (ft) ≥0.7-ft Depth	Contiguous Width (ft) ≥0.7-ft Depth	Total Width (%) ≥0.7-ft Depth	Contiguous Width (%) ≥0.7-ft Depth
50	58.0	0	0	0%	0%
100	72.0	0	0	0%	0%
150	106.0	4.0	2.5	3%	2%
200	108.5	9.5	5.5	8%	5%
300	113.0	26.5	9.0	23%	8%
400	115.0	38.0	11.0	33%	10%

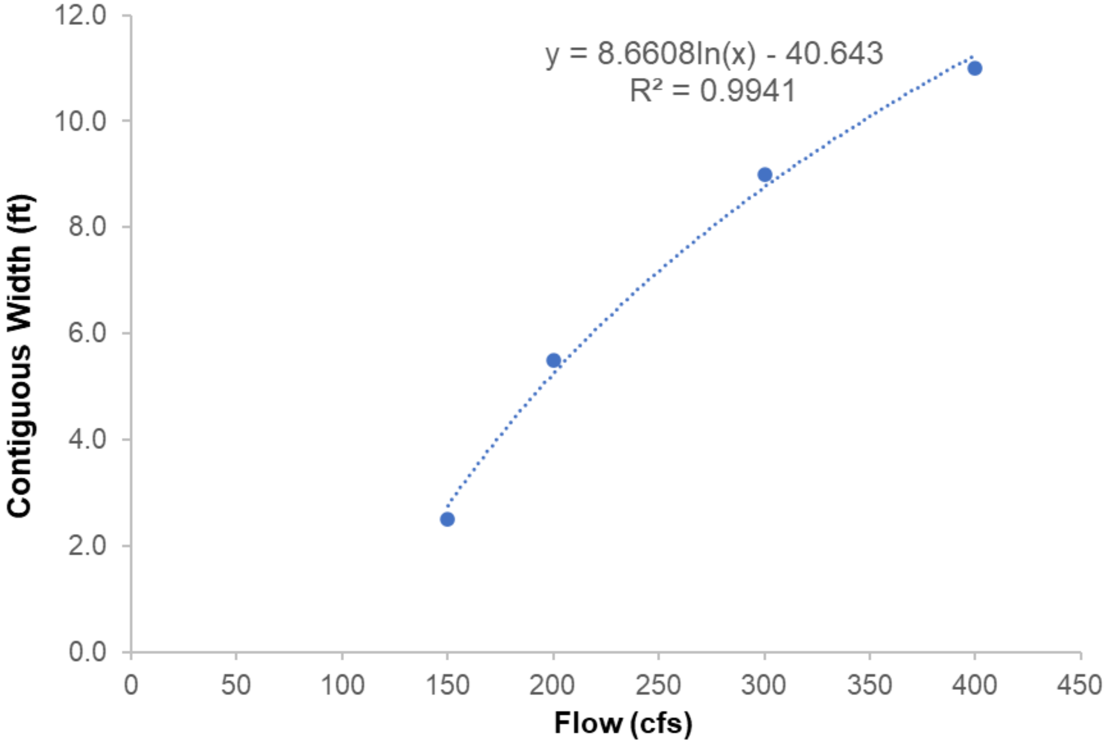


Figure 35. R20-3 River2D results based on adult steelhead meeting 0.7-ft depth criterion.

Table 9. R18-3 River 2D model results for adult steelhead meeting 0.7-ft depth criterion.

Flow (cfs)	Wetted Width (ft)	Total Width (ft) ≥0.7-ft Depth	Contiguous Width (ft) ≥0.7-ft Depth	Total Width (%) ≥0.7-ft Depth	Contiguous Width (%) ≥0.7-ft Depth
50	30.0	2.5	2.5	3%	3%
100	41.5	4.5	4.5	6%	6%
150	60.5	5.0	5.0	6%	6%
200	64.5	6.0	6.0	8%	8%
300	73.5	10.0	8.0	13%	10%
400	78.0	29.5	13.0	38%	17%

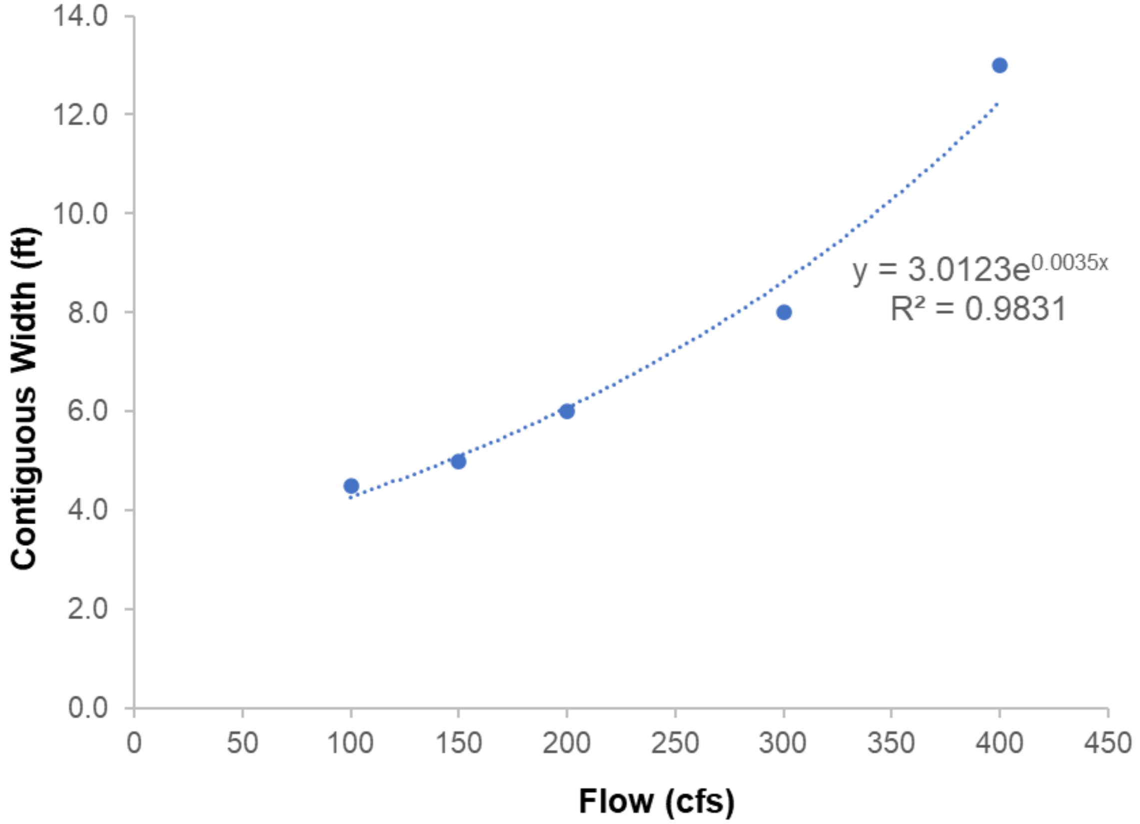


Figure 36. R18-3 River2D results based on adult steelhead meeting 0.7-ft depth criterion.

Table 10. CS4 River 2D model results for adult steelhead meeting 0.7-ft-depth criterion.

Flow (cfs)	Wetted Width (ft)	Total Width (ft) ≥0.7-ft Depth	Contiguous Width (ft) ≥0.7-ft Depth	Total Width (%) ≥0.7-ft Depth	Contiguous Width (%) ≥0.7-ft Depth
50	40.5	3.0	1.5	4%	2%
100	56.0	20.5	7.0	25%	8%
150	75.0	27.5	9.0	33%	11%
200	83.2	34.0	10.0	41%	12%

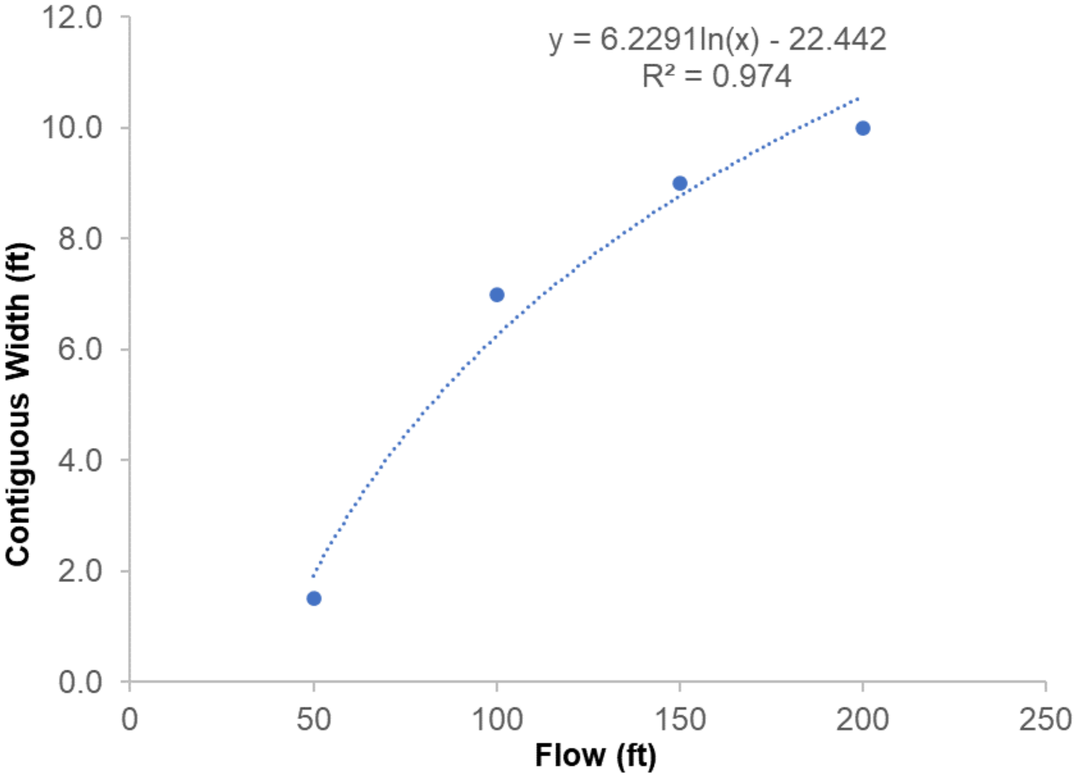


Figure 37. CS4 River2D results based on adult steelhead meeting 0.7-ft depth criterion.

5.3 Post-storm Results

The results for the six most passage-limiting Post-storm critical riffles are presented below in Table 11. For riffles assessed using the straight transect method, multiple straight transects were used if a single shallowest straight transect was not obvious. The contiguous widths providing 0.7 ft of passage depth at 100 cfs and 50 cfs were added to the summary results to quantify the widths available at lower flows. These results may differ from Table 3 where further analysis required CRA shallowest-course transects to be replaced with straight transects. Additional results from Post-storm riffle transects are provided in Appendix E.

Table 11. Post-storm model critical riffle transect summary. Transects with a dagger (†) indicates the most passage-limiting course. Abbreviations: ST=straight transect; CRA=critical riffle analysis shallowest course method.

Riffle	**Method**	**Discharge (cfs) at 25% Total Width ≥0.7-ft Depth**	**Discharge (cfs) at 10% Contiguous Width ≥0.7-ft Depth**	**Discharge (cfs) at 10 ft Contiguous Width ≥0.7-ft Depth**	**Discharge (cfs) at 5 ft Contiguous Width ≥0.7-ft Depth**	**Contiguous Width (ft) ≥0.7-ft Depth at 100 cfs**	**Contiguous Width (ft) ≥0.7-ft Depth at 50 cfs**
R23-A	ST	123	34	35	0	16.5	11.5
R23-B†	**ST**	**121**	**156**	**133**	**72**	**5.9**	**4.3**
R23-C	ST	103	140	131	59	5.8	4.8
R23-D	ST	84	100	88	43	11.4	5.8
R23-E	ST	97	135	104	37	8.9	5.8
R23-F	ST	83	115	95	16	10.3	7.1
R20-A	ST	72	107	102	6	9.5	7.1
R20-B	ST	87	123	118	13	7.2	6.0
R20-C†	**ST**	**69**	**150**	**128**	**53**	**8.3**	**4.8**
R20-D	ST	80	105	101	12	9.6	7.0
R20-E	ST	29	29	25	0	14.7	11.6
R16-CRA	CRA	54	56	83	61	13.9	2.5
R12-CRA	CRA	74	75	99	66	10.8	2.3
R8-CRA†	**CRA**	**104**	**143**	**144**	**103**	**2.6**	**0.2**
R2-CRA	CRA	54	52	77	46	13.8	5.6

The most passage-limiting areas were found in riffles R23, R20, and R8, and the most critical transects within those riffles are bolded in Table 11. Riffle R8, located towards the downstream end of the study site, was the only one of the three that was assessed using the traditional CRA shallowest-course method. The shape of the riffle crest of riffle R8 was more typical of an alluvial riffle (Figure 38) and therefore lent itself to analysis using the multi-segment shallowest course method to identify the most passage-limiting area of the riffle.

Figure 38. R8 at approximately 19 cfs. Image taken during the critical riffle survey in April 2017.

Additional results for each bolded transect are provided in Tables 12 through 14, respectively. Wetted width represents the inundated channel width at each flow. Total and contiguous widths are the portion of the wetted width meeting the 0.7-ft depth criterion at each flow. Plots of flow versus the contiguous width meeting the 0.7-ft criterion for the most critical transect at each of the three most passage-limiting riffles, R23-B, R20-C, and R8-CRA, are provided in Figures 39 through 41, respectively. Due to the non-linear relationship between flow and contiguous width at 0.7-ft depth, best-fit regression was not used (Figure 39). Instead, additional simulations were performed until the flow necessary to meet the 10- and 5-ft contiguous width criteria was narrowed to a window of 5 cfs. Linear regression was then used to estimate the flow within the 5-cfs window.

Table 12. R23-B HEC-RAS model results for adult steelhead meeting 0.7-ft depth criterion.

Flow (cfs)	Wetted Width (ft)	Total Width (ft) ≥0.7-ft Depth	Contiguous Width (ft) ≥0.7-ft Depth	Total Width (%) ≥0.7-ft Depth	Contiguous Width (%) ≥0.7-ft Depth
50	82.4	7.2	4.3	6%	4%
100	91.6	21.5	5.9	19%	5%
125	94.8	25.7	8.8	23%	8%
130	95.2	27.4	9.9	24%	9%
135	95.7	29.2	10.1	26%	9%
150	98.5	33.8	10.3	30%	9%
200	99.3	42.9	18.7	38%	17%
300	108.1	57.4	21.9	51%	20%
400	112.1	66.4	44.2	59%	39%

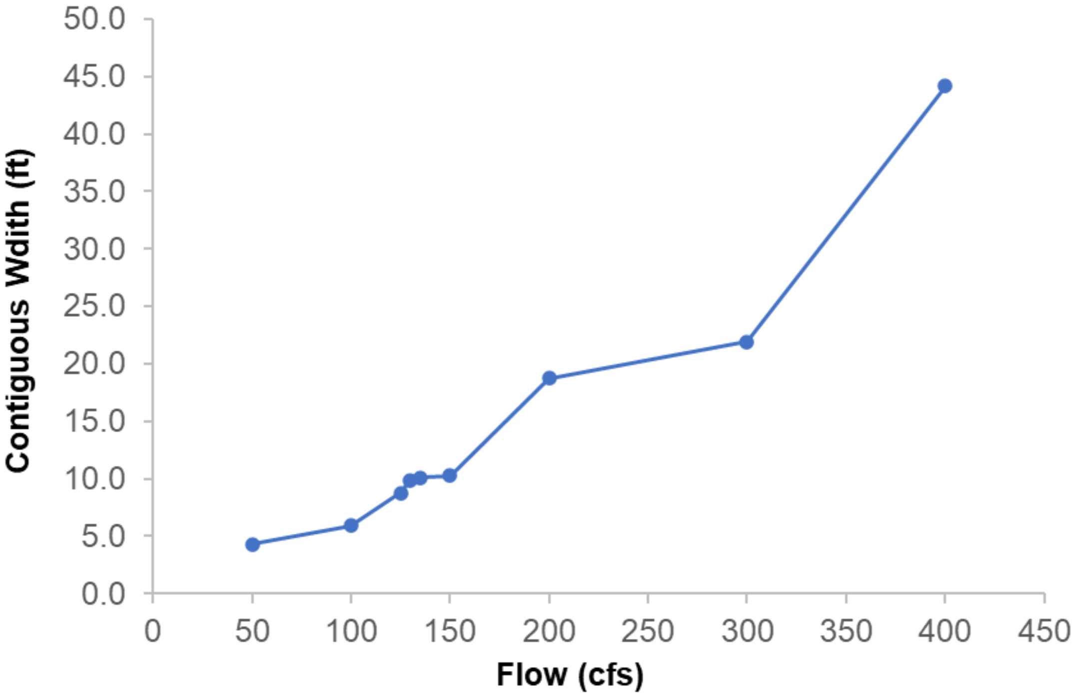


Figure 39. R23-B HEC-RAS results based on adult steelhead meeting 0.7-ft depth criterion.

Table 13. R20-C HEC-RAS model results for adult steelhead meeting 0.7-ft depth criterion.

Flow (cfs)	Wetted Width (ft)	Total Width (ft) ≥0.7-ft Depth	Contiguous Width (ft) ≥0.7-ft Depth	Total Width (%) ≥0.7-ft Depth	Contiguous Width (%) ≥0.7-ft Depth
50	98.6	17.4	4.8	15%	4%
100	107.1	40.2	8.3	35%	7%
125	110.3	51.0	9.6	44%	8%
130	110.9	56.8	10.3	49%	9%
150	112.9	61.6	11.5	53%	10%
200	113.5	71.6	13.3	62%	12%
300	114.8	90.0	34.6	78%	30%
400	115.3	95.2	40.9	83%	36%

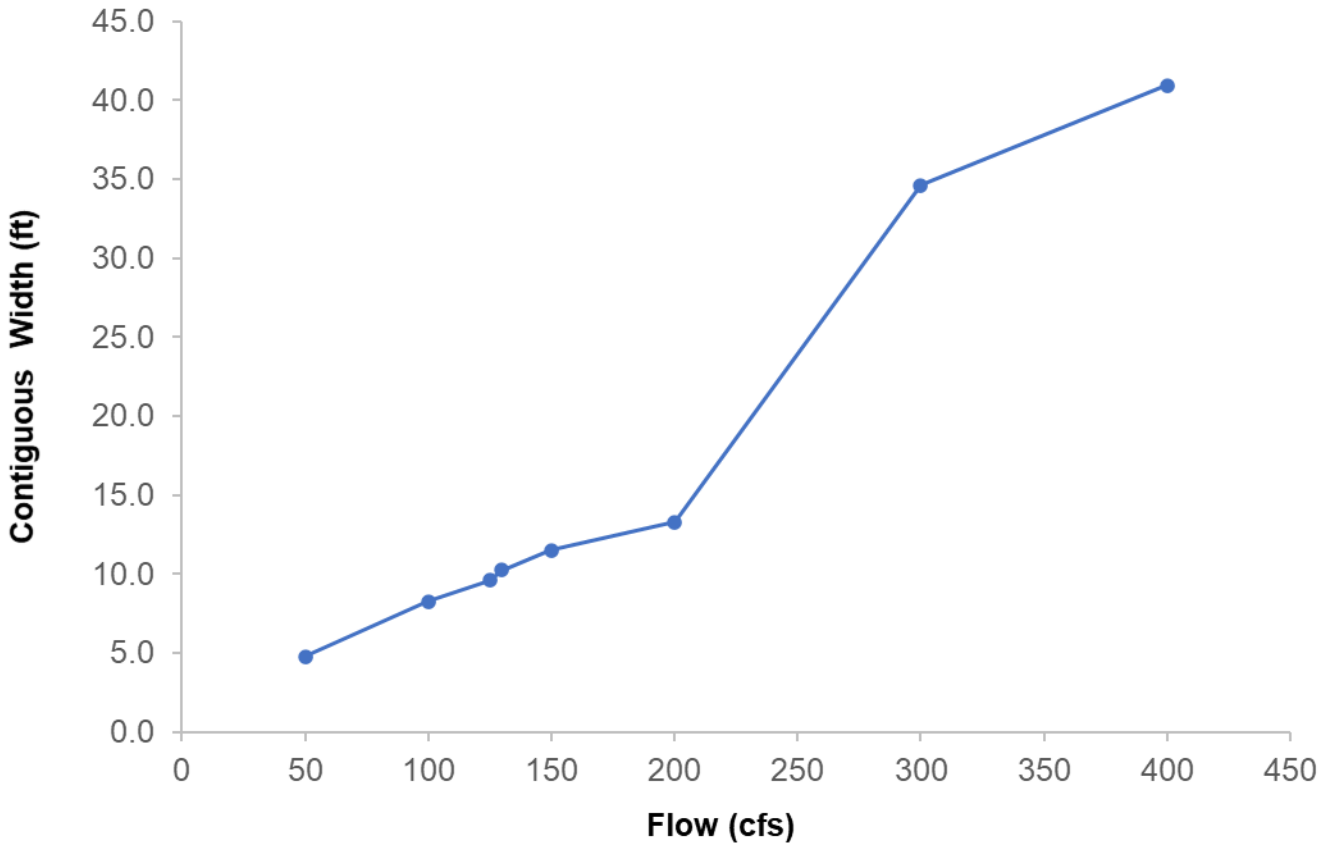


Figure 40. R20-C HEC-RAS results based on adult steelhead meeting 0.7-ft depth criterion.

Table 14. R8-CRA HEC-RAS model results for adult steelhead meeting 0.7-ft depth criterion.

Flow (cfs)	Wetted Width (ft)	Total Width (ft) ≥0.7-ft Depth	Contiguous Width (ft) ≥0.7-ft Depth	Total Width (%) ≥0.7-ft Depth	Contiguous Width (%) ≥0.7-ft Depth
50	81.1	0.2	0.2	0%	0%
100	84.9	10.2	2.6	11%	3%
105	87.0	26.9	6.5	29%	7%
140	89.1	35.8	7.5	39%	8%
145	89.1	36.9	10.4	40%	11%
150	89.1	38.1	10.4	41%	11%
200	89.9	47.7	12.6	52%	14%
300	91.9	58.9	13.9	64%	15%
400	92.5	64.4	24.7	70%	27%

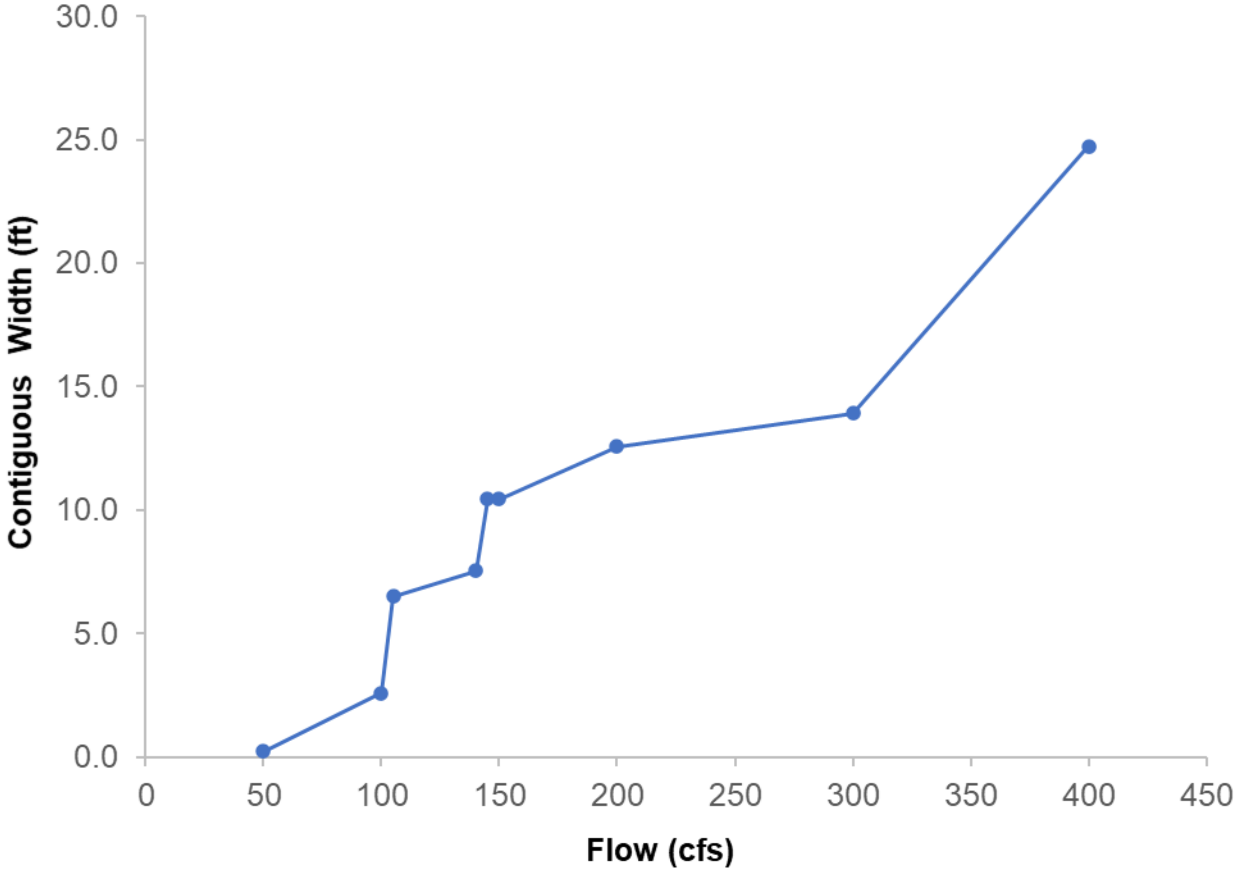


Figure 41. R8-CRA HEC-RAS results based on adult steelhead meeting 0.7-ft depth criterion.

6.0 DISCUSSION

Conditions that could potentially limit upstream migration of adult steelhead were evaluated in the Ventura River intermittent reach. A 2D hydraulic modeling approach to critical riffle analysis was selected to assess adult steelhead passage flows in a 1.3-mi long representative study area below the Santa Ana bridge. A digital terrain model of the study site was defined using topographic surveys and high-resolution LIDAR data. After high flows from a storm event substantially changed the bed topography within the study site, a second hydraulic model was developed so both Pre-storm and Post-storm conditions were represented.

Fish passage was evaluated by computing the contiguous width that met the adult steelhead minimum passage depth criterion of 0.7 ft. Many of the most passage-limiting areas in the study site consisted of wide areas of the stream channel that can be best characterized as fields of cobble and boulder substrates (Figure 8). These areas were flow-sensitive and shallow, but lacked the perceptible riffle crests and gravel or cobble substrates that characterize the critical riffles evaluated by Thompson (1972). A series of straight transects, oriented perpendicular to the direction of flow, were used to evaluate these shallow areas in the intermittent reach study site. The use of straight transects to evaluate passage-limiting areas is consistent with the fish passage evaluation performed by CMWD (2010).

The percentage-based criteria developed by Thompson (1972) of 25% total and 10% contiguous width were not designed to be applied to areas dominated by large cobble and boulder substrates and lacking a clear riffle crest. Instead, the critical riffles in the intermittent reach study site were evaluated by computing the minimum flow required to achieve a width of 10 contiguous feet at the 0.7-ft passage depth. Applying 10 ft of contiguous width criteria is consistent with several studies including the Lower Santa Clara River (Harrison et al. 2006) and Santa Maria River (Stillwater Sciences and Kear Groundwater 2012).

Model outputs were used to estimate the stream width available for fish passage along each transect over a range of flows. Either a series of straight transects or a traditional CRA shallowest course was applied to each of the seven Pre-storm and five Post-storm critical riffles. Two riffle locations from the Pre-storm model and three locations from the Post-storm model emerged as the most critically passage-limiting areas within the study site. The Pre-storm model indicated that riffles near the field-surveyed riffles R20 and R18 were the most passage-limiting (Figure 28 and Figure 29). Review of the Pre- and Post-storm riffle locations (Figure 24 and Figure 17) show that riffles R20 and R18 migrated downstream during the channel-forming flows in February 2017. The Post-storm model indicated that riffles R23, R20, and R8 were the most passage-limiting riffles (Figure 39, Figure 40, and Figure 41). Riffle R18 was not found to be critically passage-limiting in the Post-storm model. Riffle R8 in the Post-storm model was in the same portion of the site as CMWD Site 4, but in a newly formed braid of the channel.

Flow magnitudes required to meet the passage criteria (i.e., 10 ft of contiguous width meeting the 0.7-ft passage depth) differed between the Pre- and Post-storm 2D models. The Pre-storm riffles R20 and R18 required 346 and 340 cfs, respectively, to achieve 10 ft of contiguous width for fish passage. The Post-storm riffles R23, R20, and R8 required 133, 128, and 144 cfs, respectively, to achieve 10 ft of contiguous width for fish passage. The difference is most likely due to differences in the resolution of the Pre- and Post-storm DTMs. The resolution of the Pre-storm DTM was roughly one point per 10 m^2 (Table 1) versus the 0.25-m^2 resolution of the 2018 LIDAR. These resolutions are not directly comparable because points in the Pre-storm model were concentrated in topographically complex areas and sparse in topographically smooth areas. As visible in Figure 42, the resulting DTMs were markedly different. Figure 42 shows a location near R20 with the field survey-based topography resolution on the left and the 0.25 m^2 resolution LIDAR on the right. The resolution of the 2018 LIDAR data increased the level of detail in the representation of the streambed topography, allowing it to capture small variations in depth. These small variations likely increased the amount of passable depth estimated by the hydraulic model.

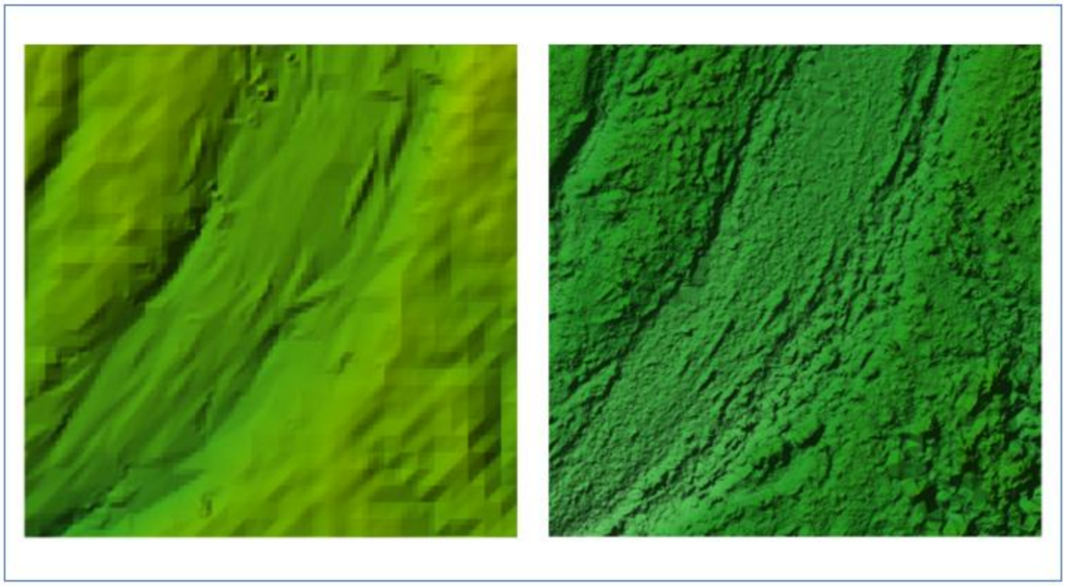


Figure 42. DTM generated from field survey points and 2005 3-meter LIDAR (left) compared to 2018 0.25-meter QL1 LIDAR (right).

This study identified that a minimum flow of 144 cfs would protect steelhead passage through the intermittent reach. This flow was based on the transect that required the highest minimum discharge to meet the criterion of 0.7 ft of water depth for 10 ft of contiguous transect width. The transect R8-CRA was considered the most critical among all riffle transects evaluated in the Post-storm model. The Post-storm model was used for this evaluation due to the superiority of the high-resolution LIDAR data used in the hydraulic model.

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