State of California
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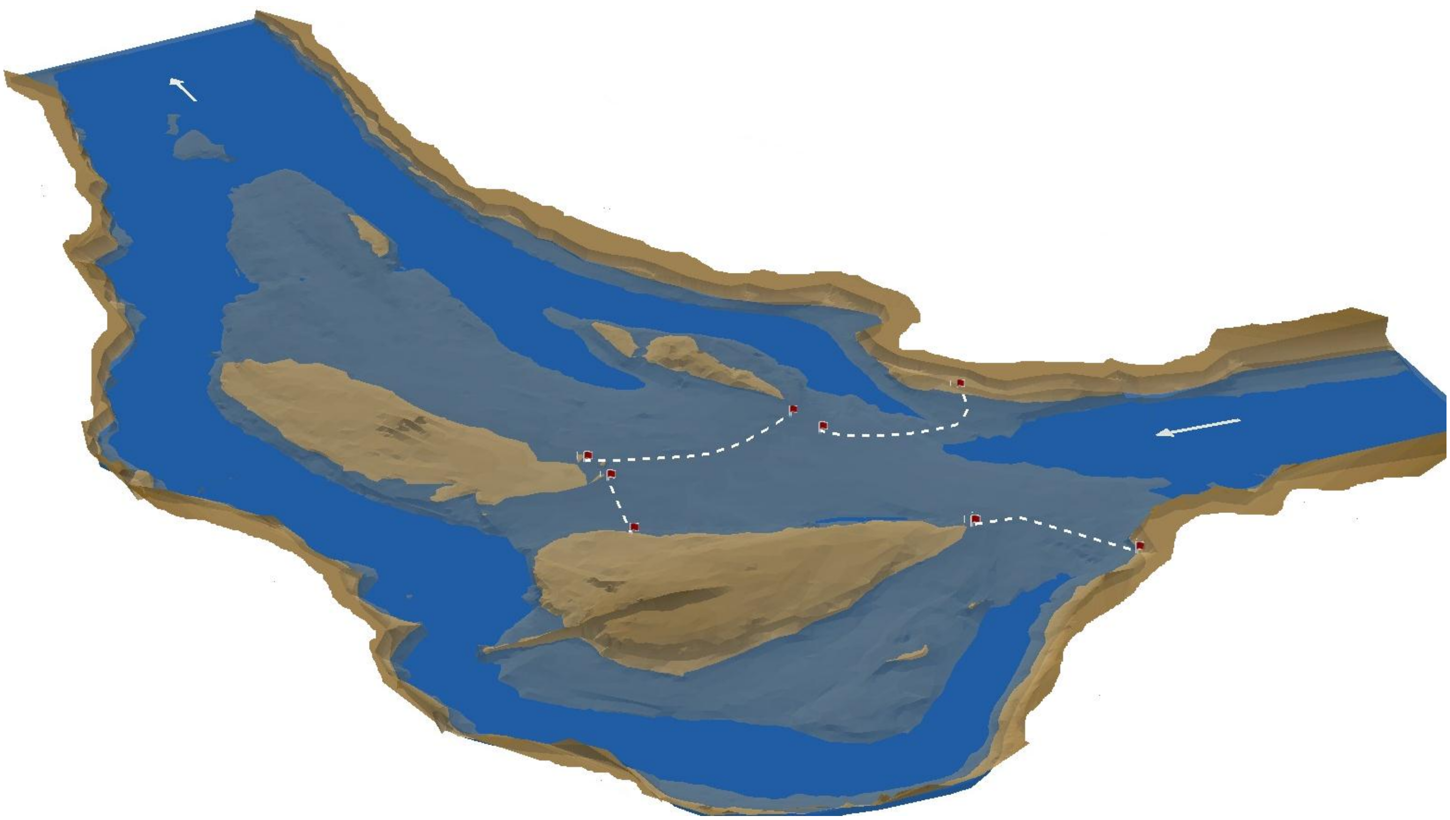
Instream Flow Evaluation
Steelhead Passage and Connectivity of Riverine and Lagoon Habitats
BIG SUR RIVER, Monterey County



STREAM EVALUATION REPORT 14-3
July 2014

Department of Fish and Wildlife
Stream Evaluation Report
Report Number 14-3

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BIG SUR RIVER, Monterey County[1]

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ABSTRACT

Instream flows for protecting steelhead (*Oncorhynchus mykiss*) passage through depth sensitive natural, low gradient, alluvial critical riffle sites were evaluated in the Big Sur River, California from 2009 - 2012. Flows were evaluated using the California Department of Fish and Wildlife critical riffle analysis protocol and the River 2D two-dimensional hydraulic and habitat model along with quantitative passage metrics and species- and lifestage-specific depth criteria. Flows identified for protecting passage and habitat connectivity at critical riffle sites between lagoon and lower river habitats were 18 cfs, 32 cfs, and 75 cfs for young-of-year, juvenile, and adult steelhead, respectively. A strong relationship ($r^2 = 0.93$) was observed between flow requirements identified by each method. Flow requirements were spatially and temporally consistent at critical riffles between the upper river and lagoon for adult steelhead, and generally indicative of a river system in equilibrium with a naturally variable flow regime, and associated intact ecological processes. An analysis of over twenty-five years of continuous flow data records indicated sufficient flows at critical riffle locations for young-of-year and juvenile steelhead were produced between 37% and 100% and between 1% and 95% of the time, respectively. The months of September and October were the most challenging months to obtain natural flows to meet young-of-year and juvenile passage and habitat connectivity flows. Flows identified for adult steelhead passage were produced naturally between 52% and 74% of the time during the core adult migratory period of January through April. Naturally produced flows for adult steelhead migration were less reliable at the beginning and end of the migration season with flow criteria being met 3% and 30% for November and May, respectively. Careful consideration of seasonal and interannual flow variability dynamics, therefore, are critical components of an effective flow management strategy for the maintenance and protection of passage and habitat connectivity flows between lagoon and upriver habitats, and are essential for the survival and longevity of steelhead in the Big Sur River and other coastal California streams.

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ABBREVIATIONS, ACRONYMS, AND CONVERSIONS

1D	one dimensional (physical habitat simulation model)
2D	two dimensional (physical habitat simulation model)
BR Mult	bed roughness multiplier
cdg	characteristic dissipative galerkin
cfs	cubic feet per second
cm	centimeter
csv	comma-separated values
DPS	distinct population segment
FGC	Fish and Game Code
fps	feet per second
ft	foot (feet) (30.5 centimeters)
GIS	geographic information system
GPS	global positioning system
IFG4	Instream Flow Group Model #4
IFIM	Instream Flow Incremental Methodology
inch	inch
km	kilometer
km^2	square kilometer
mm	millimeter
m	meter
m^2	square meter
MANSQ	manning's stage discharge
MAX F	maximum Froude number
Net Q	net flow
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
ODFW	Oregon Department of Fish and Wildlife
PHABSIM	Physical Habitat Simulation Model
PRC	Public Resources Code
Q	discharge (flow)
QI value	quality index value
RHABSIM	River Habitat Simulation Model
River2D	RIVER2D Model
RTK	real time kinematic
Sol Δ	solution change
SZF	stage of zero
TIN	triangulated irregular network
USGS	United States Geological Survey
XS	cross section
WSEL	water surface elevation
WSP	Water Surface Profile Model
YOY	young-of-year

FOREWORD

California's south-central coast steelhead (*Oncorhynchus mykiss*) populations have declined from about 25,000 spawning adults per year to fewer than 500 (NMFS 2007). Consequently, the south-central steelhead Distinct Population Segment (DPS) was listed as threatened in 1997 (NMFS 1997) and reaffirmed in 2006 (NMFS 2006). The National Marine Fisheries Service (NMFS) later issued the results of a five-year review and concluded that south-central steelhead should remain listed as threatened (NMFS 2011). All of the watersheds in the south-central coast DPS are impacted by a variety of anthropogenic stressors, but the most frequent source of threat stems from water management activities, such as diversions (Monterey County 1986; NMFS 2008).

The Big Sur River is identified on the California Department of Fish and Wildlife's (CDFW's) priority rivers and streams list (CDFW 2008) because it is a south-central steelhead stronghold (Wild Salmon Center 2010) and information is needed to determine stream flow requirements for protecting this resource. CDFW's policy is that the federal Instream Flow Incremental Methodology (IFIM) will be used to evaluate and develop instream flow requirements. The Public Resources Code (PRC) §10000-10005 outlines CDFW's responsibilities for developing and transmitting flow recommendations for priority streams to the State Water Resources Control Board (State Water Board) for consideration as set forth in 1257.5 of the Water Code. The results from this study component of an overall IFIM on the Big Sur River are intended to be used, along with other supporting information and data, to identify stream flow requirements for the Big Sur River pursuant to CDFW's PRC mandate.

INTRODUCTION

Stream flow is the dominant driver of connectivity between aquatic organisms and their riverine habitats (Wiens 2002). Loss of connectivity affects the flow of nutrients, energy, materials, and movement and viability of biota in the aquatic ecosystem (Freeman et al. 2007). Naturally occurring low stream flows combined with surface-water withdrawal for anthropogenic uses can interrupt riverine connectivity and movement opportunities for anadromous salmonids (Spina et al. 2006). Titus et al. (2010) attributed significant declines in the steelhead (*Oncorhynchus mykiss*) population of a California coastal river to surface water withdrawals and low stream flows, which resulted in blockage of their migration to historical spawning and rearing habitats.

Water depth becomes the primary variable for evaluating fish passage opportunities and riverine habitat connectivity during low stream flow conditions in low gradient alluvial river channels (Thompson 1972; Mosley 1982). Low flow conditions at depth-sensitive critical riffles (i.e., shallow riffles which are particularly sensitive to changes in stream flow due to shallow water) may impede critical life history tactics of anadromous salmonids as well as disrupting the hydrologic connectivity of natural river habitats. Thompson (1972) is a procedure developed by the Oregon Department of Fish and Wildlife (ODFW) specifically for identifying stream flow requirements needed for passage of migrating salmonids through depth-sensitive critical riffles (Bjornn and Reiser 1991; Reiser et al. 2006).

The California Department of Fish and Wildlife (CDFW) developed a critical riffle analysis procedure (CDFW 2012) based upon Thompson (1972) to evaluate and identify stream flows needed to protect anadromous salmonid passage and overall riverine habitat connectivity in California streams and rivers. The evaluation procedure draws from the Thompson (1972) methodology in procedural scope with the application of regional species- and lifestage-specific criteria relevant to California salmonids. Pursuant to CDFW (2012) methodology, a passage transect is deemed passable when a combination of minimum stream flow depths and wetted widths are greater than conditions specified by two evaluation metrics: the percentage of the total transect metric, and the contiguous percentage of the transect metric.

Thompson (1972) describes the procedure and passage metrics as follows:

"…shallow bars most critical to passage of adult fish are located and a linear transect marked which follows the shallowest course from bank to bank. At each of several flows, the total width and longest contiguous portion of the transect meeting minimum depth ... criteria are measured. For each transect, the flow is selected that meets the criteria on at least 25% of the total transect width and a continuous portion equaling at least 10% of its total width...."

The purpose of the Thompson (1972) methodology and associated transect width metrics is to provide flow conditions for physical movement of salmonids through critical riffle locations. While Thompson (1972) cautions that the relationship between flow conditions on the transect and the relative ability of a fish to pass have not been evaluated, the methodology is based upon over a decade of extensive field observations spanning all 18 drainages of Oregon by ODFW, including several hundred of the most important salmonid streams in the State (Thompson 1972). Thompson (1972), however, cautions that the purpose of the methodology is not to determine flows generally believed necessary to induce migration.

Mosley (1982) observed salmonids moving upstream in water shallower than the Thompson (1972) depth criteria but noted that they may suffer abrasion and loss of spawning condition. Ideally, there should be sufficient clearance underneath the fish so that contact with the streambed and abrasion are minimized. Other factors that are important for consideration when evaluating fish passage and habitat connectivity is consideration of length of the riffle, distance of travel, physiological condition of the fish, water temperature, and availability of resting areas (Mosley 1982).

Traditional site-specific linear or straight-transect based methods such as one-dimensional (1D) physical habitat simulation (PHABSIM) (Bovee, 1997) may not be well suited to examining aquatic habitat connectivity at long complex critical riffle sites such as those that are common among California's coastal streams and rivers. As such straight linear bank-to-bank transects may not present a realistic assessment of longitudinal habitat connectivity because the lateral based transects, typically identified perpendicular to flow from bank to bank, may not capture all the depth sensitive portions of a critical riffle as a migrating fish would encounter. As a result, straight-transect methods such as those employed in a PHABSIM analyses may not protect salmonid passage through complex depth sensitive critical riffle sites. In addition, critical riffles often have characteristics, such as significant cross-channel variation in water surface elevation, that violate assumptions of PHABSIM. Conversely, delineation of stream assessment transects following the shallowest course from bank to bank (CDFW 2012) provides for an empirical site-specific assessment of habitat connectivity and passable stream flow depths such as a migrating salmonid would encounter.

Two dimensional (2D) physical habitat simulation methodology has a demonstrated utility over straight-transect methodologies such as PHABSIM for assessing water depth and flow relationships throughout complex riverine sites (Gard 2009a; Ghanem et al. 1995; Ghanem et al. 1996; Leclerc et al. 1995). While hydraulic habitat models generally allow for modeling predictions of physical microhabitat changes associated with flow alterations (Stalnaker et al. 1995), 2D models are better suited to model stream flow depths through a contiguous reach more accurately than the 1D hydraulic habitat models because the 2D models avoid problems of the transect placement. In addition, since the data for 2D analysis are collected uniformly across and throughout the entire site, as opposed to on straight 1D transects, the 2D models allow for assessment of contiguous pathways of appropriate depths and widths needed for associated aquatic habitat connectivity throughout a complex site. With detailed bathymetry data, the model scale is small enough to correspond to the scale of microhabitat use data with contiguous depths produced on a continuous basis.

Selection of appropriate methods for an instream flow assessment is a fundamental step of the Instream Flow Incremental Methodology (IFIM; Bovee et al. 1998). Annear et al. (2004) recommends that IFIM, and instream flow evaluations in general, include broad consideration of the structure and function of riverine systems, while also providing cogitation and examination of five core components (i.e., hydrology, biology, geomorphology, water quality, and connectivity) of the riverine system. 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 (Fullerton et al. 2010), component which is especially important in California coastal salmonid streams.

The goal of this study was to evaluate flows for protecting steelhead passage and connectivity of riverine and lagoon habitats through critical riffle habitats in the Big Sur River, Monterey County. Site-specific flows are needed for steelhead lifestages including young-of-year (YOY) juveniles, 1 – 2 year-old juveniles, and migrating spawning adults. Objectives of this study include to 1) use the California critical riffle assessment procedure (CDFW 2012) and the River 2D model (Steffler and Blackburn 2002) methodologies for evaluating flows for protecting passage and habitat connectivity flows at critical riffle sites in the Big Sur River using the Thompson passage criteria metrics and compare the results between the two methodologies; and 2) examine the spatial and temporal variability of the flows identified for protecting passage and habitat connectivity for steelhead lifestages in the Big Sur River. Monterey County (1986) identifies the Thompson (1972) methodology and associated passage criteria as necessary for determining instream flows for steelhead passage in the lower Big Sur River.

DESCRIPTION OF STUDY AREA

The Big Sur River is located in southern Monterey County (Figure 1). It originates in the steep canyons of California's Ventana Wilderness within the Los Padres National Forest and flows northwesterly through federal and private lands, two state parks (Pfeiffer Big Sur and Andrew Molera), and a small lagoon before joining the Pacific Ocean about 2.8 miles (4.5 km) southeast of Point Sur. Significant tributaries include Pfeiffer-Redwood Creek, Juan Higuera Creek, Post Creek and Pheneger Creek. The Big Sur River has a watershed of approximately 60 square miles (150 km^2) with no major dams, diversions, or reservoirs. However, only the lower 7.5 miles of the river (lower Big Sur River) are accessible to anadromous steelhead for migration, spawning, and rearing. Upstream fish migration is generally thought to be prevented by a partial or complete bedrock barrier, depending on stream flow conditions (Figure 2).

The hydrology of the Big Sur River is typical of many coastal California rivers. It experiences high winter flows, low summer flows, and variable annual discharges. Most of the annual flow occurs in the winter with stream discharge reflecting local and watershed-wide rainfall patterns. Flows in winter may rise and recede rapidly in association with rainfall events, while flows in the summer tend to be more stable and predictable as they recede into the fall months. The Big Sur River is a free-flowing river, with no dams or on-stream reservoirs.

There are two U.S. Geological Survey (USGS) stream flow gages on the Big Sur River. USGS gage 11143000 is located in Pfeiffer State Park, and is upstream of all known diversions (Figure 1). It does not reflect accretion of flow from several lower river tributaries including Post, Pfeiffer-Redwood, Juan Higuera, and Pheneger creeks. USGS gage 11143000 has recorded flow data for the Big Sur River from March 1950 to the present. USGS gage 11143010 is located approximately six river miles downstream of USGS gage 11143000 in Molera State Park, and has been in operation since October 2010. USGS gage 11143010 is located downstream of all river tributaries and most diversions.

Fishery Resource

The Big Sur River is home to approximately 5 native species of freshwater fishes, including the anadromous steelhead (Table 1). There do not appear to be any introduced freshwater fishes in the study area. Steelhead use the study area year-round for migration, spawning, incubation, rearing, and/or emigration.

Table 1. Fish species occurring in the Big Sur River.

Scientific Name	**Common Name**
Lampetra tridentata	Pacific Lamprey
Oncorhynchus mykiss	Steelhead
Cottus asper	Prickly Sculpin
Cottus aleuticus	Coast Range Sculpin
Gasterosteus aculeatus	Threespine Stickleback

Steelhead are an anadromous member of the salmonid family, spending their adult life in the ocean and returning to freshwater to spawn (Shapovalov and Taft 1954; Quinn 2005). In the Big Sur River, steelhead return to the river as spawning adults between November and May (Table 2). Steelhead spawn in gravel areas throughout the river between the lagoon and the impassable bedrock barrier in the gorge area of Pfeiffer State Park. Spawning generally occurs at the tail of pools or head of riffles, where water depth, velocity, and substrate composition are favorable. Eggs are deposited in redds or nests excavated by the females, then covered with gravel. The eggs generally hatch between 80 and 120 days, depending on water temperature.

Figure 1. Lower Big Sur River watershed.

Figure 2. Photo of natural bedrock barrier and upstream end of steelhead anadromy in Big Sur River Gorge near Pfeiffer State Park.

Table 2. Life stage periodicity for south-central steelhead in the Big Sur River.

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Adult Migration												
Spawning												
Egg Incubation												
Emergence/Fry												
Juvenile Rearing												
Smolt Emigration												

The newly hatched steelhead fry remain in the gravel until the yolk-sac is absorbed. Upon emerging from the gravels fry (approximately 1.5-4 cm fork length (FL)) typically move into nearby shallow slow-water habitats to feed and grow until making the transition to YOY juvenile fish (approximately 6-9 cm FL). As they grow young steelhead typically seek deeper water and faster velocities. Young steelhead may emigrate to the ocean as YOY, or remain in the freshwater river for a year or longer before emigrating to the ocean. Young steelhead generally reach 5.5-6 inches (14-15 cm FL) or larger before smolting, a physiological change which prepares the fish for migrating to, and life in, the ocean.

METHODS

Identification of Critical Riffle Sites and Sampling Strategy

Twenty critical riffle sample sites were identified by surveying the entire length of the Big Sur River available for spawning from the lagoon mouth in Molera State Park upstream through Pfeiffer State Park. Depth profile surveys were conducted at each site and the data from each site were compared to river flow at time of measurement using either flow data obtained from USGS gage 11143000, USGS gage 11143010, or by measuring flow onsite. Onsite discharge measurements were made following procedures of Rantz (1982). Depth profile surveys were conducted during summer of 2009 to identify critical riffles in the lower 1.5 miles of stream. Riffle surveys in 2010 were expanded to include the rest of the Big Sur River. Out of the twenty critical riffles sites surveyed, the four most depth-sensitive critical riffles sites in the river were identified based upon the survey data. These sites occur in the lagoon, lower river, middle river, and upper river areas of the river and reflect the four most flow- and depth-sensitive critical riffle sites throughout the entire anadromous portion of the Big Sur River (Figure 3).

The lagoon site is located approximately 0.33 mile upstream from the river mouth. It is at the transition from the lagoon to the lower river (Figure 4), and consists of a critical riffle complex with four separate riffles (i.e., riffles A, B, C, and D). Riffle A is the longest riffle at 90 ft in length. The critical riffle analysis protocol and a 2D model were conducted at the lagoon site (Table 3). Discharge for the lagoon site was measured onsite and/or taken from USGS gage 11143010 which is located approximately 0.5 mile upstream of the lagoon site.

The lower river site is located approximately 0.50 mile upstream from the river mouth. This riffle is 152-ft long and had a critical riffle analysis done in 2009. A 2D model was also developed at this riffle in 2009, and again in 2011 to assess temporal variability (Table 3). Discharge for the lower river site was measured onsite, and/or taken from USGS gage 11143010 located approximately 0.33 mile upstream of this riffle. The middle river site is located 1.79 miles upstream from the river mouth and consists of a 47-ft. long critical riffle. A critical riffle analysis was conducted at this site in 2011. Discharge for the middle river site was taken from USGS gage 11143010 located approximately 1.0 mile downstream. The upper river site is located 3.38 miles upstream from the river mouth and consists of a 256-ft. long critical riffle. A critical riffle analysis was conducted at the upper river site in 2011. Discharge for the upper river site was measured onsite.

Figure 3. Map of critical riffle sampling sites in lower Big Sur River.

Figure 4. Schematic of lagoon site with depiction of four critical riffles (A, B, C, D), depending on flow levels, at transition of lagoon to lower Big Sur River.

Table 3. Summary of timing and use of critical riffle analysis and River 2D at sites in the Big Sur River.

Site	Critical Riffle Analysis		River 2D Model	
	2009	2011	2009	2011
Lagoon		X		X
Lower River	X		X	X
Middle River		X		
Upper River		X		

Identification of Target Flows for Sampling

Mean daily flows and percent exceedance flows for the Big Sur River at USGS gage 11143000 are presented in Figure 5 and Figure 6, respectively. Since there are no diversions or dams upstream of USGS gage 11143000, the hydrology patterns reported at USGS gage 11143000 reflect the natural unimpaired flow regime. Target sampling flows for the critical riffle analysis and 2D model were based upon the 20, 50, and 80 percent exceedance flows of USGS gage 11143000. Percent exceedance flows are typically used as a guideline for describing the watershed hydrology, as well as for making informed decisions about water resources planning and management. The percent exceedance flows between 20 and 80 percent reflect the most commonly observed flows in the stream, with the 50 percent exceedance flow reflecting the stream's natural benchmark. The 20, 50, and 80 percent exceedance flows for the Big Sur River are 100, 29, and 14 cfs, respectively.

Critical Riffle Analysis

The critical riffle analysis is an empirical instream flow method that identifies flows for protecting salmon and trout passage and overall habitat connectivity. The CDFW (2012) protocol draws from current methods (Thompson 1972) used to assess salmon and trout passage through critical riffles by the ODFW. Modifications were made by CDFW to the Thompson (1972) methodology with the application of regional species- and lifestage -specific information relevant to California salmonids. The overall concept of the procedure is based on information in "Determining Stream Flows for Fish Life" presented by Ken Thompson at the *Instream Flow Requirements Workshop* on March 15-16, 1972 (Thompson 1972).

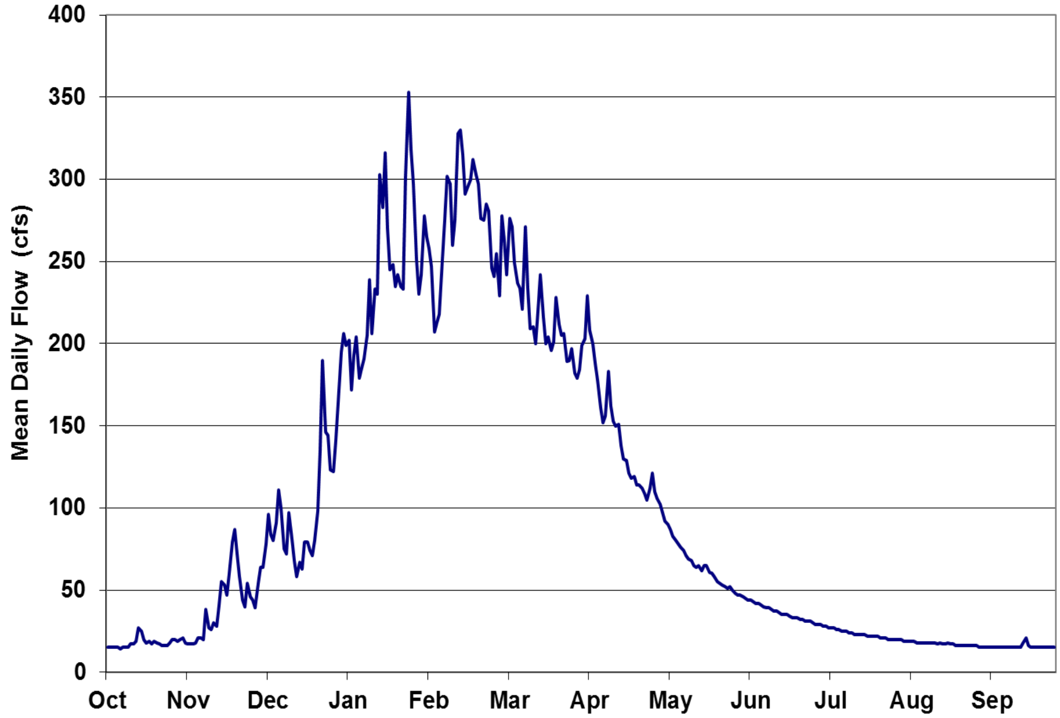

Figure 5. Mean daily unimpaired flow at USGS gage 11143000 on the Big Sur River from March 1950-2010.

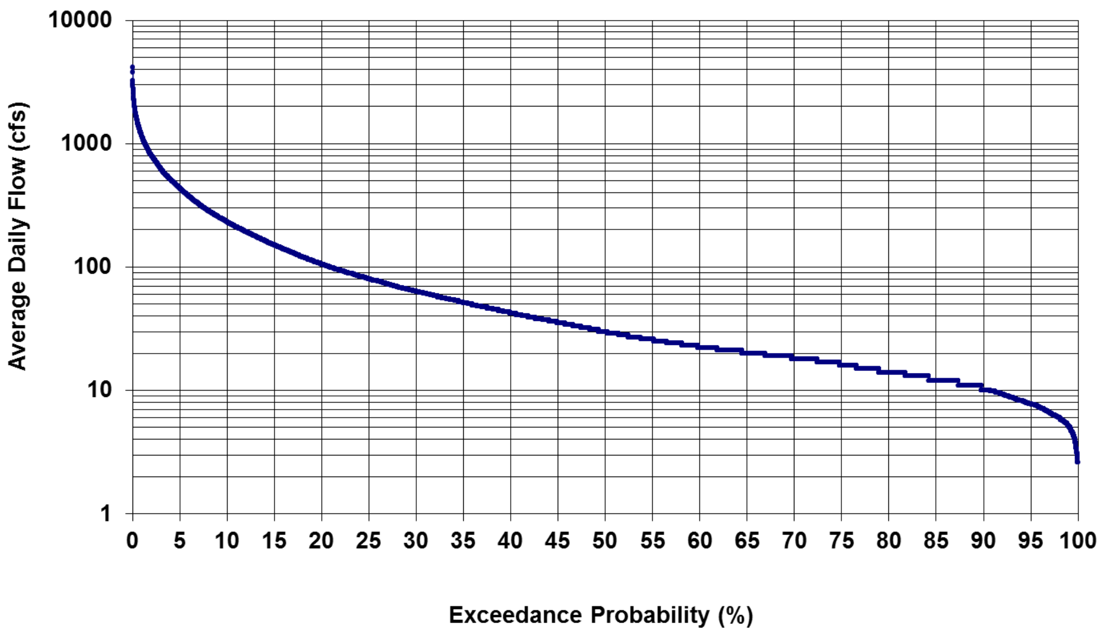

Figure 6. Percent exceedance flows using mean daily unimpaired flow at USGS gage 11143000 on the Big Sur River from 1950-2010.

The approach is to locate a critical riffle, identify a transect along the riffle's shallowest course from bank to bank (Figure 7, Figure 8, Figure 9), and measure water depth at multiple locations across the transect. Adequate water depths of sufficient width are necessary to identify passage flows and promote passage of adult and juvenile salmonids at critical riffle sites. The data from each sample event are compiled and compared to target fish species passage criteria for minimum water depth and minimum proportion of riffle width available for fish passage.

After a minimum of four to six sample events have been completed over a range of appropriate discharges (i.e., 20 – 80 percent exceedance flow range), stream discharge rates and percent of transect meeting the minimum depth criteria for the species are compiled and plotted to determine flow rates necessary for passage and habitat connectivity at critical riffle sites. Each criterion must be met and thus the higher flow rate found to meet the minimum depth criteria from either the total portion or the contiguous portion of the critical riffle may then be used to identify passage flows for the target species at the critical riffle site (Thompson, 1972).

The water depth criteria identified for protection of adult and juvenile salmonid passage through a critical riffle are listed in Table 4. The passage criteria for adults are based upon Thompson (1972) and SWRCB (2014) and are intended to provide protective passage and habitat connectivity conditions. Ideally, there should be sufficient clearance underneath the fish so that contact with the streambed and abrasion are minimized. A minimum clearance of 0.1 ft depth for salmonids is acceptable in California (SWRCB 2014). When selecting the appropriate criteria, we use the minimum depth for the adult fish if both adult and juvenile fish are known to be in the system at the same time. The critical riffle analysis and 2D model use depth criteria of 0.7 ft for adult passage, 0.4 ft for passage of 1-2 year old juveniles, and 0.3 ft for passage of YOY juvenile Big Sur River steelhead.

Table 4. Water depth criteria for steelhead passage based upon Thompson (1972) and SWRCB (2014).

Species and Lifestage	**Depth (ft.)**
Steelhead (adult)	0.7
Trout (adult, including 1-2+ juvenile steelhead)	0.4
Salmonid (young-of-year)	0.3

Figure 7. Photo of critical riffle analysis transect following shallowest course from bank to bank at Big Sur River lower river site at approximately 35 cfs.

Figure 8. Photos of Big Sur River middle river site at 57 cfs (above) and at 22 cfs (below).

Figure 9. Photo of Big Sur River upper river site at 75 cfs.

Critical Riffle Data Collection

Data for the critical riffle analysis were collected as a four- to six-part field sampling series, on the receding limb of the hydrograph. Sampling events were timed to capture the range of discharges necessary to identify passage flows for steelhead lifestages on the Big Sur River. The first data collection was typically at the highest wadeable flow of the targeted flows, with subsequent collections taken as flows decreased. However, given the natural hydrology and rainfall driven flow patterns of the Big Sur River during the rainy season, this sampling schedule was modified as field conditions warranted.

Once a riffle had been identified for critical riffle analysis, the passage transect was established, marked on each bank with flagging and rebar, and photographed. The passage transects were not linear, but instead followed the contours of the riffle along its shallowest course from bank to bank. Initial determination of the shallowest course was based upon subjective judgment but was confirmed with multiple depth measurements. Water depths were measured along each passage transect to the nearest 0.01 ft with a stadia rod. The headpin for each critical riffle transect was located on the left bank of the river looking upstream, and the tailpin on right bank looking upstream. The headpin served as the starting point for each critical riffle water depth measurement, starting from zero feet, and the tailpin served as the end point of the measurements. A temporary staff gage was used to record the stage at the beginning and end of each data collection event. Staff gage measurements were used to determine whether flow levels had changed during data collection.

River 2D Model

Two-dimensional River2D models (Steffler and Blackburn 2002) were used to determine passage flows at the lagoon and lower river sites. River2D inputs include river bed topography and roughness, the flow at the upstream end of the site, and the water surface elevation at the downstream end of the site. The minimum flows required for steelhead passage and riverine habitat connectivity are computed using the depths predicted by River2D based on the substrate and bed topography present at the site. River2D avoids problems of linear transect placement, since data are collected uniformly across the entire site (Gard 2009b). River2D is advantageous for determining passage flows through complex low gradient critical riffles because it can explicitly handle complex hydraulics, including transverse flows, across-channel variation in water surface elevations, and flow contractions/expansions (Ghanem et al. 1996; Crowder and Diplas 2000; Pasternack et al. 2004). With detailed bathymetry data, the model scale is small enough to correspond to the scale of microhabitat use data with contiguous depths produced on a continuous basis, rather than in discrete cells. As such, high densities of bed topography data points are needed within the riffle channels with additional emphasis near the riffle crests for the current study.

2D Model Sites Setup

The lagoon 2D study site was established in October 2011. The lower river 2D study site was established in November 2009. Study site boundaries (upstream and downstream) were selected so that the site included all of each critical riffle, with the downstream transect moved downstream of the critical riffle and the upstream transect moved upstream of the critical riffle to locations (single-thread channel with uniform cross-channel water surface elevation and all velocities perpendicular to the transect) that were optimal for a one-dimensional (1D) physical habitat simulation model (PHABSIM) transect. A PHABSIM transect was placed at the upstream and downstream end of each study site, and the downstream transect was modeled with PHABSIM to provide water surface elevations as an input to the 2D model. The upstream transect was used in calibrating the 2D model - bed roughness's are adjusted until the water surface elevation at the top of the site matches the water surface elevation predicted by PHABSIM.

Structural and Hydraulic Data Collection at 2D Sites

Elevational benchmarks were established at each site and we referenced all elevations to these benchmarks. Horizontal benchmarks were also established at each site and we referenced all horizontal locations (i.e., northings and eastings) to these benchmarks. The precise northing and easting coordinates and vertical elevations of two horizontal benchmarks were established for each site using survey grade Real Time Kinematic (RTK) Global Positioning System (GPS). The elevations of these benchmarks were tied into the vertical benchmarks on our sites using differential leveling.

Structural data collection for the lower river 2D site began in October 2009 and was completed in December 2009. Hydraulic data for the lower river 2009 2D model were collected in October and November 2009 (Table 3). Structural data were recollected in 2011 at the lower river site to assess temporal changes in required passable flows between the two winters. Hydraulic data for the lower river 2011 2D model were collected between May and October 2011. Flows for calibrating the 2D model were measured onsite and using USGS 11143010 for the 2009 and 2011 models.

Structural data collection for the lagoon 2D site began in October 2011 and was completed in February 2012. Hydraulic data collection for the lagoon 2D site began in October 2011 and was completed in July 2012. All flows used for calibrating the model were measured onsite. Cross section 1 (XS1) of the 2D Big Sur River lagoon site was within the lagoon's upper extent of tidal influence, and therefore hydraulic data (including water surface elevations) were collected at high and low tides to account for any tidal influence on water surface elevation and flow relationships when calibrating the model. Flows were measured at XS2 in the lagoon site, which was not affected by tidal influence during data collection events. Tide heights were obtained from Station 9413450 (NOAA 2012).

The data collected on the upstream and downstream transects included: 1) water surface elevations (WSELs), measured to the nearest 0.01 ft (0.003 m) at a minimum of three significantly different stream discharges using standard surveying techniques (differential leveling); 2) wetted streambed elevations determined by subtracting the measured depth from the surveyed WSEL at a measured flow; 3) dry ground elevations to points above bank-full discharge surveyed to the nearest 0.1 ft (0.031 m); 4) mean water column velocities measured at a mid- to high-range flow at the points where bed elevations were taken; and 5) substrate and cover classifications (Table 5, Table 6) at these same locations and also where dry ground elevations were surveyed. In between the transects, the following data were collected: 1) bed elevation; 2) horizontal location (northing and easting, relative to horizontal benchmarks); 3) substrate; and 4) cover. These parameters were collected at enough points to characterize the bed topography, substrate and cover of the site.

Water surface elevations were measured at each bank and in the middle of each 2D transect. If the difference between the three measurements was less than 0.1 ft (0.031 m), the average of these three values were considered the transect water surface elevation. If the difference in elevation exceeded 0.1 ft, the water surface elevation for the side of the river that was considered most representative was used. A top-setting wading rod and Marsh-McBirney model 2000 water velocity meter were used to measure water depth and velocities at specific intervals along each transect. All substrate data collected on the transects were assessed by one observer based on the visually-estimated average of multiple grains.

Bed topography data between the upstream and downstream transects were obtained by measuring the bed elevation and horizontal position of each sample point. We used a total station or survey-grade RTK GPS to make these measurements. Substrate was visually assessed at each point by one observer based on the visually-estimated average of multiple grains. Topography data, including substrate and cover, were also collected for a minimum of a half-channel width upstream of the upstream transect to improve the accuracy of the flow distribution at the upstream end of the sites.

Table 5. Substrate codes, descriptors and particle sizes used for Big Sur River 2D models.

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

Table 6. Cover coding system used for Big Sur River 2D models.

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

To validate the depths predicted by the 2D model, we made a minimum of 50 additional water depth validation measurements independent of those data required to construct the 2D models. Validation depth measurements were not made for the lower river site (2009) model.

Since the lower Big Sur River and lagoon are low gradient, there could be a point in the thalweg a short way downstream of each 2D site that was higher than that measured at the downstream transect thalweg simply due to natural variation in topography. This stage of zero (SZF) flow downstream of the site acts as a control on the water surface elevations at the downstream transect, and could cause errors in the WSELs. Because the true SZF is needed to accurately calibrate the water surface elevations on the downstream transect, this SZF in the thalweg downstream of the downstream transect was surveyed in using differential leveling. If the true SZF was not measured as described above, the default SZF would be the thalweg elevation at the transect.

The upstream and downstream 2D transects were modeled with PHABSIM to provide water surface elevations as an input to the River 2D hydraulic and habitat model. By calibrating the upstream and downstream transects with PHABSIM using the collected calibration WSELs, we were able to predict the WSELs for the transects at the various simulation flows that were to be modeled using River2D. The highest simulation WSELs predicted by PHABSIM for the upstream and downstream transects were used for the upstream boundary condition (in addition to flow) and the downstream boundary condition. The PHABSIM-predicted WSEL for the upstream transect at the highest simulation flow was used to ascertain calibration of the River2D model at the highest simulation flow. After the River2D model was calibrated, the WSELs predicted by PHABSIM for the downstream transect for each simulation flow were used as an input for the downstream boundary condition for River2D model production files used for the simulation flows.

The following describes the PHABSIM WSEL calibration process for the upstream and downstream transects. All data were compiled and checked before entry into PHABSIM data files. A table of substrate values was created to determine the substrate for each vertical cell measurement location (e.g., if the substrate size class was 2-4 inches (5 to 10 cm) on a transect from station 50 to 70, all of the vertical cells with station values between 50 and 70 were given a substrate coding of 2.4). Dry bed elevation data from field notebooks were entered into a spreadsheet to extend the bed profile up the banks above the WSEL of the highest flow to be modeled. An ASCII computer file produced from the spreadsheet was run through the FLOMANN program (written by Andy Hamilton, U.S. Fish and Wildlife Service) to get the PHABSIM input file and then translated into RHABSIM[4] files.

All measured WSELs used for each PHABSIM site file were checked to make sure that water was not flowing uphill. The slope for each 2D transect was computed at each measured flow as the difference in WSELs between the two 2D transects divided by the distance between the two. The slope used for each transect was calculated by averaging the slopes computed for each flow. Four to seven WSEL data sets at lower, medium, and higher flows were used. If WSELs were available for several closely spaced flows, the WSEL that corresponded with the velocity data set or the WSEL collected at the lowest flow was used in the PHABSIM data files. Calibration flows in the data files were the flows calculated from measured and/or gage readings.

The SZF, an important parameter used in calibrating the stage discharge relationship as described earlier, was determined for each transect. In general, riffle habitat types do not have backwater effects and the SZF generally represents the lowest point in the streambed across a transect. Since riffles sites in the Big Sur River and lagoon are low gradient, a transect directly upstream could contain a lower bed elevation than the adjacent downstream transect. In such cases the SZF for the downstream transect would apply to both.

The first step in the calibration procedure was to determine the best approach for WSEL simulation. Initially, the *IFG4* hydraulic model (Milhous et al. 1989) was run on each data deck to compare predicted and measured WSELs. This model produces a stage-

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[4]RHABSIM is a commercially produced software (Payne and Associates 1998) that incorporates the modeling procedures used in PHABSIM.

discharge relationship using a log-log linear rating curve calculated from at least three sets of measurements taken at different flows. Besides *IFG4*, two other hydraulic models are available in PHABSIM to predict stage-discharge relationships. These models are: 1) *MANSQ*, which operates under the assumption that the condition of the channel and the nature of the streambed controls WSELs; and 2) *WSP*, the water surface profile model, which calculates the energy loss between transects to determine WSELs. *MANSQ*, like *IFG4*, evaluates each transect independently. *WSP* must, by nature, link at least two adjacent transects. IFG4 was determined as the best hydraulic model and was used for each model to predict stage-discharge relationships.

River 2D Model Construction and Calibration

After completing the PHABSIM calibration process to arrive at the simulation WSELs that will be used as inputs to the River2D models, the next step is to construct the River2D models using the collected bed topography data. The total station data and the PHABSIM transect data were combined in a spreadsheet to create the input files (bed and substrate) for the 2D modeling program. An artificial extension one channel-width-long was added upstream of the topography data collected upstream of the study site, to enable the flow to be distributed by the model when it reached the study area, thus minimizing boundary conditions influencing the flow distribution at the upstream transect and within the study site.

The bed files contain the horizontal location (northing and easting), bed elevation and initial bed roughness value for each point. The initial bed roughness value for each point was determined from the substrate codes for that point and the corresponding bed roughness values in Table 7, with the bed roughness value for each point computed as the sum of the substrate bed roughness value and the cover bed roughness value for the point. The resulting initial bed roughness value for each point was therefore a combined matrix of the substrate and cover roughness values. The bed roughness height values for cover in Table 5 were computed as five times the average cover size[5], where cover size was measured on the Sacramento River on a representative sample of cover elements of each cover type. The bed files were exported from the spreadsheet as ASCII computer files.

A utility program, R2D_BED (Steffler 2002), was used to define the study area boundary and to refine the raw topographical data TIN (triangulated irregular network) by defining breaklines[6] following longitudinal features such as thalwegs, tops of bars and bottoms of banks. The first step in refining the TIN was to conduct a quality assurance/quality control process, consisting of a point-by-point inspection to eliminate quantitatively wrong points, and a qualitative process where we checked the features constructed in

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

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

the TIN against aerial photographs and site photographs to make sure we had represented landforms correctly. Breaklines were also added along lines of constant elevation.

Table 7. Initial bed roughness values used for Big Sur River 2D models.

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

An additional utility program, 2D_MESH (Waddle and Steffler 2002), was used to define the inflow and outflow boundaries and create the finite element computational mesh for the River2D model. R2D_MESH uses the final bed file as an input. The first stage in creating the computational mesh was to define mesh breaklines[7] which coincided with the final bed file breaklines. Additional mesh breaklines were then added between the initial mesh breaklines, and then additional nodes were added as needed to improve the fit between the mesh and the final bed file and to improve the quality of the mesh, as measured by the Quality Index (QI) value. The QI is a measure of how much the least equilateral mesh element deviates from an equilateral triangle. The final step with the R2D_MESH software was to generate the characteristic dissipative galerkin (cdg) file of the computational mesh.

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

Once a River2D model had been constructed, calibration is then required to determine that the model is reliably simulating the flow-WSEL relationship that was determined through the PHABSIM calibration process using the measured WSELs. The cdg files were opened in the River2D software, where the computational bed topography mesh was used together with the WSEL at the bottom of the site, the flow entering the site, and the bed roughness's of the computational mesh elements to compute the depths and WSELs throughout the site. The River 2D model for the lagoon was calibrated for both a high and low tide scenario. However, site surveys confirmed that the locations of the passage and connectivity transects were unaffected by tidal influence in the lagoon site at the flows and tides sampled, and thus only the low tide calibration data were used for the River 2D analyses.

The computational mesh was run to steady state at the highest flow to be simulated, and the WSELs predicted by River2D at the upstream end of the site were compared to the WSELs predicted by PHABSIM at the upstream transect. The bed roughness's of the computational mesh elements were then modified by multiplying them by a constant bed roughness multiplier (BR Mult) until the WSELs predicted by River2D at the upstream end of the site matched the WSELs predicted by PHABSIM at the upstream transect. The minimum groundwater depth was adjusted to a value of 0.16 ft (0.05 m) to increase the stability of the model. The values of all other River2D hydraulic parameters were left at their default values (upwinding coefficient = 0.5, groundwater transmissivity = 0.1, groundwater storativity = 1, and eddy viscosity parameters $\varepsilon 1 = 0.01$, $\varepsilon 2 = 0.5$ and $\varepsilon 3 = 0.1$). A stable solution will generally have a Sol Δ value of less than 0.00001 and a Net Q of less than 1% (Steffler and Blackburn 2002). Solutions for low gradient streams should usually have a maximum Froude (Max F) number of less than 1[8]. However, Max F values may exceed 1 and still be acceptable especially in situations where nodes are located either at the water's edge or where water depth is extremely shallow, typically approaching zero. In these situations, high Froude numbers at a very limited number of nodes at water's edge or in very shallow depths would be expected to have an insignificant effect on the model results.

After the River2D models were calibrated, the flow and downstream WSEL in the calibrated cdg files were changed to provide initial boundary conditions for simulating hydrodynamics of the sites at the simulation flows. The cdg file for each flow contained the WSEL predicted by PHABSIM at the downstream transect at that flow. The River 2D models were run at simulated flows between 7 cfs and 150 cfs for the lagoon site, and between 10 cfs and 100 cfs for the lower river site for both the 2009 and 2011 models. Each discharge was run in River2D to steady state. Again, a stable solution will generally have a Sol Δ value of less than 0.00001 and a Net Q of less than 1%. In addition, solutions will usually have a Max F of less than 1. Also, the WSEL predicted by the 2D model should be within 0.1 foot (0.031 m) of the WSEL measured at the upstream transect[9].

[8] This criteria is based on the assumption that flow in low gradient streams is usually subcritical, where the Froude number is less than 1 (Peter Steffler, personal communication).
[9] We have selected this standard because it is a standard used for PHABSIM (U.S. Fish and Wildlife Service 2000).

River 2D Passage Transect Delineation

Passage transects used in the River 2D analyses were identified using terrain models developed by GIS software (ESRI's ArcMap & ArcScene; Figure 10, Figure 11, Figure 12) and the corresponding River 2D model for each site (Figure 13, Figure 14, Figure 15). Depth values were extracted from the River2D model and displayed as a TIN in GIS. With the TIN, the shallowest course from bank to bank across the river was digitized in GIS. The digitized transect line was divided into tenth of a meter segments and then converted to points spread 0.10 m apart using GIS. The points were then converted to a comma-separated values (csv) computer data file of x, y locations. The csv file was used to extract depth values from the River2D model's various flow predictions.

Passage and Habitat Connectivity Assessment Criteria

The flow rates evaluated for the protection of passage and habitat connectivity at the critical riffle sites were determined for each steelhead lifestage using two quantitative criteria as described earlier (and identified as necessary by Monterey County (1986) for assessing steelhead passage in the Big Sur River): the percent total criteria and the percent contiguous criteria. If the flow rates differ between the two criteria, the higher of the two flow rates is identified as the passage flow for the critical riffle site. In other words, both criteria must be met and the highest is the passage flow required. The flow rates identified by the critical riffle analysis were derived using linear interpolation between measured flow events and the corresponding associated passage criteria values. The flow rates identified by River 2D were derived using model predictions of depths among simulated flows and the corresponding passage criteria values.

Maximum transect widths were determined independently by critical riffle analysis and River 2D. For example, the maximum transect widths for critical riffle assessments were identified based upon the empirical site measurements, while the maximum transect widths for the River 2D models were determined by use of the terrain models and corresponding River 2D depth versus flow models for each River 2D flow analysis. The maximum transect width is defined as the length of the transect following shallowest course from bank to bank without exceeding the toe of bank – the point where the streambed and one bank join. The streambed is defined as that part of the channel usually not occupied by perennial terrestrial plants, but including gravel bars, and lying between the toe of each bank.

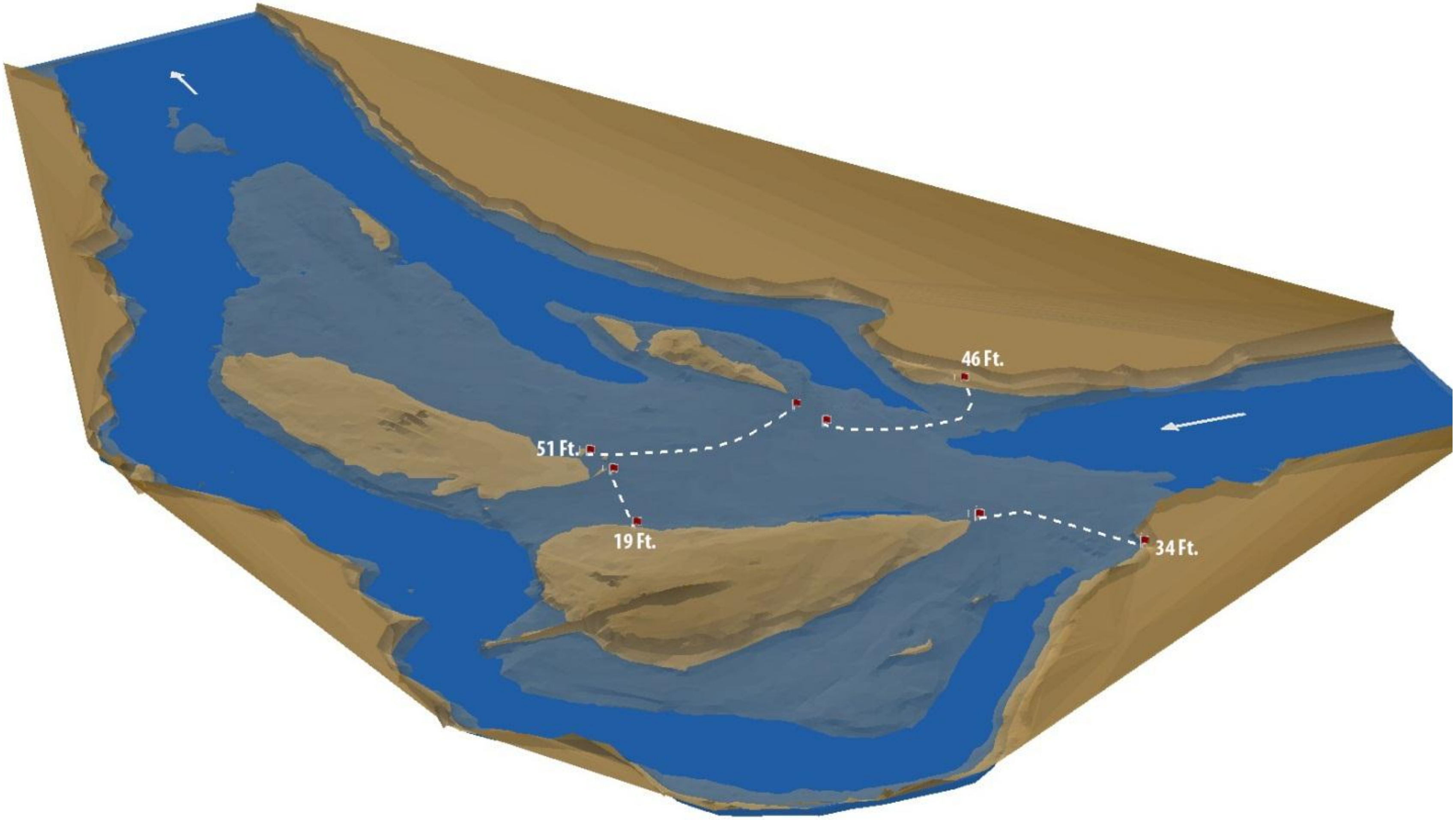


Figure 10. Terrain model with passage transect delineation for River 2D model at Big Sur River lagoon site.

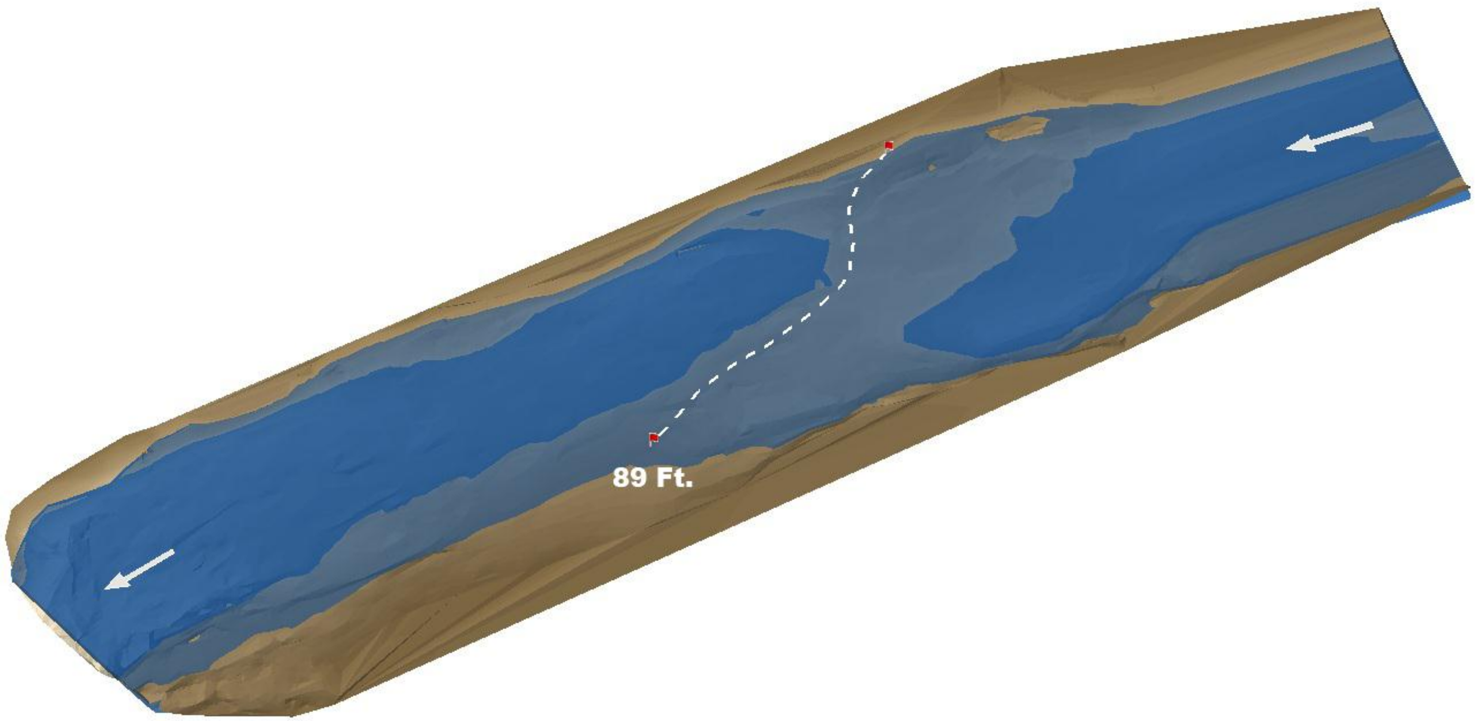


Figure 11. Terrain model with passage transect delineation for Big Sur River lower river site (2009) River 2D model.

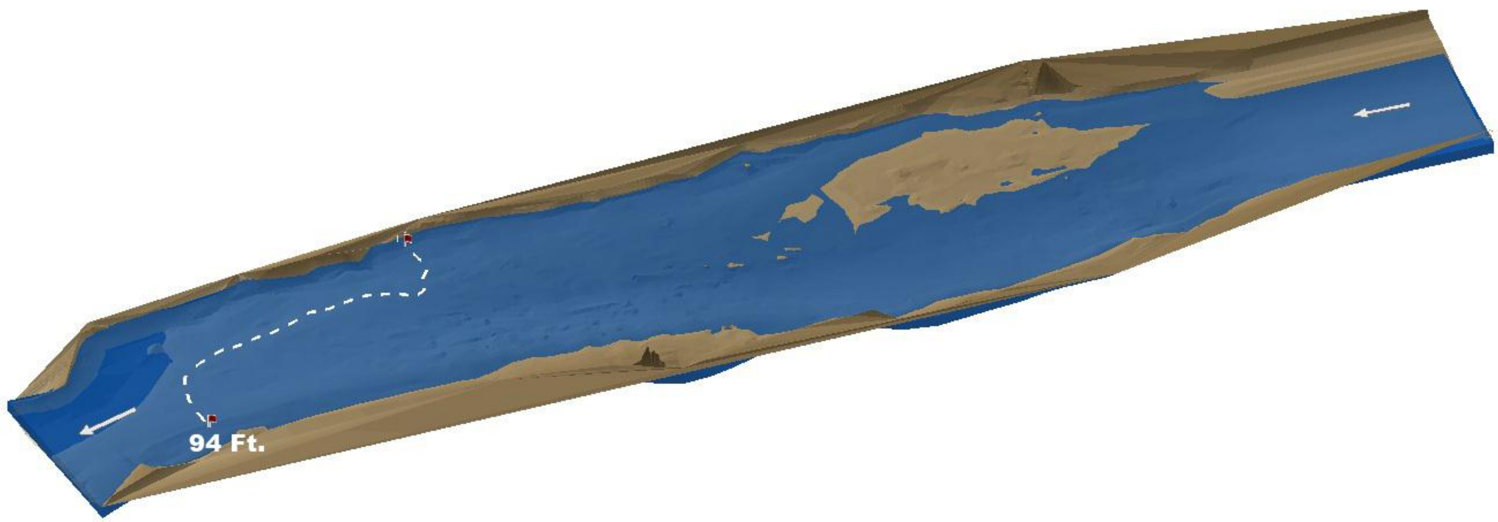


Figure 12. Terrain model with passage transect delineation for Big Sur River lower river site (2011) River 2D model.

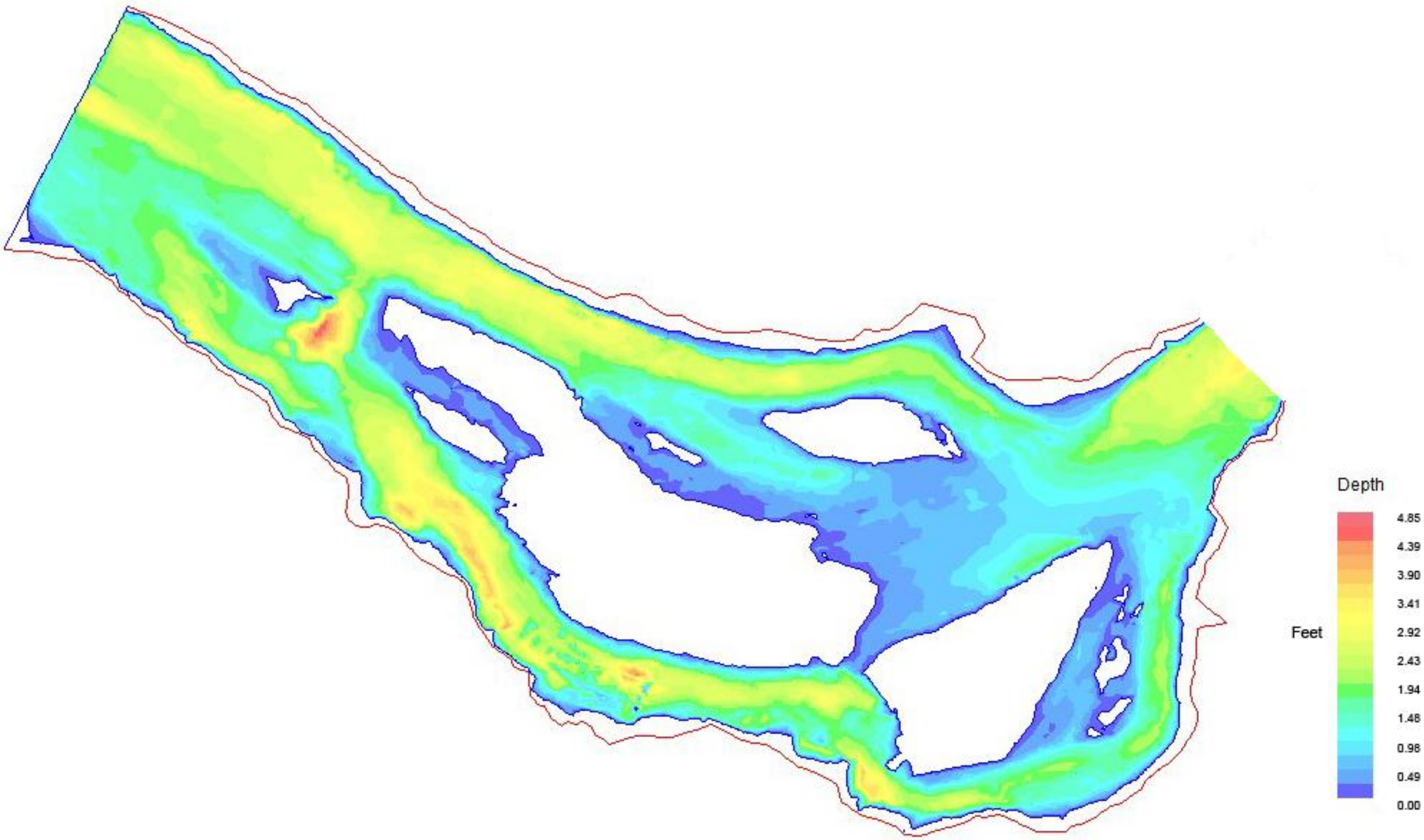


Figure 13. Depth (ft) profile schematic using River 2D for Big Sur River lagoon site at 150 cfs.

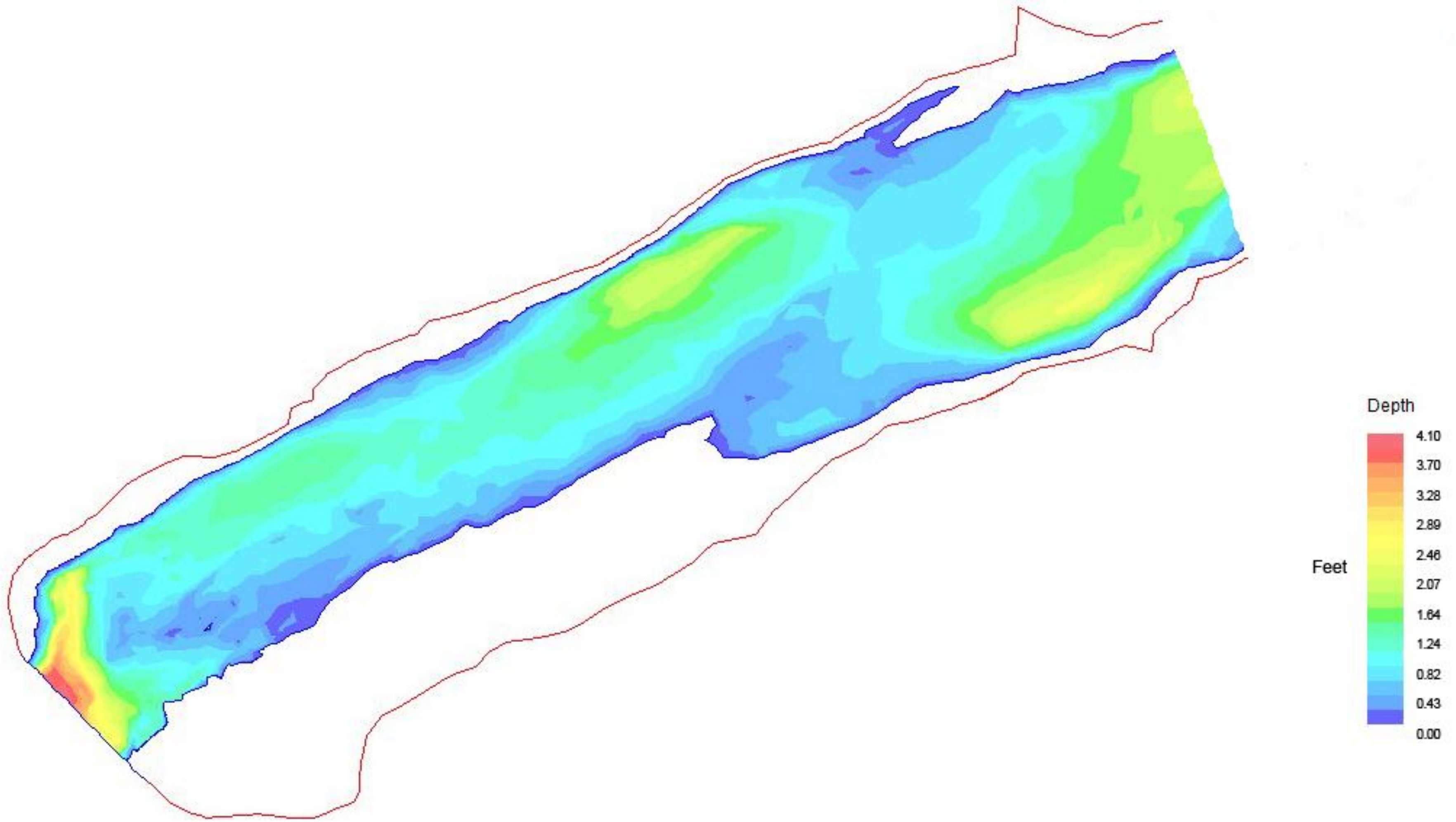


Figure 14. Depth (ft) profile schematic using River 2D for Big Sur River lower river site (2009) at 60 cfs.

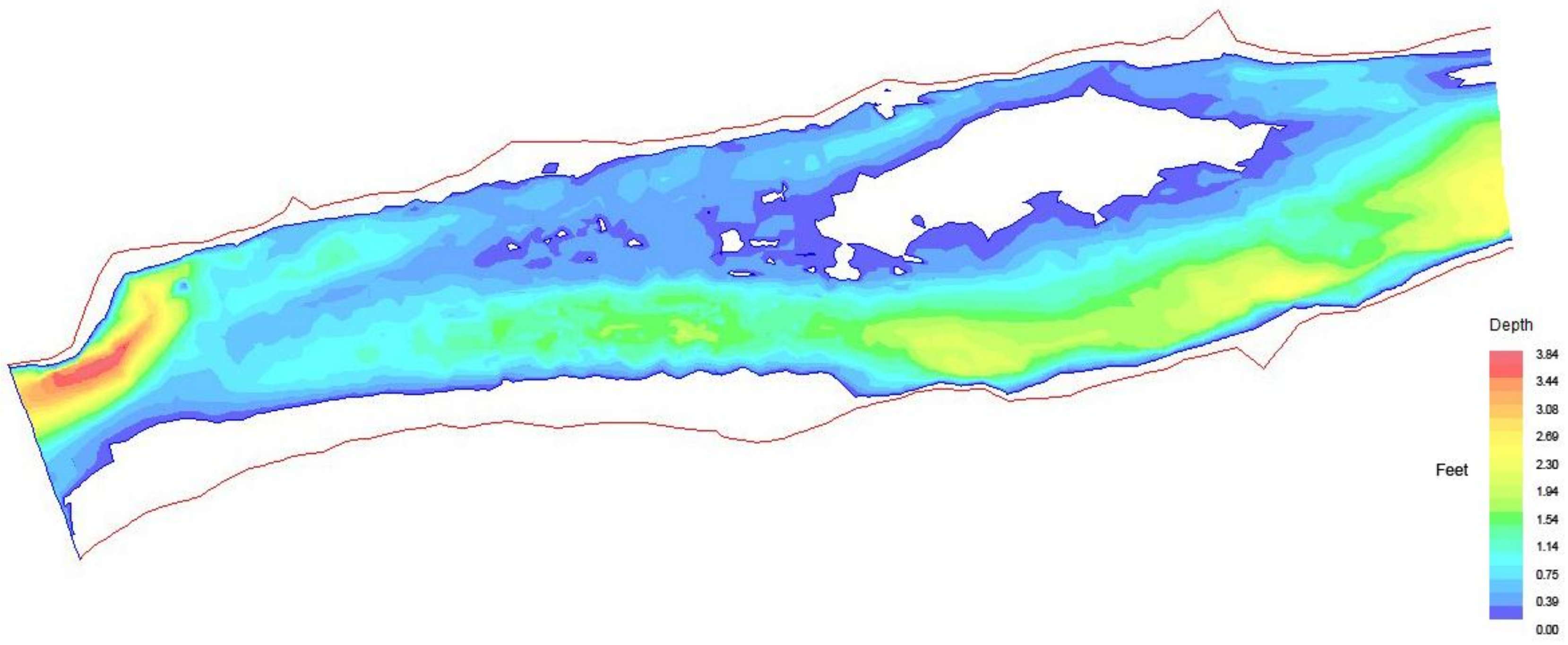


Figure 15. Depth (ft) profile schematic using River 2D for Big Sur River lower river site (2011) at 50 cfs.

Spatial and Temporal Variability of Passage and Connectivity Flows

Spatial variability occurs when a quantity that is measured at different spatial locations exhibits values that differ across the locations. Spatial variability was assessed by examination of flow results for steelhead lifestages longitudinally between lagoon, lower river, middle river and upper river sites. Temporal variability refers to the variability of time. Temporal variability was assessed at the lower river site by examination of the results of the critical riffle analyses in 2009 and the results of the River 2D model in 2009 and 2011.

Assessment of flow velocity on suitability of flows for steelhead passage and habitat connectivity was assessed using the River 2D models using 8 ft/s as an upper threshold for adults and 3 ft/s as an upper threshold for YOY juveniles. Holmes et al. (2014) documented juvenile YOY steelhead holding at locations with focal velocities as high as 3.25 ft/s (and mean column velocities as high as 4.3 ft/s). Further, earlier studies have documented that steelhead are strong swimmers, in fact the strongest among Pacific salmonids, with adults capable of prolonged swimming speeds of 4.6-13.7 feet per second (fps) and burst speeds of 13.7-26.5 fps (Bell 1990; Powers and Orsborn 1985). Conditions where high velocities can form a restriction to salmonid passage typically occur in falls and chute type habitats (Reiser et al. 2006), and were verified to not occur at critical riffle sites in the study area within the range of the flows of interest.

RESULTS

Critical Riffle Analysis

Critical riffle analyses were conducted at four sites from five to six different flows. The lagoon and middle river sites were sampled at six flows in 2011.The lower river site was sampled at five flows. The upper river site was sampled at five flows. A summary of the sample dates and corresponding flows obtained from the onsite and USGS gage measurements are outlined in Table 8.

Lagoon

The lagoon critical riffle complex contained four separate critical riffles (i.e., A, B, C, and D). During the field surveys, lagoon critical riffles B and C were identified as representing the most depth sensitive riffles of the lagoon site, and were observed to be dry at flows below 23 cfs and 42 cfs, respectively (Figure 16, Figure 17). Critical riffle D was determined to be the next most depth sensitive critical riffle behind riffles B and C at the lagoon site (Figure 18). Critical riffle A (Figure 19) was therefore identified as the riffle presenting the highest passage opportunities for steelhead through the lagoon critical riffle complex.

Table 8. Summary of sample dates and corresponding flows obtained (measured versus USGS gage) for Big Sur River critical riffle analysis.

Site	Date	Flow (cfs)	Measured vs. USGS Gage
Lagoon	5/10/11	110	USGS 11143010
	6/1/11	73	USGS 11143010
	6/8/11	145	USGS 11143010
	7/7/11	62	Measured
	8/2/11	42	Measured
	9/28/11	23	Measured
Lower River	8/19/09	13	Measured
	10/29/09	45	Measured
	11/18/09	35	Measured
	1/6/10	56	Measured
	3/29/10	179	Measured
Middle River	5/12/11	109	USGS 11143010
	6/1/11	73	USGS 11143010
	6/8/11	143	USGS 11143010
	7/7/11	57	USGS 11143010
	8/2/11	39	USGS 11143010
	9/28/11	22	USGS 11143010
Upper River	5/10/11	127	Measured
	6/1/11	94	Measured
	7/7/11	68	Measured
	8/2/11	49	Measured
	7/18/12	23	Measured

The remainder of the results for the critical riffle analysis of the lagoon site will be reported for riffles A and D which presented the highest passage opportunities for steelhead through the lagoon site.

The critical riffle analysis of riffle A in the lagoon identified 15 cfs, 32 cfs, and 75 cfs as meeting the percent total metric criteria (25% total passable width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively. The critical riffle analysis of riffle A in the lagoon identified 18 cfs, 28 cfs, and 68 cfs as meeting the percent contiguous metric criteria (10% contiguous width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively (Table 9).

Figure 16. Photos of Big Sur River lagoon critical riffle complex: Riffle B at 110 cfs (top), 62 cfs (middle), and 23 cfs (bottom).

Figure 17. Photos of Big Sur River lagoon critical riffle complex: Riffle C at 110 cfs (top), 73 cfs (middle), and 42 cfs (bottom).

Figure 18. Photos of Big Sur River lagoon critical riffle complex: Riffle D at 110 cfs (top), 62 cfs (middle), and 23 cfs (bottom).

Figure 19. Photos of Big Sur River lagoon critical riffle complex: Riffle A at 110 cfs (top), 62 cfs (middle), and 23 cfs (bottom).

The critical riffle analysis of critical riffle D in the lagoon identified 37 cfs, 51 cfs, and 131 cfs as meeting the percent total metric criteria (25% total passable width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively. The critical riffle analysis of critical riffle D in the lagoon identified 32 cfs, 48 cfs, and 86 cfs as meeting the percent contiguous metric criteria (10% contiguous width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively.

Lower River

The critical riffle analysis of the lower river site identified 18 cfs, 29 cfs, and 77 cfs as meeting the percent total metric criteria (25% total passable width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively. The critical riffle analysis of the lower river site identified 17 cfs, 15 cfs, and 58 cfs as meeting the percent contiguous metric criteria (10% contiguous width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively.

Middle River

The critical riffle analysis of the middle river site identified 32 cfs, 45 cfs, and 77 cfs as meeting the percent total metric criteria (25% total passable width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively. The critical riffle analysis of the middle river site identified 39 cfs, 42 cfs, and 65 cfs as meeting the percent contiguous metric criteria (10% contiguous width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively.

Upper River

The critical riffle analysis of the upper river site identified 40 cfs, 54 cfs, and 72 cfs as meeting the percent total metric criteria (25% total passable width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively. The critical riffle analysis of the upper river site identified 23 cfs, 27 cfs, and 44 cfs as meeting the percent contiguous metric criteria (10% contiguous width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively.

Table 9. Percent total passable flow and percent contiguous passable flow identified by critical riffle analysis for each steelhead lifestage at critical riffle sites in Big Sur River.

Critical Riffle Site	Steelhead Lifestage	Percent Total Passable Flow (cfs)	r^2	Percent Contiguous Passable Flow (cfs)	r^2
Lagoon					
Riffle A	YOY	15	.88	18	.89
	Juvenile	32	.87	28	.92
	Adult	75	.97	68	.93
Riffle D	YOY	37	.96	32	.74
	Juvenile	51	.98	48	.96
	Adult	131	.91	86	.91
Lower River					
	YOY	18	.84	17	.89
	Juvenile	29	.84	15	.59
	Adult	77	.99	58	.99
Middle River					
	YOY	32	.89	39	.83
	Juvenile	45	.96	42	.95
	Adult	77	.97	65	.94
Upper River					
	YOY	40	.92	23	.83
	Juvenile	54	.89	27	.82
	Adult	72	.92	44	.91

River 2D Model

A River 2D model was developed for the lagoon site in 2011. Two River 2D models were developed for the lower river site: one in 2009, and one in 2011. The number and density of data points collected by total station on each of the two transects, and between transects, for each 2D model study site are presented in Table 10. Table 10 also outlines the overall density of data points collected for each model. The lagoon site had the highest density of points collected with 2.20 points per meter^2 collected. The overall density of data points collected for the lower river site increased from 1.46 meter^2 in the 2009 model to 2.12 meter^2 in the 2011 model. The highest densities of bed topography data points were collected within the riffle channels with additional emphasis near the riffle crests.

Lagoon

The lagoon critical riffle complex was modeled using one 2D model which encompassed all four critical riffles. Water surface elevations and discharge were measured at four different flows at lower river site for the 2009 and 2011 River 2D models (Table 11). Water surface elevations at the lagoon site were collected at seven flows in 2012 (Table 11). Discharge measurements for the lagoon 2D site were measured onsite, and/or taken from USGS gage 11143010 located approximately 0.5 mile upstream.

Table 10. Number and density of data points collected for each River 2D model study site.

	Number of Points		
Site	**Points on Transects**	**Points Between Transects Collected with Total Station**	**Density of Points (points/m^2)**
Lower River (2009)	65	1713	1.46
Lower River (2011)	81	2466	2.12
Lagoon	124	9408	2.20

The River 2D lagoon model identified lagoon critical riffles B and C as representing the most depth sensitive riffles of the lagoon site. Critical riffle D was identified to be the next most depth sensitive critical riffle behind riffles B and C at the lagoon site. Critical riffle A was identified as the riffle presenting the highest passage opportunities for steelhead through the lagoon critical riffle complex. These results are consistent with the critical riffle analysis results.

The River 2D model analysis of critical riffle A in the lagoon identified 8 cfs, 18 cfs, and 54 cfs as meeting the percent total metric criteria (25% total passable width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively (Table 12). The River 2D model analysis of critical riffle A in the lagoon identified 7 cfs, 17 cfs, and 51cfs as meeting the percent contiguous metric criteria (10% contiguous width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively (Table 12).

Table 11. Summary of sample dates and corresponding flows when water surface elevations were measured for calibration of Big Sur River 2D models at lagoon and lower river sites.

Site	Date	Tide (ft.)	Flow (cfs)	Measured vs. USGS Gage
Lagoon				
	2/6/12	Low (-0.6)	34	Measured
	2/7/12	High (+5.7)	34	Measured
	3/21/12	Low (+0.6)	109	Measured
	3/21/12	High (+4.5)	107	Measured
	5/3/12	Low (+0.9)	63	Measured
	5/3/12	High (+3.9)	64	Measured
	7/18/12	High (+3.7)	13	Measured
Lower River (2009)				
	10/21/09	n/a	88	Measured
	10/22/09	n/a	80	Measured
	10/26/09	n/a	53	Measured
	11/16/09	n/a	35	Measured
Lower River (2011)				
	5/10/11	n/a	114	USGS 11143010
	6/21/11	n/a	79	USGS 11143010
	8/30/11	n/a	26	USGS 11143010
	10/24/11	n/a	22	USGS 11143010

The River 2D model analysis of critical riffle D in the lagoon predicted 31 cfs, 52 cfs, and 94 cfs as meeting the percent total metric criteria (25% total passable width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively. The River 2D model analysis of critical riffle D in the lagoon predicted 18 cfs, 32 cfs, and 72 cfs as meeting the percent contiguous metric criteria (10% contiguous width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively.

Lower River

The lower river site was assessed with two 2D models, one developed in 2009 and one developed in 2011. The 2009 River 2D model predicted 14 cfs, 27 cfs, and 69 cfs as meeting the percent total metric criteria (25% total passable width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively (Table 12). The 2009 River 2D model predicted 6 cfs, 16 cfs, and 59 cfs as meeting the percent contiguous metric criteria (10% contiguous width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively.

Table 12. Percent total passable flow and percent contiguous passable flow identified by River 2D models for each steelhead lifestage at critical riffle sites in Big Sur River.

Site	Steelhead Lifestage	Percent Total Passable Flow (cfs)	Percent Contiguous Passable Flow (cfs)
Lagoon			
Riffle A	YOY	8	7
	Juvenile	18	17
	Adult	54	51
Riffle D	YOY	31	18
	Juvenile	52	32
	Adult	94	72
Lower River			
2009	YOY	14	6
	Juvenile	27	16
	Adult	69	59
2011	YOY	28	12
	Juvenile	43	39
	Adult	81	79

The 2011 River 2D model for the lower river site predicted 28 cfs, 43 cfs, and 81 cfs as meeting the percent total metric criteria (25% total passable width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively (Table 12). The 2011 River 2D model for the lower river site predicted 12 cfs, 39 cfs, and 79 cfs as meeting the percent contiguous metric criteria (10% contiguous width) for protection of passage and habitat connectivity for YOY, juvenile, and adult steelhead, respectively.

Critical Riffle Analysis and River 2D Models Performance

A temporary staff gage, located near the upstream boundary of each site, was used to assess potential changes in flow that might occur during data collection. Flow levels did not change during any of the data collection events for the critical riffle assessments or for the 2D model development, and therefore did not have any effect on the performance of either method or associated data quality.

Performance of the critical riffle assessments was based upon the relationship between the flows sampled and the passage and connectivity metrics for the steelhead lifestages. Critical riffle analyses also require a sufficient number of sample events within the range of relevant flows for the passage metric criteria benchmarks. Overall, there were strong relationships between flows and the passage and habitat connectivity metrics at all sites for all steelhead lifestages (Table 9). Relationships between the percent total metric and flow ranged from an $r^2 = 0.84$ to $r^2 = 0.99$. Relationships between the percent contiguous metric and flow ranged from $r^2 = 0.59$ to $r^2 = 0.99$. More robust relationships between the passage metrics and flows were observed at critical riffle sites having five or more sample events, as well as having been sampled at flows within the 20% to 80% exceedance flow range. The lower river site (2009) produced inconsistent relationships among the passage and habitat metrics for the various lifestages with both the highest ($r^2 = 0.99$) for adult steelhead and lowest ($r^2 = 0.59$) for juvenile steelhead. This site was sampled at one large flow event (i.e., 179 cfs) for the adult steelhead lifestage, which equated to approximately a 12% exceedance value which was well above the flow and passage criteria benchmarks for the site.

Performance of River 2D models was first determined by reviewing the randomly collected depth measurements, and the depth measurements made on the upstream and downstream cross sections (i.e., XS1 and XS2), compared to model predictions of depth at the same locations and flow. Although the randomly collected depth measurements were slightly variable when compared to model simulations at the lagoon site, the results of the measured versus simulated depths on the cross section transects were generally consistent with the highest frequencies of differences being observed within $\pm$ 0.05 ft (Figure 20, Figure 21, Figure 22). Further, the highest frequencies of the lowest observed differences between measured and simulated depths were observed at XS2, which generally coincides with the passage transects for the lagoon at critical riffle A and critical riffle D. Similarly, most differences between measured and simulated validation depth values were within $\pm$ 0.10 ft at the lower river site (Figure 23). Most differences between measured and simulated depths on XS1 and XS2 at the lower river site were within $\pm$ 0.05 ft (Figure 24, Figure 25).

Performance of the River 2D models is also determined by review of the calibration procedures for WSEL simulations. The *IFG4* model (Milhous et al. 1989) was used to predict stage-discharge relationships for each of the three 2D models. Overall, the *IFG4* models were determined to have worked well for predicting stage-discharge relationships, and met the following criteria: 1) the beta value (a measure of the change in channel roughness with changes in streamflow) was between 2.0 and 4.5; 2) the mean error in calculated versus given discharges was less than 10%; 3) there was no more than a 25% difference for any calculated versus given discharge; and 4) there was no more than a 0.1 ft (0.031 m) difference between measured and simulated WSELs[10]. All *IFG4* construction and calibration parameter results were within acceptable ranges for beta values, mean error in calculated and given discharges, percent difference in calculated and given discharge, and difference in measured and simulated WSELs (Appendix A).

[10]The first three criteria are from U.S. Fish and Wildlife Service (1994) while the fourth criterion is from U.S. Fish and Wildlife Service (2011).

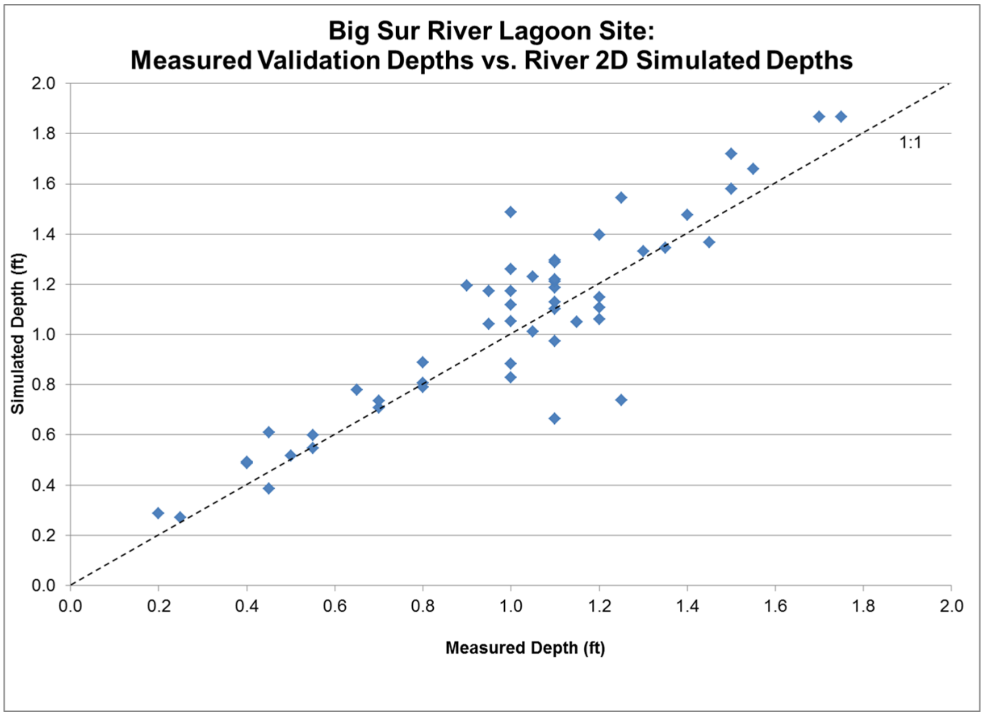


Figure 20. Measured validation depths (ft) versus River 2D model predicted depths (ft) at Big Sur River lagoon site at 25 cfs.

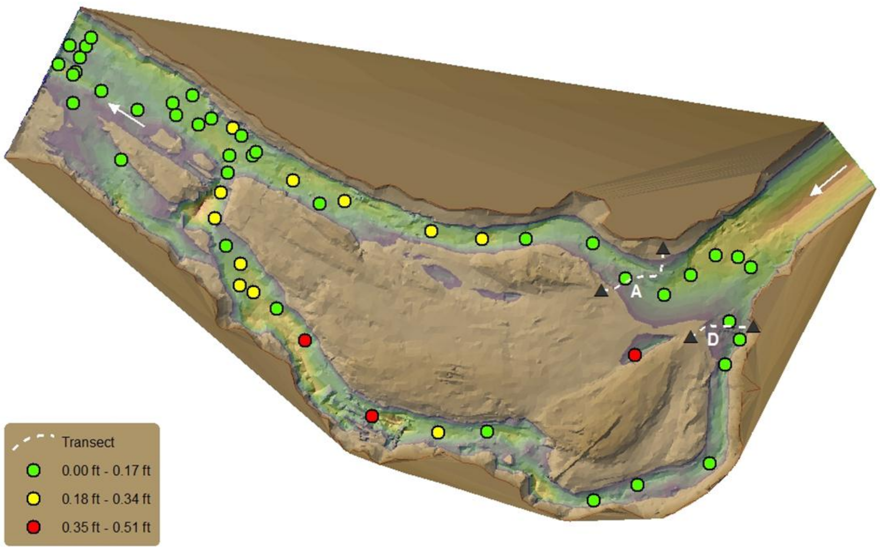
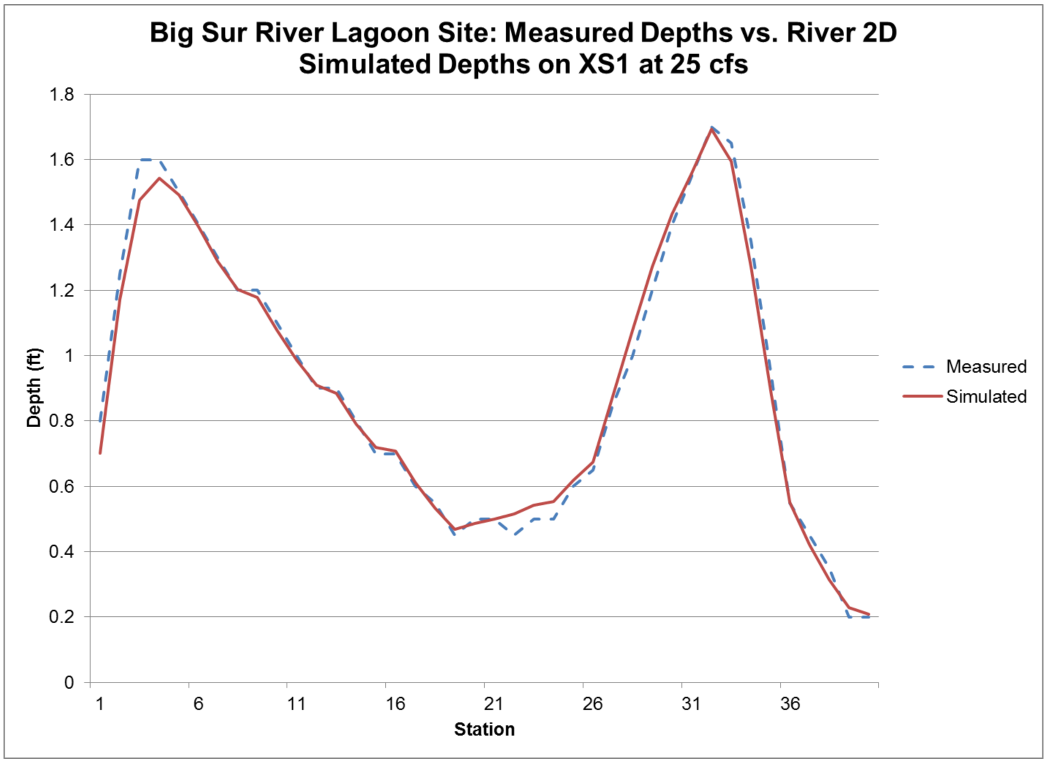


Figure 21. Terrain model of Big Sur River lagoon site showing locations and corresponding values of absolute difference between measured and predicted stream flow depths. Depths were measured on October 25, 2011 at a flow of approximately 25 cfs in the randomly selected locations.



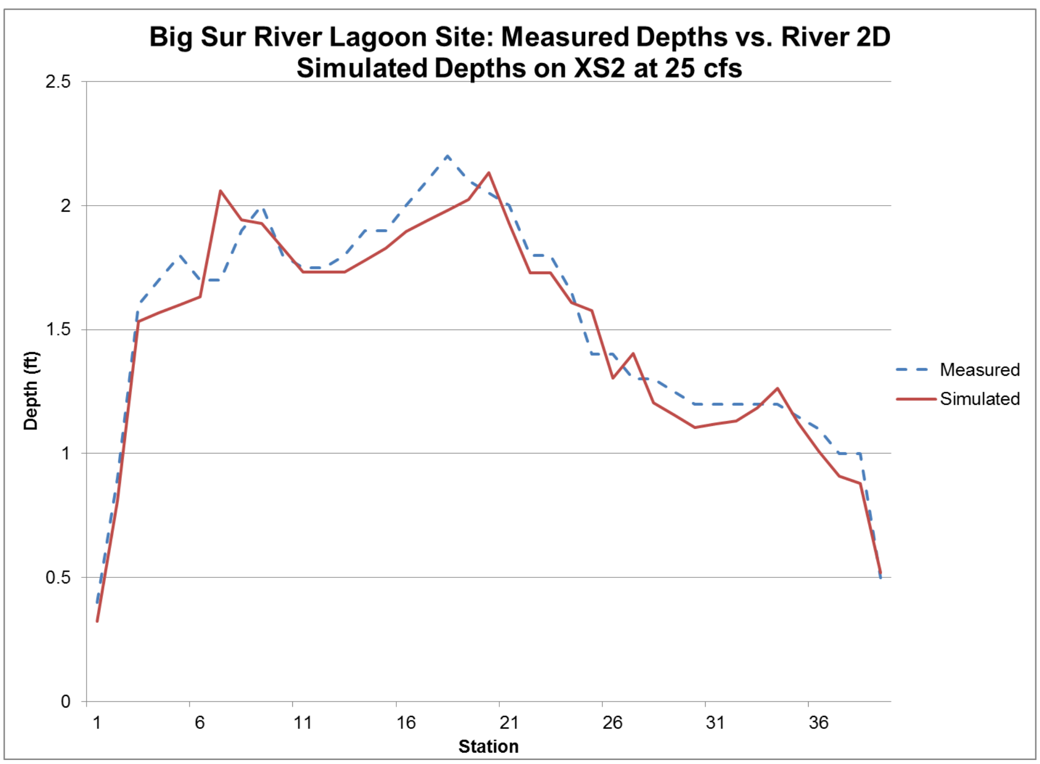


Figure 22. Measured validation depths (ft) versus River 2D model simulated depths (ft) on XS1 (above) and XS2 (below) at Big Sur River lagoon site at 25 cfs.

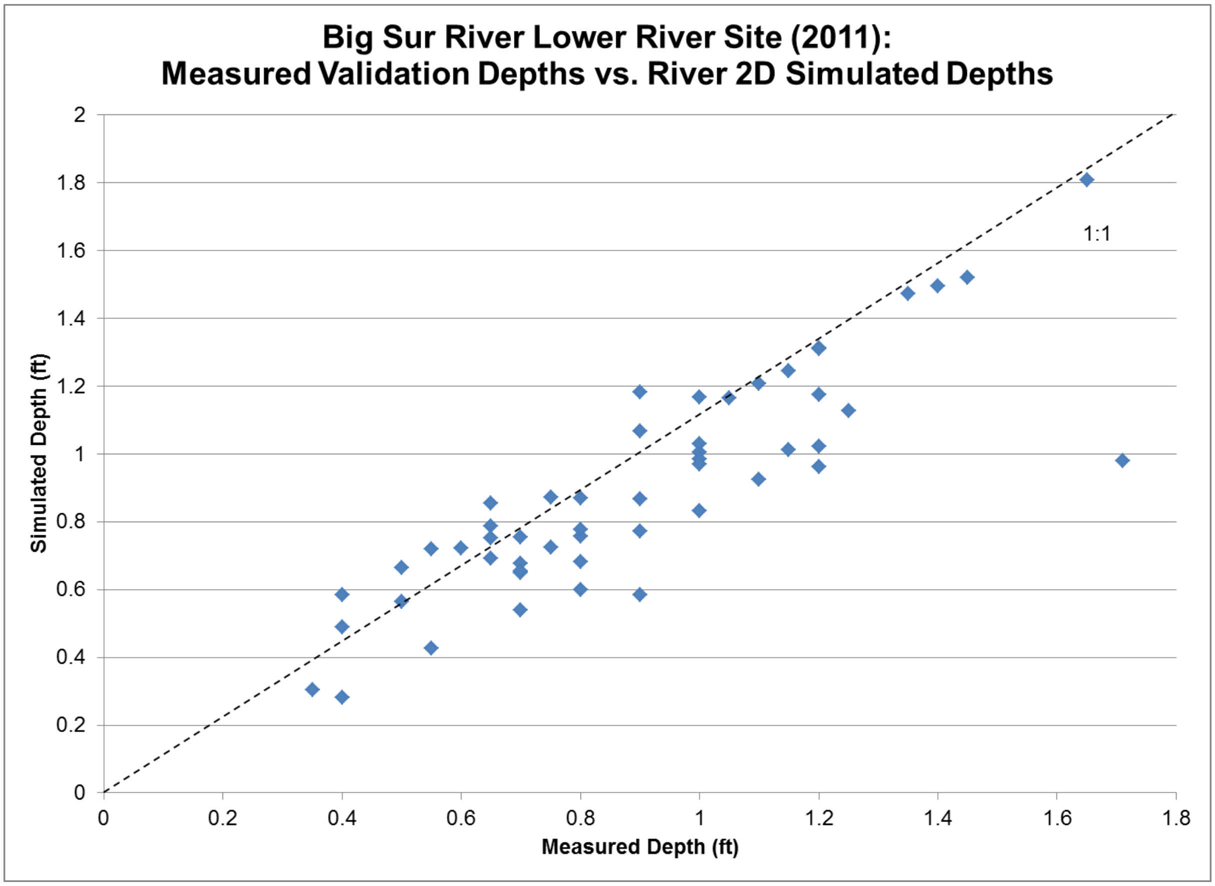
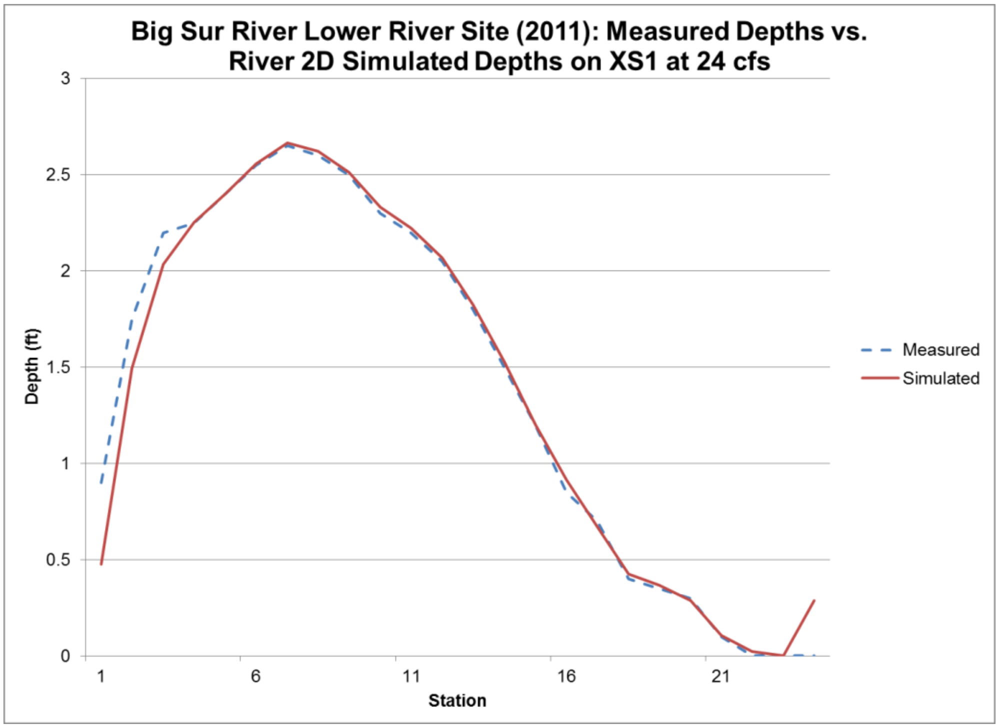


Figure 23. Measured validation depths (ft) versus River 2D model simulated depths (ft) at Big Sur River lower river site (2011) at 25 cfs.

In reviewing model performance for the lagoon site we noted a vertical datum mismatch between the bed elevation profile on the downstream boundary of the site and the immediate bed elevations moving upstream. We therefore adjusted all WSELs, SZF, and bed elevations for XS1 and recalibrated the lagoon 2D model. We contributed this vertical datum mismatch to an error during tying in the vertical benchmark for XS1 with the other vertical controls for the site. We re-ran all model prediction flows for the lagoon critical riffles and there was no difference in the flow predictions using River 2D after the adjustments made to the downstream XS1 of the lagoon site.

The 2D model construction and calibration statistics for the lagoon site before and after the recalibration of XS1 are presented in Appendix A. In general, calibration statistics were comparable before and after recalibration of XS1 with the exception of observed differences between the Net Q values.



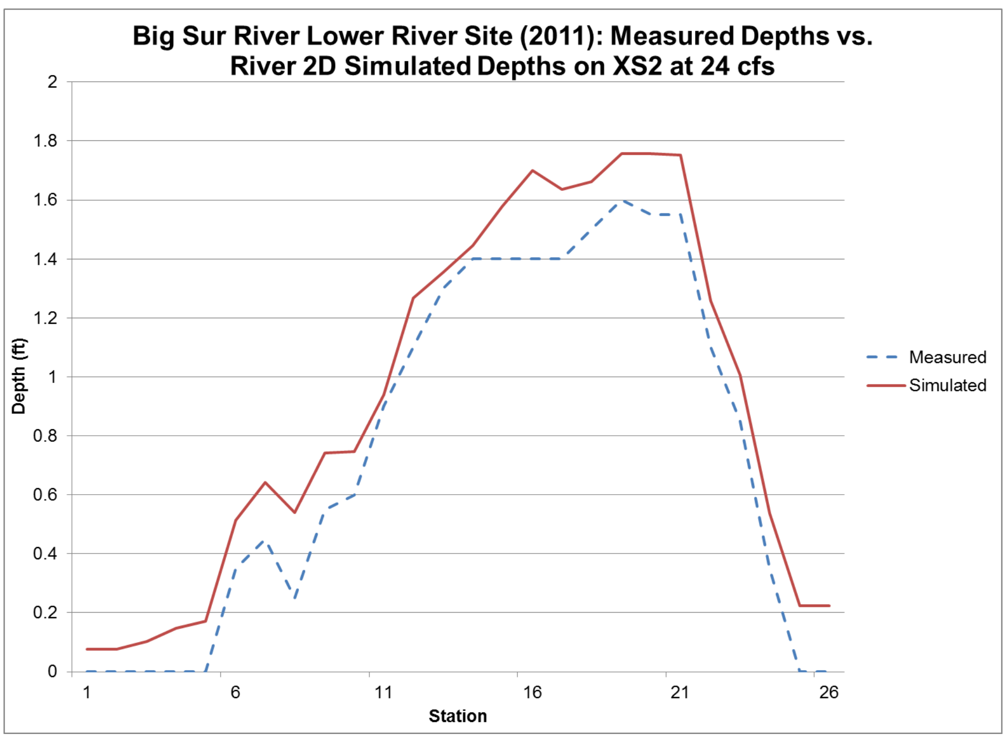
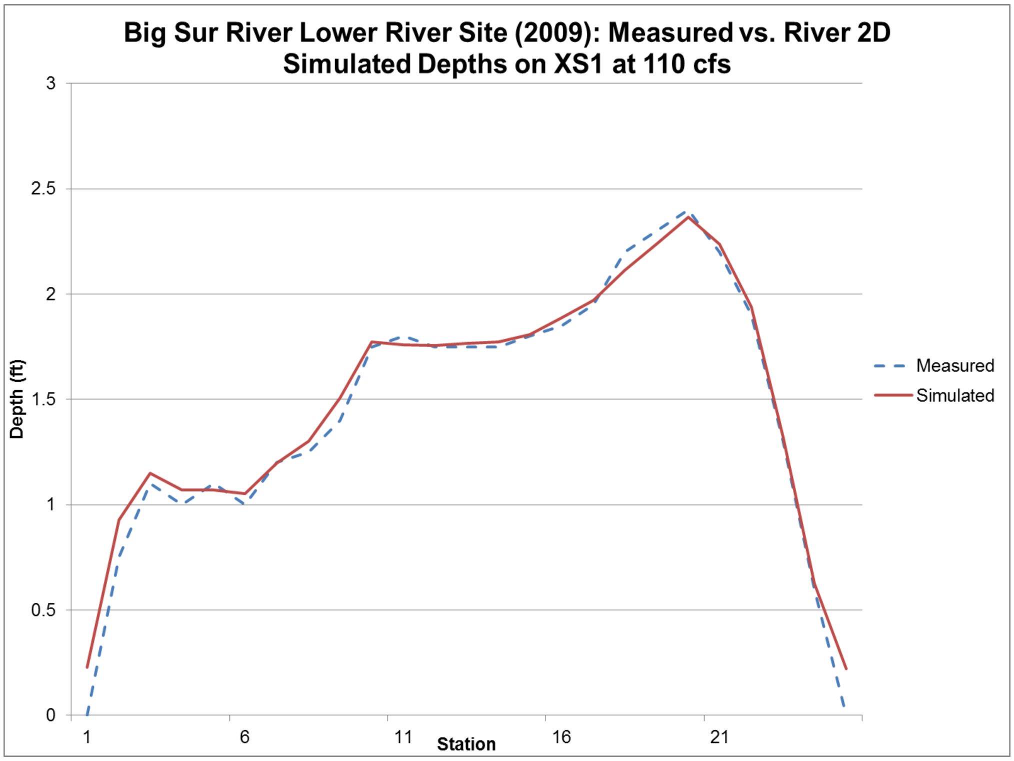


Figure 24. Measured depths (ft) versus River 2D model simulated depths (ft) on XS1 (above) and XS2 (below) at Big Sur River lower river site (2011) at 24 cfs.



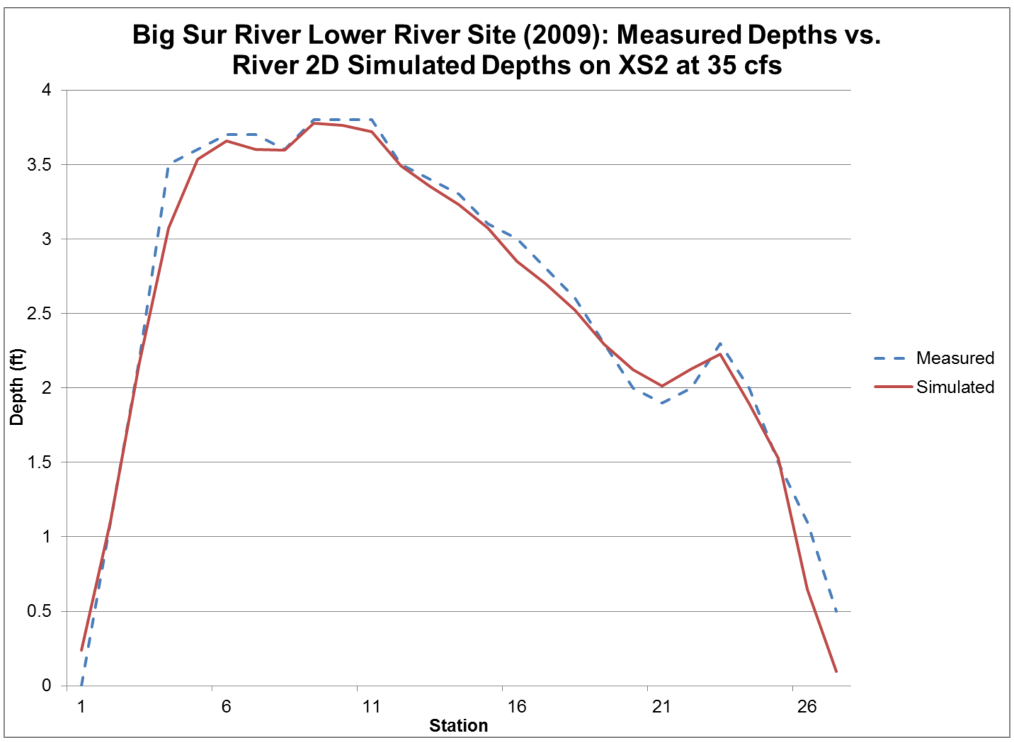


Figure 25. Measured depths (ft) versus River 2D model simulated depths (ft) on XS1 at Big Sur River lower river site (2009) at 110 cfs (above) and on XS2 at 35 cfs (below).

For example, before the XS1 was recalibrated at the lagoon site, Net Q values increased with decreasing flows. After the recalibration of XS1, the pattern of increasing Net Q with decreasing flows was generally not as evident although the highest Net Q values remained corresponding with the lowest simulated flows. Generally, however, Net Q values at the lagoon site were all greater than 1%. In comparison, the accepted level of accuracy for USGS gages is generally 5%. Using the USGS level of accuracy as a data quality threshold, all simulation flows were acceptable prior to recalibration of XS1 with the exception of the flows at or below 17 cfs. Where the net Q significantly exceeded the 5% level, we consider that a level of uncertainty applies to results for those production files. In these cases, the high net Q was due to the amount of water being passed through a very small cross-sectional profile.

Net Q values in all simulation flows at the lower river site (2009) in the range of interest (approximately 15 cfs to approximately 80 cfs) were less than 3.5% and considered acceptable in comparison to the general USGS accuracy acceptability guide. Net Q values at the lower river site (2011) were also within acceptable ranges. Therefore, the difference between the flows at the upstream and downstream boundary (Net Q) at all sites and at the flows of interest were within the same range as the accuracy for USGS gages, and were considered acceptable. Further, the majority of the corresponding solution changes (Sol Δ) at each site were less than 0.00001 and indicative of stable solutions.

Maximum Froude values differed at the lagoon site before and after the recalibration of XS1 but were acceptable within the general range of flows of interest. A similar pattern was observed with maximum Froude values at the lower river site (2011) in which values were acceptable within the general range of flows of interest. The lower river site (2009), on the other hand, had all maximum Froude values exceeding a value of 1. Although the simulation flows at each of the three River 2D sites had maximum Froude values that exceeded 1, we considered these production runs to be acceptable since the Froude number was only greater than 1 at a limited number of nodes, with the vast majority of the area within each site having Froude numbers less than 1. Again, as described in River 2D model calibration discussion, these nodes were located either at the water's edge or where water depth was extremely shallow, typically approaching zero. A high Froude number at a very limited number of nodes at water's edge or in very shallow depths would be expected to have an insignificant effect on the model results.

The performance of the River 2D models is also based upon the quality ((i.e., Quality Index (QI value)) of the computational mesh for each model, as well as the construction and calibration statistics for each 2D model. QI results for each model were 0.30 for all three models. An ideal mesh (all equilateral triangles) would have a QI of 0 to 1.0, and a value of at least 0.2 is considered acceptable (Waddle and Steffler 2002). The QI value of each of the three models was above the minimum acceptable values (Appendix B).

The results of the flows derived from the critical riffle assessment and River 2D approaches are presented in Table 13 using the higher of flow results from the critical riffle assessment results and the River 2D results for each site, steelhead lifestage, and each of the corresponding passage metrics (i.e., percent total, percent contiguous). The higher of the flow number identified from the critical riffle assessment and River 2D approaches ensures adequate protection of passage and habitat connectivity between lagoon and riverine sites and is consistent with Thompson (1972) and CDFW (2012). Overall there is a strong relationship between flows derived from the critical riffle assessment and flows derived from the River 2D model predictions for the lagoon and lower river sites (r^2 = 0.93, Figure 26).

Spatial and Temporal Variability of Flows for Passage and Connectivity

Spatial variability was assessed by examination of flow criteria results for steelhead lifestages longitudinally between lagoon, lower river, middle river and upper river sites during the 2011 sampling period. Results of the flows identified from the critical riffle analysis were generally spatially consistent for adult steelhead passage and habitat connectivity from lagoon to the upper river critical riffle sites, occurring in the 72 cfs to 77 cfs range. Flows identified for passage and habitat connectivity for YOY and juvenile steelhead lifestages generally increased spatially going upstream from the lagoon and lower river sites to the middle and upper river critical riffle sites. This is likely reflective of the wider, more depth sensitive riffle sites and corresponding interactions between substrate composition and flows observed at middle and upper river sites.

Temporal variability was assessed by examination of results of the critical riffle assessments in 2009 with the critical riffle assessment results from 2011 at the lower river site. The passage and habitat connectivity flows at the lower river site 2009 were temporally consistent with flows observed at critical riffle sites assessed in 2011. For example, flows for passage and habitat connectivity for the adult steelhead lifestage were 77 cfs for adults in 2009 at the lower river site, and were 75 cfs for adults in 2011 at the lagoon site.

Comparison of the results from the 2D models from the lower river site in 2009 and 2011 were generally consistent between the two years for adult steelhead but indicated increased flows needed for passage and connectivity for YOY and juvenile steelhead in 2011 between the two years. These findings are consistent with the results of the critical riffle analysis at lower river sites between the two years and indicated that the locations of passage and habitat connectivity for steelhead may shift spatially between critical riffles, but are generally in equilibrium within the river.

Table 13. Passable flows identified for maintaining riverine and lagoon connectivity for steelhead lifestages using the critical riffle assessments and River 2D models.

Site	**Steelhead Lifestage**	**Critical Riffle Analysis Passable Flows (cfs)**	**River 2D Model Passable Flows (cfs)**
Lagoon			
	YOY	18	8
	Juvenile	32	18
	Adult	75	54
Lower River			
	YOY	18	28
	Juvenile	29	43
	Adult	77	81
Middle River			
	YOY	39	n/a
	Juvenile	45	n/a
	Adult	77	n/a
Upper River			
	YOY	40	n/a
	Juvenile	54	n/a
	Adult	72	n/a

Flows for Protecting Steelhead Passage and Habitat Connectivity

Flows for protecting steelhead passage and habitat connectivity in the Big Sur River are presented in Table 14. Adult steelhead passage flows were consistent among the sites with a range of 72 to 77 cfs throughout the lagoon, lower, middle, and upper river critical riffles. However, flows for maintaining passage and aquatic connectivity between habitats for YOY and juvenile steelhead generally increased moving upstream from the lagoon through lower, and middle through upper river critical riffle sites with a range of 18 to 40 cfs, and a range of 32 to 54 cfs, respectively.

Table 14. Flows for protecting passage and aquatic habitat connectivity between Big Sur River and lagoon for steelhead lifestages.

Site	**Time Period**	**Steelhead Lifestage**	**Flow (cfs)**
Lagoon (River Mile 0.33)	Year Round	YOY	18
	Year Round	Juvenile	32
	November 1 – May 30	Adult	75
Lower River (River Mile 0.50)	Year Round	YOY	18
	Year Round	Juvenile	29
	November 1 – May 30	Adult	77
Middle River (River Mile 1.79)	Year Round	YOY	39
	Year Round	Juvenile	45
	November 1 – May 30	Adult	77
Upper River (River Mile 3.38)	Year Round	YOY	40
	Year Round	Juvenile	54
	November 1 – May 30	Adult	72

DISCUSSION

Critical Riffle Assessment and River 2D Flows

The critical riffle assessment and River 2D methodologies are dependent upon accurate and extensive field data. The critical riffle assessment is dependent upon adequate number of flow sample events at a relevant and representative range of flows to build a robust relationship between the habitat passage and connectivity metrics and flows. The River 2D model is dependent upon an adequate number of flow sample events with measurement of water surface elevations, as well as a detailed representative channel bed topography mesh. To develop the channel bed mesh, the River 2D model is based on a TIN methodology, which includes breaklines for spatial interpolation of nodal parameters. The physical characteristics of the channel bed required for flow modeling in River 2D are the bed elevation and the bed roughness height, which are used to develop computational meshes that will be input into River 2D. River 2D is then used to predict water depths and velocities, and evaluate and interpret streamflow and habitat relationships.

There was a strong overall relationship ($r^2 = 0.93$) between flows derived from River 2D and the critical riffle analysis using the Thompson (1972) metrics (Figure 26). However, comparison of the flows identified by the critical riffle analysis measurements and those simulated by River 2D suggest that the lagoon model is under-predicting flows needed for protection of passage and habitat connectivity, when compared to the critical riffle analysis. While it would seem a logical reason for the differences to be due to potential tidal influence and associated effect on groundwater/surface water interaction, we believe tidal influence played no role because all construction and calibration data (i.e, water surface elevations) for the lagoon River 2D model were collected at low tides, and it was clear there was no influence of tide on surface water stage because of the presence of several low gradient riffles observed downstream of the lagoon critical riffle site at all sample events. It could be expected that there would be differences in measured and simulated depths due to interactions between gradient, substrate, and complex hydraulics in coarse-bedded riffle habitats with turbulent water. However, there could also be differences due to natural effects of water year type and associated water gains and losses that may be encountered in coastal alluvial river channels near their downstream boundaries with lagoons. Based upon existing flow data records, the lower portion of the lower river reach is considered to be a losing-water reach, being especially evident in late summer and fall.

A sensitivity analysis was conducted to examine the relationship between flows and the passable width metric results. Flows of 23, 42, 62, and 73 cfs measured at the lagoon site A using critical riffle analysis resulted in approximately 0 ft (0.0 m), 1 ft (0.3 m), 2 ft (0.6 m), and 3 feet (0.9 m) of contiguous depths meeting the passage criteria for adult steelhead, respectively. A similar pattern was observed upstream at the lower river site (2009) when examining the contiguous width metric and passage criteria measured using critical riffle analysis for adult steelhead passage.

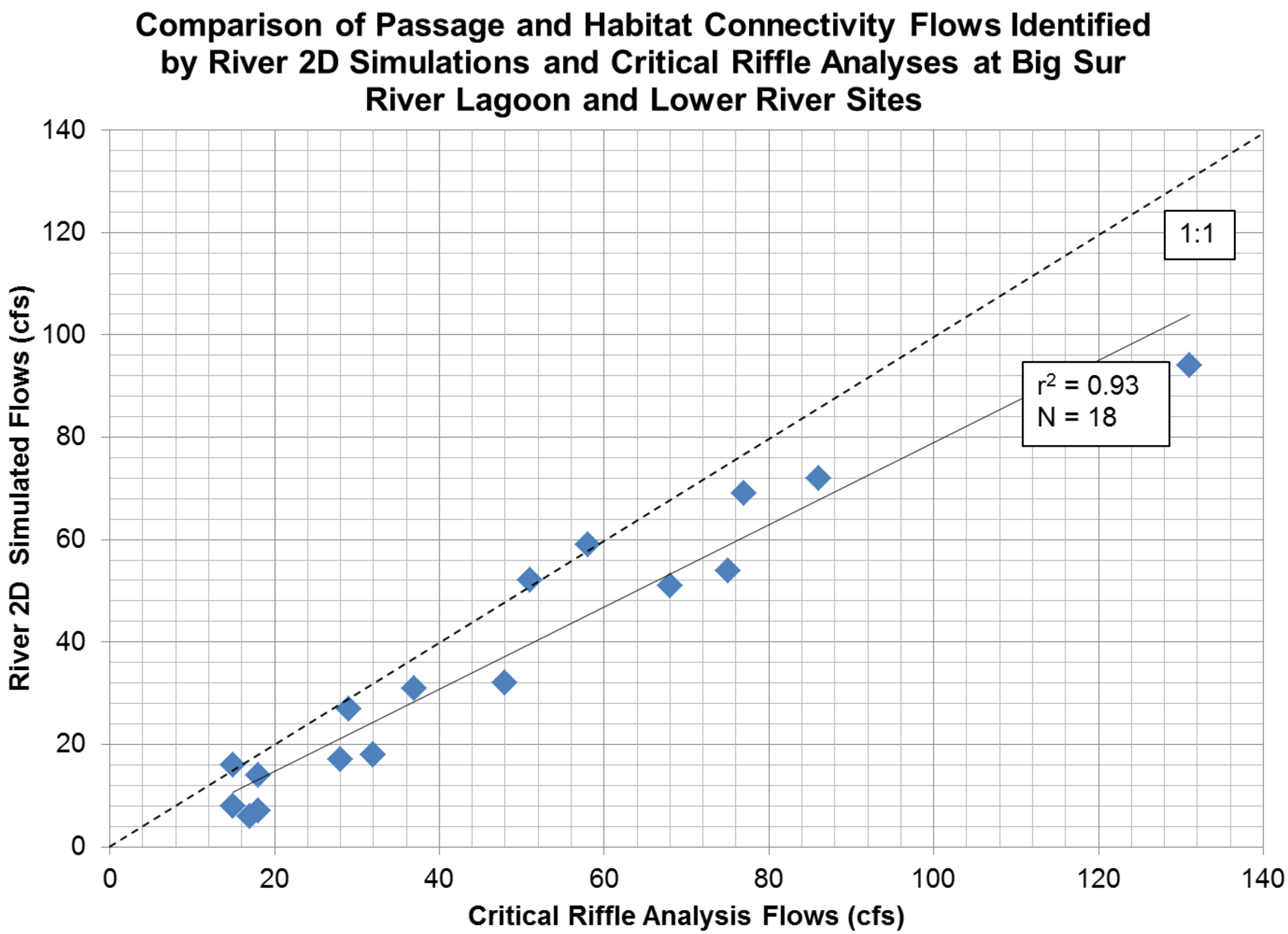


Figure 26. Plot of flows derived from critical riffle analysis versus flows simulated by River 2D models for steelhead passage and habitat connectivity at critical riffle sites in Big Sur River. Dashed line indicates a 1:1 relationship.

However, the contiguous stream width values necessary to meet the width criteria of 10% contiguous passable width were generally greater upstream at the lower river site (2009) than at the lagoon despite the overall flows for adult passage remaining relatively static between 75 - 77 cfs among the two sites. The increased contiguous values observed upstream were likely reflective of the wider channel widths and associated topographical conditions upstream. Since both the passable criteria metrics must be met and then the higher flow rate is identified to meet the minimum depth criteria from either the total portion or the contiguous portion of the critical riffle site, there is affirmation that the flows identified for passage and habitat connectivity will be sufficient to account for varying stream channel morphologies and conditions.

Identifying an accurate and representative critical riffle passage transect using the River 2D model is highly dependent upon an accurate and high resolution of bed topography data points in the areas where the critical riffles passage transects occur. The density of bed topography data points collected for each of the Big Sur River 2D models exceeded point densities commonly employed in other 2D models at alluvial riffle sites (Gard 2013; Pasternack et al. 2004). In fact, the highest point densities of each of the 2D models were collected along the shallowest course from bank to bank at each riffle. Also, all maximum transect lengths were exactly the same between the critical riffle assessment and River 2D models with the exception of the lower river site (2009) which was different by 1.0 ft. Wider transects generally require more flow for passage and connectivity. Mean and maximum depths along passage transects at the lagoon site and the lower river site also increased overall as flows increased in both the critical riffle analysis and the River 2D model predictions.

River 2D models have also been used to assess fish passage flow needs for salmonids and other migratory fish species (Grantham 2013; Reinfelds et al. 2010). The most critical factors which can affect the ability of steelhead to migrate to spawning areas or between other necessary habitats are the depth and velocity of the water flowing over shallow bars or critical riffles. We used RIVER 2D to compare depth and velocity conditions associated with passage flows derived by available desktop (i.e., steelhead passage formula (SWRCB 2014)) and site-specific (i.e., critical riffle analysis (CDFW 2013a; Thompson 1972) and riffle crest (SWRCB 2014)) methods for steelhead. The critical riffle analysis (CDFW 2013a; Thompson 1972) and the passage flows formula (SWRCB 2014) results were surprisingly comparable given that the passage formula is a “desk-top” method which involves no site-specific data from the passage riffles, and the critical riffle analysis is an entirely empirical methodology that directly reflects site-specific conditions in the riffles (Table 15). The critical riffle analysis consistently identified flows that provide for more conservative contiguous passable depth widths than the passage formula for each steelhead lifestage. Velocity conditions were not identified as potential passage impediments with either method as velocities did not exceed maximum thresholds using either the passage flow formula method or the critical riffle analysis method. The riffle crest method (SWRCB 2014), however, consistently failed to provide for any passable water depths through the natural riffle site - for any steelhead lifestage (Table 15).

Table 15. Comparison of flows derived by desktop and site-specific methods for evaluating steelhead lifestage-specific passage flows through the Big Sur River lower river critical riffle site.

Desktop Methods	Steelhead Lifestage[11]	Flow (cfs)	*Width[12] (ft)*	Velocity (ft/s) Mean	Max.	Passable?[13]
Passage Flows Formula (SWRCB 2014)	Adult	58	4.9	2.23	2.49	✓
	Juvenile	18	5.9	2.36	2.92	✓
	YOY	10	9.5	1.41	2.76	✓
Site-Specific Methods[14]						
Critical Riffle *(CDFW 2013a; Thompson 1972)*	Adult	77	10	2.4	2.62	✓
	Juvenile	29	7.3	1.9	2.79	✓
	YOY	18	14.4	1.57	2.92	✓
Riffle Crest (SWRCB 2014)	Adult	5	0.0	--	--	✗
	Juvenile	<1	0.0	--	--	✗
	YOY	<1	0.0	--	--	✗

Grantham (2013) also evaluated use of the riffle crest method for fish passage in three California coastal streams and also found that it consistently underestimated flows needed for passage largely due to the fact that shallow water barriers, such as those observed in natural riffles on the Big Sur River, persisted within riffle sites even when the minimum passage depths at the riffle crest were exceeded. It is also important to note that all methods have limitations, including the passage methods discussed above. These limitations include lack of criteria on riffle length and relationship to availability of rest areas, both which may be critical components affecting successful migration.

Although Mosley (1982) observed salmonids moving upstream in water shallower than the Thompson (1972) depth criteria, he noted that they may suffer abrasion and loss of spawning condition. Ideally, there should be sufficient clearance underneath the fish so that contact with the streambed and abrasion are minimized. Other factors that are important for consideration when evaluating fish passage and habitat connectivity is consideration of length of the riffle, distance of travel, physiological condition of the fish, water temperature, and availability of resting areas (Mosley 1982). The primary purpose of the Thompson (1972) methodology and associated transect width metrics is to provide flow conditions for physical movement of salmonids through critical riffle

[11] Adult steelhead depth criteria = 0.7 ft, juvenile steelhead = 0.4 ft, (YOY) young-of-year = 0.3 ft based upon body depth of fish plus additional 0.1 ft to avoid abrasion (SWRCB, 2014).
[12] Width based upon longest contiguous width meeting steelhead depth criteria on the passage transect.
[13] Passable assessed by evaluating longitudinal connectivity of minimum depth criteria through the riffle site at the respective flow and maximum velocity not exceeding 3.0 ft/s for juvenile steelhead and 8.0 ft/s for adult steelhead.
[14] Based upon 152 ft long critical riffle in lower river at river mile 0.50.

locations. Furthermore, Thompson (1972) cautions that the relationship between flow conditions on the transect and the relative ability of a fish to pass have not been evaluated, the methodology is based upon over a decade of extensive field observations spanning all 18 drainages of Oregon by ODFW, including several hundred of the most important salmonid streams in the State (Thompson 1972). As such, the width metrics are assumed to identify flows for passage and habitat connectivity that protect against partial or complete blockages in salmonid migration and emigration, conditions that became apparent as flows receded in the shallow depth sensitive cobble-dominated riffle habitats observed in the current study and by Grantham (2013) in other coastal California streams.

Spatial and Temporal Variability of Flows for Passage and Connectivity

Flows in California coastal streams are influenced by a Mediterranean climate, which is characterized by wet winters, dry summers, and most of the yearly rainfall occurring in the winter season. Understanding the temporal aspects of streamflow and fish lifestage-specific habitat needs is critical in identifying flows to protect fishery resources (Stalnaker et al. 1996). Steelhead and other salmonid migrations and emigrations are generally associated with rainfall and associated increased stream flow events on central coast California rivers (Shapovalov and Taft 1954). However, maintenance of passage and habitat connectivity flows during the summer and fall rearing periods are likely a more critical time period for salmonids in coastal streams because flows are naturally low and anthropogenic water demand is typically high. During California’s natural low-flow periods of summer and fall, coastal California streams are under increased diversion pressure to meet agricultural, among other competing water demands and needs during the summer growing season (Deitch et al. 2008; NMFS 2008).

Protecting passage and habitat connectivity flows even under natural, unimpaired, flow conditions is challenging and not possible during all years on many California coastal rivers and streams. Table 16 outlines the flows identified for protection of passage and habitat connectivity at the four critical riffle sites in the Big Sur River and compares those flows to flow frequency and duration summary statistics from long-term (1950–2013) monitoring data from USGS gage #11143000. Summary statistics are reported for each critical riffle site and steelhead lifestage, and are partitioned by either a November – May timeframe or a June – October timeframe. The November through May timeframe is analogous to the adult steelhead migration and spawning season. Flows identified for adult passage and habitat connectivity occurred between the lagoon and upper river sites between 43% to 45% of the time between the months of November and May and the years of 1950 and 2013. Flows identified for juvenile and YOY passage occurred during November through May most frequently at the lagoon site (69% and 86%, respectively) than at the upper river site (54% and 62%, respectively).

The June through October timeframe represents the timeframe when juvenile and YOY steelhead are in the lagoon and riverine habitats. Flows identified for juvenile and YOY steelhead passage during June through October occurred most frequently at the lagoon site (19% and 48%, respectively) and occurred less frequently at the upper river site (6% and 12%, respectively). A further analysis using 15-minute continuous flow data records compared to the passage and habitat connectivity flows from the lagoon critical riffle site identified in this study indicated sufficient flows at critical riffle locations for YOY and juvenile steelhead were produced between 37% and 100% and between 1% and 95% of the time, respectively (Table 17, Table 18). The months of September and October were the most challenging months to obtain natural flows to meet YOY and juvenile passage and habitat connectivity flows. Flows identified for adult steelhead passage at the lagoon critical riffle site were produced naturally between 52% to 74% of the time during the core adult migratory period of January through April. Naturally produced flows for adult steelhead migration were less reliable at the beginning and end of the migration season with flow criteria being met 3% and 30% for November and May, respectively.

Overall, the flows identified for protecting passage and habitat connectivity at critical riffle sites between the lagoon and upper river sites were consistent for adult steelhead. However, the locations of the most depth-sensitive critical riffle sites and associated passage transects shifted both within and between critical riffle sites. These findings, as discussed earlier, are likely linked to the energy of the river (i.e., river flow and slope) and relationships with sediment load transport capacity. Any increase in energy will allow erosion to take place resulting in an increase in sediment load. Likewise, a decrease in energy will result in deposition of some of the load. The feedback mechanisms resulting from these basic processes exhibit a dynamic form of stability, known as dynamic equilibrium (U.S. EPA 2012).

Dynamic equilibrium refers to the ability of a system to persist within a range of conditions. Maintaining this equilibrium, or “balance”, requires the presence of a series of self-correcting mechanisms. A disturbance to a river system triggers a response from these self-correcting mechanisms allowing maintenance of the dynamic equilibrium. Channel forming flows (e.g., the peak 1.5 year recurrence level flow) are one such mechanism to maintain dynamic equilibrium in a river channel (Leopold 1994). Other important factors to maintain a dynamic equilibrium include maintenance of a relatively intact riparian zone, and maintenance of a relatively intact natural flow regime. The Big Sur River currently has a naturally variable flow regime and is one of only a handful of rivers in California that does not have an on-stream dam or reservoir. Restoration and maintenance of naturally variable flow regimes provides important processes and functions for river ecosystems (Poff et al. 1997). Channel forming flows, one such component of a naturally variable flow regime, occur on the Big Sur River at approximately 1,600 cfs and have occurred regularly within the period of record. The concept of channel forming flows on Mediterranean-climate rivers, such as the Big Sur River, has recently been determined to be more a function of the large, infrequent flood flows than the common frequent small floods (Kondolf et al. 2012). With the exception of the high densities of stream-side camping sites in the upper end of anadromy, the riparian zone of the Big Sur River appears mostly intact.

Table 16. Frequency and duration summary statistics of steelhead passage and habitat connectivity flow criteria[15].

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				Spells						
Critical Riffle Site	**Steelhead Lifestage**	**Flow Criteria (cfs)**	**Season**	**Frequency (# spells)**	**Mean Duration (days)**	**Standard Deviation Duration (days)**	**Minimum Duration (days)**	**Maximum Duration (days)**	**Duration (# days)**	**Duration (% of Season days)**
Lagoon	YOY	18	Nov-May	170	67.6	82.8	1	213	11488	86%
			June-Oct	144	32.3	44.9	1	153	4657	48%
	Juvenile	32	Nov-May	236	38.9	61.9	1	212	9174	69%
			June-Oct	86	20.9	27.2	1	125	1800	19%
	Adult	75	Nov-May	244	23.9	40.2	1	162	5825	44%
Lower River	YOY	18	Nov-May	170	67.6	82.8	1	213	11488	86%
			June-Oct	144	32.3	44.9	1	153	4657	48%
	Juvenile	29	Nov-May	224	42.6	65.9	1	212	9548	71%
			June-Oct	101	20.7	28.5	1	132	2089	22%
	Adult	77	Nov-May	243	23.5	39.7	1	162	5702	43%
Middle River	YOY	39	Nov-May	230	36.6	58.5	1	200	8415	63%
			June-Oct	70	17.6	21.3	1	81	1234	13%
	Juvenile	45	Nov-May	242	32.5	54.0	1	195	7872	59%
			June-Oct	65	14.1	17.3	1	72	914	9%
	Adult	77	Nov-May	243	23.5	39.7	1	162	5702	43%
Upper River	YOY	40	Nov-May	229	36.4	57.7	1	200	8339	62%
			June-Oct	75	15.5	20.2	1	81	1160	12%
	Juvenile	54	Nov-May	252	28.4	47.7	1	185	7162	54%
			June-Oct	47	12.0	14.8	1	65	562	6%
	Adult	72	Nov-May	248	24.1	40.7	1	162	5983	45%

[15] Statistics based upon daily mean flow data from USGS# 11143000 from 1950 – 2013. Spells are defined as instantaneous flows exceeding the passage criteria separated by at least one day (24 hr).

Table 17. Monthly frequency and duration summary statistics of steelhead passage and habitat connectivity flow criteria[16] at lagoon critical riffle site.

			Spells						
Lifestage	**Month**	**Flow Criteria (cfs)**	**Frequency (# spells)**	**Mean Duration (days)**	**Standard Deviation Duration (days)**	**Minimum Duration (days)**	**Maximum Duration (days)**	**Duration (# days)**	**Duration (% of Season days)**
YOY	Jan	18	39	17.6	2.2	0.01	30.9	684.2	89%
	Feb	18	34	19.5	12.0	0.06	29.0	663.2	95%
	Mar	18	25	30.8	0.7	27.7	31.0	770.6	100%
	Apr	18	31	22.9	12.5	0.01	30.0	708.7	96%
	May	18	32	19.8	14.2	0.01	31.0	634.6	89%
	Jun	18	32	14.5	13.1	0.02	30.0	464.4	82%
	Jul	18	29	13.1	14.0	0.03	31.0	378.7	70%
	Aug	18	42	6.4	10.7	0.01	31.0	268.1	53%
	Sep	18	70	3.3	7.8	0.01	30.0	230.2	45%
	Oct	18	54	4.2	7.9	0.01	31.0	228.4	37%
	Nov	18	78	4.5	8.9	0.01	30.0	350.3	53%
	Dec	18	42	14.0	13.5	0.01	31.0	586.2	77%
Juvenile	Jan	32	41	12.7	13.0	0.01	31.0	518.7	68%
	Feb	32	30	20.2	10.8	0.68	29.0	606.4	87%
	Mar	32	32	22.8	12.7	0.03	31.0	729.0	95%
	Apr	32	38	17.0	14.3	0.01	30.0	646.7	88%
	May	32	64	7.8	12.2	0.01	31.0	499.2	70%
	Jun	32	22	14.3	13.5	0.20	30.0	314.5	55%
	Jul	32	45	4.6	9.7	0.01	31.0	207.3	38%
	Aug	32	34	2.3	5.3	0.01	26.1	79.0	16%
	Sep	32	7	0.6	0.9	0.01	2.4	3.9	1%
	Oct	32	16	2.7	4.4	0.04	18.7	43.0	7%
	Nov	32	39	2.8	5.4	0.02	30.0	110.6	17%
	Dec	32	42	8.6	10.3	0.01	31.0	359.6	47%
Adult	Jan	75	35	11.6	11.9	0.01	31.0	406.8	53%
	Feb	75	38	11.6	11.5	0.01	29.0	439.5	63%
	Mar	75	43	13.2	13.0	0.01	31.0	566.3	73%
	Apr	75	37	10.5	12.7	0.01	30.0	388.5	53%
	May	75	33	6.5	10.8	0.01	31.0	214.7	30%
	Nov	75	2	0.5	0.2	0.33	0.7	21.0	3%
	Dec	75	10	2.1	1.7	0.40	5.9	185.0	24%

[16] Statistics based upon 15 minute interval flow data from USGS# 11143000 from 10/01/88 – 4/30/2013. Spells are defined as instantaneous flows exceeding the passage criteria separated by at least 15 minutes.

Table 18. Monthly flow exceedance probability for the Big Sur River[17].

	Flow Exceedance Probability (cfs)									
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Jan	654	315	197	126	83	50	34	24	18	6.3
Feb	698	423	250	173	122	91	71	50	26	7.1
Mar	518	337	246	175	123	93	70	54	34	10
Apr	300	199	142	107	80	62	50	37	26	7.5
May	134	98	79	65	50	41	33	25	17	7.6
Jun	70	57	30	40	33	27	20	16	12	4.6
Jul	45	37	30	26	22	18	14	11	7.8	4.5
Aug	32	26	22	19	16	13	12	9.6	7.1	2.6
Sep	24	21	19	17	14	12	11	9	7.1	2.6
Oct	25	21	19	17	15	13	12	9.1	7.4	2.6
Nov	70	33	24	21	19	17	15	12	10	2.6
Dec	246	112	68	49	35	27	21	18	13	5.8

Flows for Protecting Steelhead Passage and Habitat Connectivity

The Salmon, Steelhead Trout, and Anadromous Fisheries Program Act (Fish and Game Code (FGC) Section 6900-6903.5) directs California's Department of Fish and Game (since renamed to Department of Fish and Wildlife) to manage steelhead populations for optimum production of naturally spawning sea-run adult fish. To increase production of steelhead in the Big Sur River, a California steelhead stronghold (Wild Salmon Center 2010) requires fish to have both full access to optimum spawning habitats for adults, in addition to full access to optimum rearing habitats for YOY and juvenile lifestages throughout and between lagoon and river habitats. Since survival to adult spawning fish is largely related to size of smolts at emigration to the ocean, the primary management direction for steelhead nursery streams via FGC 6900-6903.5 is to optimize production of large juvenile, or pre-smolt fish. This management directive is pertinent in the Big Sur River, as well as other coastal California rivers and streams, where rearing YOY and juvenile steelhead are dependent upon adequate passage and habitat connectivity within and between riverine and lagoon habitats.

It has been well documented that coastal California lagoons and estuaries provide important summer juvenile rearing habitat for steelhead (Shapovalov and Taft 1954; Quinones and Mulligan 2005; Bond 2006; Hayes et al. 2008). High juvenile steelhead growth rates have been reported in Scott Creek, a central California coast watershed which is approximately 80 miles (129 km) north of the Big Sur River, estuary throughout the summer time period with a near doubling of fork length from the time of entry to the

[17] Data based upon mean daily values from October 1, 1949 through September 30, 2012 from USGS 11143000.

lagoon and estuary from upriver habitats (Bond et al. 2008). Juvenile steelhead research on Scott Creek has also indicated the majority of YOY and juvenile fish reaching typical steelhead ocean entry sizes were reared in the estuary and lagoon (Hayes et al. 2008). Other important habitats for rearing juvenile steelhead in Scott Creek included both upper watershed rearing and combined estuary/lagoon and upper watershed rearing. Although the Scott Creek estuary comprises less than 5% of the Scott Creek watershed area, estuary-reared juveniles make up 85% of the returning adult spawning population as observed by tagged recaptures and scale samples (Bond 2006).

The Bond et al. (2008) and Hayes et al. (2008) studies demonstrate the importance of maintaining passage and aquatic habitat connectivity for steelhead juveniles within and between lagoon and upper watershed habitats of Scott Creek and the relationship with their overall fitness and likelihood to return as spawning adults. Ward et al. (1989) and Ward (2000) described the relationship with marine survival of steelhead and their respective size of outgoing smolts at ocean entry from the Keogh River, British Columbia. Although ocean survival rates for salmonids can be variable, survival rates for juvenile steelhead migrating to the ocean have been documented to have increased survival rates if they are larger sizes ($\geq$ 150 mm) upon entry to the ocean (Ward et al. 1989). Generally, the larger the outgoing steelhead smolt is, the higher the survival percentage to return as a spawning adult (Ward et al. 1989; Ward 2000). Rearing juvenile salmonids that made localized movements between summer habitats in small western streams in response to varying habitat quality conditions and individual preference grew faster and larger than those that did not move (Kahler et al. 2001).

Rivers and streams can be defined as having interactive pathways along one temporal dimension (time scales) and three spatial dimensions [i.e., longitudinal (upstream-downstream); lateral (channel-bank⁄floodplain); and vertical (atmosphere channel-subsurface)] (Ward and Stanford 1989). The general purpose of the critical riffle assessment method is to provide adequate water for physical movement and migration on the longitudinal dimension through critical riffles. The method is most important in streams used by anadromous fish and stream reaches where extreme width creates shallow flows critical to passage and connectivity. Thompson (1972), however, cautions that the purpose of the methodology is not to determine flows generally believed necessary to induce migration.

The ability of an organism to move freely among aquatic habitats necessary to complete its lifecycle implies that connectivity boundaries do not impede movement (Fullerton et al. 2010). Habitat connected at one time may become disconnected at other times. For example, natural (e.g., seasonal flows, water year types, forest fire) and anthropogenic (e.g., surface water diversions) influences on stream hydrographs can alter the longitudinal, lateral, and vertical boundaries of stream habitats available for fish. Fullerton et al (2010) reported limited existence of scientific assessments where habitat connectivity between habitats used by different lifestages of the same species was assessed.

Juvenile steelhead are present in the Big Sur River lagoon throughout the summer and fall, with the highest density index estimates of rearing juvenile steelhead observed in the fall time period (Allen and Riley 2012). Since steelhead may remain in freshwater for up to three years before emigrating to the ocean (Quinn 2005) maintenance of flows for protecting passage and habitat connectivity within and between important habitats are a noteworthy priority given their life history tactics and associated overall fitness identified by others (Bond et al. 2008; Hayes et al. 2008; Sogard et al. 2009). Spawning occurs throughout the Big Sur River up to the gorge, with the highest densities of spawning occurring at upstream habitats beyond the upper river critical riffle site in the current study (J. Nelson, California Department of Fish and Wildlife, personal communication). Likewise, juvenile rearing occurs through the lagoon and river (Allen and Riley 2012).

The Basin Complex Fire of 2008 burned over 90% of the Big Sur watershed (Smith et al. 2008), and resulted in short term increases in woody debris and fine sediment loads to the lower river and lagoon during the first storms of 2009. We observed burned woody debris and short term increased fine sediment loads occurring during the first few subsequent storms. While remnants of fire associated woody debris are still remaining at various locations along the river, it appeared that the fine sediments were flushed through the river and lagoon during the intense storms early in the 2009 winter season. Fine sediment depositions were not observed in critical riffles habitats during the study time period.

Flint and Flint (2012) reported summers are projected to be longer and drier in the future than in the past regardless of precipitation trends. While water supply could be subject to increased variability (reduced reliability) due to greater variability in precipitation, water demand is likely to steadily increase because of increased evapotranspiration rates and climatic water deficit during the extended summers. Extended dry season conditions and the potential for drought, combined with unprecedented increases in precipitation, could serve as additional stressors on water quantity and habitat in coastal California streams and rivers.

In conclusion, fragmentation of aquatic habitat at critical riffles due to low flows, either natural or anthropogenic in nature, can result in reduction in the total amount of habitat available for salmonids to carry out their life cycles in coastal streams. At low flows, critical riffles may become natural barriers to upstream and downstream passage for steelhead, which in turn may prevent or delay adults from moving to and from spawning areas, prevent or delay smolts from migrating downstream to staging areas in brackish waters of lagoons and estuaries before the ocean, as well as prevent or delay rearing juvenile salmonids (i.e., steelhead) from being able to move between adequate summer freshwater rearing habitats, seek productive feeding areas, and avoid predation. Optimizing passage and habitat connectivity is an important management objective. Without adequate maintenance of flows for juvenile passage and habitat connectivity flow needs the Big Sur River would not produce the optimal numbers of returning spawning adults. The late summer and fall juvenile rearing time period is critical to YOY and juvenile steelhead survival. Generally, the late summer and fall time period on coastal California streams is when conditions typically become stressful for salmonids due to the natural reduction in flow and habitat. Further, results of the current study indicate sufficient flows for passage and habitat connectivity of steelhead lifestages are not always naturally available in the Big Sur River. Careful consideration of seasonal and interannual flow variability dynamics, therefore, are critical components of an effective flow management strategy for the maintenance and protection of passage and habitat connectivity flows between lagoon and upriver habitats, and are essential for the survival and longevity of steelhead in the Big Sur River and other coastal California streams.

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APPENDICES

Appendix A. River 2D model construction and calibration statistics.

Model construction and calibration statistics for IFG4 transect cross sections (XSEC) for each Big Sur River 2D model.

Lagoon

XSEC	BETA COEFF.	% MEAN ERROR	DIFFERENCE (MEASURED vs. PREDICTED)								
1	3.06	4	25.5 cfs		34 cfs		63 cfs		109 cfs		**FLOW**
			96.1	96.11	96.21	96.19	96.39	96.39	96.59	96.6	**WSEL: MEASURED AND PREDICTED**
			5.7%		6.9%		0.8%		2.5%		**PERCENT DIFFERENCE FLOW**
2	3.35	9.6	25.5 cfs		34 cfs		63 cfs		109 cfs		**FLOW**
			98.26	98.29	98.42	98.37	98.57	98.56	98.74	98.77	**WSEL: MEASURED AND PREDICTED**
			11.8%		15.9%		1.6%		8.1%		**PERCENT DIFFERENCE FLOW**

Lower River (2009)

XSEC	BETA COEFF.	% MEAN ERROR	DIFFERENCE (MEASURED vs. PREDICTED)								
1	2.81	1.6	35 cfs		53 cfs		86 cfs		110 cfs		**FLOW**
			97.58	97.59	97.81	97.79	98.07	98.07	98.23	98.24	**WSEL: MEASURED AND PREDICTED**
			1.8%		3.1%		0.6%		0.8%		**PERCENT DIFFERENCE FLOW**
2	3.13	3.2	35 cfs		53 cfs		86 cfs		110 cfs		**FLOW**
			99.85	99.86	100.02	100.00	100.18	100.18	100.28	100.29	**WSEL: MEASURED AND PREDICTED**
			2.8%		6.1%		3.4%		0.1%		**PERCENT DIFFERENCE FLOW**

Lower River (2011)									
XSEC	**BETA COEFF.**	**% MEAN ERROR**	**DIFFERENCE (MEASURED vs. PREDICTED)**						
1	2.61	2.07	22 cfs		77 cfs		117 cfs		**FLOW**
			98.06	98.06	98.51	98.52	98.75	98.74	**WSEL: MEASURED AND PREDICTED**
			0.87%		3.16%		2.22%		**PERCENT DIFFERENCE FLOW**
2	2.64	6.39	22 cfs		77 cfs		117 cfs		**FLOW**
			99.87	99.88	100.54	100.48	100.7	100.76	**WSEL: MEASURED AND PREDICTED**
			1.45%		0.91%		8.41%		**PERCENT DIFFERENCE FLOW**

Lagoon 2D model construction and calibration summary statistics.

Flow (cfs)	Net Q (%)	Sol Δ	Max F
150	1.1%	<0.000001	3.04
145	1.4%	<0.000001	0.90
140	1.5%	<0.000001	0.95
130	1.3%	<0.000001	1.09
125	1.6%	<0.000001	1.57
120	1.5%	<0.000001	1.98
115	1.5%	<0.000001	4.54
110	1.6%	<0.000001	3.18
105	1.7%	<0.000001	2.37
100	1.8%	<0.000001	2.07
95	1.8%	<0.000001	2.63
93	1.8%	<0.000001	2.49
90	1.8%	<0.000001	2.94
85	1.7%	<0.000001	1.91
80	2.4%	<0.000001	2.03
75	2.2%	<0.000001	2.10
73	2.1%	<0.000001	1.44
70	2.1%	<0.000001	1.49
63	2.0%	<0.000001	2.00
62	2.7%	<0.000001	2.30
60	2.8%	<0.000001	0.83
55	2.9%	<0.000001	0.74
53	2.9%	<0.000001	0.79
50	2.8%	<0.000001	0.72
45	3.3%	0.000002	0.74
42	3.3%	<0.000001	0.78
40	3.2%	<0.000001	0.82
37	3.4%	<0.000001	0.99
35	3.6%	<0.000001	0.86
30	3.8%	<0.000001	0.87
23	3.8%	<0.000001	0.91
20	4.2%	<0.000001	0.92
17	5.2%	<0.000001	0.98
15	5.9%	<0.000001	1.01
10	7.2%	0.000002	1.09
7	9.4%	<0.000001	0.53

Lagoon 2D model construction and calibration summary statistics with recalibrated XS1.

Flow (cfs)	Net Q (%)	Sol Δ	Max F
150	5.4%	<0.000001	4.70
100	10.0%	<0.000001	1.13
90	9.6%	<0.000001	1.20
80	9.4%	<0.000001	1.25
70	10.2%	<0.000001	1.43
60	8.3%	<0.000001	1.65
50	6.2%	<0.000001	2.68
45	5.7%	0.000002	3.00
40	6.0%	0.000006	1.03
30	5.9%	<0.000001	1.29
25	1.2%	<0.000001	0.88
20	10.2%	<0.000001	1.01
15	12.8%	<0.000001	1.01
10	19.8%	<0.000001	1.06
7	25.2%	<0.000001	1.00

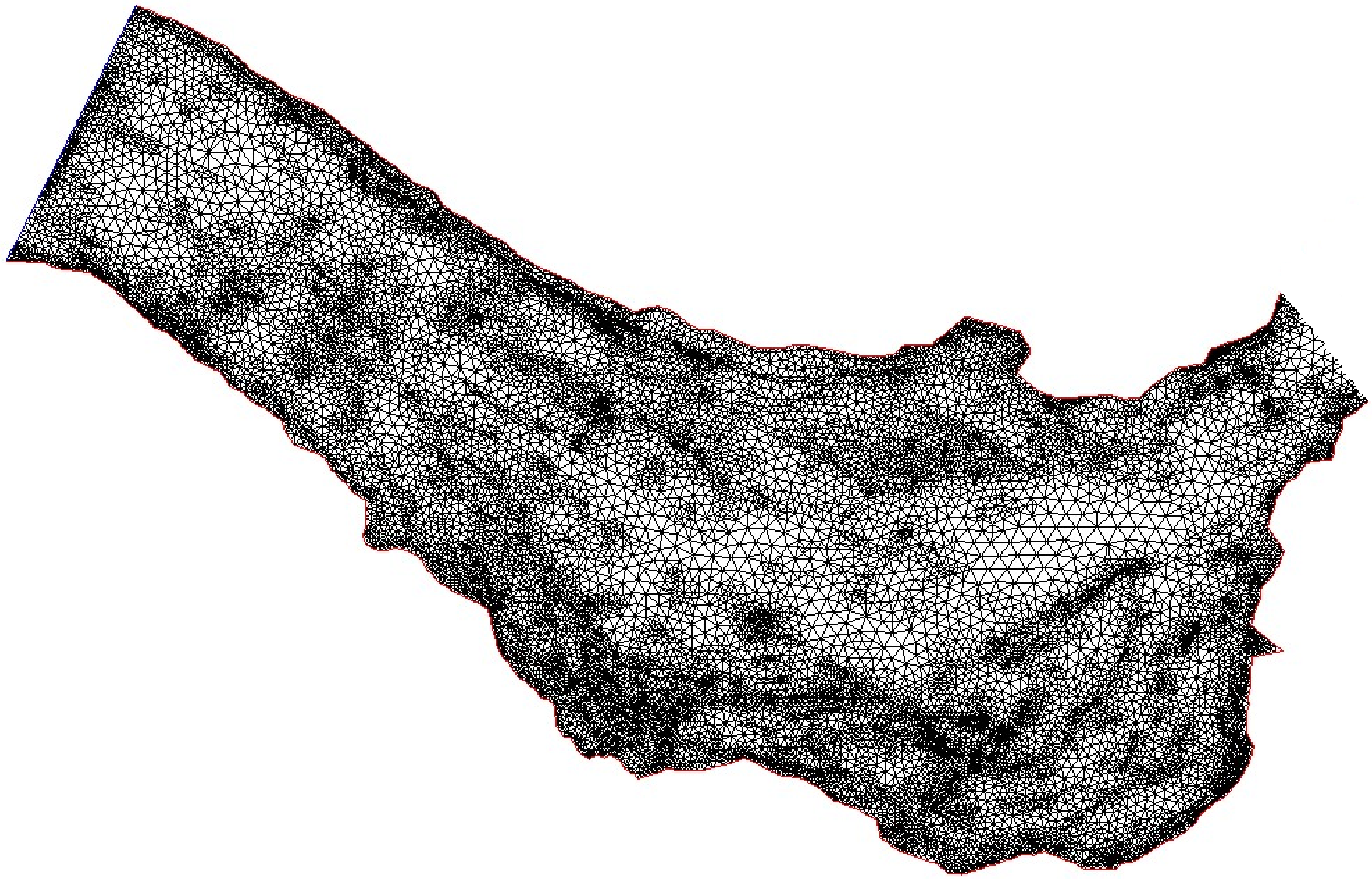
Lower river (2009) 2D model construction and calibration summary statistics.

Flow (cfs)	Net Q (%)	Sol Δ	Max F
179	0.4%	< 0.000001	1.21
100	0.2%	< 0.000001	1.43
90	0.2%	< 0.000001	1.51
80	0.2%	< 0.000001	1.63
70	0.3%	0.000005	1.86
68	0.3%	< 0.000001	2.11
60	0.4%	< 0.000001	2.69
56	0.4%	< 0.000001	3.14
50	0.5%	< 0.000001	3.63
45	0.6%	< 0.000001	4.14
40	0.7%	0.000002	4.68
35	0.8%	0.000006	4.97
30	1.5%	< 0.000001	5.74
28	1.3%	< 0.000001	5.8
25	1.6%	< 0.000001	5.87
20	2.2%	< 0.000001	6.11
15	3.4%	< 0.000001	8.82
13	5.1%	< 0.000001	6.58
10	6.0%	< 0.000001	46.49
5	12.4%	< 0.000001	94.83

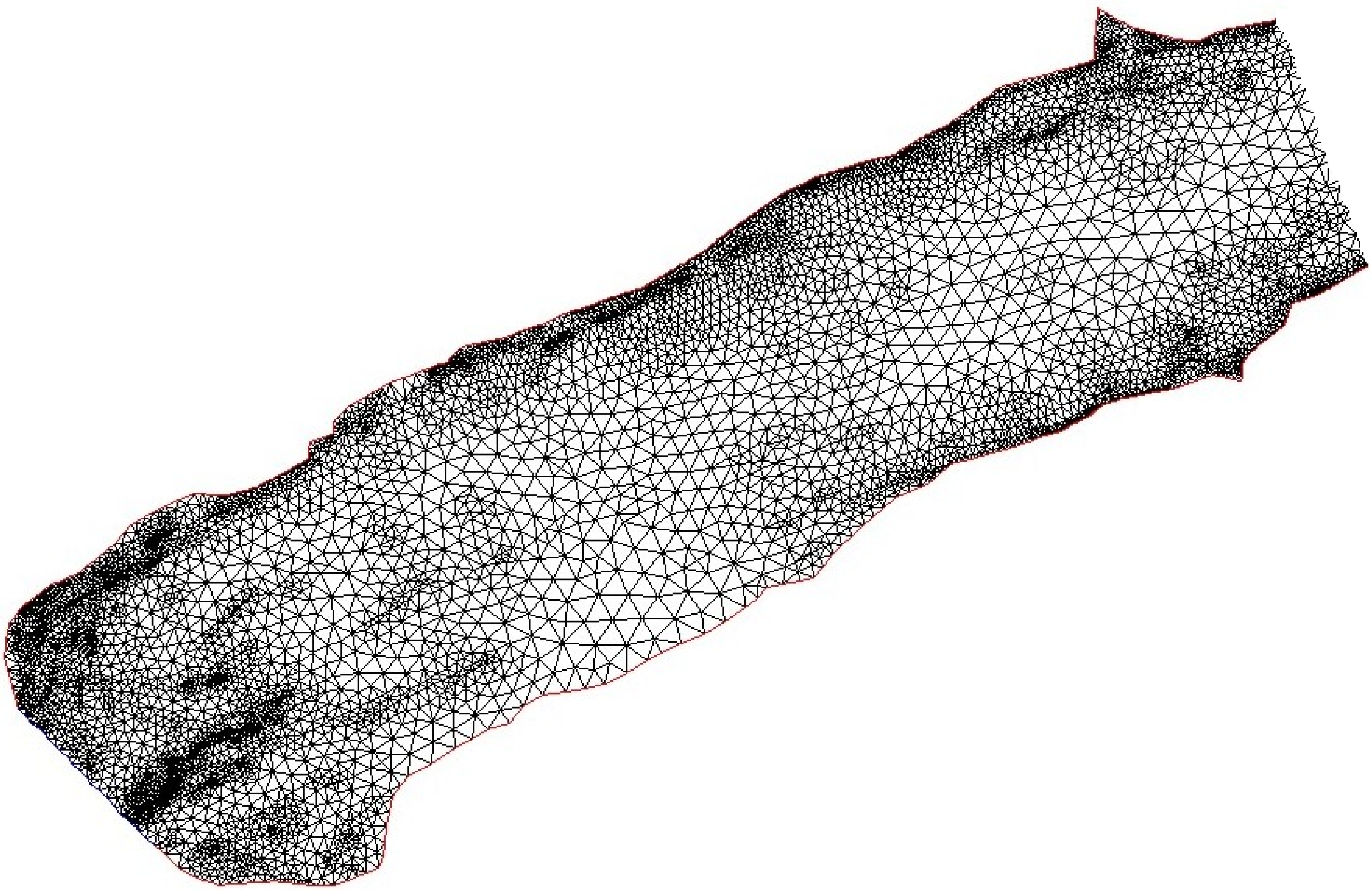
Lower river (2011) 2D model construction and calibration summary statistics.

Flow (cfs)	Net Q (%)	Sol Δ	Max F
100	0.1%	< 0.000001	1.14
95	0.1%	< 0.000001	1.15
90	0.1%	< 0.000001	1.17
82	0.1%	0.000005	1.25
80	0.1%	< 0.000001	1.29
75	0.1%	< 0.000001	1.33
70	0.2%	< 0.000001	1.36
60	0.2%	< 0.000001	1.28
55	0.2%	< 0.000001	0.87
50	0.3%	< 0.000001	0.84
45	0.2%	< 0.000001	0.89
43	0.2%	< 0.000001	0.87
40	0.3%	0.000002	0.87
35	0.8%	< 0.000001	0.87
30	1.3%	< 0.000001	0.90
27	1.1%	< 0.000001	0.92
25	1.2%	< 0.000001	0.94
24	1.1%	< 0.000001	0.94
20	1.1%	0.000006	1.00
15	1.3%	< 0.000001	1.32
10	0.0%	< 0.000001	1.10

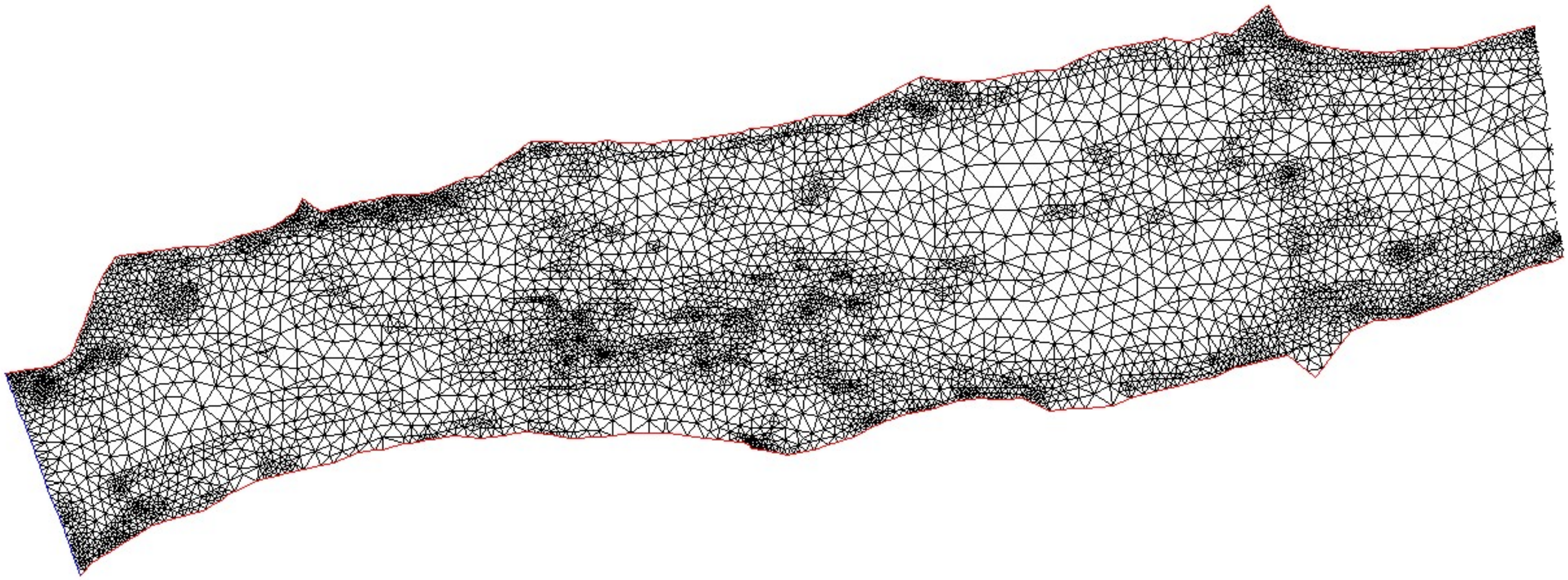
Appendix B. River 2D computational meshes.



Computational mesh for River 2D model at Big Sur River lagoon.



Computational mesh for River 2D model at Big Sur River lower river (2009) site.



Computational mesh for River 2D model at Big Sur River lower river (2011) site.

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