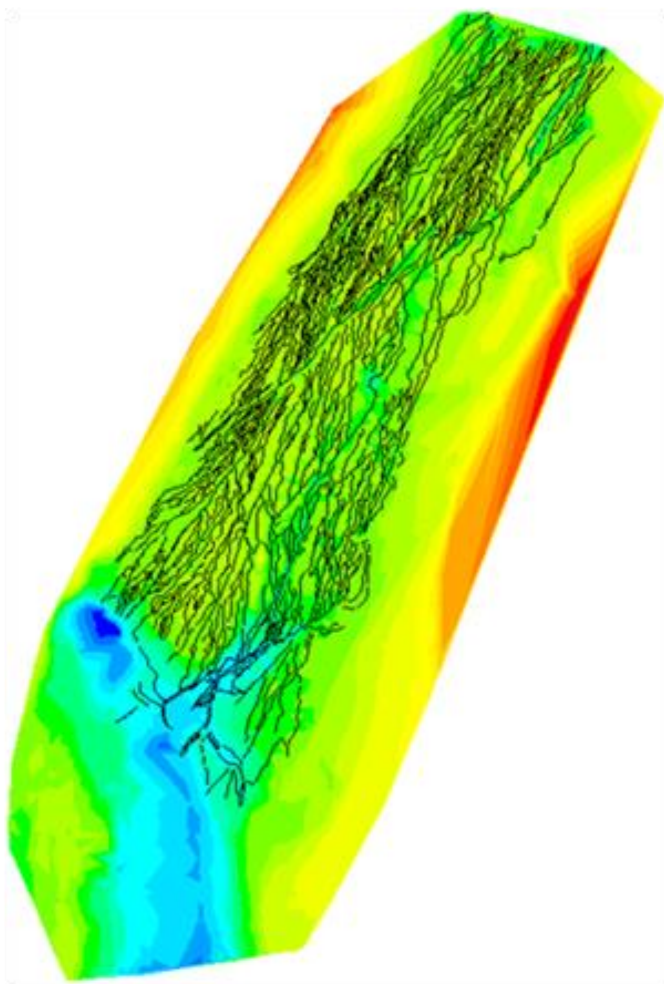
State of California
Natural Resources Agency
California Department of Fish and Wildlife

INSTREAM FLOW EVALUATION: Upstream Spring-Run Chinook Salmon Passage in BUTTE CREEK, California



STREAM EVALUATION REPORT 16-1

February 2016

Department of Fish and Wildlife
Stream Evaluation Report
Report No. 16-1

INSTREAM FLOW EVALUATION OF UPSTREAM SPRING-RUN CHINOOK SALMON PASSAGE IN BUTTE CREEK, CALIFORNIA

February 2016

John Laird	Edmund G. Brown Jr.	Charlton H. Bonham
Secretary for Resources	Governor	Director
Natural Resources Agency	State of California	Department of Fish and Wildlife

Stream Flow Evaluation
for
Spring-run Chinook Salmon Upstream Passage in
Butte Creek, California

William Cowan[1] and Mark Gard[2]

ABSTRACT

Passage conditions for adult spring-run Chinook salmon (SRCS) (*Oncorhynchus tshawytscha*) through a bedrock formation (River Mile or RM 43) and depth sensitive, natural, low gradient, alluvial critical riffles (RM 36) were investigated in Butte Creek, California from 2012 – 2013. Passage conditions for adult SRCS were evaluated using River2D, a two-dimensional hydraulic and habitat model (Steffler and Blackburn 2002) and the California Department of Fish and Wildlife critical riffle analysis protocol (CDFW 2012). Quantitative passage criteria included species and life stage-specific depth. River2D was used to predict the amount of channel width meeting the minimum depth criteria for adult SRCS over a range of simulated flows. The data and analysis generated by the study and this report will be used by the CDFW Instream Flow Program to develop flow criteria for adult SRCS migrating upstream through Lower Butte Creek to reach summer holding and spawning habitat in upper Butte Creek.

[1] California Department of Fish and Wildlife, Water Branch, 830 “S” Street, Sacramento, CA 95811
[2] U.S Fish and Wildlife Service, 2800 Cottage Way, Suite W-2605, Sacramento, CA 95825

TABLE OF CONTENTS

ABSTRACT v
TABLE OF CONTENTS vii
LIST OF TABLES ix
LIST OF FIGURES x
LIST OF APPENDICES xii
ABBREVIATIONS, ACRONYMS, AND CONVERSIONS xiii
PREFACE xiv
INTRODUCTION 1
DESCRIPTION OF STUDY AREA 1
  Watershed Hydrology and Water Supply Operations 5
  Fishery Resource 12
PROBLEM STATEMENT 13
STUDY GOALS AND OBJECTIVES 14
METHODS 14
  Methods Selected 15
  Identification of Passage Limiting Sites and Sampling Strategy 15
  River2D approach to evaluate the Lahar formation 16
    River2D Model 16
    Lahar Passage Assessment Criteria 17
  Critical Riffles 19
    Critical Riffle Passage Assessment Criteria 20
    Critical Riffle Analysis using River2D Hydraulic Model 20
SITE SELECTION 22
  Passage Limiting Riffle Survey and Riffle Assessment 22
  Critical Riffle Site Selection 27
DATA COLLECTION 30
  Site Boundaries and Survey Controls 33
  Stage/Discharge Hydraulic Data Collection at 2D Sites 34
  Lahar Site Pressure Transducer 36
  VAKI Riverwatcher 37
  Terrain Model Data Collection 39
Two-Dimensional Hydraulic Model Construction and Calibration 41
  PHABSIM WSEL Calibration 42
  RIVER2D Model Construction 44
  RIVER2D Model Calibration 46
  RIVER2D Model Depth Validation 47
  RIVER2D Model Simulation Flow Runs 47
  RIVER2D Passage Transect Delineation 47
RESULTS 50
  River2D Model Development for Passage Assessment Results 50
    PHABSIM WSEL Calibration 50
    RIVER2D Model Construction 51
    RIVER2D Model Calibration 51
    RIVER2D Model Depth Validation 51

RIVER2D Model Simulation Flow Runs 52
Passage Assessment River2D Results 52
Lahar Site 52
Riffle Sites 60
Pressure Transducer and VAKI Data 63
DISCUSSION 69
River2D Model Discussion 70
PHABSIM WSEL Calibration 70
RIVER2D Model Construction 70
RIVER2D Model Calibration 70
RIVER2D Model Depth Validation 72
RIVER2D Model Simulation Flow Runs 73
Contiguous Width and Flow Magnitude 74
Flow Probability 74
Pressure Transducer and VAKI Data 75
CONCLUSION 75
ACKNOWLEDGEMENTS 77
LITERATURE CITED 78
APPENDICES 82

LIST OF TABLES

Table 1. Regulated Exceedance Flows, in cubic feet per second (cfs), for February March, April, May, and June in Lower Butte Creek. 7
Table 2. Unimpaired Exceedance Flows, in cubic feet per second (cfs), for February March, April, May, and June in Lower Butte Creek. 8
Table 3. Passage Limiting Riffle Survey Schedule. 23
Table 4. Riffle Survey Results. 25
Table 5. Summary of sample dates and corresponding flows when water surface elevations were measured for calibration of Butte Creek River2D models. 35
Table 6. VAKI Riverwatcher passage counts. 38
Table 7. Substrate codes, descriptors and particle sizes used for Butte Creek River2D models. 39
Table 8. Cover coding system used for Butte Creek River2D models. 40
Table 9. Number and density of data points collected for each River2D model study site. 41
Table 10. Initial bed roughness height values used for Butte Creek River2D models. .. 44
Table 11. Results of the Lahar site hydraulic model. 53
Table 12. Riffle 95 River2D model results. 61
Table 13. Riffle 96 River2D model results. 62
Table 14. Riffle 97 River2D model results. 63
Table 15. Frequency of Nodes with Froude Number (FN) >1.0 71
Table 16. Exceedance percentages of study selected flow levels. 75

LIST OF FIGURES

Figure 1. Map of Butte Creek study reach. 2
Figure 2. Map of Butte Creek watershed. 3
Figure 3. Primary study site. 4
Figure 4. Lahar Formation, view facing upstream towards Durham Mutual Diversion Dam and Fish Ladder. 5
Figure 5. Daily mean flows and water temperatures downstream of Durham Mutual Dam. 6
Figure 6. Percent exceedance flows for February. 8
Figure 7. Percent exceedance flows for March. 9
Figure 8. Percent exceedance flows for April. 10
Figure 9. Percent exceedance flows for May. 11
Figure 10. Percent exceedance flows for June. 12
Figure 11. Streambed transition from alluvium to Lahar formation. 14
Figure 12. Aerial view of Lahar formation. 19
Figure 13. Critical riffle analysis transect following shallowest course from bank to bank at Riffle 97 at approximately 402 cfs. 21
Figure 14. Walking across a riffle crest searching for the shallowest thalweg depth. 23
Figure 15. Riffle 95 at 64 cfs, view facing upstream. 25
Figure 16. Riffle 96 at 64 cfs, view facing upstream. 26
Figure 17. Riffle 97 at 64 cfs, view facing downstream towards Midway Road. 26
Figure 18. Critical Riffles 95, 96, and 97 upstream of Midway Road with the flashboards in-place at Gorrill Diversion. 28
Figure 19. Critical Riffles 95, 96, and 97 upstream of Midway Road with the flashboards removed from Gorrill Diversion. 29
Figure 20. RTK GPS survey of Lahar Site. 31
Figure 21. Data points collected with RTK GPS and total station (green dots) and control points used for terrestrial LIDAR (red points) for the Lahar site. 32
Figure 22. Boat-mounted ADCP. 33
Figure 23. Stage of zero flow diagram. 36
Figure 24. Pressure transducer mounted in PVC casing downstream of Lahar site. 37
Figure 25. VAKI Riverwatcher installed in the fish ladder adjoining Durham Mutual Diversion Dam. 38
Figure 26. Riffle 95 shallowest course bank to bank. 48
Figure 27. Riffle 96 shallowest course bank to bank. 48
Figure 28. Riffle 97 shallowest course bank to bank. 49
Figure 29. Lahar Site – Discharge versus width with depth ≥ 0.9 ft. 54
Figure 30. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 120 cfs. Scale in meters. 55
Figure 31. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 240 cfs. Scale in meters. 56
Figure 32. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 405 cfs. Scale in meters. 57

Figure 33. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 120 cfs. The limiting width was equal to approximately 1 foot. Scale in meters. 58
Figure 34. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 240 cfs. The limiting width was equal to approximately 3 feet. Scale in meters. 59
Figure 35. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 405 cfs. The limiting width was equal to approximately 7.5 feet. Scale in meters. 60
Figure 36. Lahar site 2014 pressure transducer rating curve. 64
Figure 37. Lahar site 2015 pressure transducer rating curve. 65
Figure 38. Water temperatures and flows at the Lahar in 2014. Gaps in the flow curve reflect flows that exceeded the upper end of the 2014 rating curve (630 cfs). 66
Figure 39. Water temperatures and flows at the Lahar in 2015. Gaps in the flow curve reflect flows that exceeded the upper end of the 2015 rating curve (425 cfs). 66
Figure 40. Cumulative percentage of fish passing per day through the VAKI Riverwatcher. 67
Figure 41. 2014 Lahar site daily monitoring data. 68
Figure 42. 2015 Lahar site daily monitoring data. 69
Figure 43. Lahar site at approximately 116 cfs. Supercritical area of abrupt grade change on the west side of the site (Top) and the turbulent entrance to the east side of the site (Bottom). 72
Figure 44. Riffle 96 Supercritical flow condition at 153 cfs. 74

LIST OF APPENDICES

Appendix A. RHABSIM WSEL Calibration 83
Appendix B. Velocity Adjustment Factors........ 87
Appendix C. Bed Topography of Study Sites 91
Appendix D. Computational Meshes of Study Sites. 96
Appendix E. 2-D WSEL Calibration 100
Appendix F. Depth Validation Statistics........ 102
Appendix G. Simulation statistics. 109
Appendix H. River2D model outputs for Riffle 95, 96, and 97. 114
Appendix I. 2014 and 2015 Time Series for the Lahar Site 119
Appendix J. Sample Froude Number Plots 128

ABBREVIATIONS, ACRONYMS, AND CONVERSIONS

1D	one dimensional (physical habitat simulation model)
2D	two dimensional (physical habitat simulation model)
7DADM	7-day average of the daily maximum
ADCP	acoustic doppler current profiler
BCD	Butte Creek at Durham (stream gaging station)
BR Mult	bed roughness multiplier
cdg	characteristic dissipative galerkin
cfs	cubic feet per second
cm	centimeter
CRA	critical riffle analysis
csv	comma-separated values
CDWR	California Department of Water Resources
FN	Froude number
FRCS	fall-run Chinook salmon
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 (2.54 centimeters)
LIDAR	light detection and ranging
m^2	square meter
MANSQ	Manning's stage discharge
MAX F	maximum Froude number
Net Q	net flow
NMFS	National Marine Fisheries Service
ODFW	Oregon Department of Fish and Wildlife
PHABSIM	Physical Habitat Simulation Model
PRC	Public Resources Code
QI value	quality index value
RHABSIM	River Habitat Simulation Model
RIVER2D	RIVER2D Model
RM	river mile
RTK	real time kinematic
Sol Δ	solution change
SOP	standard operating procedure
SRCS	spring-run Chinook salmon
SZF	stage of zero flow
TIN	triangulated irregular network
USGS	United States Geological Survey
XS	cross section
WSEL	water surface elevation
WSP	Water Surface Profile Model

PREFACE

Butte Creek has the largest self-sustaining wild population of SRCS in the Sacramento River watershed (NMFS 2014). It is listed on the California Department of Fish and Wildlife's (Department) priority stream list, developed under Public Resources Code (PRC) §10001, which identifies streams where minimum instream flow criteria are needed to assure the continued viability of stream-related fish and wildlife.

Butte Creek is also identified as a priority stream in:

- ❖ United States Fish and Wildlife Service (USFWS) 2001 Final Restoration Plan for the Anadromous Fish Restoration Program: A Plan to Increase Natural Production of Anadromous Fish in the Central Valley of California;
- ❖ National Marine Fisheries Service (NMFS) 2014 Final Recovery Plan for the Evolutionary Significant Units of Sacramento River Winter-Run Chinook Salmon and Central Valley SRCS and the Distinct Population Segments of the Central Valley SRCS;
- ❖ SWRCB 2010 Instream Flow Studies for the Protection of the Public Trust Resources: A Prioritized Schedule and Estimate of Cost; and
- ❖ The Delta Stewardship Council 2013 Final Delta Plan.

The primary objective of the Department's Instream Flow Program is to develop scientific information on the relationships between flow and available stream habitats, and to determine what flows are needed to maintain healthy conditions for fish and wildlife. Different species and salmonid life stages, such as spawning, rearing, or migration, require different habitats to be accessible. The relationship between flow and the specific habitat required is unique and should be evaluated through specialized instream flow techniques. The Department has interest in assuring that stream flows are maintained at levels that are adequate for the long-term protection, maintenance and proper stewardship of aquatic resources.

This document describes the watershed hydrology, fisheries resources, study site selection, data collection, assessment methodology, and results for the purpose of developing flow criteria for adult SRCS migrating upstream through the valley section of Lower Butte Creek. Flow recommendations are developed by the Department separately and are not presented in this technical report.

INTRODUCTION

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

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, aquatic habitat connectivity is an equally important and often overlooked component which is especially essential for adult SRCS to reach cool-water summer holding pools (Dunbar et al. 1998; Fullerton et al. 2010).

DESCRIPTION OF STUDY AREA

The study reach extends from Western Siphon to the Parrot Phelan Diversion Dam (Figure 1). The headwaters of Butte Creek are located in Butte Creek Meadows (Meadows) at an elevation of over 7,000 feet (CSUC 1998). From the Meadows the creek cuts down through a canyon section before spilling onto the Sacramento Valley floor (Figure 2). Stream channel deposits in the study reach are a mix of sand and gravel sized material eroded from the Chico and Tuscan Formations (Harwood et al. 1981). Department staff observed cobble sized material also mixed in with the historic sand and gravel channel deposits. As Butte Creek enters the valley floor near Durham Mutual Diversion Dam (Figure 2) the stream channel encounters exposed portions of the Tuscan Formation (Saucedo and Wagner 1992). The Tuscan Formation covers the mid-section of the watershed, approximately 2,000 square miles from Marysville to Oroville (Lydon 1968). The Tuscan Formation is the result of a Pliocene volcanic mudflow commonly referred to as lahar (Lydon 1968). The deposit is composed of angular and subangular volcanic and metamorphic fragments in a matrix of gray-tan volcanic mudstone (Harwood et al. 1981; Lydon 1968).

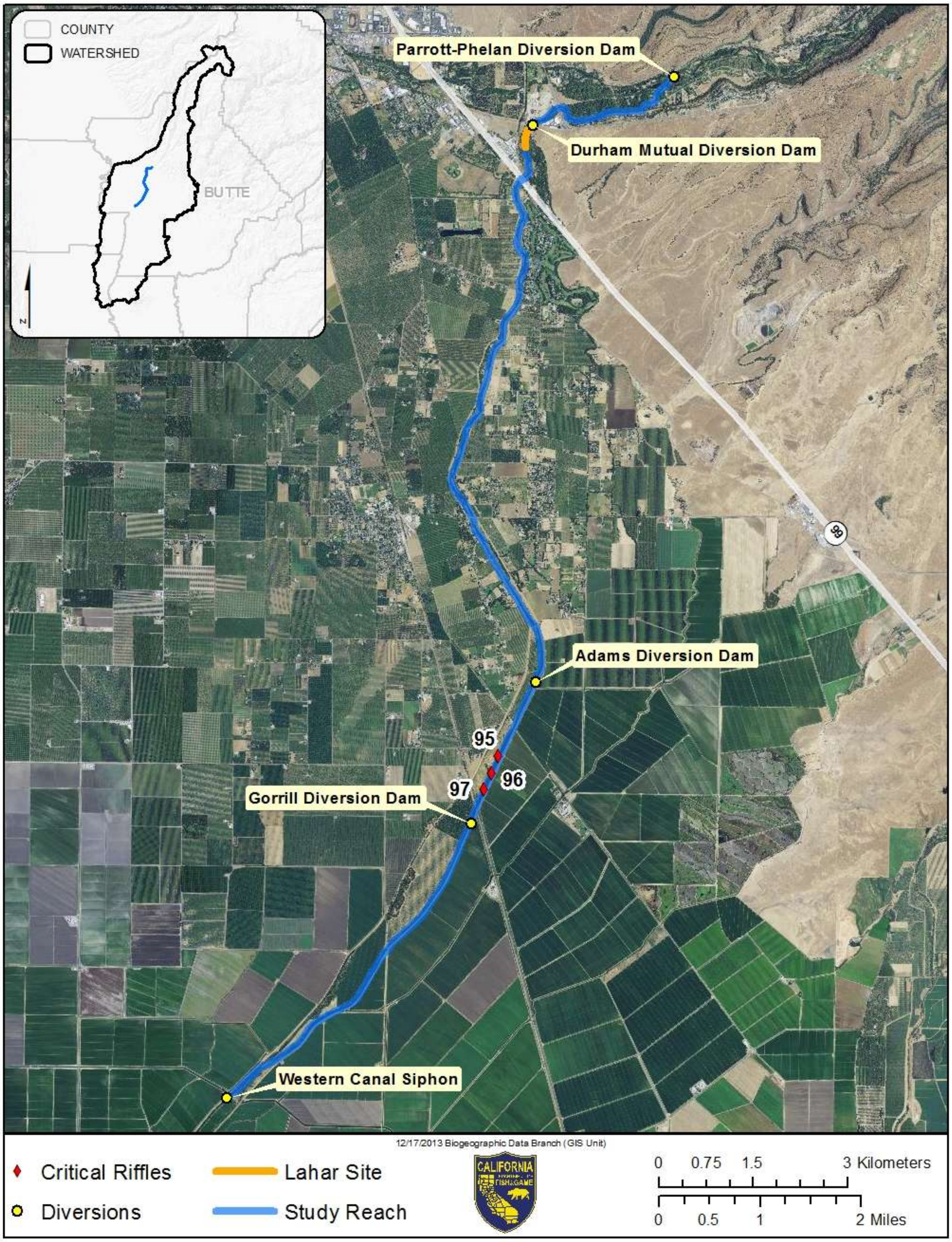


Figure 1. Map of Butte Creek study reach.

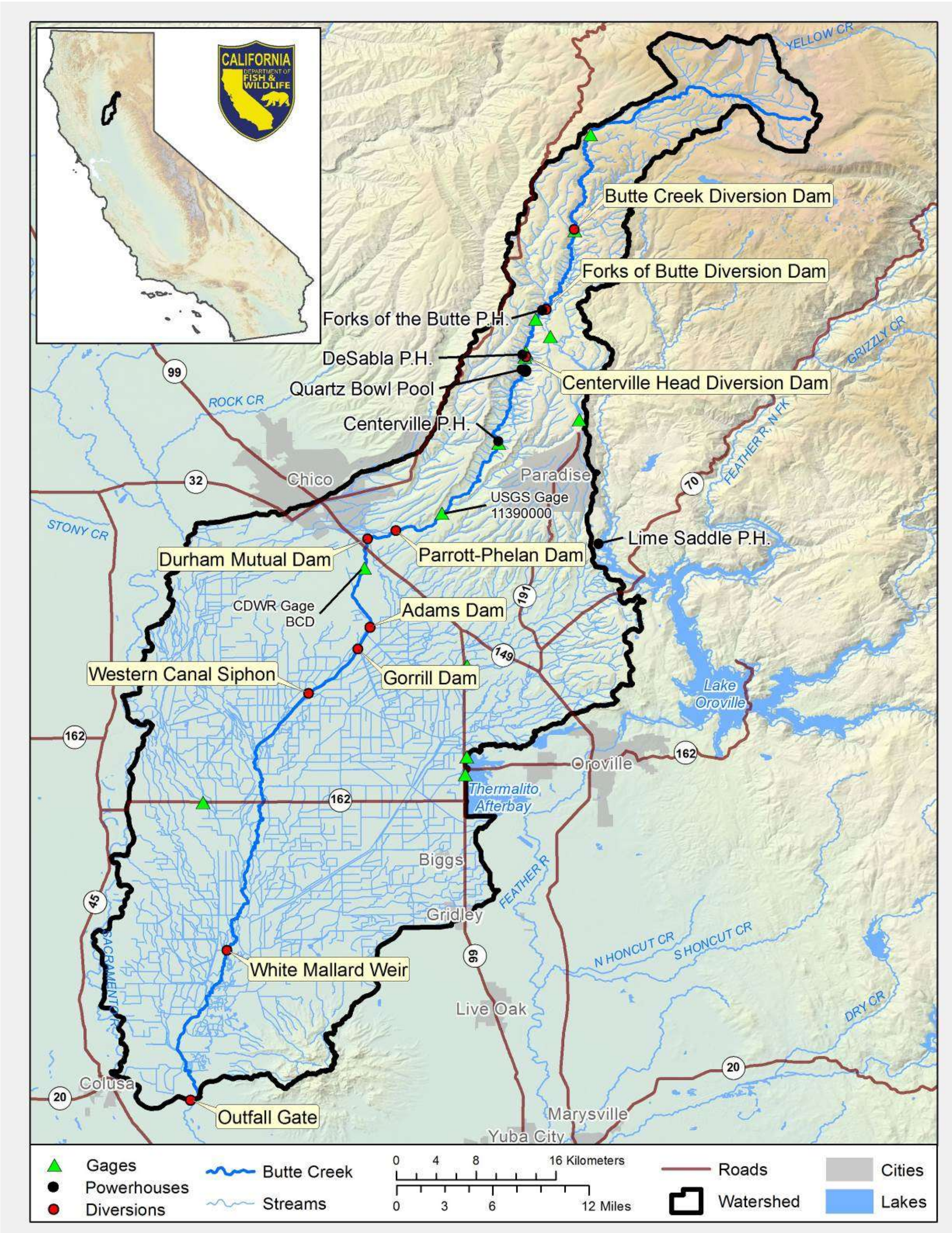


Figure 2. Map of Butte Creek watershed.

A stream reach is defined as a homologous stream segment based upon gradient, geomorphology, hydrology, riparian zone types, flow accretion, diversion influence, and channel structure. The limits of the project stream reach extend 13 river miles from Parrot-Phelan Diversion Dam downstream to the Western Siphon.

Department staff identified a section of Butte Creek near the Highway 99 bridge overpass where a portion of the Tuscan Formation is exposed, as the primary location for fish passage assessment. The Durham Mutual Diversion Dam is located a short distance upstream from the Highway 99 bridge overpass (Figure 3). Several hundred yards downstream of the Durham Mutual Diversion Dam the stream channel bed transitions from alluvial sand and gravel deposits to exposed bedrock comprised of the Tuscan Formation (Figure 4). The formation extends up to the dam; however, above the dam the stream channel transitions back to alluvial deposits. The exposed portion of Tuscan Formation below Durham Mutual Diversion Dam is referred to in this report simply as the Lahar formation or Lahar. Water drains over and through the Lahar via a complex braided network of trenches and gullies varying in depth. Remnant alluvial deposits (sand, gravel, and cobble) still remain in deep areas of the Lahar especially where velocities are low. Region staff reported observing adult SRCS cueing up in a shallow pool downstream of the Lahar during the 2000’s after restoration activities were completed. Staff observed SRCS holding in a shallow pool downstream of the Lahar during study reconnaissance in May, 2013.

Figure 3. Primary study site.

Figure 4. Lahar Formation, view facing upstream towards Durham Mutual Diversion Dam and Fish Ladder.

Watershed Hydrology and Water Supply Operations

The hydrology of Butte Creek is typical of many Central Valley Californian rivers that drain from the Sierra Nevada, comprising high winter flows, low summer flows, and variable annual discharges. Most of the flow occurs in the winter and spring with stream discharge reflecting local and watershed-wide snow and rainfall patterns. Figure 5 shows spring and summer flows below Durham Mutual Diversion Dam, calculated by subtracting diversions from flows measured at U.S. Geological Survey (USGS) gage Station 11390000, and water temperature patterns measured at the California Department of Water Resources (CDWR) gage Butte Creek near Durham (BCD), located below Durham Mutual Diversion Dam, between 2008 and 2015. Generally, flow level and temperature are inversely proportional, temperatures rise during the spring-run months as flows recede.

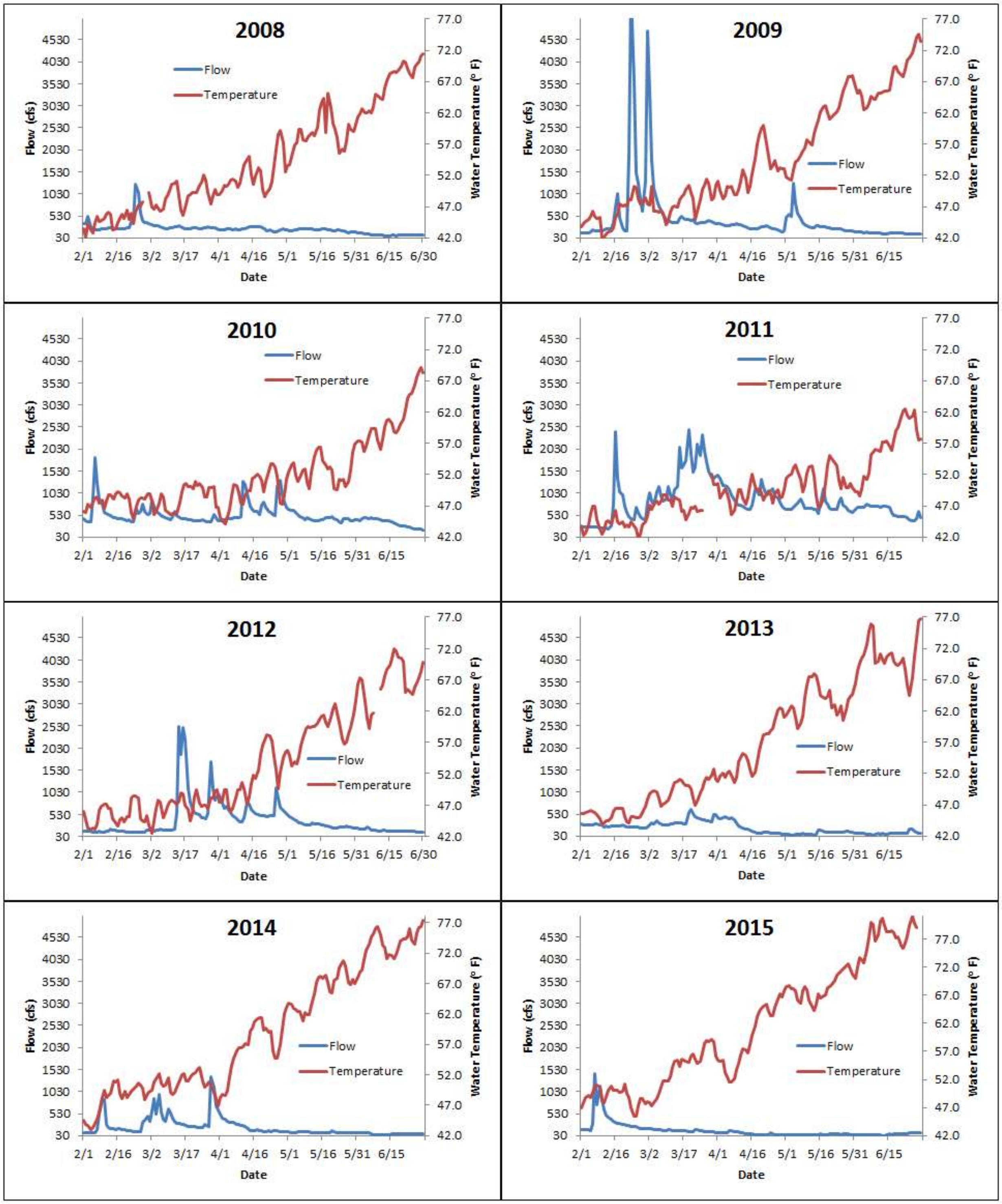


Figure 5. Daily mean flows and water temperatures downstream of Durham Mutual Dam.

Pacific Gas and Electric provided data on unimpaired and regulated daily average flows at the Centerville Powerhouse for the period October 1, 1957 to September 30, 2005, in their DeSabla-Centerville Hydroelectric Project FERC No. 803-068 Supplemental Initial

Study Report (Pacific Gas and Electric, 2007)[3]. The DeSabla-Centerville Hydroelectric Project is operated as a run-of-the-river system (SWRCB 2015); project operations are not consumptive. However, water imported from the Feather River is added to Butte Creek through Toad Town Canal, above Centerville Powerhouse and the study reach. The contribution of imported water is recorded as part of the total Butte Creek flow at the USGS gage Station 11390000, located in between Centerville Powerhouse and the study reach. To estimate unimpaired flow in Butte Creek, the average daily flows from the monitoring station on Toad Town Canal, BW-12, were subtracted from the USGS gage flows recorded downstream. The record for USGS gage Station 11390000 for the period 1931 to present includes flows from the West Branch Feather River as part of the Desabla Centerville hydroelectric project operated by Pacific Gas and Electric, and thus represents regulated flows.

The likelihood of a particular flow returning to the study reach was calculated by means of a flow duration analysis, which describes the percentage of time a stream discharge is equaled or exceeded. The likelihood is expressed as a percentage of exceedance probability and referred to as the exceedance flow. 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 (Bovee et al. 1998). The percent exceedance of mean daily regulated flows and unimpaired flows for February, March, April, May, and June are plotted in Figures 6 through 10, respectively. Regulated and unimpaired exceedance flows are summarized in Tables 1 and 2, respectively.

Table 1. Regulated Exceedance Flows, in cubic feet per second (cfs), for February March, April, May, and June in Lower Butte Creek.

	Flows (cfs)				
Exceedance	**February**	**March**	**April**	**May**	**June**
90%	171	299	291	199	139
80%	249	361	366	272	166
70%	311	419	415	318	190
60%	394	474	478	365	218
50%	473	558	538	415	246
40%	573	640	617	495	281
30%	748	751	719	584	321
20%	1050	937	894	704	381
10%	1670	1450	1180	892	493

[3] Pacific Gas and Electric (2007) gives data from October 1, 1985 to September 30, 2005.

Table 2. Unimpaired Exceedance Flows, in cubic feet per second (cfs), for February March, April, May, and June in Lower Butte Creek.

Flows (cfs)					
Exceedance	**February**	**March**	**April**	**May**	**June**
90%	149	214	219	147	90
80%	207	289	276	185	103
70%	286	346	329	217	119
60%	351	419	378	255	134
50%	420	493	435	309	157
40%	531	576	510	383	185
30%	725	698	602	474	218
20%	1051	911	743	607	284
10%	1672	1414	957	815	400

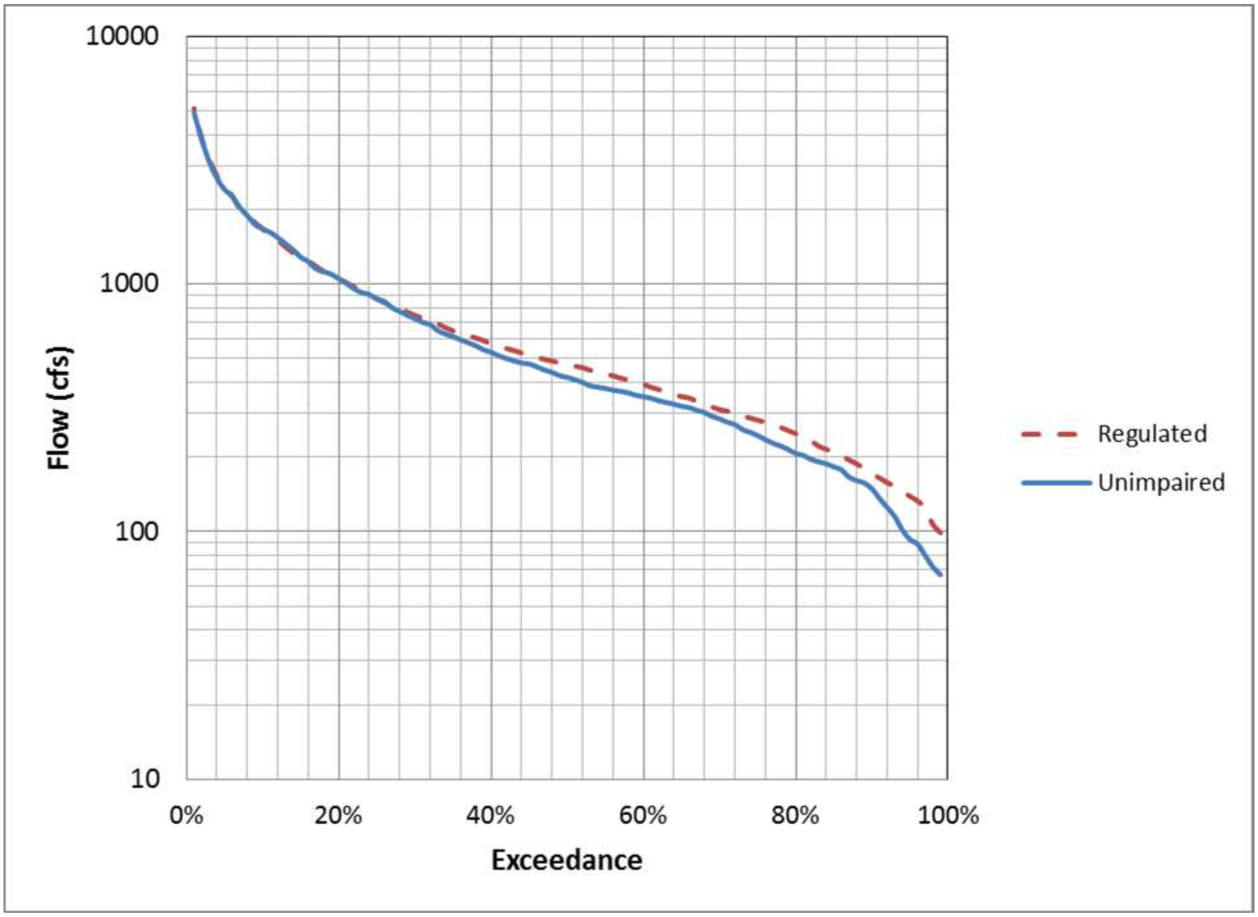


Figure 6. Percent exceedance flows for February.

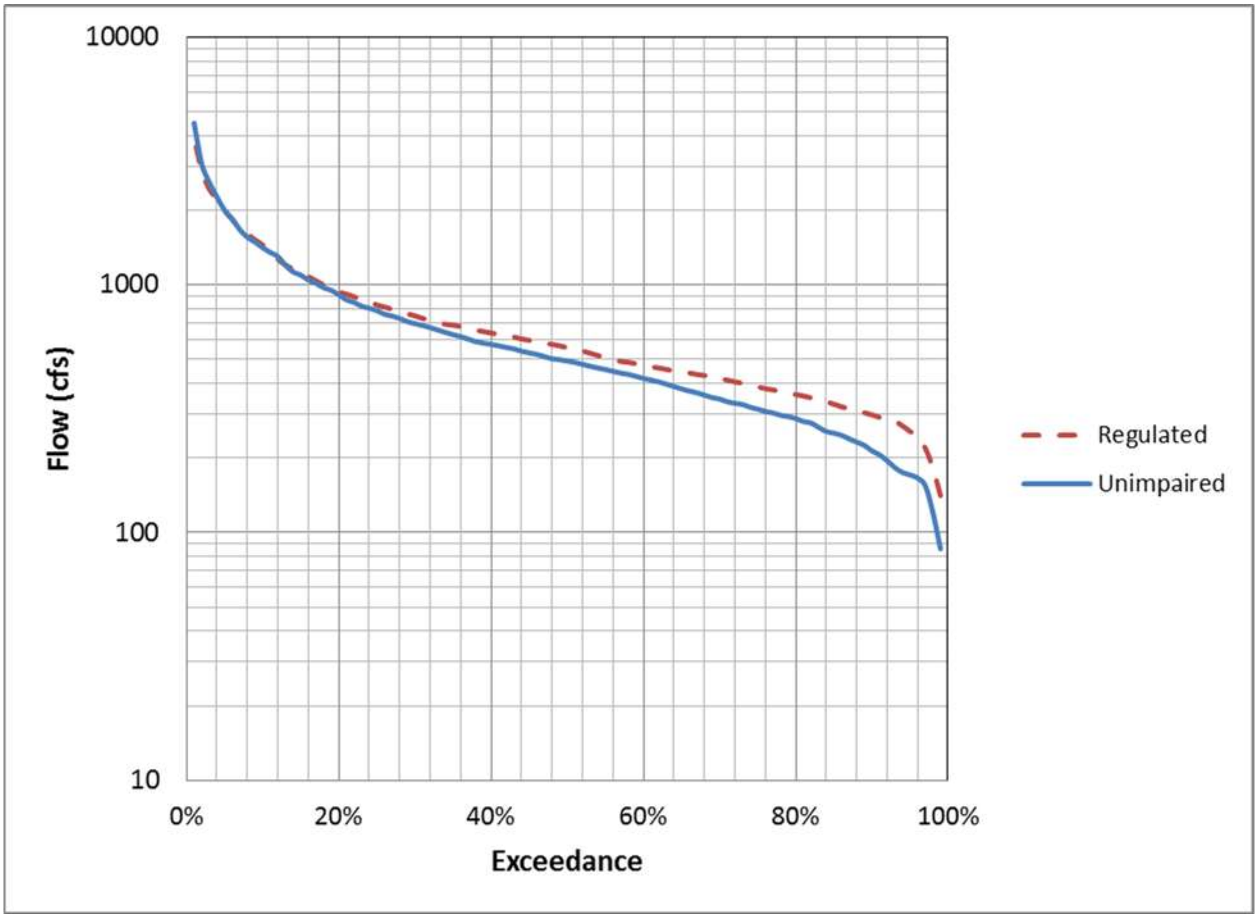


Figure 7. Percent exceedance flows for March.

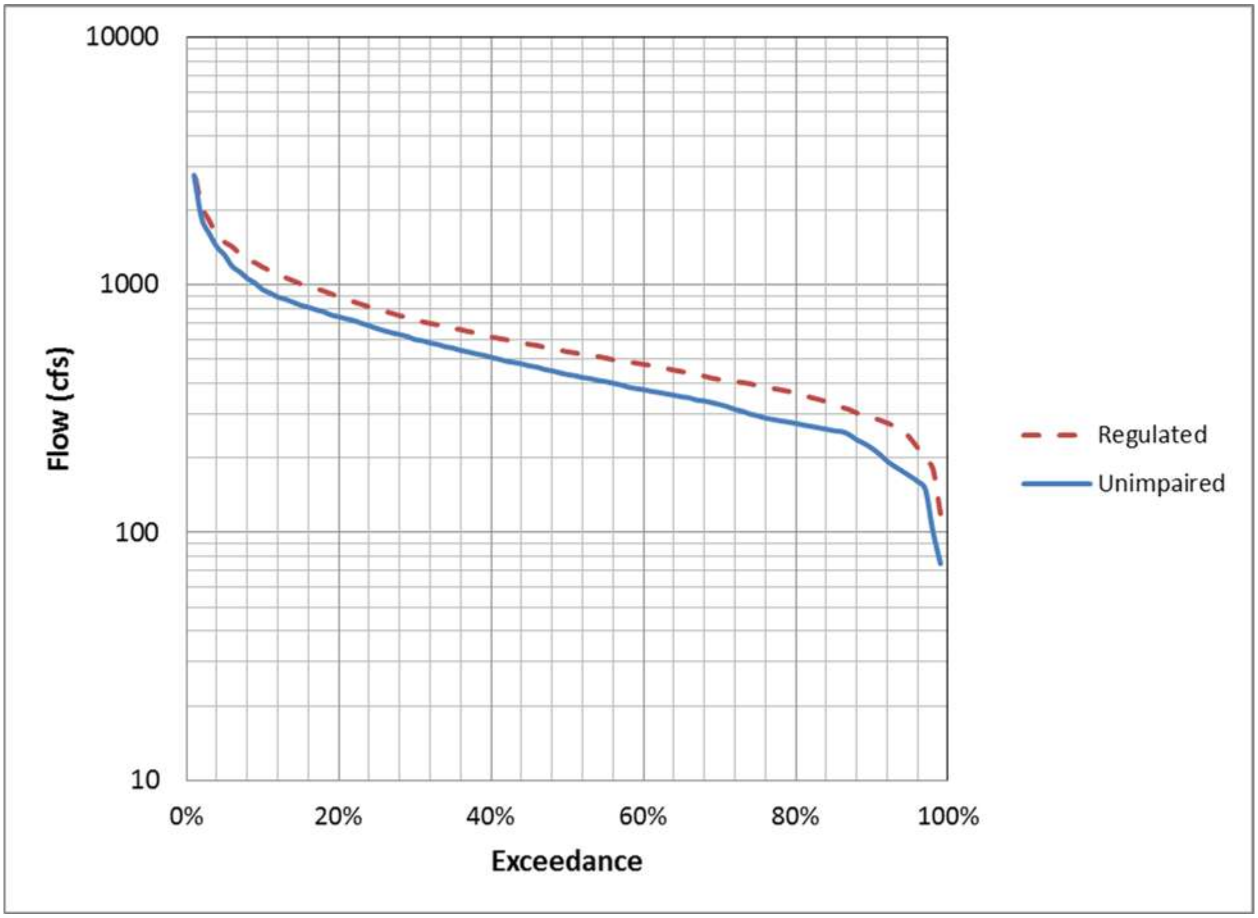


Figure 8. Percent exceedance flows for April.

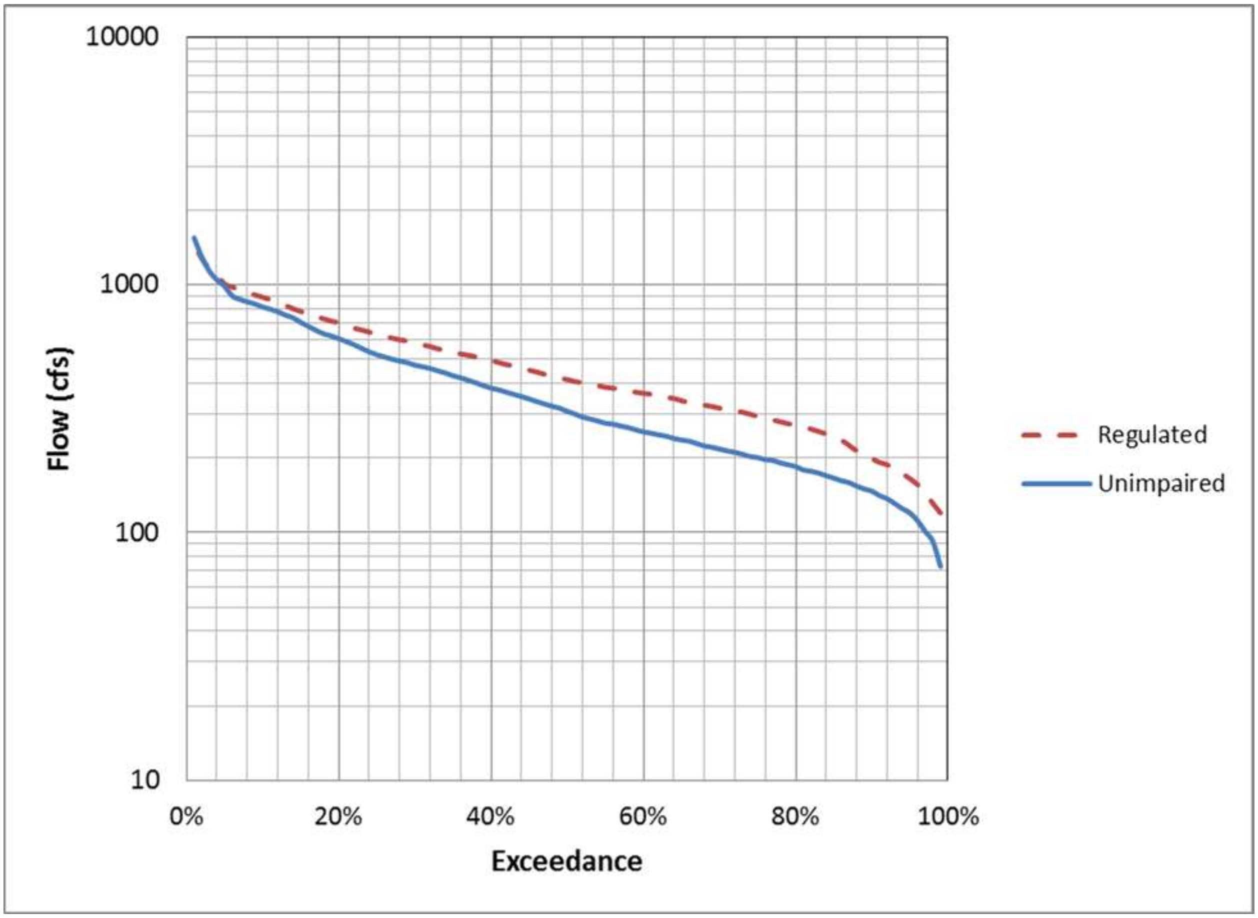


Figure 9. Percent exceedance flows for May.

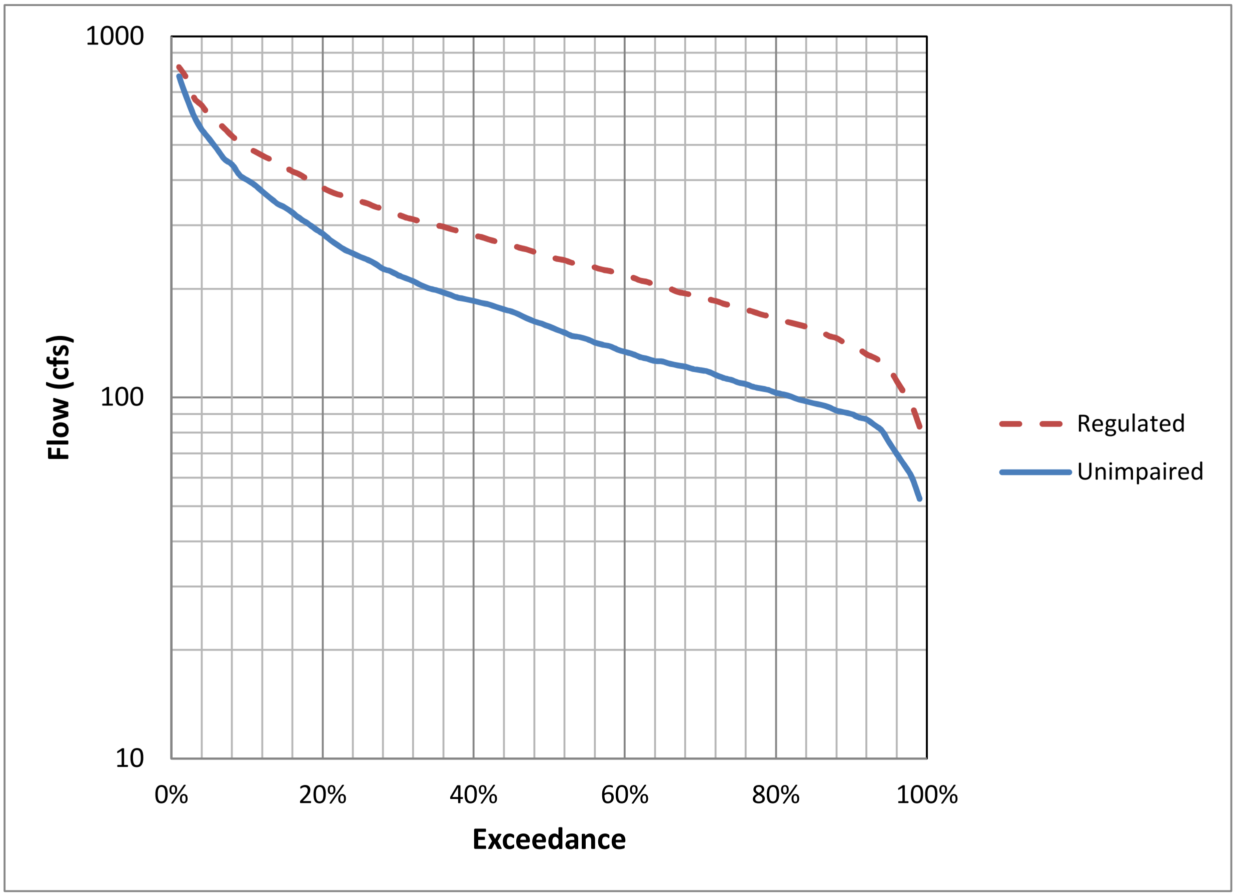


Figure 10. Percent exceedance flows for June.

Fishery Resource

Adult SRCS migrate from the Sacramento River into Butte Creek from mid-February[4] through June, hold in cool-water pools upstream of the study reach during July and August, and spawn in September and October[5]. SRCS are documented to spawn in Butte Creek starting above the Parrot-Phelan Diversion Dam extending up to the Quartz Bowl Pool (Figure 2; CDFW 2009). Quartz Bowl Pool (QBP) represents the upstream migratory limit to SRCS in most years. Early arrival of SRCS and optimal flows are required for SRCS to pass above QBP. CDFW has only documented SRCS advancing

---

[4] Prior to the VAKI system at Durham Mutual Diversion Dam, CDFW has observational data at the Parrott-Phelan screw traps that note presence of SRCS adults in February, Garman and McReynolds (2009). The VAKI system has confirmed that in 2014 and 2015.

[5] Spawning data are collected from early September to the end of October, Garman and McReynolds (2009).

above QBP twice since 1994, 1995 and 2003. Above QBP, upstream migration is limited by Centerville Head Dam.

USFWS completed an instream flow study in 2003 for SRCS spawning habitat in Upper Butte Creek, upstream of Parrot-Phelan Diversion Dam. CDFW submitted minimum instream flow recommendations to the State Water Resources Control Board (State Water Board) for Upper Butte Creek in 2009, based on the work completed by USFWS. However, downstream impediments in the Sacramento Valley section of Butte Creek limit access to adult holding and spawning habitat (Mosser et al. 2013).

PROBLEM STATEMENT

It has been apparent to Department staff that under certain stream conditions a seasonal barrier to adult SRCS exists near the Highway 99 bridge overpass on Lower Butte Creek. Department staff have observed migrating SRCS halt upstream of the bridge overpass where the channel bed changes from alluvial deposits to bedrock (the Lahar formation) and then retreat to a holding pool downstream, Figure 3. Those fish, unable to migrate further upstream, are usually stranded. Department staff, with the help of the local community and other agencies, has tried to rescue stranded fish from the pool in the past; however, steep banks leading down to the pool make access difficult and rescue attempts have been unsuccessful (Mosser et al. 2013).

The primary goal of this study is to investigate the Lahar formation as a barrier to fish passage as well as to identify any other deterrents to adult SRCS passage into Upper Butte Creek. Two main passage concerns with the Lahar formation have been expressed by the Department: 1) the upstream transition or passageway from the alluvial deposits onto the Lahar is steep, especially under low flow conditions, creating a potential jump barrier (Figure 11); and 2) the passageway(s) for fish within the Lahar are not obvious or centralized. Water flows through and over the Lahar along many different pathways and therefore, under low flow conditions drainage is not efficiently centralized for fish passage. It is hypothesized that the lack of clear hydraulic connectivity within the formation creates added stress and a barrier to passage, especially later in the migration season when lower flows are combined with elevated temperatures.

Figure 11. Streambed transition from alluvium to Lahar formation.

STUDY GOALS AND OBJECTIVES

The goal of this study is to identify flow regimes that may support adult SRCS passage through the bedrock outcropping known as the Lahar as well as to assess any other deterrents to fish passage located in the valley section of Butte Creek, Butte County. Site-specific flow assessment is needed for adult SRCS because of the unique nature of the Lahar formation. Objectives of this study include: 1) evaluation of passage impediments through use of the River2D model (Steffler and Blackburn 2002) and Critical Riffle Analysis (CRA; CDFW 2012) methodologies for identification of flows necessary to protect passage of SRCS through Lower Butte Creek; and 2) to examine the temporal variability of passage flows identified.

METHODS

While there are numerous methods of passage assessment, no single method fits all stream types or conditions; therefore, the method selected is dependent on the study site selected (i.e., channel geology, size, location, source). To assess potential passage impediments in Lower Butte Creek, reconnaissance field trips and preliminary surveys were conducted along the entire lower 13 miles.

Methods Selected

Both the Lahar formation and several alluvial riffles were identified as potential passage impediments and were evaluated to understand the relationship between flow and adult SRCS upstream migration. The complex hydraulics of the Lahar formation were evaluated using the predictive two-dimensional (2D) model River2D; this model was determined to be best suited for identification of flows at which the depths and wetted widths required for SRCS passage are available in the confined and complex Lahar. Selected alluvial riffles were also evaluated using a combination of River2D hydraulic models and the CRA method (CDFW 2012). CRA involves selecting the shallowest course from bank to bank across a critical riffle site and measuring water depth along that course at selected flow levels. The length of the shallowest course and depth data collected at each flow are used to create empirical relationships of the percent total and contiguous width available to migrating fish. 2D models were prepared to simulate the hydraulics at the riffle sites and predict depths and widths over a range of flow regimes. 2D models were used in favor of collecting empirical data points at distinct flows for two main reasons: 1) 2D modeling is a more rigorous way to develop the depth, width, flow relationships where resolution is needed in small increments of flow on the scale of 5 cfs; 2) placement of flashboards at Gorrill Dam downstream of the riffle sites limited the time available to collect the necessary number of distinct flows along the receding limb of the spring hydrograph.

The Department has employed 2D modeling in the past to evaluate hydraulic regimes at potential passage barriers. Holmes et al. (2015) compared fish passage flows derived from River2D modeling with flows derived from the empirical CRA method (Thompson 1972). A high coefficient of correlation (r^2=0.93) was found for flows predicted using 2D modeling with flows derived from the CRA method.

A predictive temperature model was not necessary for the study; temperature data is available within the study reach at multiple monitoring stations. Temperature monitoring stations include the USGS stream gage near Covered Bridge (USGS Station 11390000; Figure 2), the recently installed VAKI Riverwatcher (VAKI) located at Durham-Mutual Diversion Dam and fish ladder (Figures 1 and 2), a temporary thermograph placed below the Lahar formation for the purpose of the study, and at the CDWR stream gage BCD located just downstream of Durham-Dayton Highway (Figure 2).

Identification of Passage Limiting Sites and Sampling Strategy

The section of Lower Butte Creek evaluated in this study is commonly referred as the valley section or valley floor. Lower Butte Creek in the valley section is dominated by alluvial deposits with some portions of exposed bedrock of the Tuscan Formation (Saucedo and Wagner, 1992). South of the town of Chico, Butte Creek flows out from the canyon onto the valley floor. The area below Durham-Mutual diversion where the streambed is exposed to the Tuscan bedrock is indicative of the transition from canyon to valley gradient. The Tuscan bedrock is volcanoclastic in origin and commonly referred to as the Lahar formation. The braided network of the Lahar formation is unlike other braided rivers, because the braids are not composed of alluvial sands, silts, gravels, and cobbles, but instead are composed of rigid bedrock. Consequently, the Lahar formation can act as a barrier to fish passage by constricting flow through the confined ridged bedrock channels and by interrupting the natural course of the stream thalweg.

It is hypothesized that the Lahar formation is hindering adult SRCS migration into the Upper Butte Creek watershed because of its rigid pathways; however, since the Department was not sure if the Lahar was the only deterrent to adult SRCS migration, other problematic areas were assessed. The valley section of Lower Butte Creek is predominately an alluvial bed stream with exposed substrate and a broad channel width. Riffles were identified as potentially limiting features for passage if flows did not allow for critical depths to be maintained for salmonid passage over them during migration periods. Therefore, riffles were surveyed and three were identified as critical riffles for further passage assessment.

River2D approach to evaluate the Lahar formation

The Lahar formation is rigid bedrock outcropping that cannot be evaluated through methods such as Thompson (1972) or Tennant (1976), as these methods are designed to be used with steady state alluvial channels. Therefore, the River2D model[6] was used for predicting upstream passage due to its ability to capture the complex hydraulics present in the Lahar site. Outputs of River2D, including; depth, velocity, water surface elevation profiles, and flow distribution, are crucial in evaluating upstream passage through the Lahar formation as the formation is affected by flow. Typically in alluvial rivers, riffles control upstream passage; in Butte Creek, the Lahar formation has been identified as the controlling passage limiting area for upstream adult SRCS migration.

River2D Model

River2D inputs include the bed topography, bed roughness height, and the water surface elevation at the downstream end of the site. The upstream and downstream hydraulic control transects in River2D are evaluated using 1D (one-dimensional) physical habitat simulation (PHABSIM). The PHABSIM inputs are bed topography and water surface elevation. The amount of habitat present in the site is computed using the depths and velocities predicted by River2D, and the substrate and cover present in the site.

[6] River2D Version 0.93 November 11, 2006 by P. Steffler, A. Ghanem, J. Blackburn and Z. Yang.

The data for 2D modeling can be collected with a stratified sampling scheme, with higher intensity sampling in areas with more complex or more quickly varying microhabitat features, and lower intensity sampling in areas with uniformly varying bed topography and uniform substrate and cover. Bed topography and substrate/cover mapping data can be collected at a very low flow, with the only data needed at high flow being water surface elevations at the upstream and downstream ends of the site, and flow and edge velocities for validation purposes. In addition, alternative habitat suitability criteria, such as measures of habitat diversity, can be used.

The upstream and downstream transects were modeled with PHABSIM to provide water surface elevations as an input to the River2D model (Steffler and Blackburn 2002). By calibrating the upstream and downstream transects with PHABSIM, using the collected calibration water surface elevations (WSELs), the WSELs for transects at the various simulation flows modeled using River2D could be predicted. Calibration of the River2D models could be completed using the highest simulation flow. The highest simulation WSELs predicted by PHABSIM for the upstream and downstream transects could be 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 at the highest simulation flow, the WSELs predicted by PHABSIM for the downstream transect for each simulation flow were used as an input for the downstream boundary condition for River2D model production files for the simulation flows.

Lahar Passage Assessment Criteria

The parameters used to evaluate flow regimes for adult SRCS migrating through the Lahar formation are as follows:

1) Depth equal to or greater than 0.9 feet;
2) Change in water surface elevation across the potential jump barrier near the downstream end of the Lahar formation;
3) Maximum darting speed in the potential jump barrier;
4) Percentage of flow in the main channel in the lower portion of the Lahar formation (Figure 12).

Widths were evaluated incrementally in River2D by running the Lahar River2D model at different flows, and using the model output to compute the width at each flow. Depth criteria for salmon and steelhead were evaluated in detail by R2 Resource Consultants (R2) as part of the scientific basis report prepared for the State Water Board North Coast Instream Flow Policy, effective August 6, 2007[7]. R2 performed a comprehensive literature review to identify quantitative criteria for fish upstream passage and spawning habitat availability. The results of the literature review are presented in *Appendix G – Approach for Assessing Effects of Policy Element Alternatives on Upstream Passage*

[7] Updated March 14, 2008

and Spawning Habitat Availability (Appendix G) (R2 2007). The depth criterion for migrating adult SRCS of 0.9 feet, used here to evaluate both the Lahar formation and the riffles, was referenced from Table G-4 of Appendix G for Chinook salmon.

Gallagher (1999) provides formulas for maximum jumping height and darting speed based on fish length; using the average length of adult SRCS in Butte Creek of 2.38 feet, Garman and McReynolds (2009), the formulas give a maximum jump height of 5.6 feet and a maximum darting speed of 19 feet/sec. Gallagher (1999) also states that the depth of the plunge pool should be at least 1.25 times the change in water surface elevation across a jump, and that the gradient of a cascade should be less than 45 degrees for a location to allow upstream passage. These criteria were used to evaluate a potential passage limiting area fish swim past entering the Lahar Site.

The Lahar formation splits into a network of rigid channels as flow moves downstream. Percentage of the flow in the main channel was monitored to ensure the analysis evaluated the channel where fish were most likely to be expected to pass.

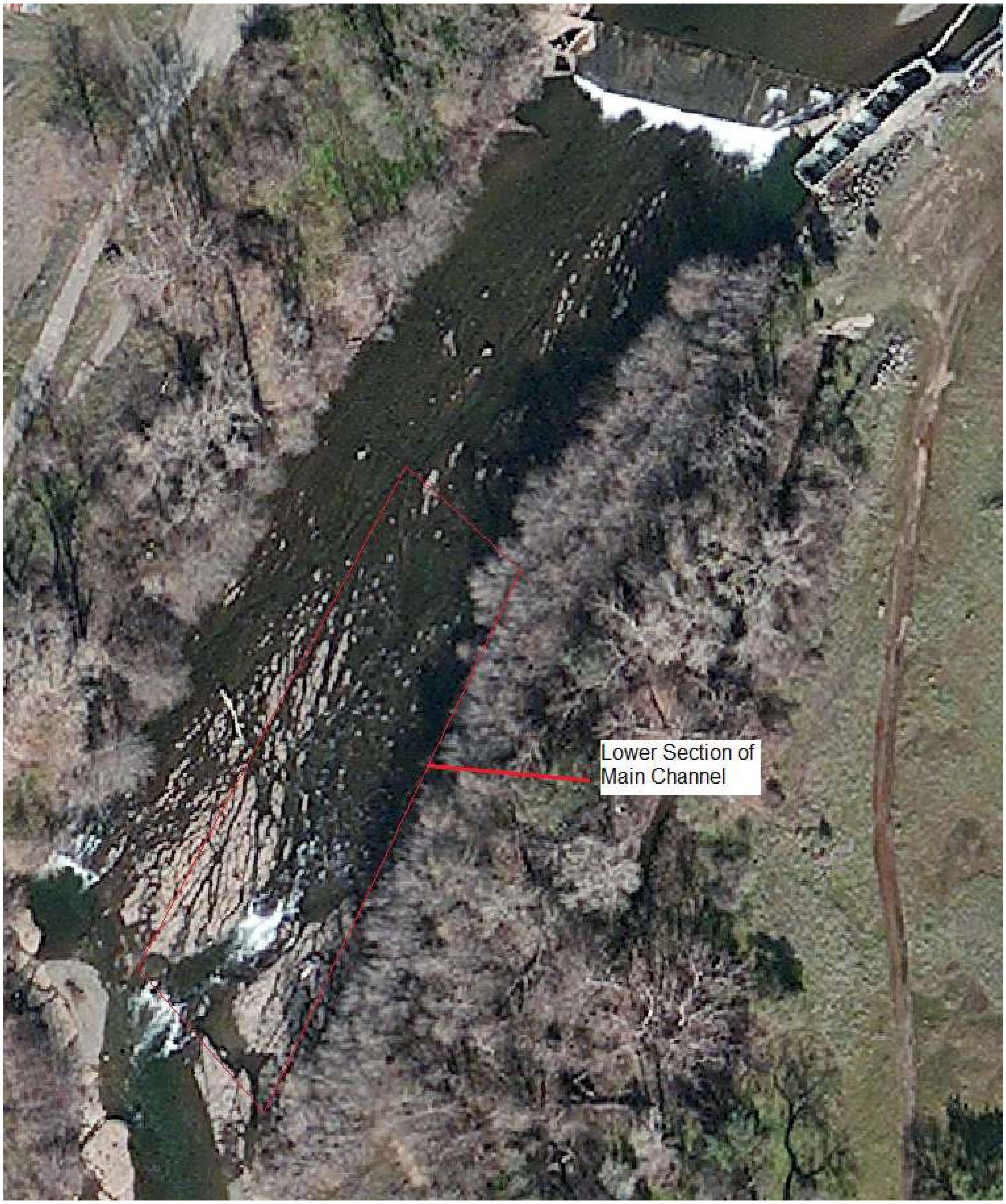


Figure 12. Aerial view of Lahar formation.

Critical Riffles

Typically passage assessments based in alluvial river systems focus on riffles. Standard methods used to estimate the amount of flow needed to make a riffle passable have been developed (e.g., Wetted Perimeter, Habitat Retention, Critical Riffle Analysis, River2D, PHABSIM). Thompson (1972) is a field-based procedure for identifying stream flows needed for passage of migrating salmonids through critical riffles (Bjornn and Reiser 1991; Reiser et al. 2006). The overall concept is based on information from "Determining Stream Flows for Fish Life" presented by Ken Thompson at the *Instream Flow Requirements Workshop* on March 15-16, 1972 (Thompson 1972). Based upon the Thompson method, the Department recently developed a CRA Standard Operating Procedure (SOP; CDFW 2012) to identify stream flows needed for salmonid passage through critical riffles sites so that habitat connectivity is maintained in California streams and rivers. The Department draws from the Thompson methodology in procedural scope, with the application of regional species-and life stage-specific criteria relevant to California salmonids (CDFW 2012). Using the Thompson methodology, a transect across the shallowest course from bank to bank in a stream channel is deemed passable when a combination of minimum stream flow depths and wetted widths are greater than conditions specified by two evaluation parameters: the percentage of the total transect width and the contiguous percentage of the transect width meeting a predetermined life stage-specific depth criteria (Thompson 1972).

The purpose of the Thompson methodology and associated transect width criteria is to provide flow conditions for physical movement of salmonids through critical riffle locations. While Thompson 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 Oregon Department of Fish and Wildlife (ODFW) including several hundred of the most important salmonid streams in Oregon. Thompson caveats that the purpose of the methodology is to assess passage conditions at riffles and not to determine flows generally believed necessary to induce migration (Thompson 1972).

Critical Riffle Passage Assessment Criteria

River2D was used to estimate depths and widths of flow within each riffle site. In the riffle sites only adult SRCS body depth was considered when analyzing passage conditions. The same adult SRCS body depth criteria of 0.9 feet used to evaluate the Lahar Site was also used to evaluate the riffles. The assessment considers the percentage based width criteria used in the CRA method (CDFW 2012). Excessive velocities were not assumed present in the riffles during the spring-run. This assumption was confirmed by checking velocities predicted by the River2D model runs for each riffle. The riffle sites were all low gradient and did not present jumping barriers to SRCS.

Critical Riffle Analysis using River2D Hydraulic Model

The critical riffle analysis is an instream flow method that identifies flows necessary for salmon and trout passage and overall habitat connectivity. The Department protocol draws from current methods such as Thompson (1972) to assess salmon and trout passage through critical riffles. Modifications were made by the Department to the Thompson (1972) methodology with the application of regional species and life stage specific information relevant to California salmonids and by employing 2D hydraulic simulation, River2D. For the Butte Creek study, the Department's approach was to locate critical riffles, identify the shallowest course from bank to bank (Figure 13), and measure the water depth profile of the shallowest course at flows ideally ranging from 20 to 80 percent exceedance.

In this study, a topographic model was developed for each critical riffle selected. Critical riffles were surveyed from the top of left bank to the top of right bank and from the upstream to the downstream extent including the shallowest course from bank to bank. A stage/discharge rating curve was developed for each site to simulate flows within the range of 20 to 80 percent exceedance. Estimates of depth and width along the shallowest course from each River2D simulation were compared to target fish species passage criteria for minimum water depth and minimum proportion of riffle width available for fish passage.

Figure 13. Critical riffle analysis transect following shallowest course from bank to bank at Riffle 97 at approximately 402 cfs.

After flows are simulated over a range of appropriate discharges (i.e., 20 – 80 percent exceedance flow range) in River2D, 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).

SITE SELECTION

Although the Lahar site is believed to be the site most limiting to passage, it is a unique formation and does not necessarily represent the remainder of the stream channel. The remainder of the study reach was surveyed for potential impediments to SRCS upstream migration.

Passage Limiting Riffle Survey and Riffle Assessment

A riffle survey was conducted for the purpose of identifying passage limiting areas for adult SRCS migration. The survey was conducted from Parrot-Phelan Diversion to Western Siphon, over three successive days from November 5 through 7, 2012. The study reach was effectively divided into three sub-reaches based on the progress made each day: day one from Parrot-Phelan to Highway 99 (sub-reach 1), day two from Highway 99 to two kilometers downstream of Durham-Dayton Highway (sub-reach 2), and day three from two kilometers downstream of Durham-Dayton Highway to Western Siphon (sub-reach 3).

Criteria were developed to evaluate riffles during the survey to ensure that the most critical were evaluated. Riffle selection criteria included, depth at the shallowest point of the thalweg and wetted width measured perpendicular to flow across the point of the shallowest thalweg depth. The criteria assumes thalweg depth decreases with receding flow levels and that riffles with larger wetted widths require incrementally greater amounts of flow to increase depth for passage, as compared to riffles with narrower wetted widths.

The location of the critical riffle was recorded with a Global Positioning System (GPS) unit, the thalweg depth along the shallowest course was measured with a wading rod, and the wetted width was measured with an electronic distance meter (Figure 14). Since the surveys were completed over multiple days, discharge measurements were taken each day, maintaining comparability between the riffles with respect to thalweg depth (Table 3).

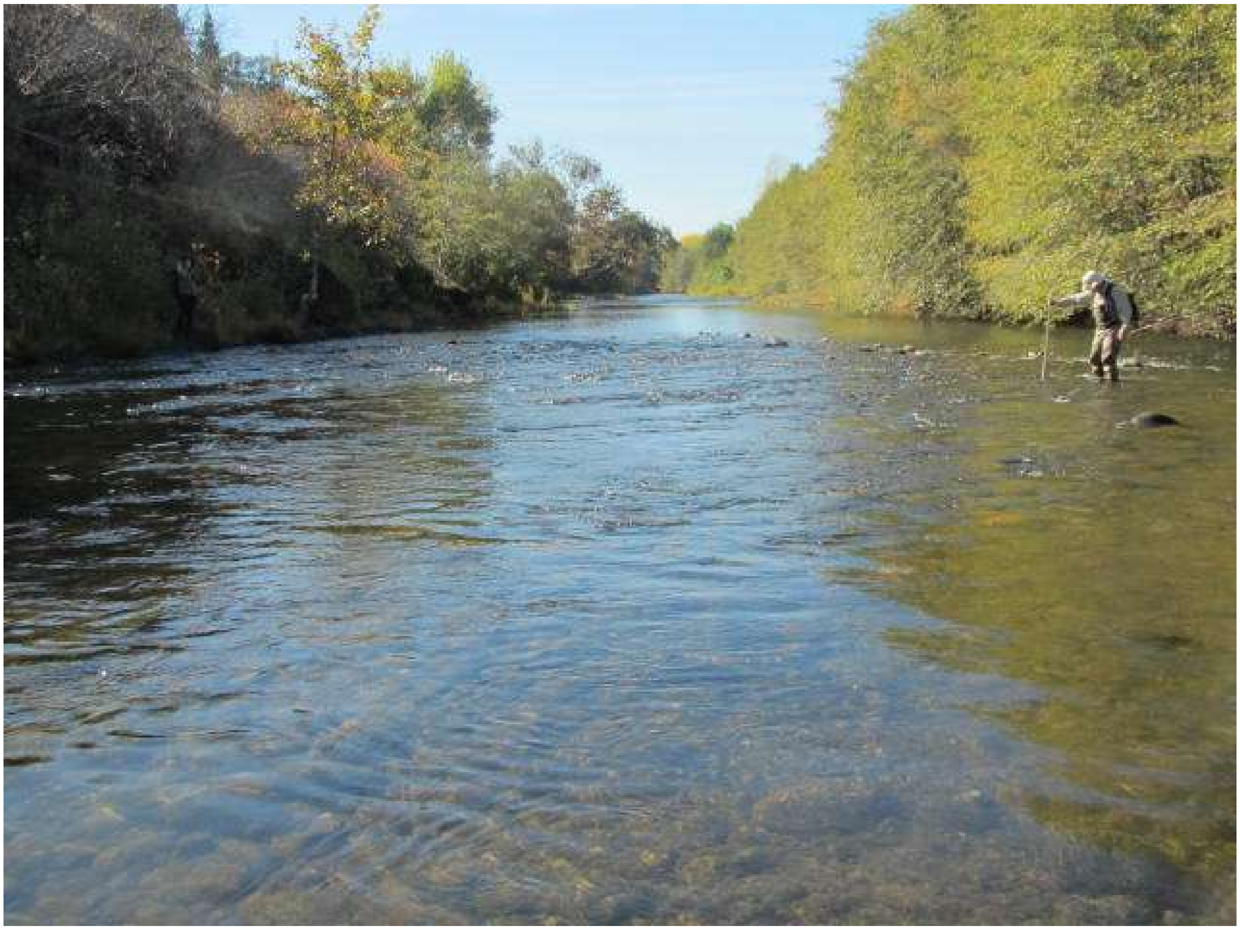


Figure 14. Walking across a riffle crest searching for the shallowest thalweg depth.

Table 3. Passage Limiting Riffle Survey Schedule.

Day	Sub-reach #	Riffles Surveyed	Sub-reach Description	Sub-Reach Discharge (cfs)
November 5, 2012	1	1 – 36	Parrot-Phelan to HWY 99	71.8
November 6, 2012	2	37 – 89	HWY 99 to Durham-Dayton HWY + 2 km	72.5
November 7, 2012	3	90 - 112	Durham-Dayton HWY + 2 km to Western Siphon	64.0

Discharge measured in sub-reaches 1 and 2 on the first two days of the survey were within 5% of one another. The flow in sub-reach 3 on the third day of the survey was lower by about 8 cfs from the previous two days, a difference of approximately 11-12%. River2D model results from Site 95, in sub-reach 3, were used to confirm that the expected change in water surface level would not affect ranking of the riffles together that were surveyed on different days. The estimated difference in WSEL between flows modelled at 60 and 70 cfs was found to be two hundredths of a foot or 0.02 feet. That difference is less than a half of a tenth of a foot and is not expected to have had any impact on the ranking of the riffles used in site selection.

One hundred and twelve riffles were identified and inventoried during the three day survey. During the survey at each riffle site, staff measured along the shallowest course and recorded the depth and channel width at the deepest point. The riffles were ranked by width and depth, widest to narrowest, and shallowest to deepest, respectively. Widths of all 112 riffles surveyed ranged from 351 feet to 32 feet and depths from 0.4 feet to 2 feet. The fifteen widest and shallowest riffles are presented in Table 4. Ranking by width was relatively simple when compared to ranking by thalweg depth. Riffle width was found to be unique for each riffle, where as many riffle thalwegs were found to have equal depths. In the case where the widths were equal, for example riffles 12 and 51, rank was determined by thalweg depth. Conversely, many of the riffles were found to have similar thalweg depths. Width was used to rank riffles with equal depth.

Riffles 95 and 97 located upstream of Midway Road (Figure 1) were found to be both the widest and shallowest riffles of the 112 surveyed. Riffle 96, located in between riffles 95 and 97, was also found to be one the shallowest and widest riffles surveyed. Digital images taken during the survey of riffles 95, 96, and 97, are shown in Figures 15, 16, and 17, respectively.

Table 4. Riffle Survey Results.

Riffles Ranked by Depth			Riffles Ranked by Width		
Rank	Riffle #	**Depth (ft)**	Rank	Riffle #	**Width (ft)**
1	**97**	0.4	1	**95**	351
2	**95**	0.5	2	**97**	182
3	65	0.6	3	16	149
4	62	0.6	4	51	146
5	74	0.6	5	90	142
6	66	0.7	6	65	137
7	**96**	0.7	7	68	134
8	12	0.7	8	66	129
9	51	0.8	9	73	129
10	90	0.8	10	**96**	128
11	73	0.8	11	12	127
12	71	0.8	12	14	123
13	6	0.8	13	62	123
14	7	0.8	14	91	122
15	56	0.8	15	11	116

*Selected riffles are bolded.

Figure 15. Riffle 95 at 64 cfs, view facing upstream.

Figure 16. Riffle 96 at 64 cfs, view facing upstream.

Figure 17. Riffle 97 at 64 cfs, view facing downstream towards Midway Road.

Critical Riffle Site Selection

Riffles 95 and 97 were selected as sites to evaluate passage limiting flow conditions in the alluvial valley section downstream of the Lahar formation. These two riffles were chosen because they were the two most passage limiting sites based on field survey rankings. Riffle 96 was also evaluated because the topography of the riffle was below the upstream hydraulic boundary used to complete the River2D model of Riffle 97. Based on the results of the riffle survey, Riffle 96 was more typical of the other shallow riffles located in the creek. The sites selected were located near a major roadway, Midway Road, making egress quick and safe at varying flow levels. The sites were accessed via the existing levee system and did not require access through private property.

All three riffles selected are located a short distance upstream of the diversion operated by Gorrill Ranch (Gorrill Diversion). Current diversion operations by Gorrill Ranch include placing flashboards into Butte Creek for the purpose of supplying the Ranch’s gravity fed diversion; the flashboards are typically placed in the Creek each year after April 15th. Once the flashboards are in place, the creek pools behind the Gorrill Diversion; this pooling inundates the riffles and alleviates any fish passage issues in the area (Figure 18). The flashboards are removed in the fall, typically sometime between October 15th and November 1st. Figure 19 shows the riffles in relation to Gorrill Diversion once the flashboards are removed.

The riffles are inundated from mid-April through mid-October; however, SRCS start migrating into Butte Creek sometime in February continuing through April. This means the shallow riffles pose potential passage problems during the spring-run when the flashboards are not in place. The timing of the flashboards installation is not subject to any prior agreement and subsequently is at the discretion of Gorrill Ranch. In spring of 2013, when data was collected at the riffles, the flashboards were not installed until the last week of April.

Riffles 95 and 97 are very long longitudinal riffles with large cobble bar sections that remain shallow at higher flow levels (Figures 15 and 17). These bars segregate flows through the riffles creating a quasi-braided system. To evaluate the changing flow network through these quasi-braided systems, over a range of flows, River2D models were developed for the riffles. The 2D model for riffle 97 also includes riffle 96 because there was no suitable boundary condition location between the two riffles. Riffle 96 is the most representative riffle of the three selected, as compared to other critical riffles in Butte Creek, and the results from riffle 96 were used to consider conditions expected to be symptomatic of the rest of the study reach.

Figure 18. Critical Riffles 95, 96, and 97 upstream of Midway Road with the flashboards in-place at Gorrill Diversion.

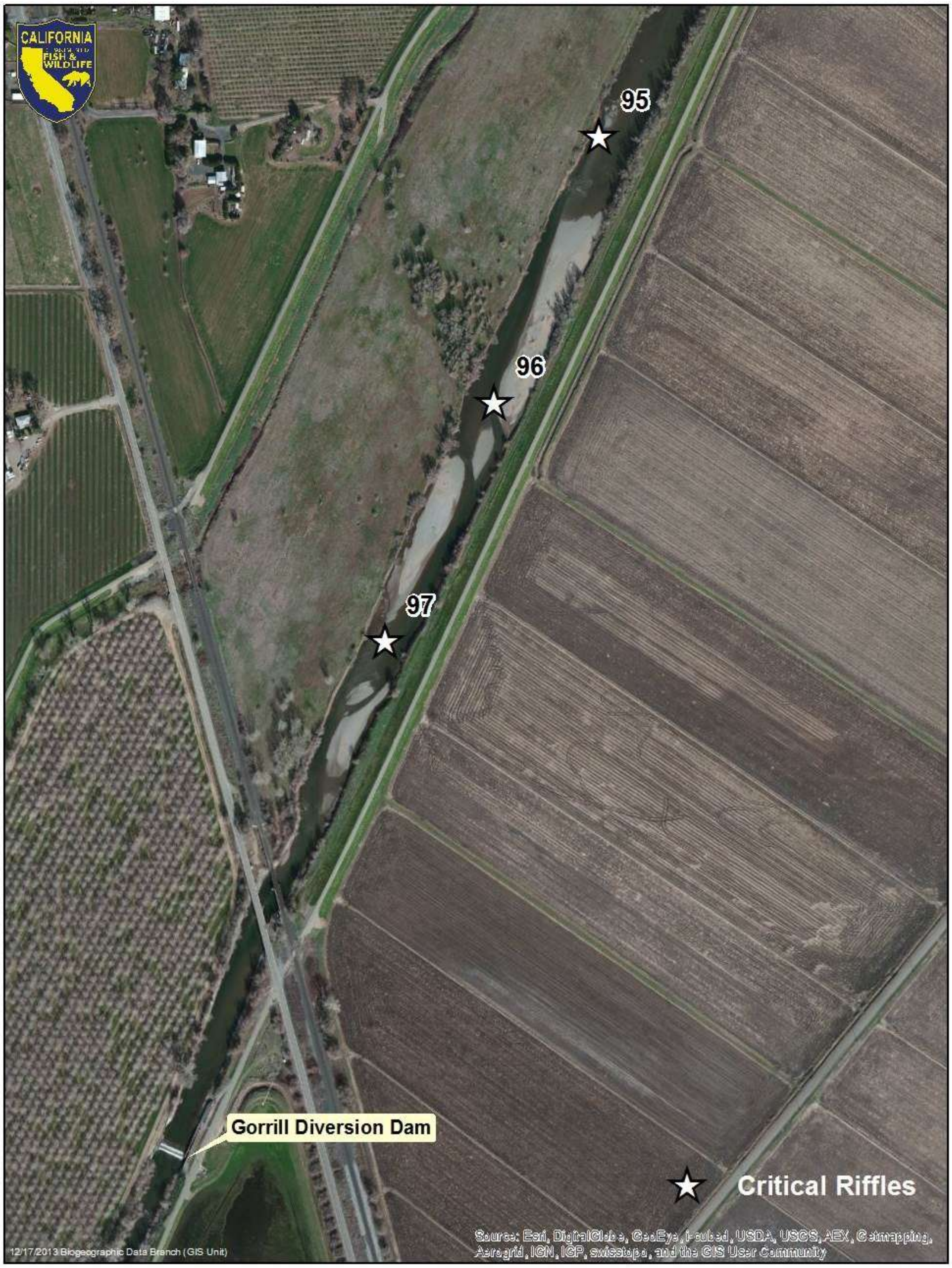


Figure 19. Critical Riffles 95, 96, and 97 upstream of Midway Road with the flashboards removed from Gorrill Diversion.

DATA COLLECTION

Two types of streambed conditions were sampled for the study: 1) eroded bedrock, the Lahar formation, consisting of a braided network of flow paths, and 2) the alluvial riffles, sites upstream of Midway Road. Steps involved in data collection necessary to prepare the 2D models for the Lahar formation and riffle sites included:

1) Established site boundaries and survey controls;
2) Developed stage/discharge rating curves for the site boundaries;
3) Established temporary stream stage monitoring station downstream of the Lahar Site using a pressure transducer;
4) Collected topography data used to develop terrain models; and
5) For the Lahar site terrain model, explicitly mapped breakline features, such as individual channels through the Lahar formation and tops of ridges between channels.

The Lahar formation presented challenges to developing a 2D hydraulic model. The complexity of the site topography required a higher point density per square meter be collected as compared with the alluvial riffles sites. Differences between measured and simulated hydraulic conditions were expected to be less than optimal, despite a high density of topographic data, due to the topographic complexity. Topographic complexity and the presence of overhanging vegetation along margin areas combined to make surveying those areas difficult and time consuming.

Several different topographic survey methods were necessary to collect the points for the terrain model as follows: terrestrial Light Detection and Ranging (LIDAR), survey grade Real Time Kinematic (RTK) Global Positioning System (GPS), and total station topographic survey. The majority of the site points were collected using LIDAR. LIDAR can collect many points quickly, but is limited by the presence of canopy cover and submerged terrain; it cannot penetrate through water. RTK GPS was used to survey the explicit breakline features and submerged areas (Figure 20). RTK GPS is also limited by canopy cover. The topography along the margins, limited by canopy cover from LIDAR and RTK GPS, was surveyed using total station. The Lahar site survey points and area are shown graphically in Figure 21. The red dots in the figure indicate where the LIDAR equipment was placed to survey the exposed bedrock.


Figure 20. RTK GPS survey of Lahar Site.

The topography of the two riffle sites was less complex than the Lahar site, therefore the density of points required per meter to adequately describe the surface in the terrain models was lower. LIDAR was not required; the majority of points were captured using RTK GPS. Total station was still used for the areas obscured by canopy cover. Unlike the Lahar site, the riffle sites contained deeper areas that, at the time of the surveys, were flowing too strong to safely wade. As a result, USFWS employed their boat-mounted acoustic doppler current profiler (ADCP; Figure 22) in these areas.

Figure 21. Data points collected with RTK GPS and total station (green dots) and control points used for terrestrial LIDAR (red points) for the Lahar site.

Figure 22. Boat-mounted ADCP.

Site Boundaries and Survey Controls

The three 2D study sites were established in December 2012 (i.e., the Lahar, and two riffle sites). Study site boundaries were placed upstream and downstream of the passage assessment areas. The downstream and upstream transects were located for optimal physical habitat simulation model (PHABSIM) performance where the channel section properties were as close to the following as possible:

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

A 1D 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 values are adjusted in the 2D model until the water surface elevation at the top of the site matches the water surface elevation predicted by PHABSIM. Transect pins (headpins and tailpins) were marked on each river bank above the 700 cfs water surface level using rebar driven into the ground and/or lag bolts placed in tree trunks. Survey flagging was used to mark the locations of each pin.

Vertical benchmarks, which consisted of lag bolts driven into the base of trees, were established at each site to serve as the relative vertical elevations to which all elevations (streambed and water surface) were referenced. Horizontal benchmarks, which consisted of fence posts driven into the ground, were also established at each site to serve as the horizontal locations to which all horizontal locations (northings and eastings) were referenced. The precise northing and easting coordinates and vertical elevations of two horizontal benchmarks were established for each site using survey-grade RTK GPS. The elevations of these benchmarks were tied into the vertical benchmarks on our sites using differential leveling.

Stage/Discharge Hydraulic Data Collection at 2D Sites

Hydraulic data for the three 2D models were collected in December 2012 through July 2013. Flows for calibrating the 2D models were measured onsite, except for the December 2012 data collected at the Lahar formation. Flows for that data were calculated by subtracting the Parrott Phelan diversion from the flow from the USGS gage Station 11390000. There were no other diversions at that time between the USGS gage and the Lahar.

Water surface elevations at the three sites (i.e., Lahar, Site 95, and Site 96/97) were collected at five sample events in 2012 and 2013 (Table 5). Discharge measurements for the three sites were measured onsite (Table 5) except for the December 2012 data collected at the Lahar. Depth and velocity measurements on the transects were collected at the Lahar formation at 232 cfs, at Site 95 at 323 cfs, and at Site 96/97 at 350 cfs.

Table 5. Summary of sample dates and corresponding flows when water surface elevations were measured for calibration of Butte Creek River2D models.

Site	**Date**	**Flow (cfs)**
Lahar	12/10/2012	417
	2/22/2013	232
	4/18/2013	149
	5/10/2013	114
	7/9/2013	22.6
95	12/12/2012	323
	1/23/2013	238
	3/19/2013	277
	3/21/2013	635
	4/18/2013	153
96/97	12/12/2012	350
	1/23/2013	238
	3/19/2013	277
	3/21/2013	635
	4/18/2013	153

Water surface elevations were measured along both banks and in the middle of each transect. The water surface elevations at each transect were derived by averaging the values, except when the difference in elevation exceeded 0.1 foot (0.031 m), in which case the water surface elevation for the side of the river that was considered most representative was used. Starting at the water's edge, water depths, and velocities were measured at set intervals using a wading rod and Marsh-McBirney model 2000 velocity meter. The stations for the dry ground elevation measurements were measured using a measuring tape. All substrate and cover data on the transects were assessed by one observer and were made based on the visually-estimated average of multiple grains.

The stage of zero flow is the WSEL that would be present at a flow of zero. For sites where there was a gradual gradient change in the vicinity of the downstream transect, there could be a point in the thalweg a short way downstream of the site that was higher than that measured at the downstream transect thalweg simply due to natural variation in topography (Figure 23). The stage of zero 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 stage of zero flow is needed to accurately calibrate the WSELs on the downstream transect, the stage of zero flow in the thalweg downstream of the downstream transect was surveyed using differential leveling. If the true stage of zero flow was not measured as described above, the default stage of zero flow would be the thalweg elevation at the transect.

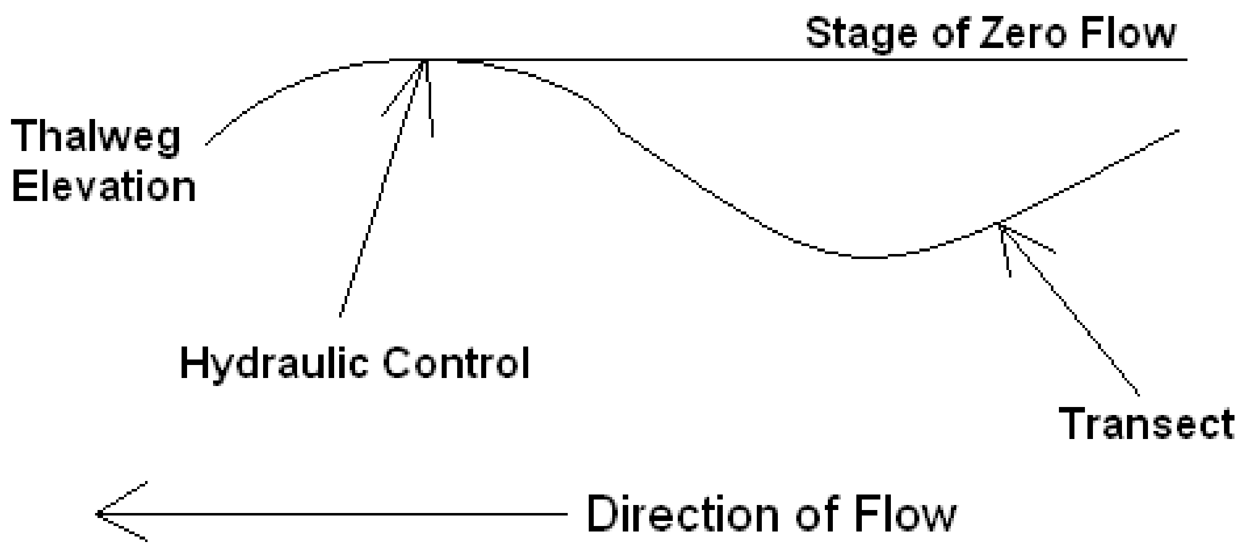


Figure 23. Stage of zero flow diagram.

Lahar Site Pressure Transducer

For the Lahar, a Solinst Model 3001 Levelogger Edge pressure transducer was placed at the downstream site boundary to refine the downstream boundary condition, as well as to collect water temperature data, and serve as a gage to determine flows at the Lahar formation. A Solinst Barologger Edge was installed on high ground next to the Lahar to correct the pressure transducer data for atmospheric pressure. The pressure transducer was placed in a stilling well consisting of a 1 ½ inch diameter PVC pipe with ¼ inch holes drilled in the lower foot of the pipe to allow water to equilibrate in the pipe. The pipe was mounted at an angle and attached to two metal T-fence posts to ensure the pressure transducer elevation would not change during data collection (Figure 24). The pressure transducer was attached to one end of a stainless steel cable with loops at each end; the loop at the other end of the cable went through a padlock inserted through a hole drilled through the pipe. The length of cable used resulted in the pressure transducer being located an inch from the lower end of the pipe. WSELs measured at the pressure transducer location were used to calculate the elevation of the pressure transducer and, together with measured discharges, to develop a rating curve for the gage.

Figure 24. Pressure transducer mounted in PVC casing downstream of Lahar site.

VAKI Riverwatcher

A VAKI Riverwatcher (VAKI) was installed in the Durham Mutual Fish ladder in January, 2014, by staff from CDFW, Figure 25. Counts of fish passing through the VAKI were collected over the last two critically dry years, 2014 and 2015.

Figure 25. VAKI Riverwatcher installed in the fish ladder adjoining Durham Mutual Diversion Dam.

The VAKI device records fish movement through the ladder; the data is used to estimate the number of SRCS that pass through the fish ladder in both the upstream and downstream direction. The number SRCS passing by month for 2015 and 2014 is summarized in Table 6.

Table 6. VAKI Riverwatcher passage counts.

Month	2015 Number of Fish	2014 Number of Fish
February	247	289
March	1218	2295
April	338	1939
May	149	154
June	-12	57
Total	1939	4734

Terrain Model Data Collection

Data collection for the three 2D sites began in December 2012 and was completed in April 2013 (Table 5). The data collected on the upstream and downstream transect included: WSELs measured to the nearest 0.01 foot (0.003 m) at a minimum of three significantly different stream discharges using standard surveying techniques (differential leveling); wetted streambed elevations determined by subtracting the measured depth from the surveyed WSEL at a measured flow; dry ground elevations to points above bank-full discharge surveyed to the nearest 0.1 foot (0.031 m); mean water column velocities measured at a mid to- high-range flow at the points where bed elevations were taken; and substrate and cover classification (Tables 7 and 8) at these same locations and also where dry ground elevations were surveyed. In between these transects, bed elevation, horizontal location (i.e., northing and easting, relative to horizontal benchmarks), substrate, and cover were collected. These parameters were collected at enough points to characterize the bed topography, substrate, and cover of the site.

Table 7. Substrate codes, descriptors and particle sizes used for Butte Creek River2D 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 8. Cover coding system used for Butte Creek River2D 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

Bed topography data were collected between the upstream and downstream transects by obtaining the bed elevation and horizontal location of individual points with a total station or survey-grade RTK GPS, while the cover and substrate were assessed using the same technique used for the transects. Topography data, including substrate and cover data, 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. Bed topography data for the deepest and faster portions of Sites 95 and 96/97 were collected with a combination of an ADCP and a survey-grade RTK GPS unit. For each traverse with the ADCP, the RTK GPS recorded the horizontal location and WSEL at the starting and ending location. The WSEL of each ADCP traverse was then used together with the depths from the ACDP to determine the bed elevation of each point along the traverse. Substrate and cover polygons were mapped for the areas sampled with the ADCP; the vertices of these polygons were recorded with the survey-grade RTK GPS unit. Additional topography data for the dry bedrock portions of the Lahar were collected using a Maptek model 4400 terrestrial LIDAR unit. Based on observations of the bedrock area, all terrestrial LIDAR data points were assigned a substrate code of nine and a cover code of one.

To validate the depths predicted by the 2D model, depth measurements were collected using a wading rod equipped with a Marsh-McBirney model 2000 velocity meter. The horizontal locations and bed elevations were recorded by taking a measurement with the survey-grade RTK GPS at each point where depth was measured. A minimum of 50 representative points were measured per site.

For the Lahar, the highest densities of bed topography points were collected on the bedrock formation. The highest densities of bed topography data points in Sites 95 and 96/97 were collected within the riffle channels with additional emphasis near the riffle crests. Validation depths were collected at flows of 232 cfs for the Lahar, at 238 and 323 cfs for Site 95, and at 350 and 421 cfs for Site 96/97.

The number and density of data points collected on each of the two transects, and between transects, for each 2D model study are presented in Table 9. Table 9 also outlines the overall density of data points collected for each model. The Lahar had the highest density of points collected with 7.2 points per square meter collected.

Table 9. Number and density of data points collected for each River2D model study site.

Site	Number of Points		Density of Points (points/m^2)
	Points on Transects	Points Between Transects	
Lahar Site	114	95,308	7.2
Site 95	125	4,161	0.28
Site 96/97	81	7,725	0.30

Two-Dimensional Hydraulic Model Construction and Calibration

Model construction included seven phases as follows:

1) Development of stage/discharge relationship boundary conditions for the 2D model using PHABSIM;
2) Development of digital terrain models for each site, the Lahar formation model explicitly included the breaklines delineated in the field; and
3) Built, best-fit computational mesh for each site terrain model;
4) Calibrated 2D models fitting upstream discharge with downstream water surface elevation;
5) Depth validation;
6) Performed hydraulic simulations at numerous flows; and
7) Passage transect delineation (riffle sites only).

PHABSIM WSEL Calibration

The upstream and downstream transects were modeled with the PHABSIM component of IFIM to provide WSELs as an input to the River2D hydraulic and habitat model (Steffler and Blackburn 2002) used in this study. By calibrating the upstream and downstream transects with PHABSIM using the collected calibration WSELs, WSELs could be predicted for the transects at the various simulation flows being modeled with River2D. River2D models were calibrated using the highest simulation flow. The highest simulation WSELs predicted by PHABSIM for the upstream and downstream transects were used for the initial upstream boundary condition (in addition to flow) and the downstream boundary condition. The PHABSIM-predicted WSEL for the upstream transect at the highest simulation flow was used to ascertain calibration of the River2D model at the highest simulation flow. After the River2D model was calibrated at the highest simulation flow, the WSELs predicted by PHABSIM for the downstream transect for each simulation flow were used as an input for the downstream boundary condition for River2D model production files 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 and cover ranges/values was created to determine the substrate and cover for each vertical/cell (e.g., if the substrate size class was 2-4 inches (5 to 10 cm) on a transect from station 50 to 70, all of the verticals with station values between 50 and 70 were given a substrate coding of 2.4). Dry bed elevation data in field notebooks were entered into the spreadsheet to extend the bed profile up the banks above the WSEL of the highest flow to be modeled. An ASCII file produced from the spreadsheet was run through the FLOMANN program[8] to get the PHABSIM input file and then translated into RHABSIM[9] files.

A separate PHABSIM file was constructed for each study site. All of the measured WSELs were checked to make sure that water was not flowing uphill. The slope for each transect was computed at each measured flow as the difference in WSELs between the two transects divided by the distance between the two. The slope used for each transect was calculated by averaging the slopes computed for each flow. A total of four or five WSEL sets at low, medium, and high flows were used. If WSELs were available for several closely spaced flows, the WSEL that corresponded with the velocity set or the WSEL collected at the lowest flow was used in the PHABSIM data files. Calibration flows in the data files were the flows measured on site, except for the December 2012 data collected at the Lahar which was calculated by subtracting the Parrott Phelan diversion from the flow from the USGS gage Station 11390000. There were no other diversions at that time between the USGS gage and the Lahar formation.

---

[8] Written by Andy Hamilton, U.S. Fish and Wildlife Service, 1998.

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

The stage of zero flow (SZF), an important parameter used in calibrating the stage discharge relationship, was determined for each transect and entered into PHABSIM. In habitat types without backwater effects (e.g., riffles and runs), this value generally represents the lowest point in the streambed across a transect. However, if a transect directly upstream contains a lower bed elevation than the adjacent downstream transect, the SZF for the downstream transect applies to both. In some cases, data collected in between the transects showed a higher thalweg elevation than either transect; in these cases the higher thalweg elevation was used as the SZF for the upstream transect.

The first step in the calibration procedure is to determine the best approach for WSEL simulation. Initially, the *IFG4* hydraulic model (Milhous et al. 1989) was run on each dataset to compare predicted and measured WSELs. This model produces a stage-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; *MANSQ*, which operates under the assumption that the condition of the channel and the nature of the streambed controls WSELs and *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,* the most versatile of these models, is considered to have worked well if the following criteria are met: 1) the beta value (a measure of the change in channel roughness with changes in streamflow) is between 2.0 and 4.5; 2) the mean error in calculated versus given discharges is less than 10%; 3) there is no more than a 25% difference for any calculated versus given discharge; and 4) there is no more than a 0.1 foot (0.031 m) difference between measured and simulated WSELs[10]. *MANSQ* is considered to have worked well if the second through fourth of the above criteria are met, and if the beta value parameter used by *MANSQ* is within the range of 0 to 0.5. The first *IFG4* criterion is not applicable to *MANSQ*.

WSP is considered to have worked well if the following criteria are met: 1) the Manning's n value used falls within the range of 0.04 - 0.07; 2) there is a negative log-log relationship between the reach multiplier[11] and flow; and 3) there is no more than a 0.1 foot (0.031 m) difference between measured and simulated WSELs. The first three *IFG4* criteria are not applicable to *WSP*.

Velocity Adjustment Factors (VAFs)[12] were examined for all of the simulated flows as a potential indicator of problems with the stage-discharge relationship. The acceptable range of VAF values is 0.2 to 5.0 and the expected pattern for VAFs is a monotonic increase with an increase in flows USFWS (1994).

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

RIVER2D Model Construction

After completing the PHABSIM calibration process to arrive at the simulation WSELs for use as inputs to the RIVER2D model, construction of the RIVER2D model using the collected bed topography data can begin. The total station, RTK GPS, ADCP and terrestrial LIDAR data, and the PHABSIM transect data were combined in a spreadsheet to create input files (bed and substrate) for the 2D modeling program. An artificial extension one channel-width-long was added upstream of the topography data collected, upstream of the study site, to enable the flow to be distributed by the model when it reached the study area. This extension minimized boundary conditions influencing the flow distribution at the upstream transect and within the study site. For Site 95, a downstream boundary extension was also added to the model, using the upstream transect of Site 96/97 as the downstream end of the downstream extension. The downstream extension was needed for this site to improve model performance due to effects of boundary conditions at the downstream end of Site 95.

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 and cover codes for that point and the corresponding bed roughness values in Table 10, with the bed roughness value for each point computed as the sum of the substrate bed roughness value and the cover bed roughness value for the point. The resulting initial bed roughness value for each point was therefore a combined matrix of the substrate and cover roughness values. The bed roughness values for substrate in Table 10 were computed as five times the average particle size[13]. The bed roughness height values for cover in Table 10 were computed as five times the average cover size, where the cover size was measured on the Sacramento River on a representative sample of cover elements of each cover type. The bed files were exported from the spreadsheet as ASCII files. For the Lahar site, the breaklines delineated in the field were specified in the initial bed file.

Table 10. Initial bed roughness height values used for Butte Creek River2D 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

[13] 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).

Substrate Code	Bed Roughness (m)	Cover Code	Bed Roughness (m)
3.5	0.5	5	1.93
4.6	0.65	5.7	2.59
6.8	0.9	7	0.28
8	1.25	8	2.97
9	0.05, 0.76, 2[14]	9	0.29
10	1.4	9.7	0.57
		10	3.05

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[15] 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 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.

An additional utility program, R2D_MESH (Waddle and Steffler 2002), was used to define the inflow and outflow boundaries and create the finite element computational mesh for the RIVER2D model. R2D_MESH uses the final bed file as an input. The first stage in creating the computational mesh was to define mesh breaklines[16] which coincided with the final bed file breaklines. Additional mesh breaklines were then added between the initial mesh breaklines, and then additional nodes were added as needed to improve the fit between the mesh and the final bed file and to improve the quality of the mesh, as measured by the Quality Index (QI) value. An ideal mesh (all equilateral triangles) would have a QI of 1.0. A QI value of at least 0.2 is considered acceptable (Waddle and Steffler 2002). The QI is a measure of how much the least equilateral

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

[15] 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).

[16] 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).

mesh element deviates from an equilateral triangle. The final step with the R2D_MESH software was to generate the computational mesh (cdg) file.

RIVER2D Model Calibration

Once a River2D model has been constructed, calibration is required to determine that the model is reliably simulating the flow-WSEL relationship 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 heights of the computational mesh elements to compute the depths, velocities, and WSELs throughout each site. The basis for the current form of River2D is given in Ghanem et al. (1995). The computational mesh was run to steady state at the highest flow simulated 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. Calibration was considered to have been achieved when the WSELs predicted by River2D at the upstream transect were within 0.1 foot (0.031 m) of the WSEL predicted by PHABSIM. In cases where the simulated WSELs at the highest simulation flow varied across the channel by more than 0.1 foot (0.031 m), the highest measured flow within the range of simulated flows for River2D calibration was used. The bed roughness heights of the computational mesh elements were modified by multiplying them by a constant bed roughness height multiplier (BR Mult) until the WSELs predicted by River2D at the upstream end of the site matched the WSELs predicted by PHABSIM at the top transect. The minimum groundwater depth was adjusted to a value of 0.05 m to increase the stability of the model. The values of all other River2D hydraulic parameters were left at their default values (upwinding coefficient = 0.5, groundwater transmissivity = 0.1, groundwater storativity = 1, and eddy viscosity parameters ε_1 = 0.01, ε_2 = 0.5 and ε_3 = 0.1).

The upstream transect was calibrated using the methods described above, varying the BR Mult until the simulated WSEL at the upstream transect matched the measured WSEL at the upstream transect. A stable solution generally has a solution change (Sol Δ) of less than 0.00001 and a net flow (Net Q) of less than 1% (Steffler and Blackburn 2002). WSELs predicted by the 2D model are expected to be within 0.1 foot (0.031 m) of the WSEL measured at the upstream transects[17].

Depth averaging models like River2D are most readily applied to subcritical stream conditions, maximum Froude Number (Max F) of less than 1.0 (<1.0)[18]. The parameter Max F is often used as a calibration tool to verify the simulated flow regime was subcritical and the water surface at any given point was stable. As stream gradients increase and/or large substrates are introduced to the stream bed, flow conditions

[17] We have selected this standard because it is a standard used for PHABSIM USFWS (2000).

[18] This criterion is based on the assumption that flow in low gradient streams is usually subcritical (laminar), where the Froude number is less than 1.0.

transition from Laminar (subcritical) to transient to turbulent with vertical mixing (supercritical). The Froude Number (FN) is greater than 1.0 (>1.0) in supercritical conditions. Depths are more variable at any given point in supercritical conditions. River2D is capable of predicting depths in subcritical, supercritical, and transient conditions, but because of the variable water surface, predicted depths are less reliable than predictions made in subcritical areas, Max F <1.0.

RIVER2D Model Depth Validation

Depth validation is the final step in the preparation of the hydraulic models for use in passage simulation. Depths predicted by River2D were compared with measured depths along the upstream and downstream control transects and at 50 randomly selected sites within the modelled area to determine the accuracy of the model's predictions of depths.

RIVER2D Model Simulation Flow Runs

After the River2D models are calibrated, the flow and downstream WSEL in the calibrated cdg file are 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 River2D model was run at simulated flows between 20 cfs and 630 cfs for all three sites. 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%.

RIVER2D Passage Transect Delineation

River2D was used to develop the flow versus width and depth relationships needed to assess passage in the riffles using the CRA method (CDFW 2012). The shallowest course from bank to bank was recorded in the field using a RTK GPS (Figures 26, 27, and 28) for riffles 95, 96, and 97, respectively. The surveyed points were converted to a csv file of x, y locations. The csv file was used to extract depth values from the River2D model’s various flows.

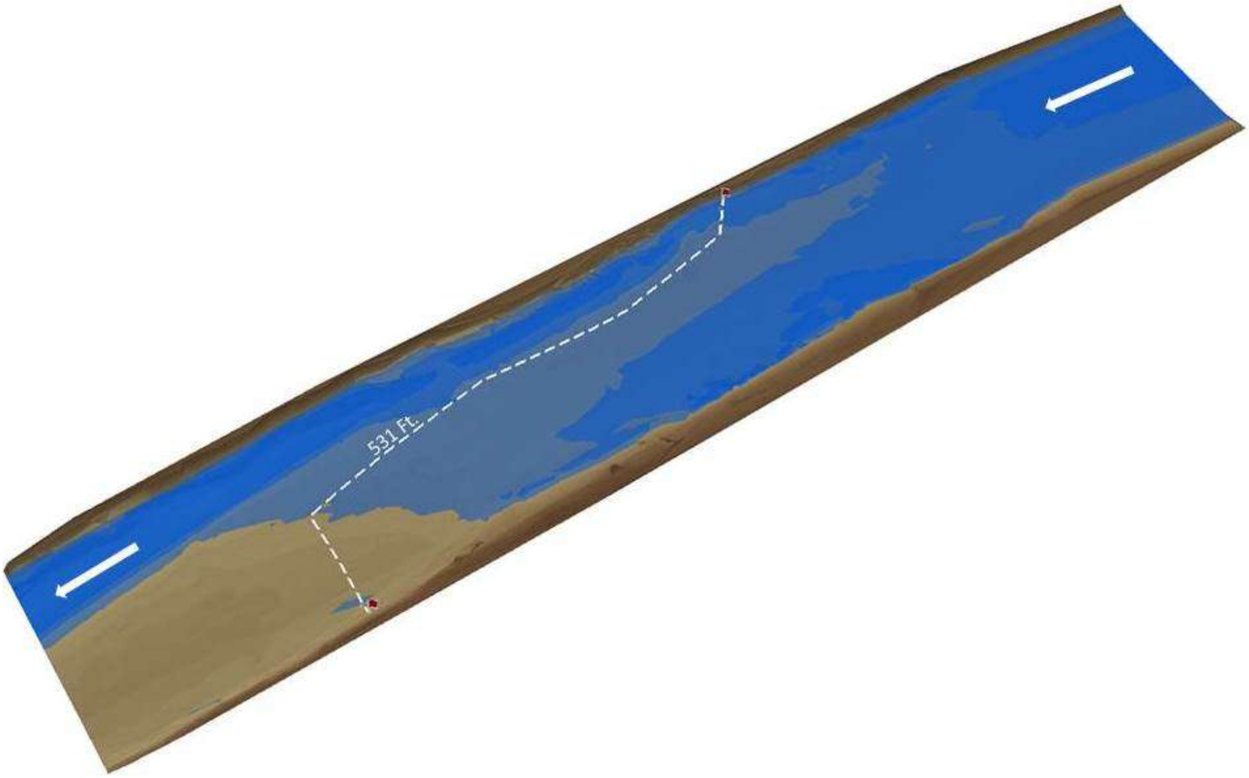


Figure 26. Riffle 95 shallowest course bank to bank.

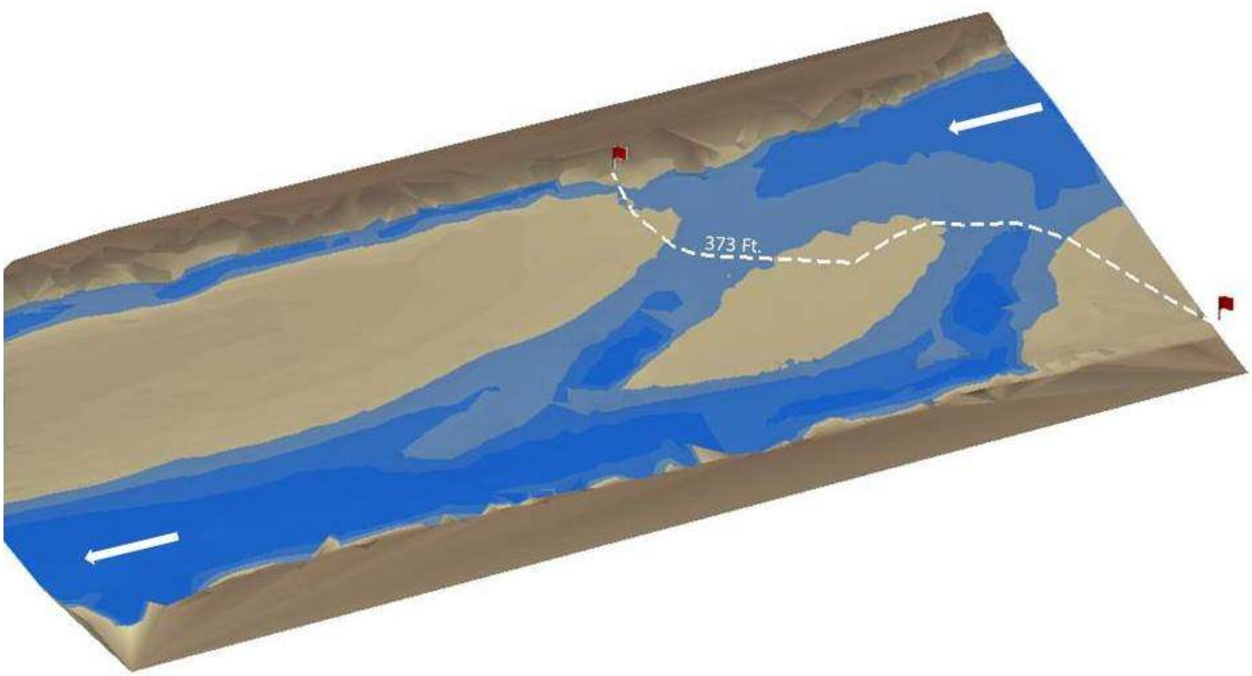


Figure 27. Riffle 96 shallowest course bank to bank.

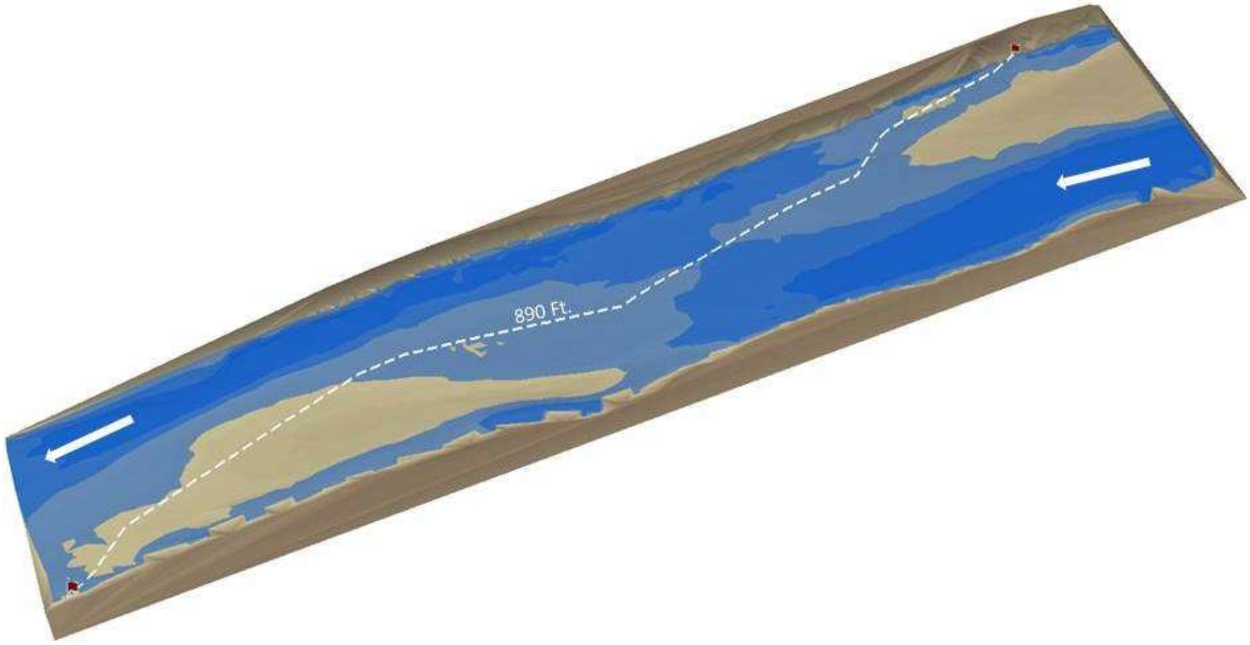


Figure 28. Riffle 97 shallowest course bank to bank.

RESULTS

This section presents the results of using 2D modeling techniques to predict the relationship between flow magnitude and area available to adult SRCS in terms of contiguous channel width and depth. This section also presents the overall performance results of the 2D models used to assess passage at the Lahar and riffles 95, 96, and 97. Results presented in this section are in summary format; detailed information is provided in the appendices. Provided with the modeling results are results from the VAKI installed prior to the 2014 spring-run in the Durham Mutual fish ladder and the pressure transducer installed downstream of the Lahar site. The VAKI and pressure transducer data from 2014 and 2015 were combined to reveal when and under what flow conditions adult SRCS ascended through the fish ladder.

River2D Model Development for Passage Assessment Results

A River2D model was developed for the Lahar formation, as well as the critical riffle sites. Riffle sites 96 and 97 were combined when creating the River2D model as a result of their close proximity to one another. The two sites shared the same discharge transect and the transition from the downstream end of 96 into the upstream control of 97 was seamless. In addition, there was no suitable upstream or downstream boundary location (single-thread channel) between Riffles 96 and 97. The outcomes of each River2D model with respect to WSEL calibration, construction, overall model calibration, depth validation, and simulated flow runs are discussed below.

PHABSIM WSEL Calibration

No problems with water appearing to flow uphill due to measurement error or inaccuracies were found for any of the three study sites. A total of five WSEL sets at low, medium, and high flows were used for all three sites. For five of the six transects, *IFG4* met the criteria described in the methods for *IFG4* (Appendix A). 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), with the exception of the beta value for Lahar XS1[19], which was less than 2.0. None of the transects deviated significantly from the expected pattern of VAFs (Appendix B). Only Site 96/97 XS1 at the lowest five flows deviated slightly from the expected pattern of VAFs. VAF values for all transects (ranging from 0.09 to 1.61) were all within an

[19] XS1 refers to the downstream transect for each site, while XS2 refers to the upstream transect for each site. XS is an abbreviation for cross section transect.

acceptable range for all transects, with the exception of the lowest flow for Lahar XS1 and Site 96/97 XS2 and the lowest three flows for Site 95 XS1.

RIVER2D Model Construction

The bed topography of the sites is shown in Appendix C. The finite element computational mesh (TIN) for each of the study sites is shown in Appendix D. As shown in Appendix E, the meshes for all sites had QI values of 0.30. The percentage of the original bed nodes for which the mesh differed by less than 0.1 foot (0.03 m) from the elevation of the original bed nodes ranged from 59% to 93% (Appendix E).

RIVER2D Model Calibration

For the Lahar formation, the highest measured flow (417 cfs), within the range of simulated flows, was used for calibration instead of the simulated WSELs at the highest simulation flow of 630 cfs. This was done because the WSEL of the simulated flow varied across the channel by more than 0.1 foot (0.031 m), thus resulting in the River2D simulated WSELs differing from the PHABSIM simulated WSELs by more than 0.1 foot (0.031 m). Sites 95 and 96/97 were calibrated at 630 cfs, the highest simulation flow. The calibrated cdg files all had a solution change of less than 0.00001, with the net flow (Q) for sites 95 and 96/97 less than 1% (Appendix E). In contrast, the net Q for the Lahar site calibrated cdg file was 4.2%. The calibrated cdg file for all study sites had a maximum Froude Number of greater than 1 (Appendix E). For the Lahar, calibrated at the highest measured flow, the calibrated cdg file had WSELs that were generally within 0.1 foot (0.031 m) of the PHABSIM simulated WSEL at the highest measured flow. However, the maximum WSEL difference exceeded the 0.1 foot (0.031 m) criterion with inclusion of an off-channel area in which WSELs were not measured; once removed the maximum WSEL difference did not exceed the 0.1 foot (0.031 m) criterion. Both study sites calibrated at 630 cfs (Sites 95 and 96/97) had calibrated cdg files with WSELs that were within 0.1 foot (0.031 m) of the PHABSIM predicted WSELs (Appendix E).

RIVER2D Model Depth Validation

For all of the sites, there was a very strong correlation (greater than 0.95) between predicted and measured depths (Appendix F). Comparisons of measured versus predicted depths for the Lahar, Site 95, and Site 96/97 models are presented in Appendix F. Although the randomly collected depth measurements were slightly variable when compared to model simulations at the Lahar, 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 $\pm$ 0.10 ft. Most differences between measured and simulated validation depth values were within $\pm$ 0.14 ft at Site 95. Most differences between measured and simulated depths on XS1 and XS2 at Site 95 were within $\pm$ 0.06 ft. Similarly, most differences between measured and simulated validation depth values were within ± 0.12 ft at Site 96/97. Most differences between measured and simulated depths on XS1 and XS2 at Site 96/97 were within ± 0.10 ft.

RIVER2D Model Simulation Flow Runs

Simulation flows included 20 to 100 cfs by 10 cfs increments, 100 to 300 cfs by 20 cfs increments and 300 to 630 cfs by 30 cfs increments. Additional simulation flows from 40 to 120 cfs and 200 to 220 cfs by 5 cfs increments were added for the Lahar, as well as 140 to 160 cfs by 5 cfs increments for Site 96/97, and 390 to 420 cfs by 5 cfs increments for all three sites. Overall, the model simulation performance was within acceptable ranges. For example, all corresponding solution changes (Sol) were less than 0.00001 (Appendix G). Net flow values (net Q) were less than 1% for 20 of 44 flows for the Lahar, all but two flows for Site 96/97, and all but nine flows for Site 95. For all three sites, maximum Froude values exceeded a value of 1 at all flows (Appendix G).

Passage Assessment River2D Results

River2D was used to generate estimates of flow depth, width, and velocity in the Lahar site and the riffles over a range of simulation flows.

Lahar Site

The results of the Lahar hydraulic modeling are summarized in Table 10 below. The hydraulic jump present near the downstream end of the formation does not appear to control passage success. At all flows, the difference in water surface elevation across the potential jump barrier is substantially less than the maximum jump height of 5.6 feet, the maximum velocity in the potential jump barrier is substantially less than the maximum darting speed of 19 feet/sec, the depth of the plunge pool is much more than 1.25 times the difference in water surface elevation across the jump, and the gradient of the 4.9-foot-long jump is much less than 45 degrees. The percentage of flow in the main channel in the lower portion of the Lahar is consistently around two-thirds, and varies little as a function of flow.

Depth and the amount of contiguous depth present are likely the most important factor controlling upstream passage in the Lahar Site. The River2D outputs were used to identify the critical flow paths through the Lahar site and estimate the flow depth and width in those pathways. The first two columns of Table 11 are plotted in Figure 29. Significant changes in the amount of width meeting the minimum depth of 0.9 feet are present between 115 to 120 cfs, 220 to 240 cfs, and 400 to 405 cfs.

Table 11. Results of the Lahar site hydraulic model.

Flow (cfs)	Width with depth ≥ 0.9 ft	WSEL Δ across jump barrier (ft)	Plunge depth (ft)	Jump Gradient (%)	Jump Max Velocity (ft/s)	Main Channel Flow
630	12.27	0.20	5.9	1.18	6.49	64%
600	9.54	0.20	5.9	1.17	6.43	64%
570	9.33	0.20	5.9	1.19	6.39	64%
540	8.78	0.20	5.8	1.20	6.35	64%
510	8.51	0.20	5.8	1.19	6.30	64%
480	8.17	0.20	5.7	1.20	6.24	64%
450	7.85	0.21	5.7	1.23	6.16	64%
420	7.63	0.21	5.6	1.22	6.09	64%
415	7.62	0.21	5.6	1.22	6.08	65%
410	7.56	0.21	5.6	1.22	6.07	65%
405	7.52	0.21	5.6	1.22	6.06	65%
400	5.06	0.21	5.6	1.22	6.04	65%
395	5.06	0.21	5.6	1.22	6.03	65%
390	4.11	0.20	5.5	1.18	6.03	65%
360	3.93	0.21	5.5	1.22	5.93	65%
330	3.80	0.21	5.4	1.26	5.83	65%
300	3.66	0.22	5.3	1.28	5.75	65%
280	3.53	0.22	5.3	1.32	5.69	65%
260	3.13	0.23	5.2	1.36	5.63	65%
240	2.98	0.24	5.1	1.42	5.59	65%
220	2.44	0.25	5.0	1.48	5.57	65%
215	2.34	0.26	5.0	1.51	5.57	65%
210	2.30	0.26	5.0	1.53	5.56	65%
205	2.19	0.27	5.0	1.56	5.56	64%
200	1.70	0.27	4.9	1.58	5.57	65%
180	1.69	0.27	4.9	1.59	5.57	72%
160	1.46	0.32	4.7	1.91	5.69	64%
140	1.38	0.36	4.6	2.13	5.81	64%
120	1.34	0.40	4.4	2.34	5.95	64%
115	0.60	0.41	4.4	2.39	6.00	64%
110	0.60	0.41	4.3	2.44	6.04	64%
105	0.60	0.42	4.3	2.46	6.10	64%
100	0.59	0.42	4.2	2.49	6.19	64%
95	0.48	0.42	4.2	2.50	6.21	64%
90	0.47	0.43	4.2	2.53	6.26	64%
85	0.30	0.44	4.1	2.58	6.31	64%
80	0.28	0.45	4.1	2.64	6.36	64%
75	0.28	0.46	4.0	2.72	6.40	64%

Flow (cfs)	Width with depth ≥ 0.9 ft	WSEL Δ across jump barrier (ft)	Plunge depth (ft)	Jump Gradient (%)	Jump Max Velocity (ft/s)	Main Channel Flow
70	0.28	0.48	4.0	2.80	6.45	64%
65	0.24	0.49	3.9	2.89	6.47	64%
60	0.23	0.51	3.9	3.00	6.50	64%
55	0.23	0.53	3.8	3.12	6.53	64%
50	0.23	0.55	3.7	3.25	6.56	64%
45	0.21	0.57	3.7	3.38	6.56	63%
40	0.19	0.59	3.6	3.49	6.53	64%
30	0	0.61	3.5	3.61	6.39	64%
20	0	0.65	3.3	3.83	6.17	66%

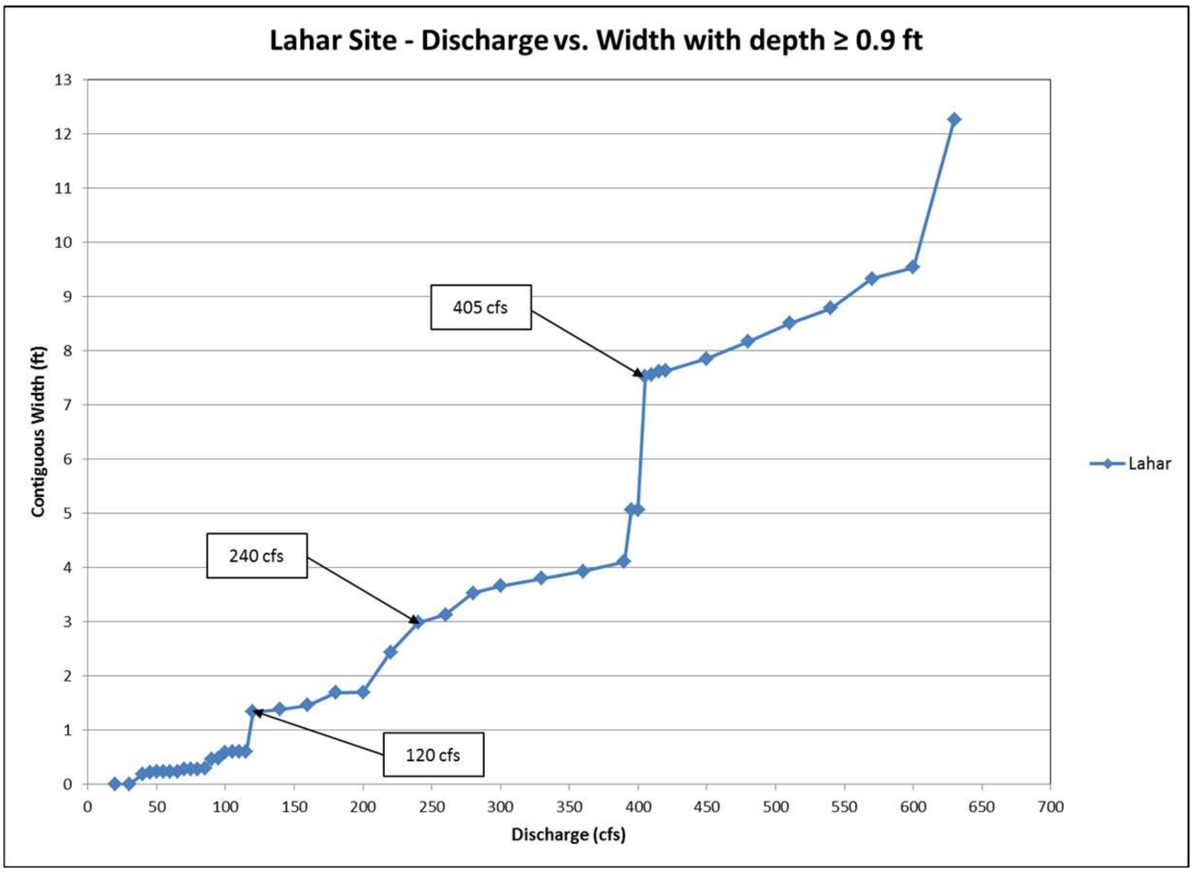


Figure 29. Lahar Site – Discharge versus width with depth ≥ 0.9 ft.

A strength of the River2D program is graphic displays of analysis parameters such as depth. The River2D model predicted where pathways were present that may support adequate depth for passage. Figures 30, 31, and 32 display flow depth in the lower portion of the Lahar site at the three flows levels identified in Figure 29. The figure's depth scale is in units of meters, 0.9 feet is approximately equal to 0.274 meters. The graphic output was adjusted to only display depths greater than 0.27 meters, slightly less than the minimum depth criteria. The River2D outputs display pathways through the lower portion of the Lahar site flows split around a large dry area in the lower Lahar formation; assessment of depth indicates that only one side of the split contains channels deep enough for migrating SRCS to pass through without abrasion. Available depth and width increase with increasing flow level. Passage is expected to occur primarily in the southeast side of the formation where depths are greatest in some of the eroded gullies. This area is highlighted at the three flow levels; 120, 240, and 405 cfs, in Figures 33, 34, and 35, respectively. Even the ‘passable’ side of the formation contains locations that are critical choke points for upstream migration where the width of the bedrock channel meeting the depth criteria is limited.

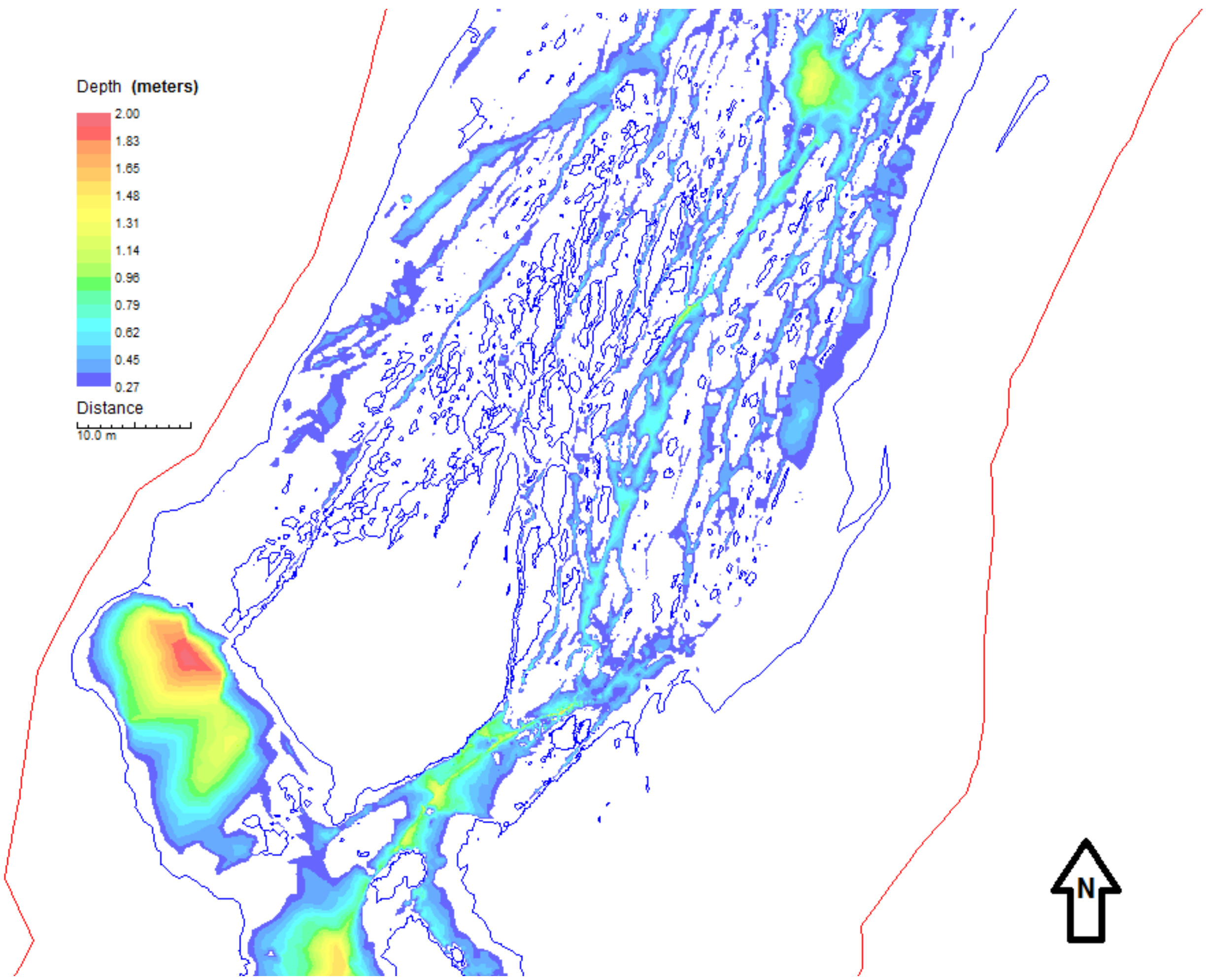


Figure 30. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 120 cfs. Scale in meters.

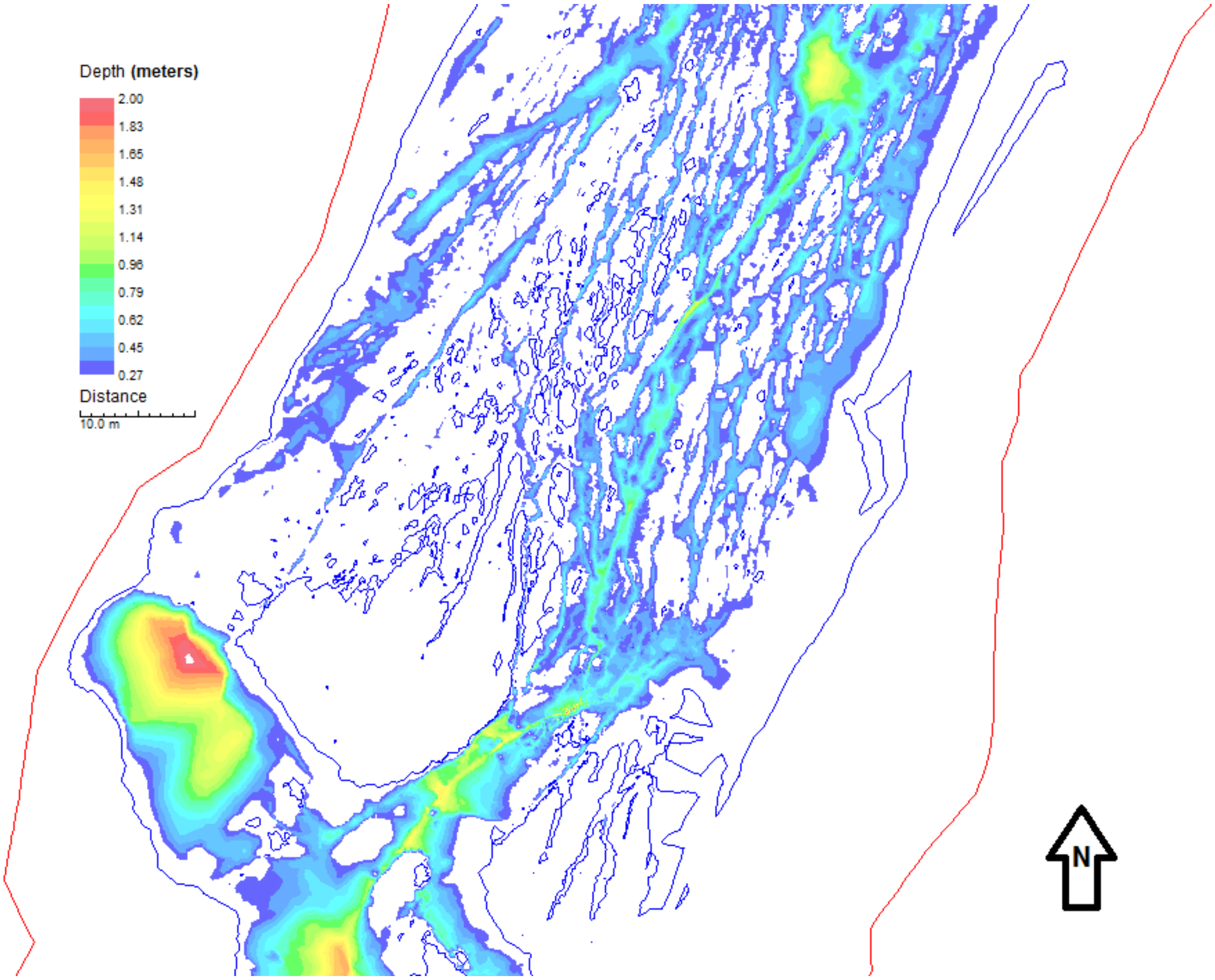


Figure 31. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 240 cfs. Scale in meters.

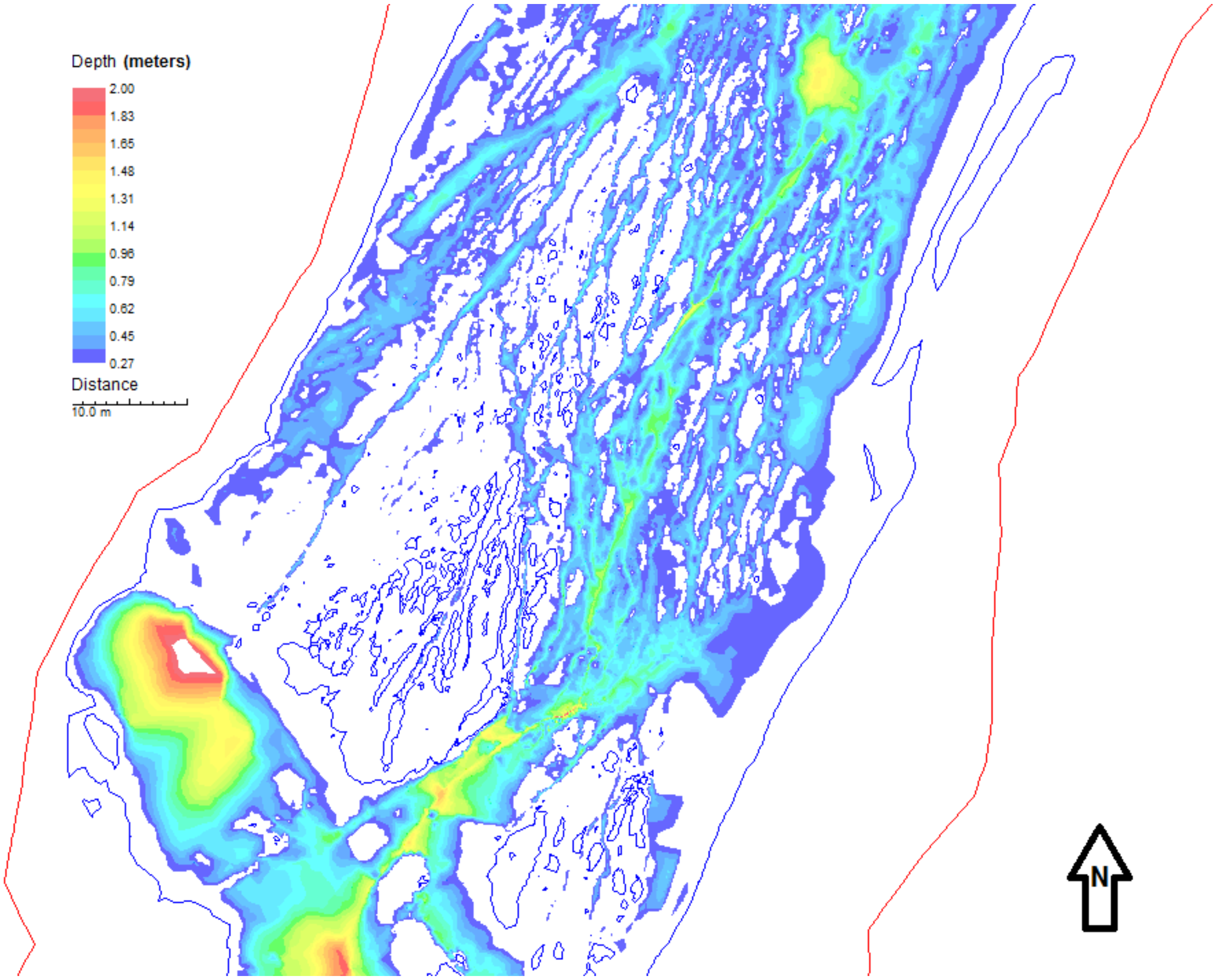


Figure 32. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 405 cfs. Scale in meters.

The results of the width assessment in the Lahar site (Table 20) indicated the narrowest width available to migrating fish in the Lahar site at 120 cfs is approximately 1 foot. The limiting width area, referred to as a choke point, was found in the lower portion of the Lahar site (Figure 33).

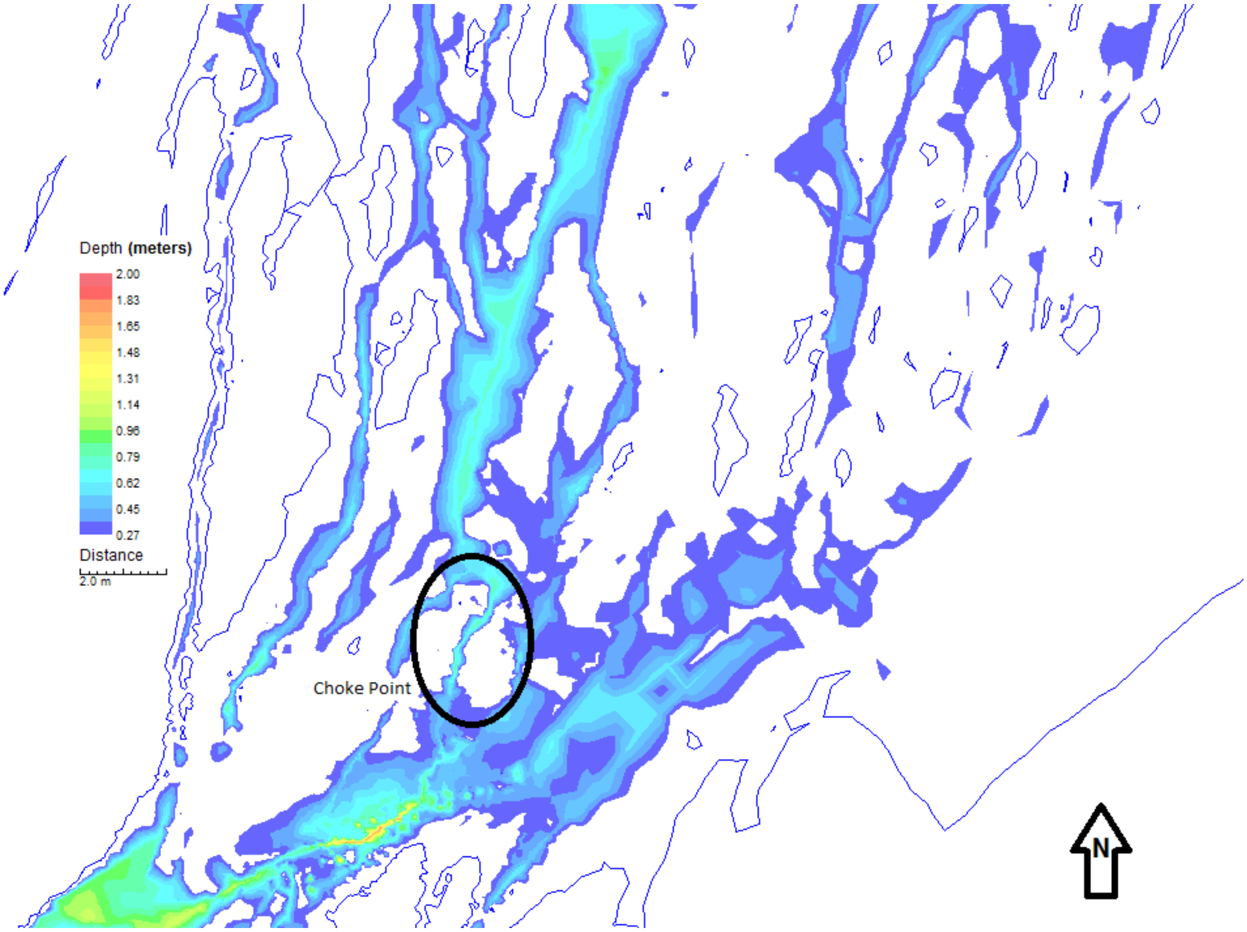


Figure 33. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 120 cfs. The limiting width was equal to approximately 1 foot. Scale in meters.

Width in the narrowest pathway was found to increase abruptly to approximately 3 feet at 240 cfs. The choke point to passage at 240 cfs is in the same area of the Lahar site as was found at 120 cfs (Figure 32). Inspection of Figure 34 reveals another difference between passage conditions at 120 and 240 cfs. Not only is the limiting pathway wider, but there are now two pathways available through this area.

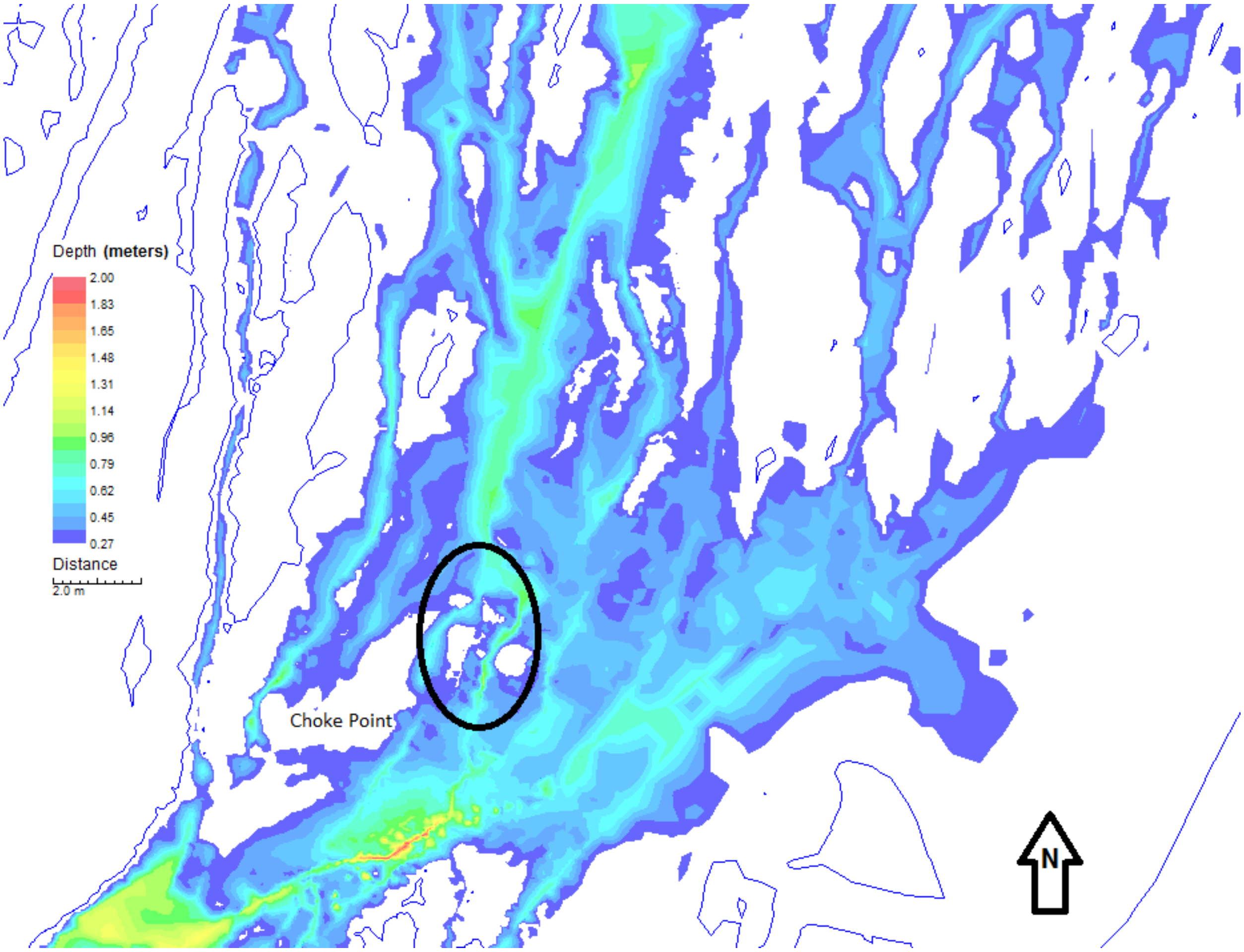


Figure 34. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 240 cfs. The limiting width was equal to approximately 3 feet. Scale in meters.

The narrowest width estimated at 405 cfs was 7.5 feet (Figure 35). Passage conditions did not appear to be limited by depth or width once the flow level reached 405 cfs.

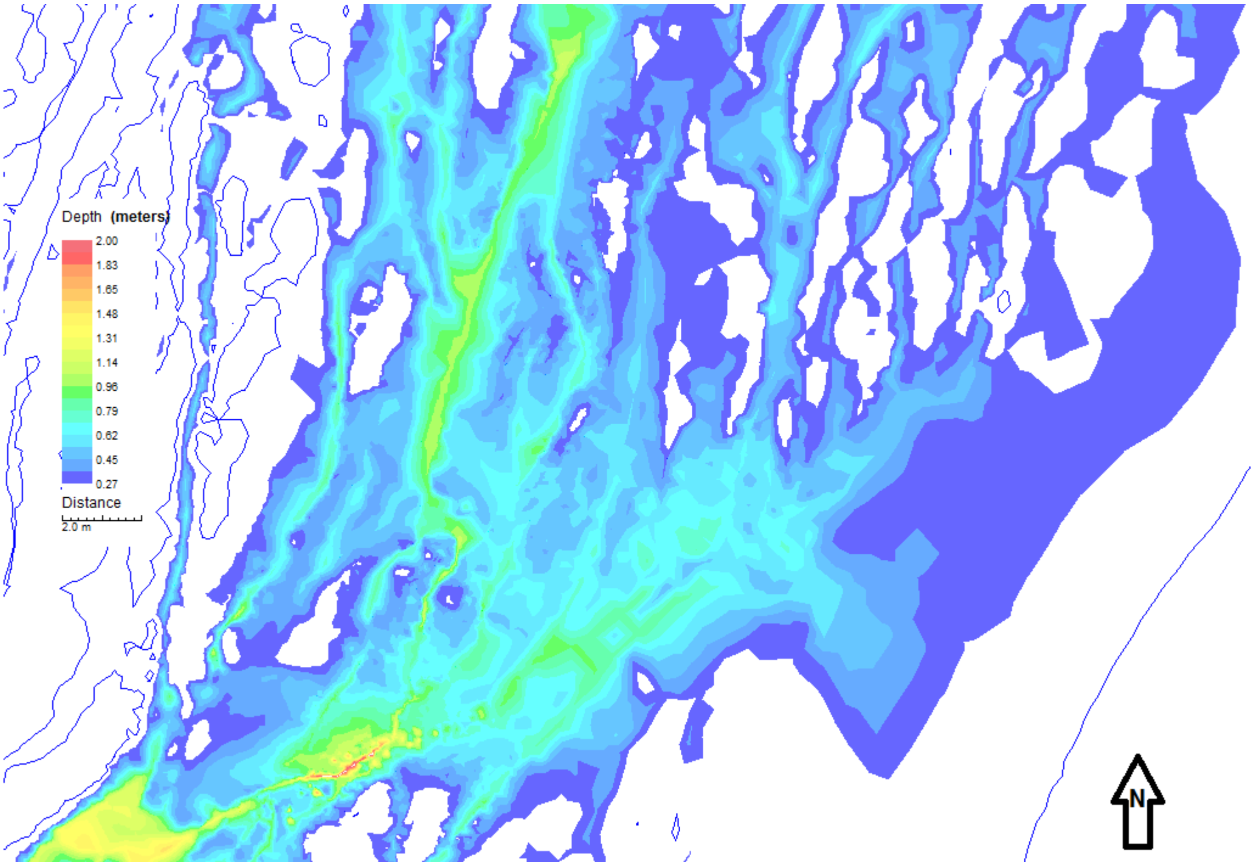


Figure 35. River2D graphic of water depth above 0.9 feet (0.27 meters) in the Lahar site at 405 cfs. The limiting width was equal to approximately 7.5 feet. Scale in meters.

Riffle Sites

The River2D model was also used to estimate the amount of wetted width and depth in the three riffles, 95, 96, and 97, along the shallowest course from bank to bank. Results were generated over the range of flows sampled in the field. The River2D model was used to compute the total and maximum contiguous width at each flow simulated. The widths were divided by the maximum wetted width of each critical riffle path to determine the percentage of total and contiguous width at each simulated flow. The width versus flow results for each riffle are summarized in Tables 12, 13, and 14. The tables are abbreviated, including only the highest flow level where no passage width meeting the depth criteria for adult SRCS was detected. Flows simulated below this level are reported in Appendix H. Initial simulations were run at 20 cfs intervals under 300 cfs and at 30 cfs intervals over 300 cfs. Additional simulations were added to resolve the flow level where abrupt changes in passage widths occurred in the riffle sites. The complete results are presented in tabular format in Appendix H, Tables H-1 through H-3.

Table 12. Riffle 95 River2D model results.

Target Species: Adult SRCS				
Depth Criteria =/> 0.9 (ft)				
Maximum Wetted Width = 470 ft.				
Flow (cfs)	**Total Width (ft)**	**Percent of Total Width**	**Contiguous Width (ft)**	**Percent of Contiguous Width**
630	221	47%	150	32%
600	176	37%	120	26%
570	162	34%	100	21%
540	118	25%	50	11%
510	84	18%	41	9%
480	43	9%	39	8%
450	38	8%	38	8%
420	37	8%	37	8%
390	34	7%	34	7%
360	30	6%	30	6%
330	21	4%	21	4%
325	20	4%	20	4%
320	10	2%	8	2%
315	6	1.3%	6	1.3%
310	6	1.3%	6	1.3%
305	6	1.3%	6	1.3%
300	5	1.1%	5	1.1%
280	5	1.1%	5	1.1%
260	3	0.6%	3	0.6%
240	3	0.6%	3	0.6%
220	1	0.2%	1	0.2%
200	1	0.2%	1	0.2%
180	0	0%	0	0%

Table 13. Riffle 96 River2D model results.

Target Species: Adult SRCS				
Depth Criteria =/> 0.9 (ft)				
Maximum Wetted Width = 384 ft.				
Flow (cfs)	**Total Width (ft)**	**Percent of Total Width**	**Contiguous Width (ft)**	**Percent of Contiguous Width**
630	178	46%	77	20%
600	167	44%	72	19%
570	166	43%	72	19%
540	123	32%	42	11%
510	98	26%	40	10%
480	74	19%	31	8%
450	57	15%	29	8%
420	44	11%	27	7%
390	42	11%	26	7%
360	41	11%	25	7%
330	35	9%	24	6%
300	29	8%	19	5%
280	27	7%	17	5%
260	26	7%	17	4%
240	25	7%	16	4%
220	25	7%	16	4%
200	24	6%	15	4%
180	19	5%	10	3%
160	19	5%	10	3%
145	18	5%	10	3%
140	6	2%	3	1%
120	1	0.3%	1	0.3%
100	0	0%	0	0%

Table 14. Riffle 97 River2D model results.

Target Species: Adult SRCS				
Depth Criteria =/> 0.9 (ft)				
Maximum Wetted Width = 676 ft.				
Flow (cfs)	**Total Width (ft)**	**Percent of Total Width**	**Contiguous Width (ft)**	**Percent of Contiguous Width**
674	181	27%	180	27%
644	166	25%	165	24%
630	145	21%	145	21%
600	120	18%	120	18%
570	115	17%	115	17%
540	100	15%	100	15%
510	95	14%	95	14%
480	80	12%	80	12%
450	46	7%	38	6%
420	36	5%	30	4%
415	30	4%	20	3%
410	30	4%	20	3%
405	21	3%	20	3%
400	19	3%	10	2%
395	17	2%	3	0.4%
390	4	0.6%	2	0.3%
360	0	0%	0	0%

Pressure Transducer and VAKI Data

The 2014 rating curve for the pressure transducer located at the downstream end of the Lahar formation (Figure 36) was developed from twelve flow measurements made at the Lahar, ranging from 22.6 to 417 cfs, along with the pressure transducer data at the times that the flow measurements were made. The data indicated that there were three distinct log-log linear portions of the rating curve: up to 71 cfs, from 71 to 232 cfs, and greater than 232 cfs. Accordingly, the rating curve was developed by performing regressions of the log of flow versus the log of (stage – SZF) for the data in each of the above three flow ranges[20]. One data point (at 93 cfs) was omitted from the regressions because it was an outlier. The resulting regression equations were as follows:

Flows < 71 cfs: log (flow) = 1.965 + 1.574 x log (stage – 214.1)
Flows 71-232 cfs: log (flow) = 2.012 + 2.047 x log (stage – 214.1)

[20] These methods are consistent with the equation entry method for developing rating curves in Sauer (2002).

Flows > 232 cfs: log (flow) = 1.593 + 4.410 x log (stage – 214.1)

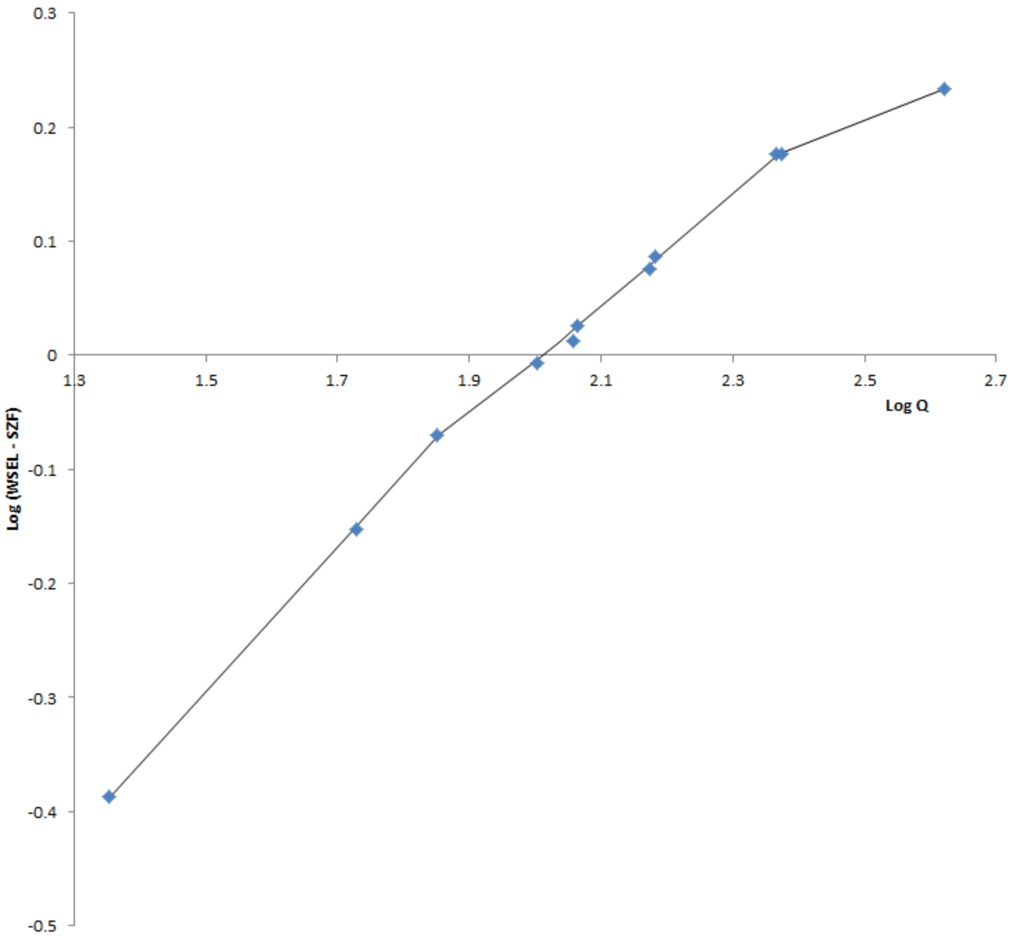


Figure 36. Lahar site 2014 pressure transducer rating curve.

The 2015 rating curve for the pressure transducer located at the downstream end of the Lahar formation (Figure 37) was developed from five flow measurements made at the Lahar, ranging from 7 to 170 cfs, along with the pressure transducer data at the times that the flow measurements were made. The data indicated that there were three distinct log-log linear portions of the rating curve: up to 26.6 cfs, from 26.6 to 119 cfs, and greater than 119 cfs. Accordingly, the rating curve was developed by performing regressions of the log of flow versus the log of (stage – SZF) for the data in each of the above three flow ranges. The resulting regression equations were as follows:

Flows < 26.6 cfs: log (flow) = 2.813 + 3.912 x log (stage – 213.93)
Flows 26.6-119 cfs: log (flow) = 1.894 + 2.453 x log (stage – 213.93)
Flows > 119 cfs: log (flow) = 1.964 + 1.577 x log (stage – 213.93)

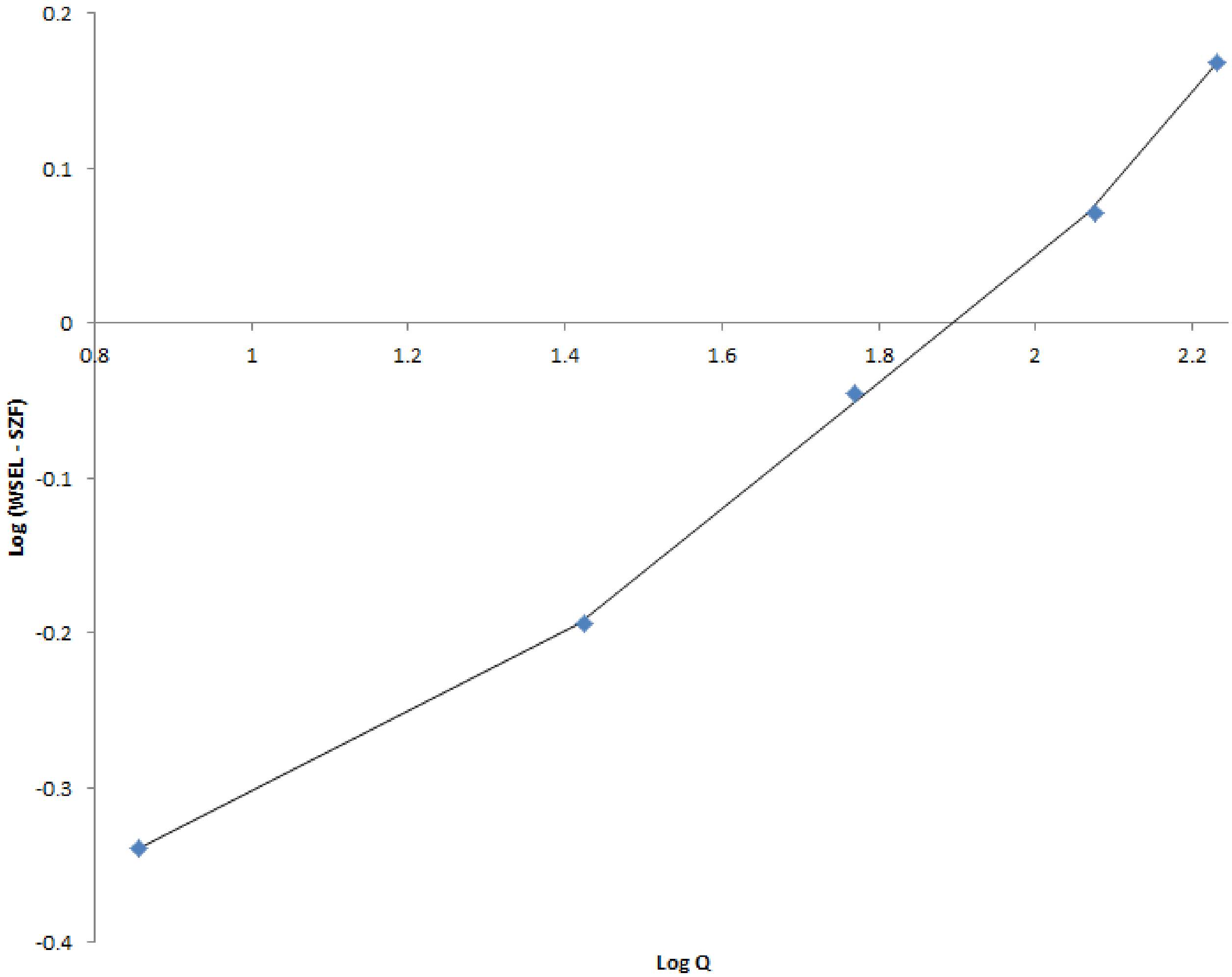


Figure 37. Lahar site 2015 pressure transducer rating curve.

Water stage and water temperature data collected from the pressure transducer (Figures 38 and 39) represent conditions prior to, during, and after the upstream migration period of adult SRCS in 2014 and 2015.

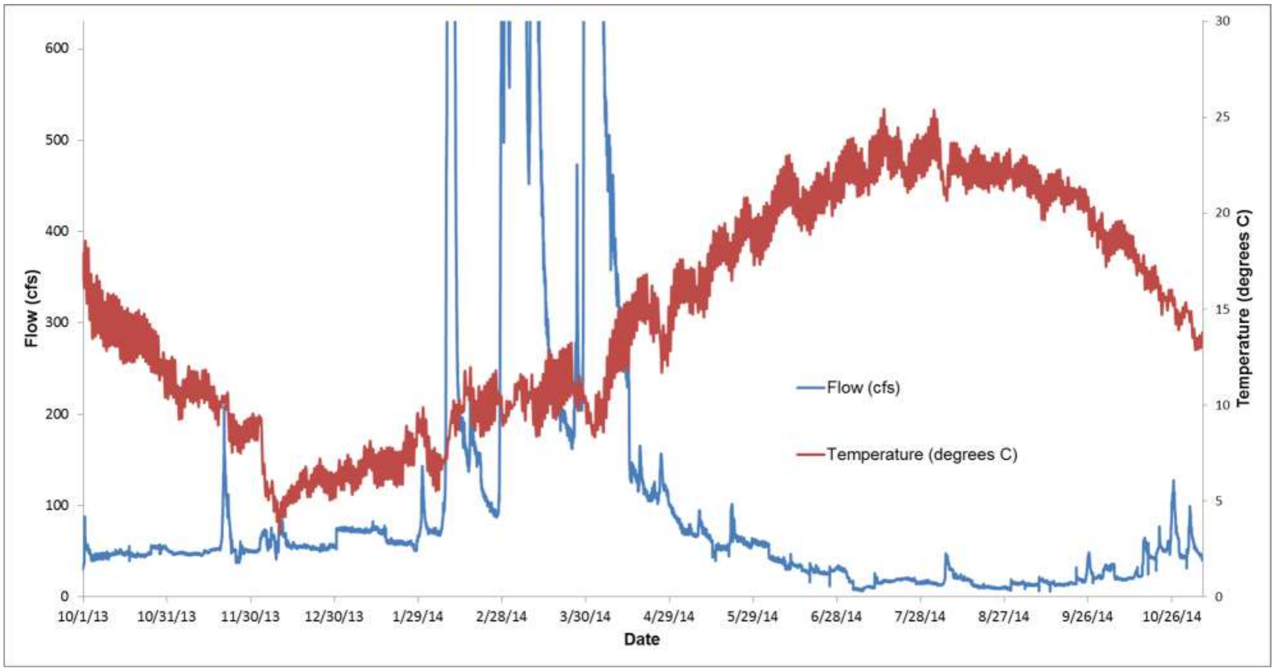


Figure 38. Water temperatures and flows at the Lahar in 2014. Gaps in the flow curve reflect flows that exceeded the upper end of the 2014 rating curve (630 cfs).

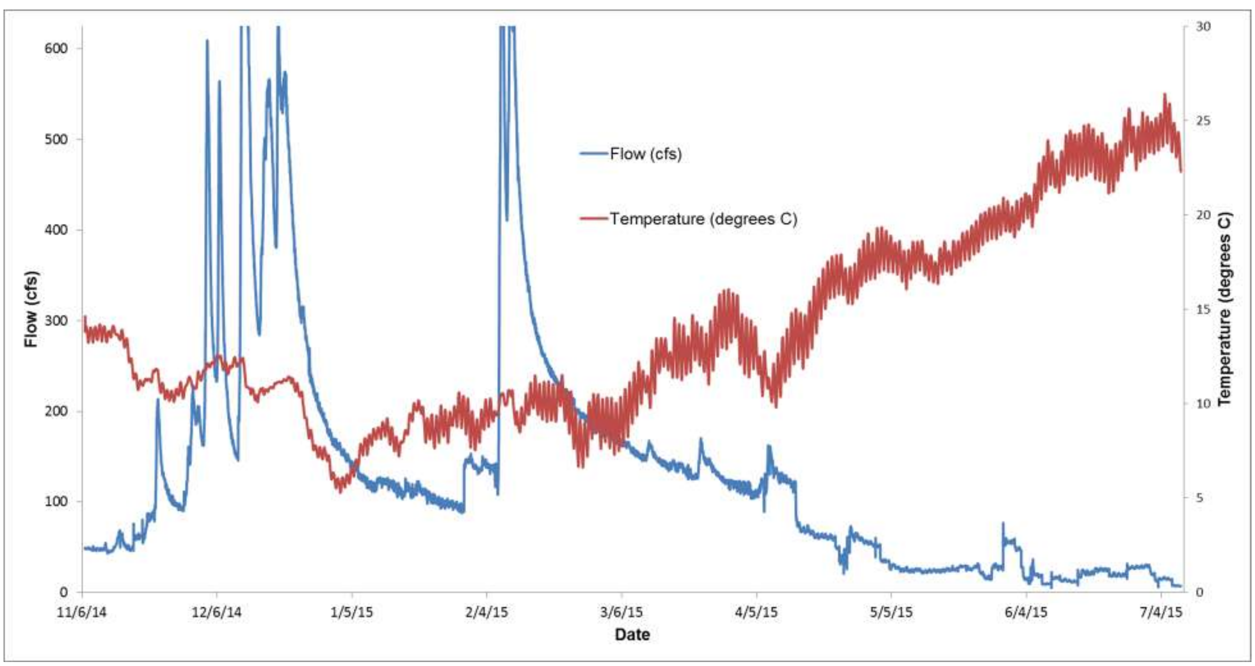


Figure 39. Water temperatures and flows at the Lahar in 2015. Gaps in the flow curve reflect flows that exceeded the upper end of the 2015 rating curve (425 cfs).

Concurrently, fish passage data was recorded at the VAKI just upstream of the Lahar site (in the Durham Mutual Diversion Dam fish ladder) during the 2014 and 2015 spring-runs. Fish count data were reported as cumulative daily totals; the daily counts and daily cumulative percentage of the run passing are reported in Appendix I. Note, in June of 2014 and May and June of 2015, the number of fish passing downstream exceeded the number passing upstream resulting in negative counts through the VAKI device. The cumulative percent of the spring-run passing through the VAKI device by day in 2014 and 2015 is given Figure 40. In 2014, VAKI data showed adult SRCS migrating upstream past Durham Mutual Dam from February 14 to June 28. In 2015 the first fish passed through the VAKI device almost a year to the day later on February 13, 2015. The last fish in 2015 passed upstream through the VAKI device on June 8, 20 days earlier than in 2014. By April 22 in 2014 and April 25 in 2015, 90% of the spring-run had passed into the upper watershed (Figure 40).

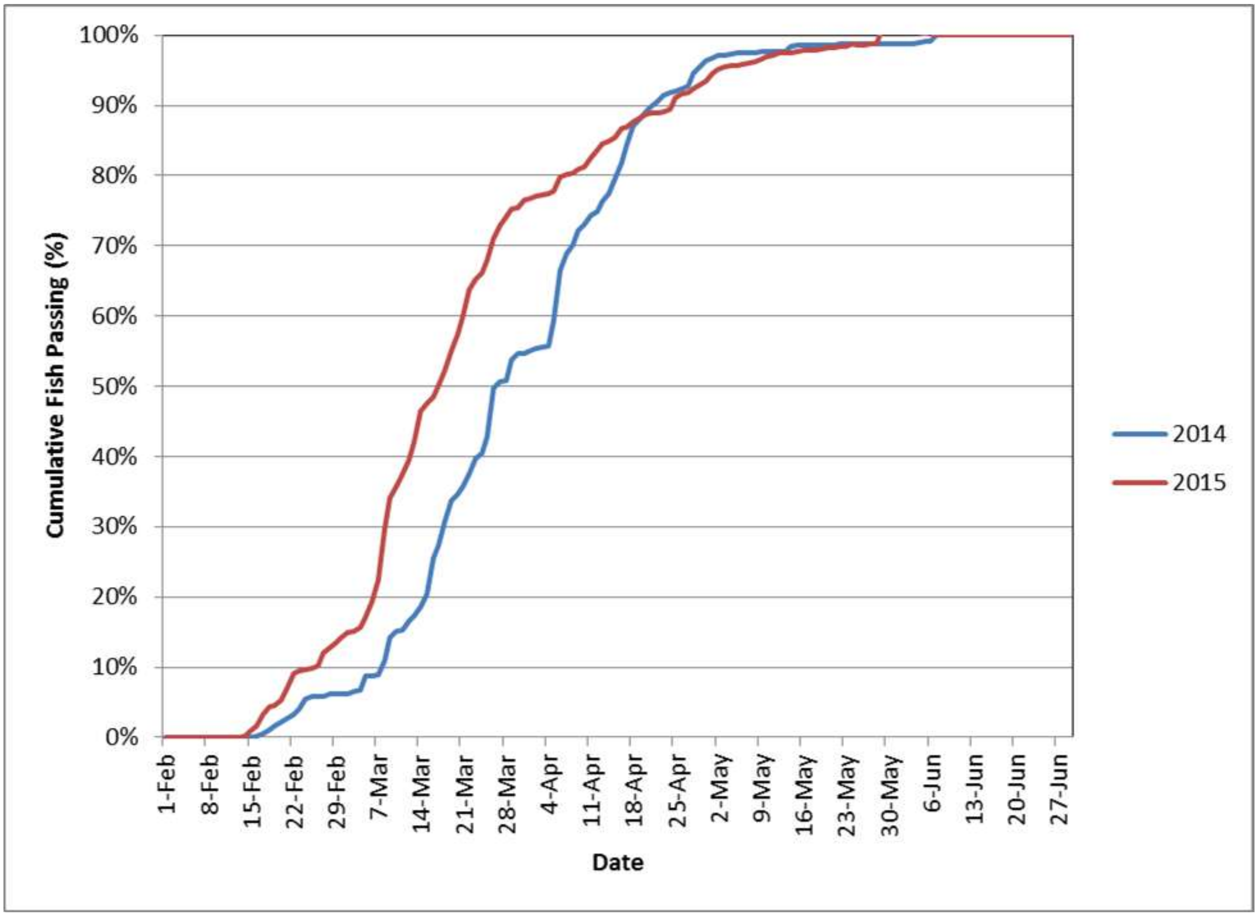


Figure 40. Cumulative percentage of fish passing per day through the VAKI Riverwatcher.

Table I-1 in the appendix provides the daily time series of all the monitoring data collected at the Lahar site in 2014. The two axes in the figure below (Figure 41) give the daily counts of fish passing the VAKI device and the average daily flow at the Lahar site for 2014. The day that water temperature first reached 18 degrees Celsius is demarcated on the figure by the vertical dashed line. The 7-day average of the daily maximum (7DADM) first reached 18 degrees Celsius on May 15 and did not fall back below 18 degrees Celsius for the remainder of the 2014 spring-run.

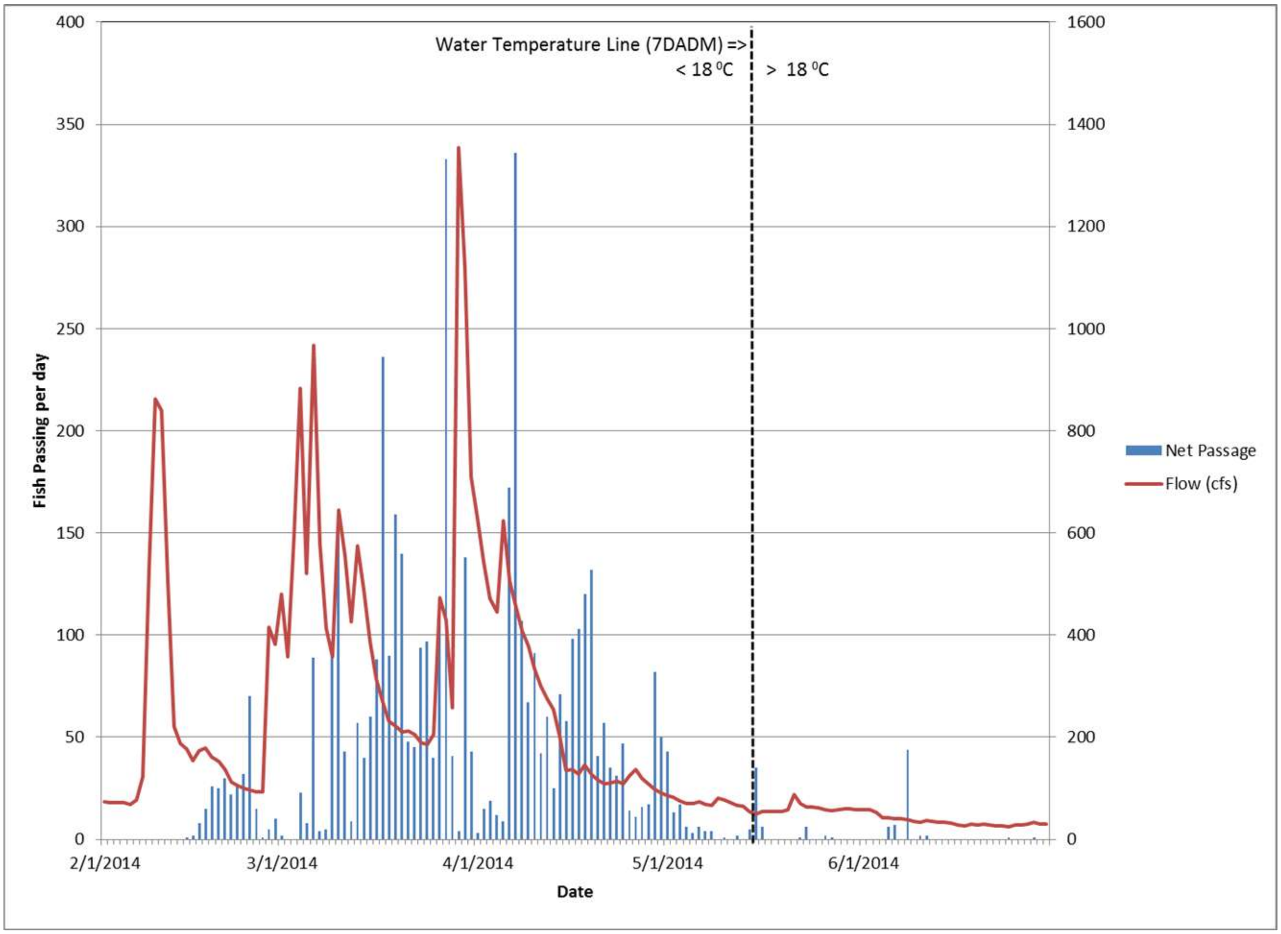


Figure 41. 2014 Lahar site daily monitoring data.

Table I-1 in the appendix provides the daily time series of all the monitoring data collected at the Lahar site in 2015. The two axes figure below (Figure 42) gives the daily counts of fish passing the VAKI device and the average daily flow at the Lahar site for 2015. The day that water temperature first reached 18 degrees Celsius is demarcated on the figure by the vertical dashed line. The 7DADM first reached 18 degrees Celsius on April 30 and did not fall back below 18 degrees Celsius for the remainder of the 2015 spring-run.

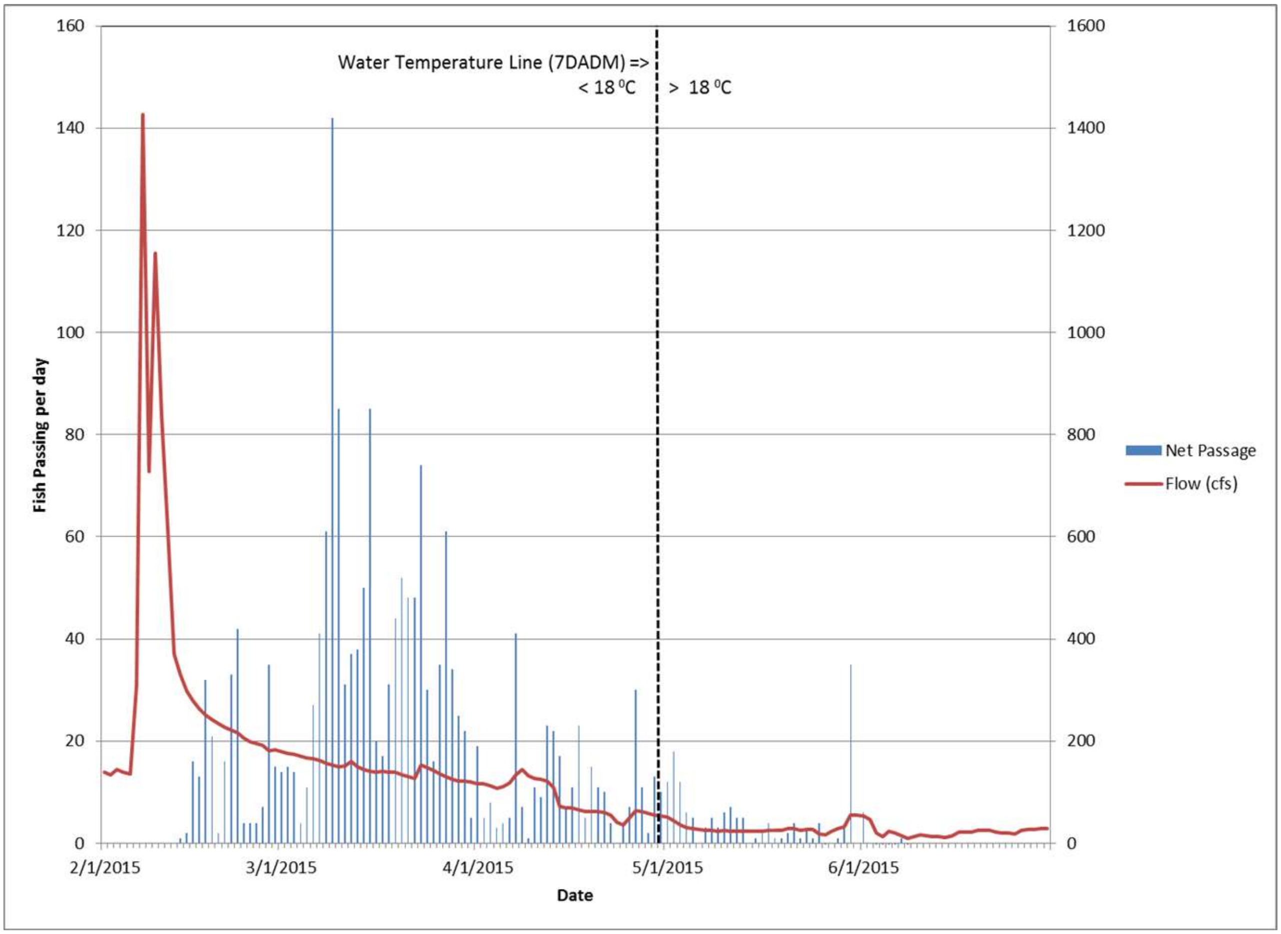


Figure 42. 2015 Lahar site daily monitoring data.

DISCUSSION

This technical report focuses on documenting the rationale selected to assess passage limiting conditions affecting adult SRCS migrating through the study reach and the results of models used to predict conditions over a range of flows characterized by flow depth, width and velocity. Discussion is limited to topics concerning the performance of the 2D models compared with recommended standards, the results of the 2D models, and the likelihood of those flow levels occurring in the study reach.

River2D Model Discussion

2D models were developed to assess wetted width, flow depth, and velocity in all the study sites. The performance of the River2D model when applied to the Lahar formation and critical riffles is discussed below.

PHABSIM WSEL Calibration

The low beta value for Lahar XS1 was due to an unusually strong downstream hydraulic control; given that this transect could be calibrated for flows between 23 and 417 cfs, the calibration of this transect is considered to be acceptable. The low VAF values for the lowest three flows for Site 95 XS1, the lowest flow for Lahar XS1 and Site 96/97 XS2, and the slight deviation in the expected pattern of VAFs for the lowest five flows for Site 96/97 XS1 were due to strong backwater effects of the hydraulic controls as well as a result of the velocity set being collected at relatively high flows. These low VAF values and slight deviation from the expected pattern of VAFs are considered to be acceptable since the transects were only used to develop stage-discharge relationships for the River2D models.

RIVER2D Model Construction

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

RIVER2D Model Calibration

Generally, the highest simulation flow modeled in River2D is calibrated using the WSELs predicted by PHABSIM at the same flow. At higher flow levels, WSELs can vary substantially across the channel, which can make calibration with PHABSIM results difficult. WSELs at the highest simulation flow predicted using PHABSIM were found to differ by more than 0.1 feet from the River2D results. Further attempts to calibrate the model using WSELs predicted by PHABSIM were unsuccessful. The highest flow simulations were calibrated using the WSELs measured in the field within the range of simulated flows.

The calibration simulation was considered to be acceptable for all three study sites, even though Max F was greater than 1.0. Plots of FN were evaluated for each site and simulation flow to identify areas where River2D predicted transient or supercritical flow. Sample FN plots are provided in Appendix J at one simulation flow per site where limiting passage width for adult SRCS was approximately equal to one foot. Plots show the majority of FN values were <1.0. The proportion of nodes with FN values >1.0 in each site is summarized in Table 15.

Table 15. Frequency of Nodes with Froude Number (FN) >1.0.

Site	Flow (cfs)[21]	Number of Nodes	Number of Nodes FN>1	Nodes FN>1/All Nodes
Lahar	120	100,320	1966	1.96%
Site 95	200	27,218	12	0.04%
Site 96/97 (Riffle 96)	120	21,957	121	0.55%
Site 96/97 (Riffle 97)[22]	390	21,957	66	0.30%

In the Lahar site, River2D predicted nodes with FN >1.0 concentrated in areas at the downstream end of the site (Figure 42) where surface water conditions were previously observed by staff to be turbulent or subject to sharp grade changes. The plots in Appendix J were compared with digital images and aerial imagery to confirm that locations where FN exceeded 1.0 in the model were consistent with naturally turbulent areas in the site or areas subjected to sharp grade changes. Plots were further evaluated where clusters of nodes with FN >1.0 occurred near assumed passageways for adult SRCS. In the southeast end of the site where adult SRCS are assumed pass through the Lahar site, the concentrated area of FN >1.0 was found to be adjacent to, but not in, the depth sensitive areas of adult passage.

Nodes with FN >1.0 were also present in the riffles. Staff compared the location of the shallowest course for each riffle (Figures 26, 27, and 28) to confirm the areas of FN >1.0 did not occur where River2D was used to predict passage depths. Riffle 95 had the lowest percentage of nodes with FN > 1.0 and the nodes did not occur along the shallowest course line. The most nodes with FN >1.0 were found in the split channel run immediately downstream of riffle 96 (Figure J-3). High velocity and low depth conditions were observed in the channel splits downstream of the riffle crest (Figure 43). River2D model Site 96/97 was evaluated to determine where the FN >1.0 nodes were located in relation to the shallowest course line. The FN >1.0 nodes were found near, but downstream of the shallowest course line. Riffle 97 was included in the same River2D site model as riffle 96, but only one small concentration of nodes FN >1.0 were found in riffle 97 near the west bank (Figure J-4), and were located downstream of the shallowest course line.

For all three sites, field staff observed supercritical flow and hydraulic jumps while collecting calibration data. All attempts were made to reduce the Net Q and the results

[21] Flows in the column represent where a minimum of one foot of width was available to migrating adult SCRS along a continuous path through each site.
[22] Riffle 97 was evaluated at 390 cfs because at that flow level one foot of contiguous width meeting the minimum depth criteria for SRCS was first present, but no nodes of FN > 1.0 were in the riffle area. The 66 nodes of FN > 1.0 were present in the area of Riffle 96.

included in the report represent staff efforts to reach the best calibration of the complex Lahar site. For the Lahar, the simulated WSEL only differed by more than 0.1 feet from the measured WSEL in an off-channel area where WSEL data was not collected. Accordingly, it was concluded that the 2D calibration for this site was acceptable.

Figure 43. Lahar site at approximately 116 cfs. Supercritical area of abrupt grade change on the west side of the site (Top) and the turbulent entrance to the east side of the site (Bottom).

RIVER2D Model Depth Validation

Differences in magnitude of depths in most cases are likely due to aspects of the bed topography of the site that were not captured in our data collection, and differences between the underlying bed topography and the computational mesh. For portions of the Lahar site with rapidly varying topography, such as at XS2, we were unable to perfectly match the computational mesh to the underlying bed topography, despite having a computational mesh with over 100,000 nodes. Differences between measured and simulated depths for the east side of Site 96/97 XS1 were due to WSELs varying across the cross-section by more than 0.1 foot. Since bed elevations were computed from measured depths and WSELs on the east side of the channel, and the downstream boundary condition was based on WSELs measured on the west side of the channel (which was more representative of the WSELs of the cross-section than those on the east side), the simulated depths on the east side of the channel (computed as the difference between the WSEL and bed elevation) were greater than the measured depths. Since the River2D model was validated for all three sites, we conclude that the depth validation was acceptable for all three sites.

RIVER2D Model Simulation Flow Runs

For all three sites, field staff observed supercritical flow and hydraulic jumps while collecting calibration data. In the case of the Lahar at 240, 260, 300 and 400 cfs, where the net Q exceeded the 5% level, attempts were made to reduce Net Q and the results included in the report represent the best calibration results attainable at this complicated site. We consider that a level of uncertainty applies to the results from these production files. The simulated MAX F numbers exceeding a value of 1 reflected the presence of isolated areas with supercritical flow (fast shallow flow) in all three sites; by definition, areas with supercritical flow have FN values exceeding 1.0.

Figure 44. Riffle 96 Supercritical flow condition at 153 cfs.

Contiguous Width and Flow Magnitude

The contiguous width available to migrating adult SRCS changed abruptly at discrete flow levels in each site. Within the confined bedrock gullies of the Lahar site, contiguous width meeting the minimum passage depth for adult SRCS changes abruptly at several flow levels, most notably from:

- 0.6 to 1.34 feet between 115 and 120 cfs;
- 2.44 to 2.98 feet between 220 and 240 cfs; and
- 5.06 to 7.52 feet between 400 and 405 cfs.

Flow Probability

As stated above, the maximum contiguous width of passable depth increased abruptly at the Lahar site then plateaued at three distinct flow levels, 120, 240, and 405 cfs. The likelihood of those flows expressed as exceedance percentage by month are provided in Table 15 with respect to both estimated unimpaired hydrology and the regulated record from USGS stream gage Station 11390000.

Table 16. Exceedance percentages of study selected flow levels.

Hydrologic Record	Highlighted Flow Levels	Flow (cfs)		
		120	240	405
	Month	Exceedance		
Unimpaired Record WYs 1958-2005	February	92%	75%	52%
	March	98%	87%	62%
	April	98%	88%	55%
	May	95%	64%	38%
	June	69%	26%	10%
Regulated Record WYs 1931-2014	February	97%	81%	58%
	March	99%	96%	72%
	April	99%	95%	73%
	May	99%	85%	51%
	June	95%	52%	18%

Pressure Transducer and VAKI Data

The ability to draw inferences on fish passage from the VAKI data is limited, given that there are only two years of data, and that both years were extremely dry. Further, effects of water temperature are difficult to assess, given that 98.5% and 92.9% of the fish had already passed before the 7DADM had exceeded 18 degrees Celsius in 2014 and 2015, respectively. The VAKI data does suggest that upstream passage flows are needed for the period of mid-February through late June, although most of the biological benefit of higher flows for upstream fish passage would be during March and April.

CONCLUSION

Conditions that could potentially limit upstream migration of SRCS were evaluated for the valley section of Lower Butte Creek. Three passage limiting sites were identified using anecdotal information provided by Region staff and through a walking survey of the study reach. Three sites were selected and included a bedrock outcropping and three alluvial riffles, where one site contained two separate riffles. 2D models were developed at each site to evaluate passage limiting conditions based on flow depth, width, and velocity. Passage conditions in the exposed bedrock site, the Lahar site, were assessed by identifying the most depth and width limited pathway for upstream migration at each flow level simulated. Passage conditions at the riffles were assessed by identifying the shallowest course from bank to bank and using the model to output the depth and width along the course at each simulated flow level. Those results are presented in Tables 10 through 13 for the Lahar and riffles sites, respectively. Additionally, the report considers two seasons of site specific creek stage, water temperature, and fish passage data (Figures 37 through 41). This information will be used by the Department to recommend flows for SRCS utilizing Lower Butte Creek. Flow criteria are developed separately of the scientific process presented above, and are not incorporated into this technical report.

ACKNOWLEDGEMENTS

The data in this report were collected with assistance of the following Department of Fish and Wildlife staff: Daniel Rankin (Water Branch), Don Baldwin (Water Branch), Mike Hancock (Water Branch), Diane Haas (Water Branch), Paige Uttley (Water Branch formerly SWRCB) Candice Heinz (Water Branch), Jeffrey Shu (Water Branch), and Mary Olswang (Fisheries Branch). The following State Water Resources Control Board staff also assisted with data collection: Dan Schultz, Will Anderson and Dan Worth.

LITERATURE CITED

Annear, T., I. Chisholm, H. Beecher, A. Locke, and 12 other coauthors. 2004. Instream Flows for Riverine Resource Stewardship, Revised Edition. Instream Flow Council, Cheyenne, Wyoming. 268 pp.

Bjornn, T.C. and D.W. Reiser. 1991. Habitat Requirements of Salmonids in Streams, from: Meehan, W.R. (Ed.) 1991. Influences of Forest Rangeland Management of Salmonid Fishes and Their Habitats (Special Publication of the *American Fisheries Society*). 19:83-138.

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

California State University, Chico (CSUC). Butte Creek Watershed Project, Existing Conditions Report. August 1998.

CDFW. 2009. Minimum Instream Flow Recommendations: Butte Creek, Butte County. California Department of Fish and Wildlife Instream Flow Program, 16 pp. April 21, 2009. Available at: https://www.wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/Studies/Butte-Creek-Study.

CDFW. 2012. Critical Riffle Analysis for Fish Passage in California. California Department of Fish and Wildlife Instream Flow Program Standard Operating Procedure DFG-IFP-001. 2015 Update. 24 p.
Available at: https://www.wildlife.ca.gov/Conservation/Watersheds/Instream-Flow/SOP

Delta Stewardship Council. 2013. The Delta Plan Ensuring a reliable water supply for California, a healthy Delta ecosystem, and a place of enduring value. 347 pp.

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

Freeman, M.C., C.M. Pringle, and C.R. Jackson. 2007. Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. *Journal of the American Water Resources Association* 43(1) 5-14.

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

Gallagher, A. S. 1999. Barriers. Pages 135-147 *in* M. B. Bain and N. J. Stevenson, editors. Aquatic habitat assessment: common methods. American Fisheries Society, Bethesda, Maryland.

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

Garman, C. and McReynolds, T. 2009. Butte and Big Chico Creeks spring-run Chinook salmon, *Oncorhynchus tshawytscha* life history Investigation 2007-2008. California Department of Fish and Game, Inland Fisheries Division, North Central Region.

Harwood, D., E. Helley and M. Doukas. 1981. Geologic map of the Chico monocline and northeast part of the Sacramento Valley. U.S.G.S. Reston, VA.

Holmes, R.W., D.E. Rankin, M. Gard, and E. Ballard. 2015. Evaluation of Steelhead Passage Flows Using Hydraulic Modeling on an Unregulated Coastal California River. *River Research* DOI:10.1002/rra.2884

Lydon, Philip A. 1968. *Geology and Lahars of the Tuscan Formation, Northern California.* In: R.R. Coats, R.L. Hays, and C.A. Anderson eds., Studies in Volcanology, a memoir in honor of Howel Williams: Geological Society of America, Memoir 116.

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

Mosely, M.P. 1982. Critical depths for passage in braided rivers, Canterbury, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 16: 351-357.

Mosser, C.M., L.C. Thompson and J.S. Strange. 2013. Survival of captured and relocated adult spring-run Chinook salmon *Oncorynchus tschawytscha* in a Sacramento River tributary after cessation of migration. *Environmental Biology of Fish* 96: 405-417.

National Marine Fisheries Service (NMFS) 2014. Recovery Plan for the Evolutionarily Significant Units of Sacramento River Winter-run Chinook salmon and Central Valley Spring-run Chinook Salmon and the Distinct Population Segment of Central Valley Steelhead. Appendix A: Central Valley Watershed Profiles. Sacramento Protected Resources Division. July 2014. Available from: http://www.westcoast.fisheries.noaa.gov/publications/recovery_planning/salmon_steelhead/domains/california_central_valley/final_recovery_plan_07-11-2014.pdf [November 6, 2014].

Pacific Gas and Electric. 2007. DeSabla-Centerville Hydroelectric Project FERC No. 803-068. Supplemental Initial Study Report. Fifth Quarterly Progress Report. Volume I of III (Sections 6.1 and 6.2). Filed with the Federal Energy Regulatory Commission on January 16, 2007.

Payne and Associates. 1998. RHABSIM 2.0 for DOS and Window's User's Manual. Arcata, CA: Thomas R. Payne and Associates.

R2 Resource Consultants (R2), 2007. Appendix G: Approach for Assessing Effects of Policy Element Alternatives on Upstream Passage and Spawning Habitat Availability. R2 Resource Consultants, Inc. Updated March 14, 2008 Administrative Draft prepared for the California State Water Resources Control Board, Division of Water Rights as part of the North Coast Instream Flow Policy: Scientific Basis and Development of Alternatives Protecting Anadromous Salmonids. Accessed from: http://www.waterboards.ca.gov/waterrights/water_issues/programs/instream_flows/policy_development.shtml

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

Saucedo, G.J. and Wagner, D.L. 1992. Geologic Map of the Chico quadrangle. California Division of Mines and Geology.

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

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

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

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

State Water Resources Control Board (SWRCB). 2010. Policy for Maintaining Instream Flows in Northern California Coastal Streams. Division of Water Rights, State Water Resources Control Board, California Environmental Protection Agency. Sacramento, CA. Accessed online at: http://www.waterboards.ca.gov/waterrights/water_issues/programs/instream_flows/docs/ab2121_0210/adopted050410instreamflowpolicy.pdf

State Water Resources Control Board (SWRCB), Stillwater Sciences, and Louis Berger Group. April 2015. Initial Study Document, CEQA Checklist, and Mitigated Negative Declaration for the Desabla-Centerville Hydroelectric Project, Butte County, California. 94 pp.

Tennant, D. L. 1976. Instream flow regimens for fish, wildlife, recreation, and related environmental resources, in Orsborn, J. F. and Allman, C. H. (Eds), Proceedings of the Symposium and Specialty Conference on Instream Flow Needs II. American Fisheries Society, Bethesda, Maryland. P. 359–373.

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

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

U.S. Fish and Wildlife Service (USFWS). 2000. Effects of the January 1997 flood on flow-habitat relationships for spring-run Chinook salmon and spring-run Chinook salmon in the Lower American River. U.S. Fish and Wildlife Service, Sacramento, CA. http://www.fws.gov/sacramento/fisheries/Instream-Flow/Documents/American River Effects of 1997 Flood Final Report.pdf

U.S. Fish and Wildlife Service (USFWS). 2001. Final Restoration Plan for the Anadromous Fish Restoration Program: A Plan to Increase Natural Production of Anadromous Fish in the Central Valley of California. 146 pp.

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

Wiens, J.A. 2002. Riverine landscapes: taking landscape ecology into the water. *Freshwater Biology* 47: 501-539.

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

APPENDICES

Appendix A. RHABSIM WSEL Calibration

Stage of Zero Flow Values

Study Site	XS # 1 SZF (ft)	XS # 2 SZF (ft)
Lahar	214.1	219.1
Site 95	128.1	129.8
Site 96/97	124.8	128.1

Calibration Methods and Parameters Used

Study Site	XS #	Flow Range (cfs)	Calibration Flows (cfs)	Method	Parameters
Lahar	1, 2	20-630	22.6, 114, 149, 232, 417	IFG4	- - -
Site 95	1	20-630	153, 238, 277, 635	IFG4	- - -
Site 95	2	20-630	153, 238, 277, 323, 635	IFG4	- - -
Site 96/97	1, 2	20-630	153, 238, 277, 350, 635	IFG4	- - -

Lahar

XSEC	BETA COEFF.	% MEAN ERROR	DIFFERENCE (MEASURED vs. PREDICTED)										
1	1.79	2.4	22.6	23.1	114	113	149	155	232	231	417	434	**FLOW: MEASURED AND PREDICTED (CFS)**
			2.00%		0.90%		4.30%		0.60%		4.10%		**FLOW DIFFERENCE**
			214.51	214.51	215.13	215.12	215.32	215.39	215.63	215.62	216.17	216.22	**WSEL: MEASURED AND PREDICTED** (FT)
			0.00		0.01		0.07		0.01		0.05		**WSEL DIFFERENCE (FT)**
2	3.95	5.2	22.6	21.4	114	130	149	150	232	220	417	407	**FLOW: MEASURED AND PREDICTED (CFS)**
			5.40%		13.60%		0.60%		5.20%		2.40%		**FLOW DIFFERENCE**
			220.31	220.29	220.84	220.9	221.02	221.02	221.28	221.25	221.61	221.59	**WSEL: MEASURED AND PREDICTED (FT)**
			0.02		0.06		0.00		0.03		0.02		**WSEL DIFFERENCE (FT)**

Site 95

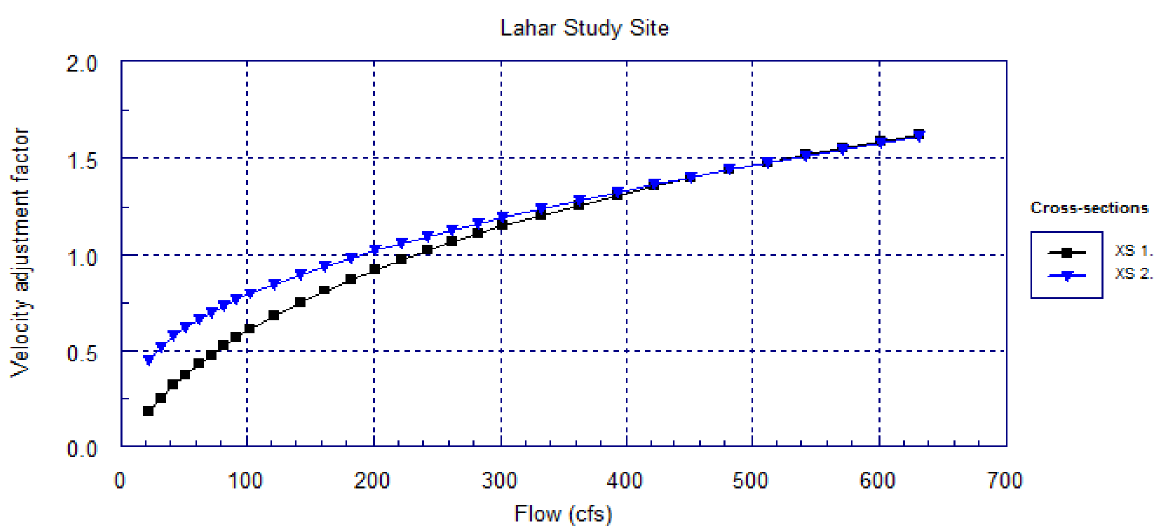
XSEC	BETA COEFF.	% MEAN ERROR	DIFFERENCE (MEASURED vs. PREDICTED)										
1	2.6	1.3	153	151	238	238	277	284	635	629			**FLOW: MEASURED AND PREDICTED (CFS)**
			1.60%		0.10%		2.60%		1.00%				**FLOW DIFFERENCE**
			129.45	129.44	129.69	129.69	129.77	129.79	130.43	130.42			**WSEL: MEASURED AND PREDICTED** (FT)
			0.01		0.00		0.02		0.01				**WSEL DIFFERENCE (FT)**
2	3.06	3.2	22.6	22.9	114	106	149	154.2	232	240	417	418	**FLOW: MEASURED AND PREDICTED (CFS)**
			1.20%		7.40%		3.50%		3.50%		0.20%		**FLOW DIFFERENCE**
			131.07	131.07	131.31	131.27	131.33	131.35	131.41	131.43	131.83	131.83	**WSEL: MEASURED AND PREDICTED** (FT)
			0.00		0.04		0.02		0.02		0.00		**WSEL DIFFERENCE (FT)**

Site 96/97													
XSEC	**BETA COEFF.**	**% MEAN ERROR**	**DIFFERENCE (MEASURED vs. PREDICTED)**										
1	2.6	1.3	153	154	238	234	277	286	350	352	635	639	**FLOW: MEASURED AND PREDICTED (CFS)**
			0.60%		1.70%		3.30%		0.50%		0.60%		**FLOW DIFFERENCE**
			126.27	126.27	126.55	126.54	126.62	126.64	126.82	126.82	127.34	127.34	**WSEL: MEASURED AND PREDICTED** (FT)
			0.00		0.01		0.02		0.00		0.00		**WSEL DIFFERENCE (FT)**
2	3.36	5.2	153	158	238	242	277	244	350	365	635	659	**FLOW: MEASURED AND PREDICTED (CFS)**
			3.10%		1.60%		11.90%		4.40%		3.80%		**FLOW DIFFERENCE**
			129.34	129.35	129.52	129.53	129.65	129.59	129.68	129.7	129.99	130.01	**WSEL: MEASURED AND PREDICTED** (FT)
			0.01		0.01		0.06		0.02		0.02		**WSEL DIFFERENCE (FT)**

Appendix B. Velocity Adjustment Factors.

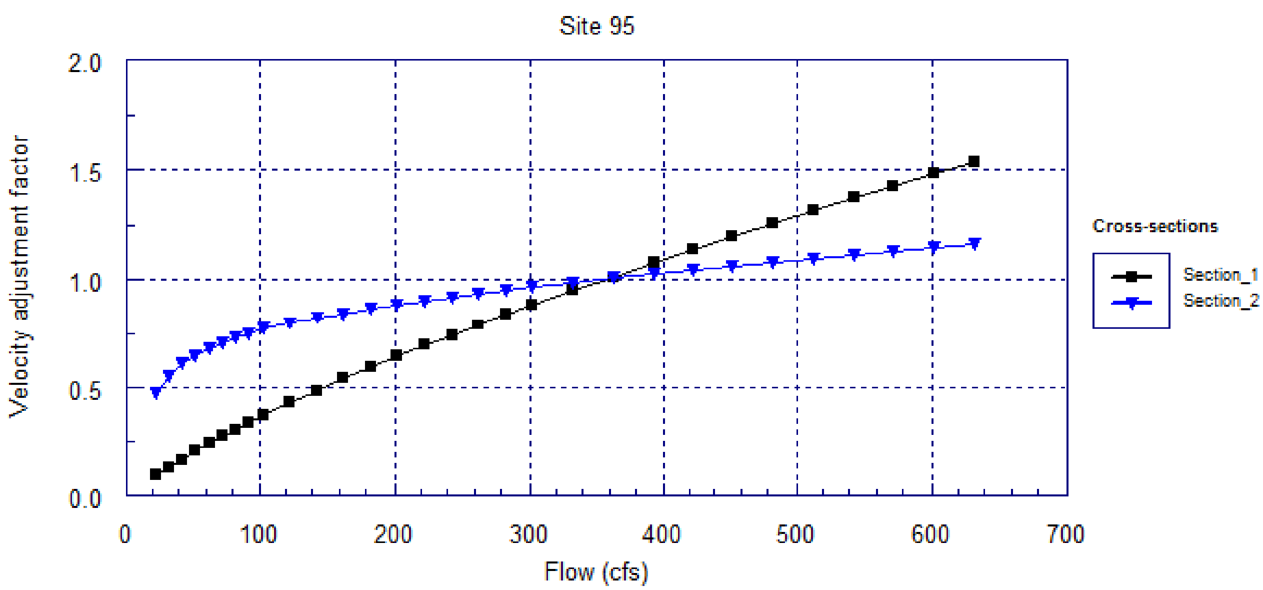
Lahar Study Site

	Velocity Adjustment Factors	
Discharge (cfs)	Xsec 1	Xsec 2
20	0.18	0.44
40	0.31	0.57
50	0.37	0.62
60	0.42	0.66
70	0.47	0.69
80	0.52	0.73
90	0.56	0.76
100	0.60	0.79
120	0.68	0.84
160	0.81	0.94
200	0.92	1.02
240	1.02	1.09
280	1.11	1.16
330	1.20	1.24
390	1.31	1.32
450	1.40	1.40
510	1.48	1.47
570	1.55	1.54
630	1.61	1.61



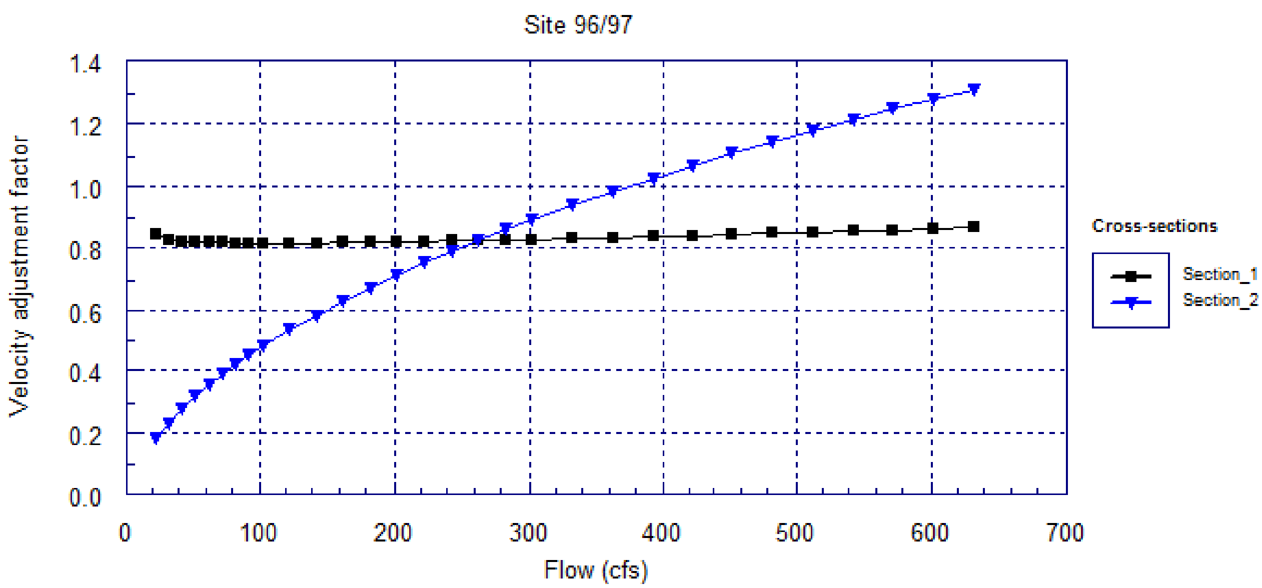
Study Site 95

	Velocity Adjustment Factors	
Discharge (cfs)	Xsec 1	Xsec 2
20	0.09	0.47
40	0.17	0.60
60	0.24	0.67
80	0.30	0.72
100	0.36	0.76
140	0.48	0.82
180	0.59	0.86
220	0.69	0.90
260	0.78	0.93
300	0.88	0.96
360	1.01	1.00
420	1.13	1.04
480	1.25	1.08
540	1.37	1.11
600	1.48	1.14
630	1.53	1.16



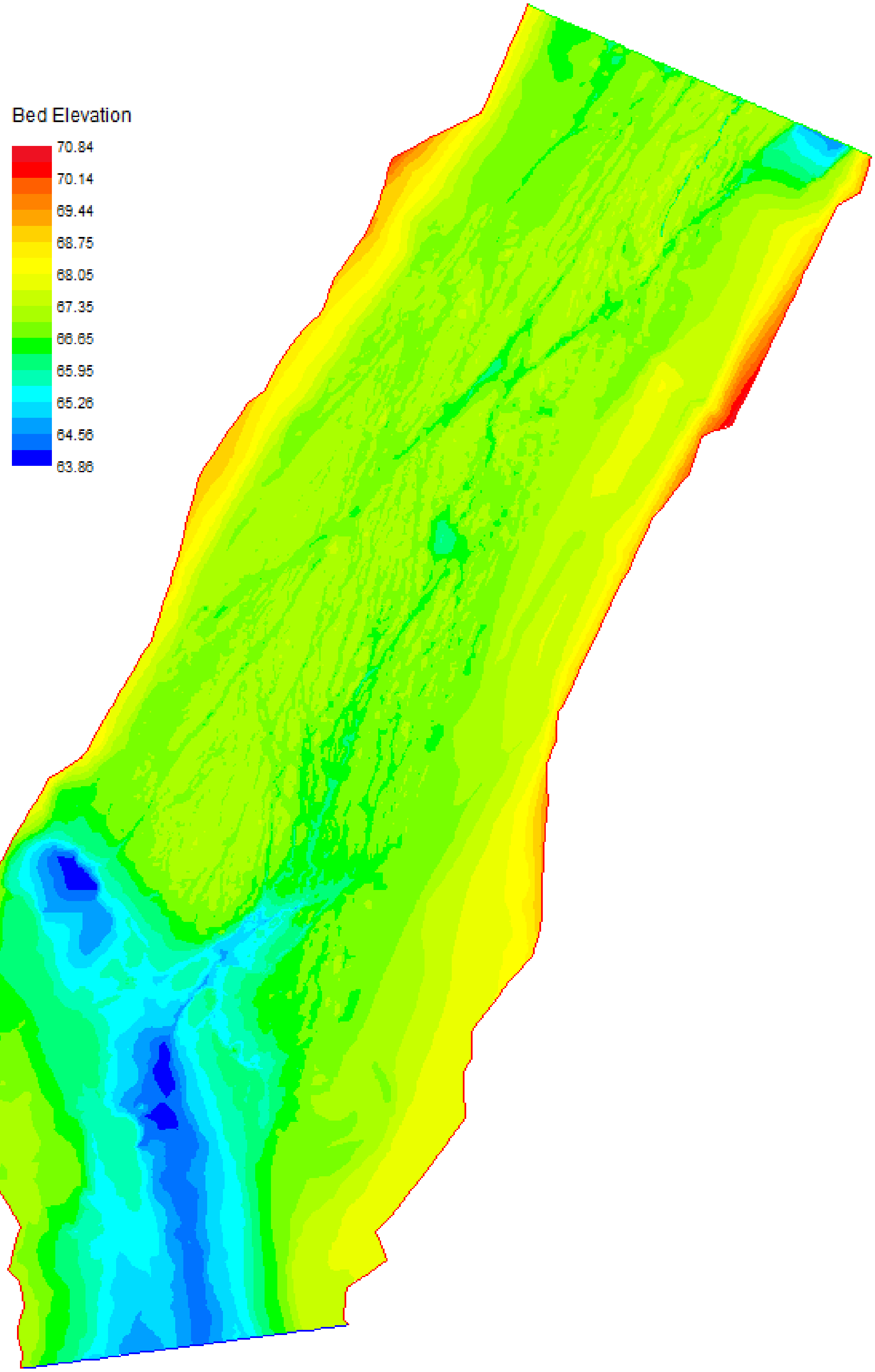
Study Site 96/97

	Velocity Adjustment Factors	
Discharge (cfs)	Xsec 1	Xsec 2
20	0.84	0.18
40	0.82	0.27
60	0.81	0.35
80	0.81	0.42
100	0.81	0.48
140	0.81	0.58
180	0.82	0.67
220	0.82	0.75
260	0.82	0.82
300	0.83	0.89
360	0.83	0.98
420	0.84	1.06
480	0.84	1.14
540	0.85	1.21
600	0.86	1.28
630	0.86	1.31



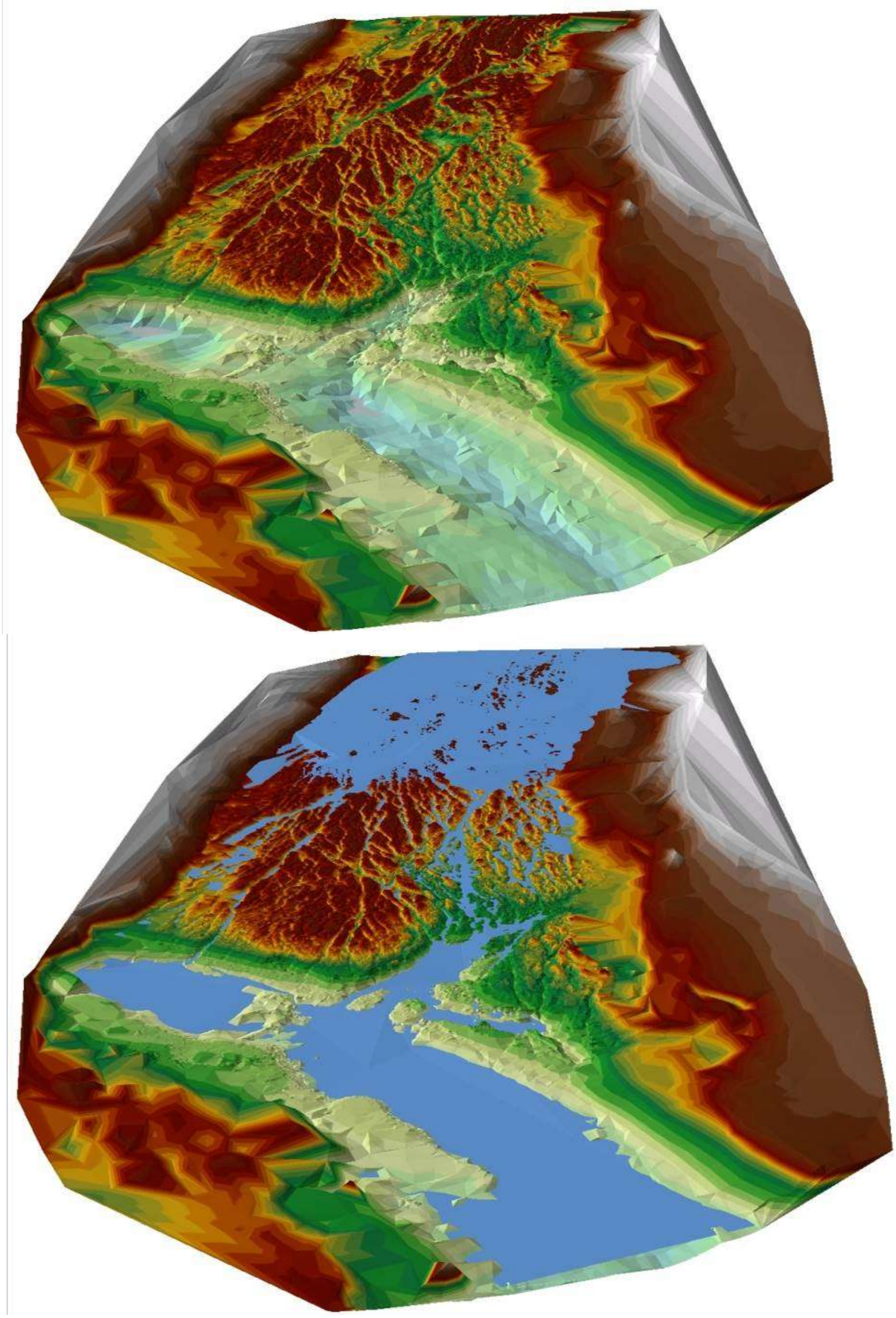
Appendix C. Bed Topography of Study Sites

Lahar Study Site

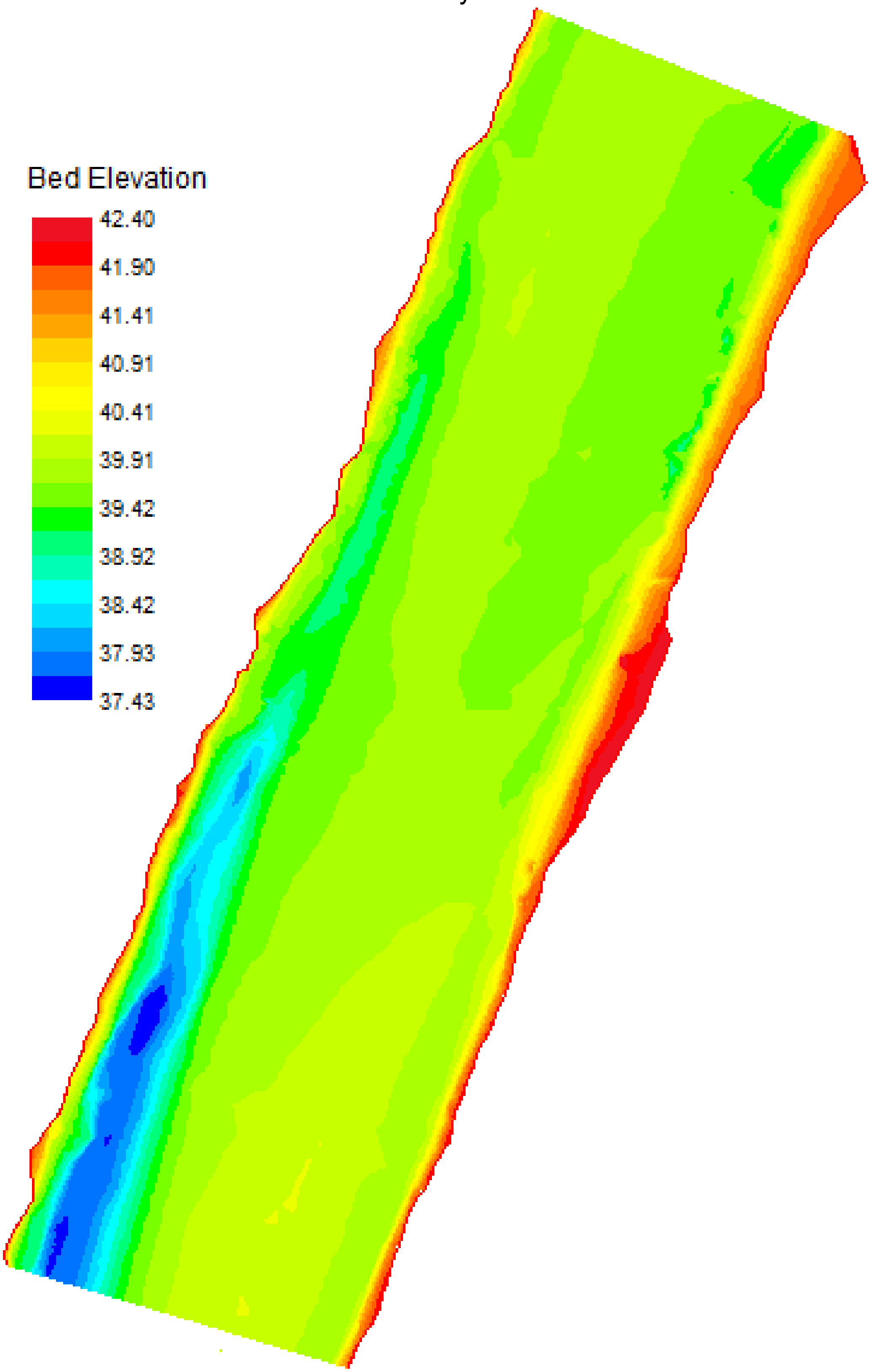


Units of Bed Elevation are meters.

Lahar Study Site Digital Terrain Model

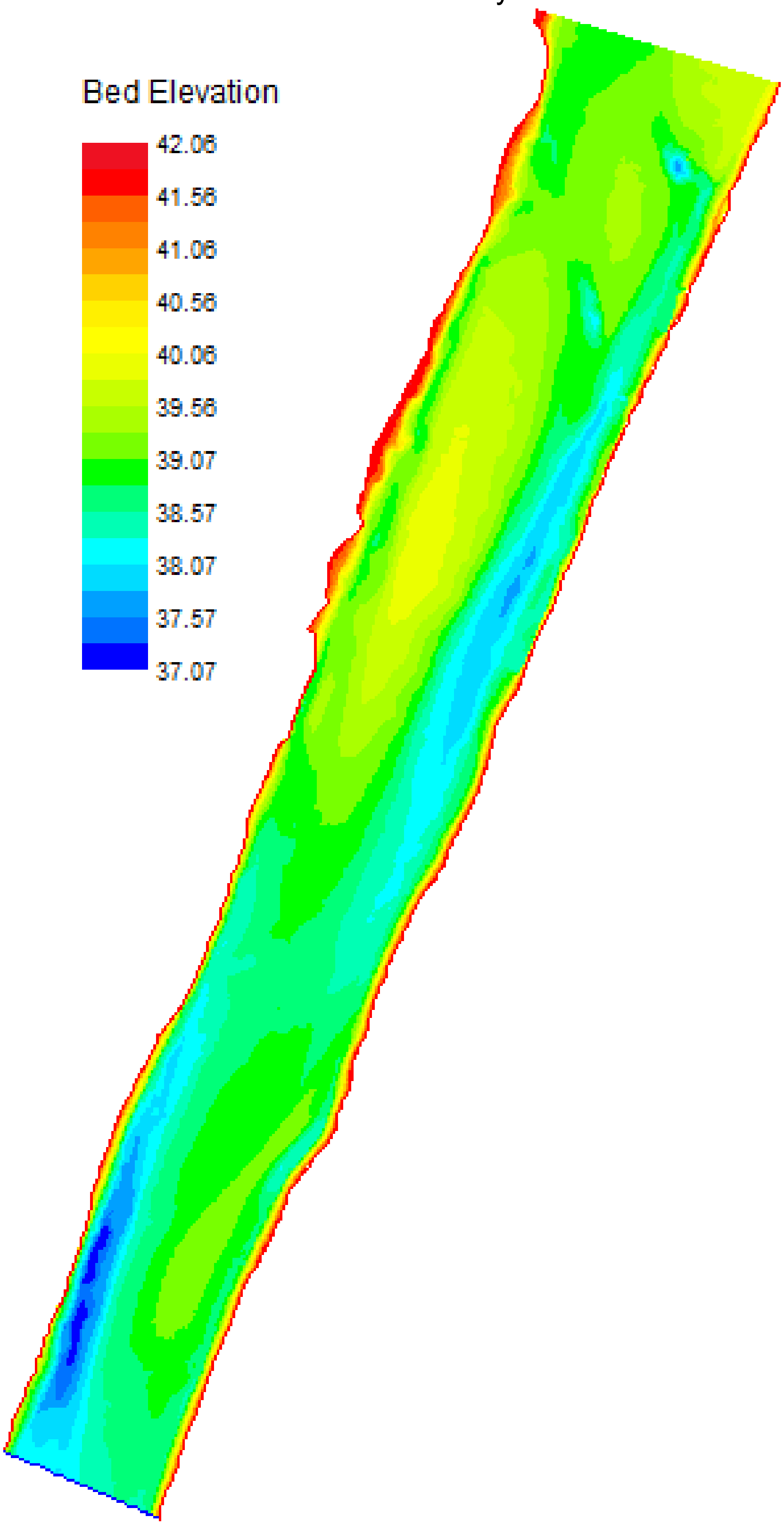


Study Site 95



Units of Bed Elevation are meters.

Study Site 96/97

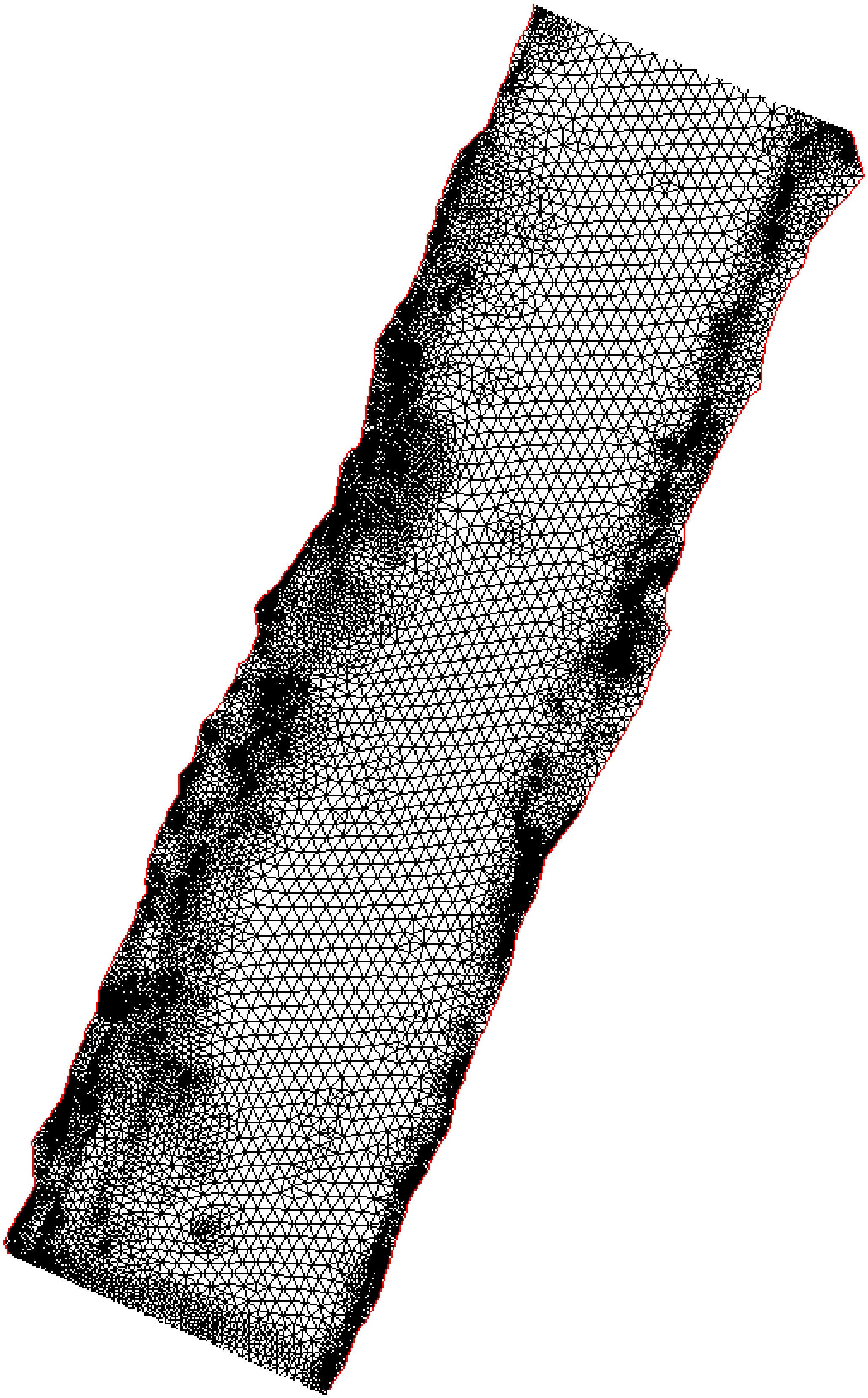


Units of Bed Elevation are meters.

Appendix D. Computational Meshes of Study Sites.

Lahar Study Site

Study Site 95



Study Site 96/97

Appendix E. 2-D WSEL Calibration

Calibration Statistics[23]

Site Name	% Nodes within 0.1'	Nodes	QI	Net Q	Sol Δ	Max F
Lahar	59%	100,369	0.30	4.2%	0.000001	5.97
Site 95	93%	21,957	0.30	0.01%	0.000006	1.59
Site 96/97	93%	27,218	0.30	0.02%	0.000008	1.26

Lahar

		Difference (measured vs. pred. WSELs, absolute value, feet)		
XSEC	BR Mult[24]	Average	Standard Deviation	Maximum
2	0.3	0.05	0.03	0.19

Site 95

		Difference (measured vs. pred. WSELs, absolute value, feet)		
XSEC	BR Mult	Average	Standard Deviation	Maximum
2	0.35	0.01	0.01	0.03

Site 96/97

		Difference (measured vs. pred. WSELs, absolute value, feet)		
XSEC	BR Mult	Average	Standard Deviation	Maximum
2	0.5	0.05	0.02	0.10

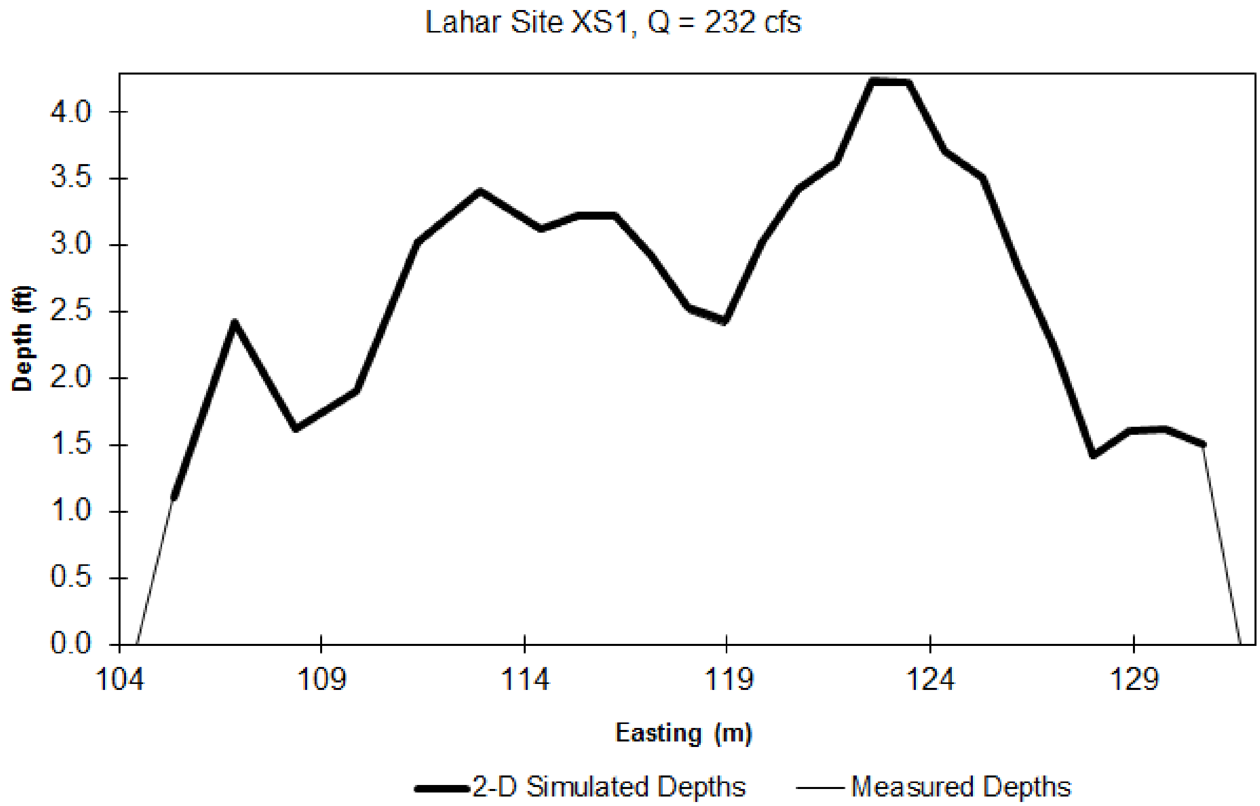
[23] QI = Quality Index, Net Q = Net Flow, Sol Δ = Solution change, Max F = Maximum Froude Number
[24] BR Mult = Bed Roughness Multiplier

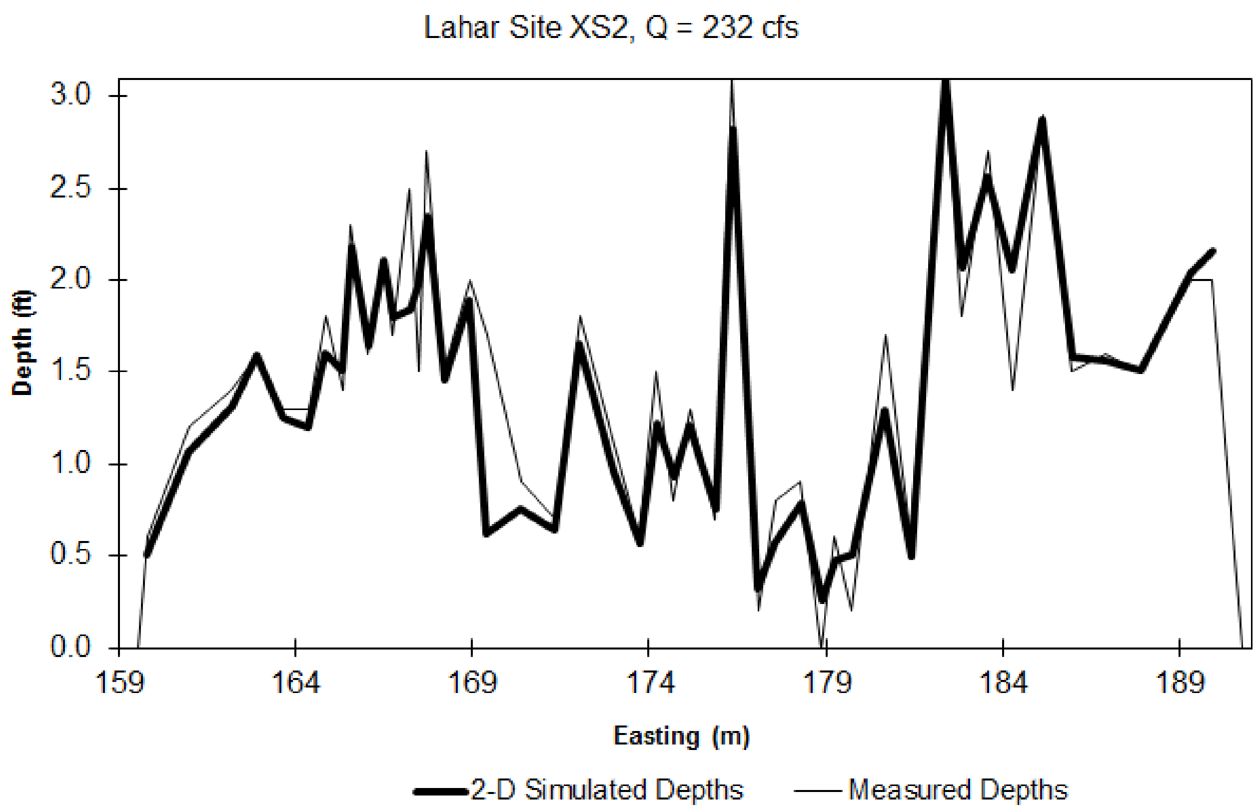
Appendix F. Depth Validation Statistics

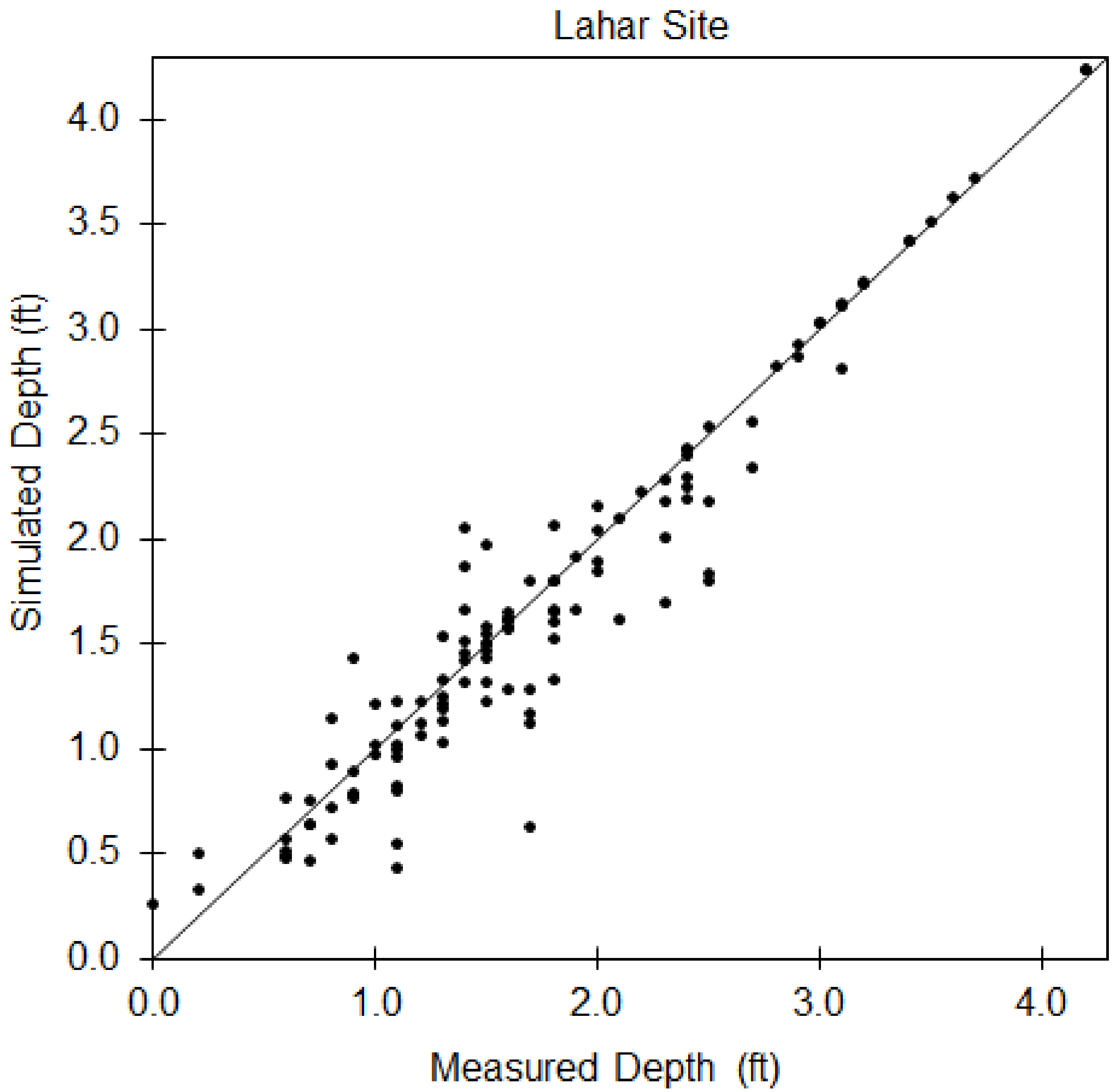
Site Name	Number of Observations	Correlation Between Measured and Simulated Depths
Lahar	121	0.96
Site 95	106	0.98
Site 96/97	96	0.99

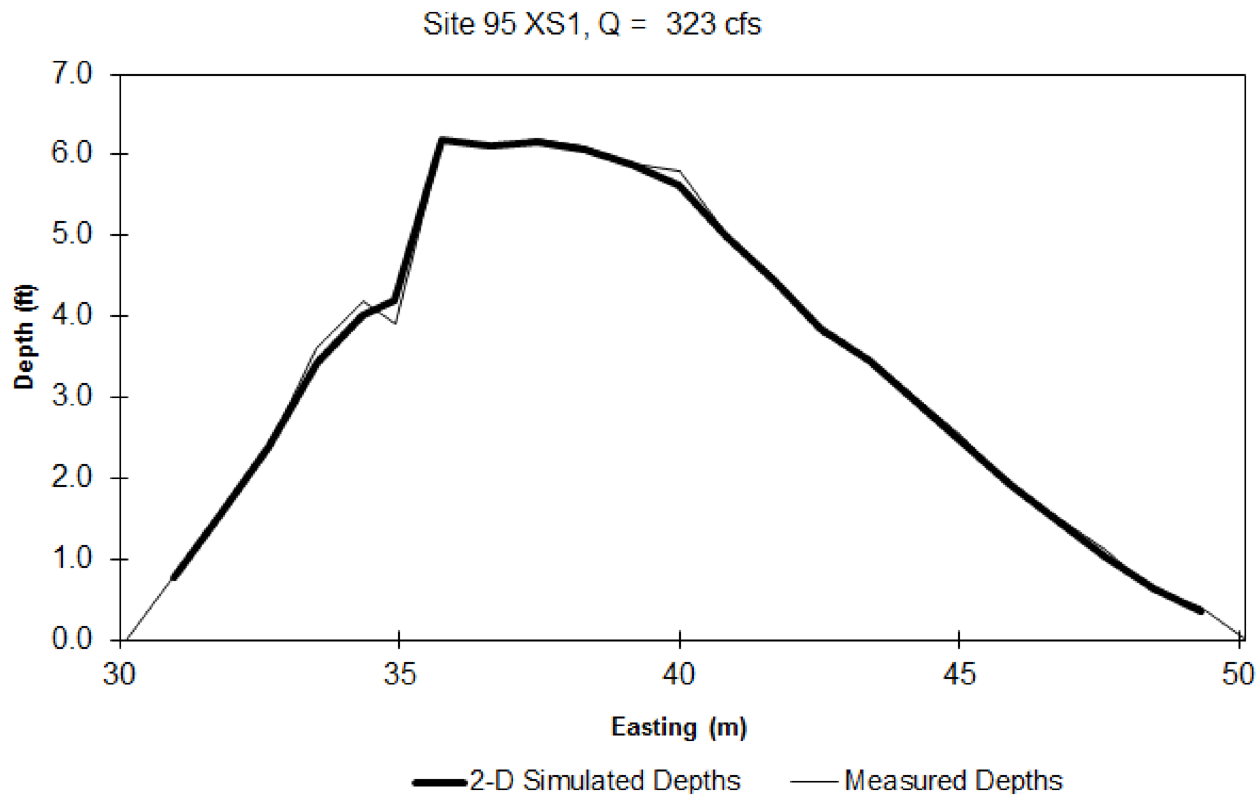
Difference (measured vs. pred. depths, absolute value, ft)

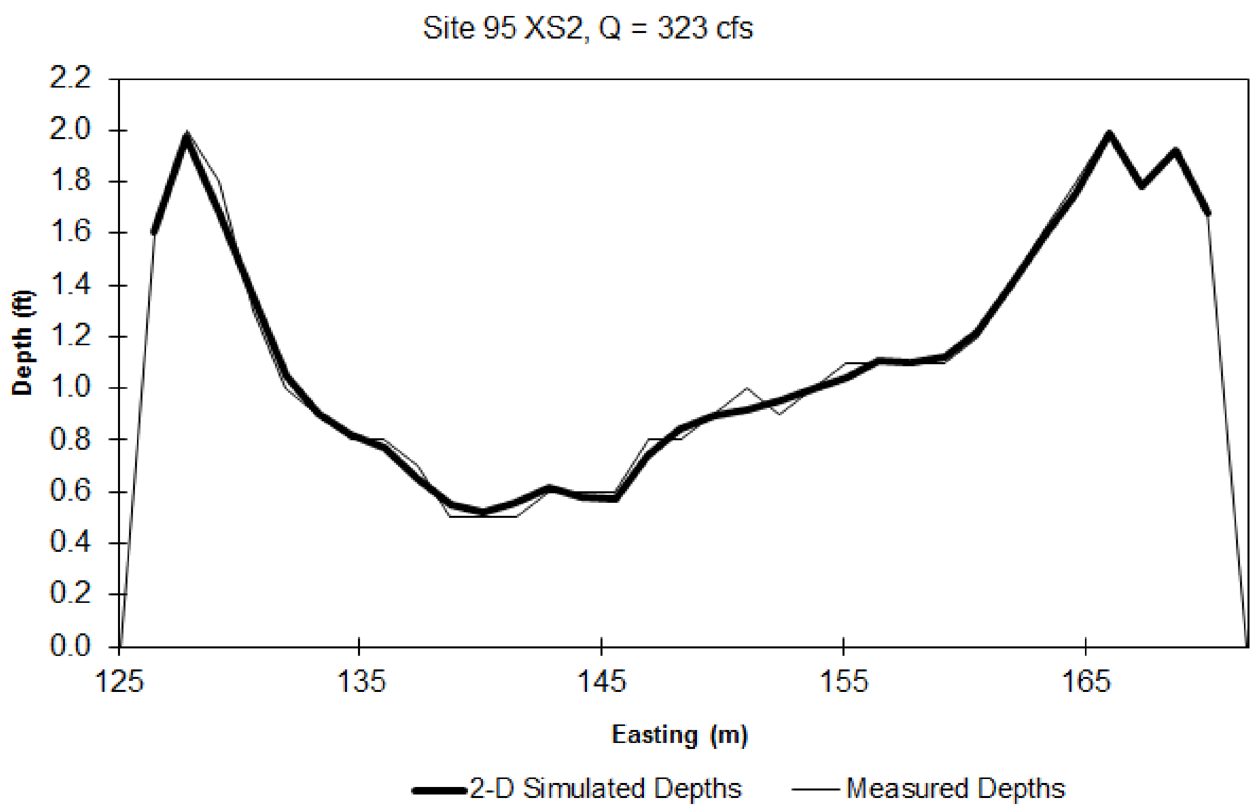
Site Name	Average	Standard Deviation	Maximum
Lahar	0.2	0.2	1.1
Site 95	0.1	0.2	1.8
Site 96/97	0.1	0.1	0.3

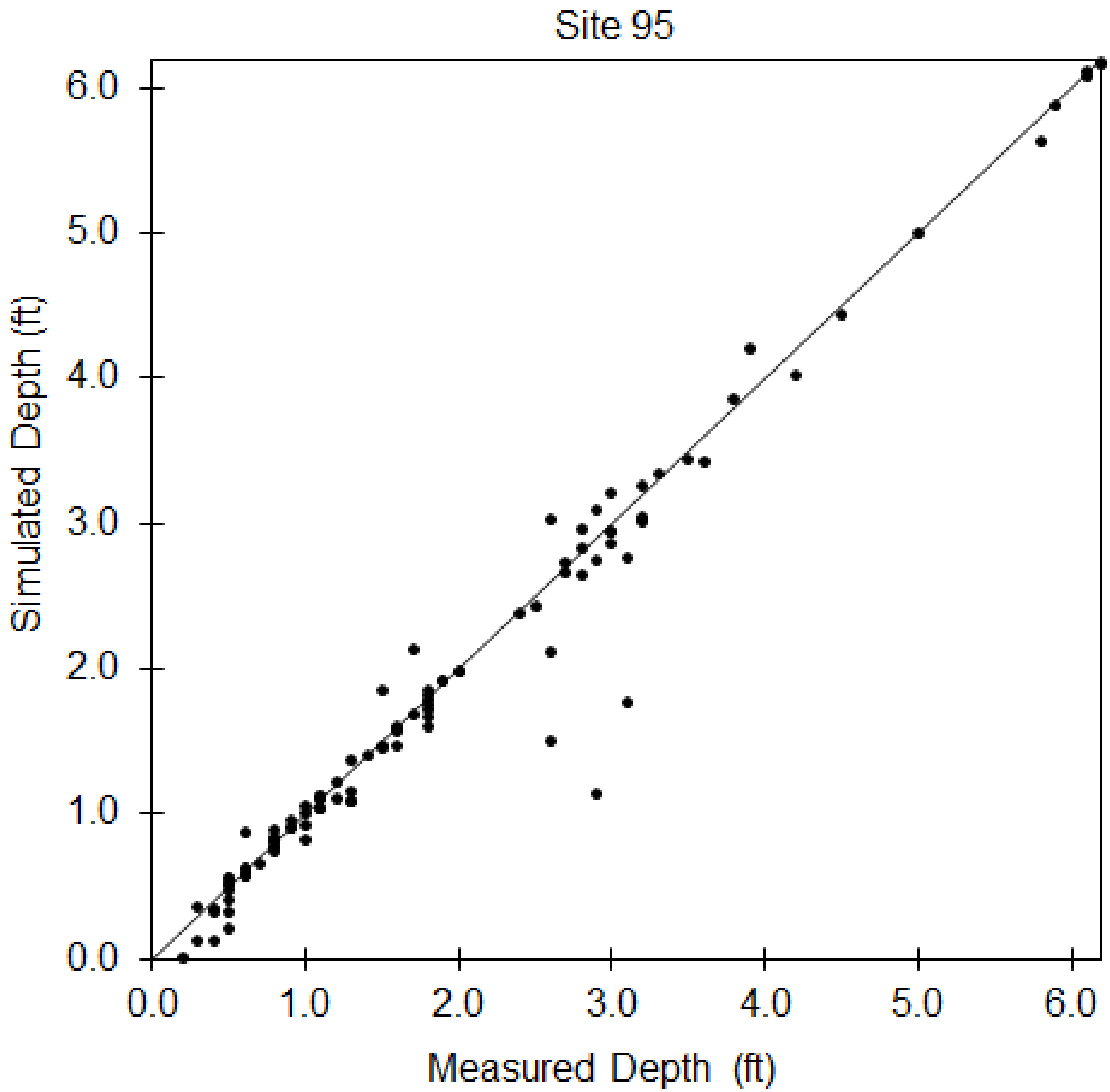

Lahar Site XS1, Q = 232 cfs
Depth (ft)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
104
109
114
119
124
129
Easting (m)
2-D Simulated Depths
Measured Depths


Lahar Site XS2, Q = 232 cfs
Depth (ft)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
159
164
169
174
179
184
189
Easting (m)
2-D Simulated Depths
Measured Depths

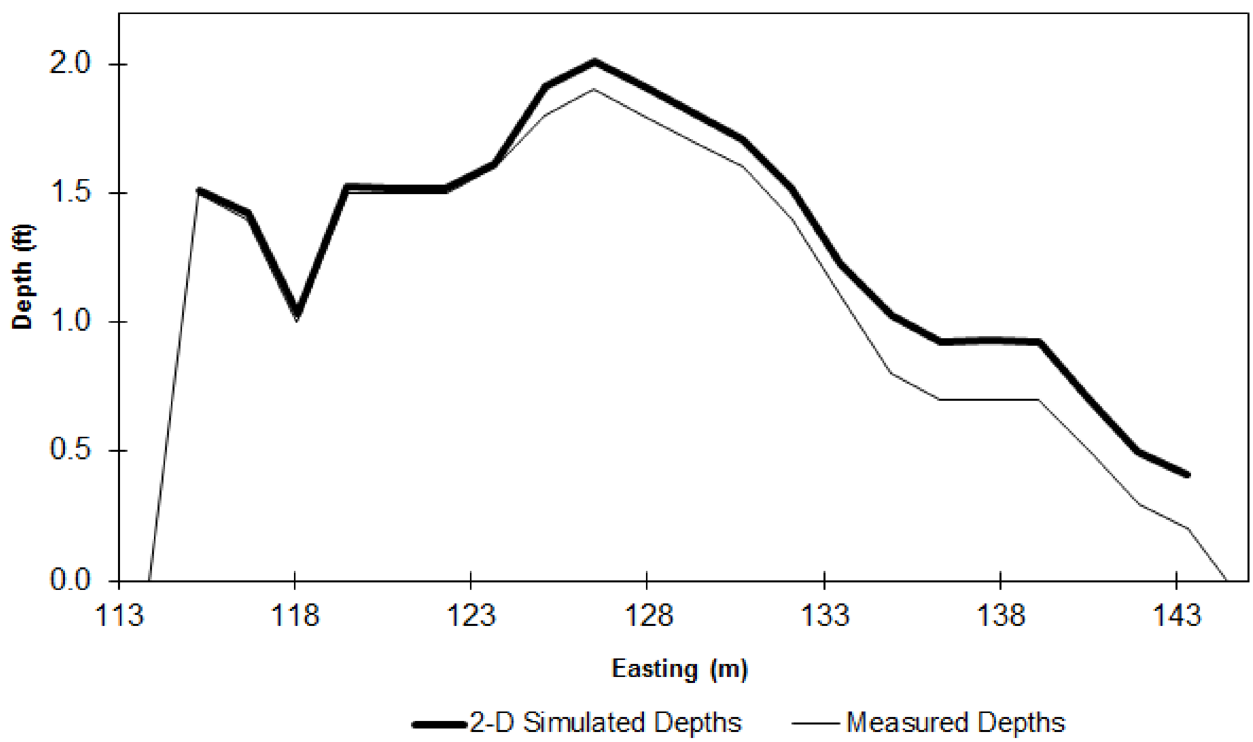

Lahar Site
Simulated Depth (ft)
Measured Depth (ft)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


Site 95 XS1, Q = 323 cfs
Depth (ft)
Easting (m)
2-D Simulated Depths
Measured Depths

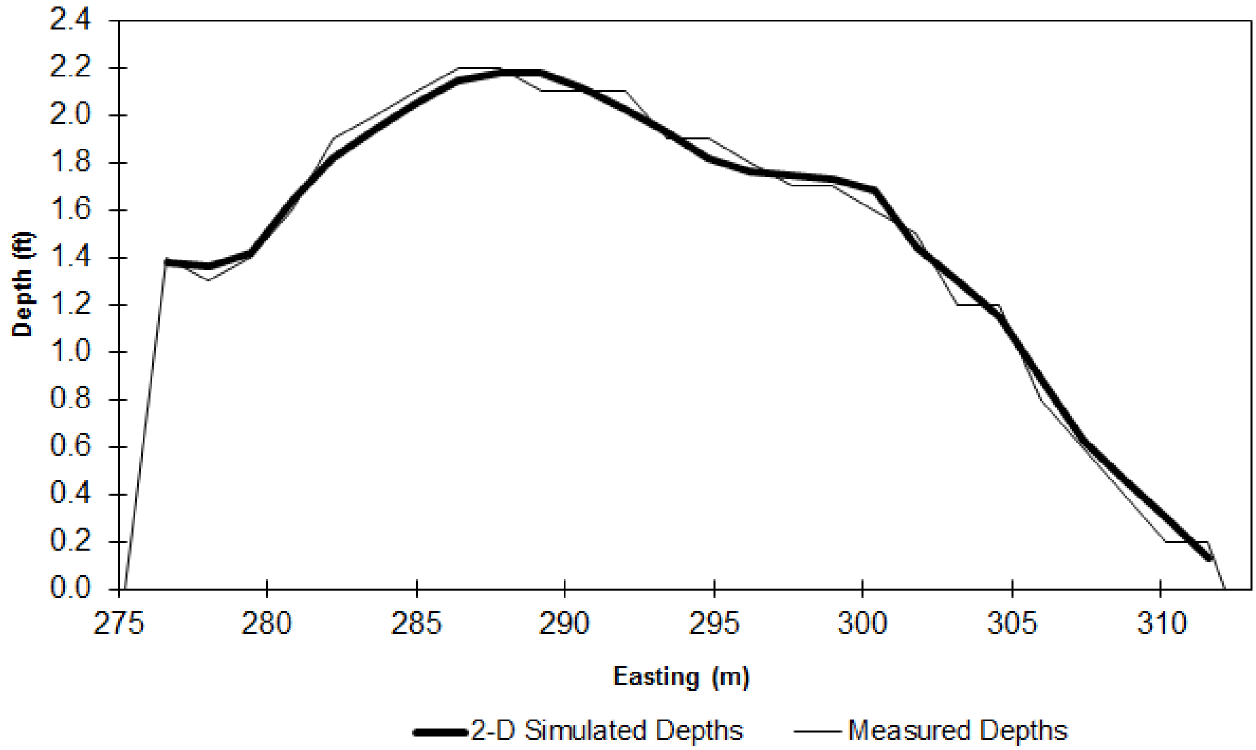

Site 95 XS2, Q = 323 cfs
Depth (ft)
Easting (m)
2-D Simulated Depths
Measured Depths

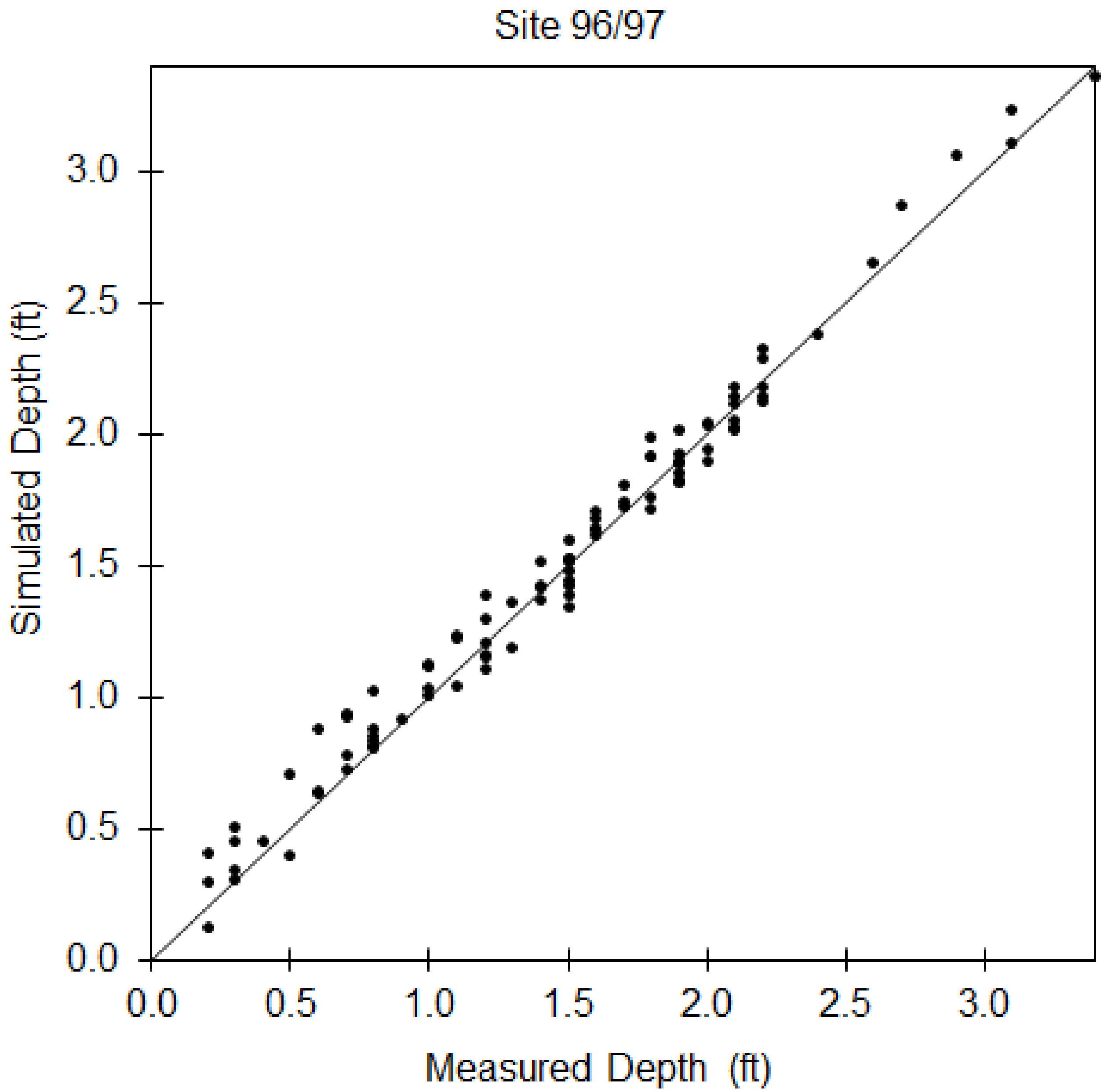

Site 95
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Simulated Depth (ft)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Measured Depth (ft)

Site 96/97 XS1, Q = 350 cfs



Site 96/97 XS2, Q = 350 cfs




Site 96/97
Simulated Depth (ft)
Measured Depth (ft)
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Appendix G. Simulation statistics.

Lahar Site 2D Model			
Flow (cfs)	Net Q	Sol Δ	Max F
630	1.3%	0.000002	11.22
600	1.6%	0.000002	13.85
570	2.2%	0.000002	16.01
540	1.0%	0.000001	20.48
510	0.7%	0.000007	26.44
480	4.0%	0.000002	7.88
450	4.9%	0.000002	7.28
420	0.7%	0.000001	5.85
415	3.8%	0.000001	6.17
410	3.8%	0.000002	7.18
405	3.6%	0.000002	8.79
400	7.4%	0.000002	5.98
395	2.1%	0.000002	6.98
390	2.7%	0.000001	7.82
360	1.7%	0.000001	8.67
330	3.0%	0.000001	17.75
300	6.2%	0.000001	5.60
280	2.4%	0.000001	6.62
260	7.3%	0.000001	6.18
240	5.9%	0.000001	10.41
220	2.3%	0.000005	6.65
200	2.1%	0.000003	9.54
180	5.0%	0.000003	9.69
160	1.7%	0.000003	8.69
140	0.04%	0.000003	5.09
120	0.03%	<0.000001	4.77
115	0.05%	<0.000001	4.55
110	0.04%	0.000003	4.78
105	0.02%	0.000003	4.99
100	0.5%	0.000008	5.19
95	0.1%	0.000002	5.55
90	0.2%	0.000002	10.87
85	0.05%	<0.000001	6.94
80	0.1%	0.000005	9.43
75	0.03%	0.000002	8.42
70	0.4%	<0.000001	4.96
65	0.07%	<0.000001	5.52
60	0.1%	<0.000001	6.41
55	0.08%	<0.000001	9.40
50	0.2%	0.000003	6.54
45	0.1%	0.000002	7.19
40	1.1%	0.000002	7.53
30	0.2%	0.000004	10.81

20	1.1%	<0.000001	9.12

Site 95 2D Model			
Flow (cfs)	**Net Q**	**Sol Δ**	**Max F**
630	0.01%	0.000006	1.59
600	0.2%	0.000003	1.70
570	0.002%	0.000001	1.85
540	0.9%	0.000005	1.97
510	1.3%	0.000005	2.05
480	1.1%	0.000007	2.11
450	1.0%	0.000007	2.24
420	2.5%	0.000007	2.36
390	0.4%	<0.000001	2.58
360	3.4%	<0.000001	2.54
330	0.9%	0.000005	2.21
325	0.04%	0.000005	2.17
320	0.1%	0.000006	2.16
315	0.3%	0.000006	2.18
310	0.6%	0.000006	2.21
305	0.2%	0.000008	2.24
300	0.3%	0.000007	2.26
280	0.5%	0.000008	2.19
260	0.05%	0.000005	2.04
240	0.9%	<0.000001	2.11
220	2.6%	0.000001	1.99
200	3.6%	0.000007	1.71
180	2.5%	0.000001	2.02
160	1.7%	0.000007	2.38
140	0.1%	0.000007	2.13
120	0.2%	0.000007	1.86
100	0.1%	0.000007	1.55
90	0.6%	0.000006	1.61
80	0.1%	0.000007	1.64
70	0.4%	0.000008	1.49
60	0.1%	0.000007	1.25
50	0.4%	0.000004	1.04
40	0.2%	0.000007	1.04
30	0.3%	0.000003	1.08

20	0.2%	0.000006	1.19

Site 96/97 2D Model			
Flow (cfs)	**Net Q**	**Sol Δ**	**Max F**
630	0.02%	0.000008	1.26
600	0.01%	0.000001	1.22
570	0.002%	0.000002	1.02
540	0.001%	0.000002	1.03
510	0.02%	0.000002	1.13
480	0.01%	0.000002	1.19
450	0.02%	0.000002	1.19
420	0.004%	0.000001	1.18
415	0.01%	0.000002	1.17
410	0.008%	0.000002	1.17
405	0.02%	0.000002	1.20
400	0.005%	0.000001	1.22
395	0.003%	0.000002	1.25
390	0.001%	0.000002	1.27
360	0.02%	0.000001	1.35
330	0.1%	0.000001	1.33
300	0.1%	0.000003	1.3
280	0.2%	0.000007	1.35
260	0.2%	0.000007	1.29
240	0.2%	0.000007	1.41
220	0.1%	0.000008	1.46
200	0.1%	0.000009	1.46
180	0.1%	0.000005	1.60
160	0.1%	0.000004	1.64
155	0.1%	0.000008	1.69
150	0.2%	0.000009	1.71
145	0.09%	0.000009	1.78
140	0.03%	0.000007	1.74
120	0.1%	0.000007	1.79
100	0.1%	0.000008	1.79
90	0.1%	0.000001	1.79
80	0.2%	0.000001	1.76
70	0.4%	0.000002	1.71
60	0.3%	0.000002	1.67

50	0.3%	0.000002	1.69
40	0.6%	0.000002	1.69
30	1.3%	0.000001	1.55
20	2.5%	<0.000001	1.65

Appendix H. River2D model outputs for Riffle 95, 96, and 97.

Table H-1. River2D model run results of total and contiguous width meeting the minimum depth criteria for adult SRCS in feet (ft) for Site 95.

Target Species: Adult Spring-run Chinook salmon		
Depth Criteria =/> 0.9 (ft)		
Flow (cfs)	**Total (ft)**	**Contiguous (ft)**
630	221	150
600	176	120
570	162	100
540	118	50
510	84	41
480	43	39
450	38	38
420	37	37
390	34	34
360	30	30
330	21	21
325	20	20
320	10	8
315	6	6
310	6	6
305	6	6
300	5	5
280	5	5
260	3	3
240	3	3
220	1	1
200	1	1
180	0	0
160	0	0
140	0	0
120	0	0
100	0	0
90	0	0
80	0	0
70	0	0
60	0	0
50	0	0
40	0	0
30	0	0
20	0	0

Table H-2. River2D model run results of total and contiguous width meeting the minimum depth criteria for adult SRCS in feet (ft) for Site 96/97 riffle 96.

Target Species: Adult spring-run Chinook salmon		
Depth Criteria =/> 0.9 (ft)		
Flow (cfs)	**Total (ft)**	**Contiguous (ft)**
630	178	77
600	167	72
570	166	72
540	123	42
510	98	40
480	74	31
450	57	29
420	44	27
390	42	26
360	41	25
330	35	24
300	29	19
280	27	17
260	26	17
240	25	16
220	25	16
200	24	15
180	19	10
160	19	10
155	19	10
150	19	10
145	18	10
140	6	3
120	1	1
100	0	0
90	0	0
80	0	0
70	0	0
60	0	0
50	0	0
40	0	0
30	0	0
20	0	0

Table H-3. River2D model run results of total and contiguous width meeting the minimum depth criteria for adult SRCS in feet (ft) for Site 96/97 riffle 97.

Target Species: Adult spring-run Chinook salmon		
Depth Criteria =/> 0.9 (ft)		
Flow (cfs)	Total (ft)	Contiguous (ft)
674	181	180
644	166	165
630	145	145
600	120	120
570	115	115
540	100	100
510	95	95
480	80	80
450	46	38
420	36	30
415	30	20
410	30	20
405	21	20
400	19	10
395	17	3
390	4	2
360	0	0
330	0	0
300	0	0
280	0	0
260	0	0
240	0	0
220	0	0
200	0	0
180	0	0
160	0	0
140	0	0
120	0	0
100	0	0
90	0	0
80	0	0
70	0	0
60	0	0
50	0	0
40	0	0

30	0	0
20	0	0

Appendix I. 2014 and 2015 Time Series for the Lahar Site

Table I-1. 2014 Time Series for the Lahar Site.

Date	Max. Temp. (C)	7DADM (C)	Avg. flow (cfs)	Net Passage	Cumulative net passage	Cumulative passage	Limiting Width (ft)
2/7/2014	7.4		122	0			1.34
2/8/2014	8.3		528	0			8.67
2/9/2014	9.3		863	0			12.27
2/10/2014	10.3		839	0			12.27
2/11/2014	10.0		504	0			8.44
2/12/2014	10.3		222	0			2.47
2/13/2014	9.97	9.37	188	0	0		1.69
2/14/2014	11.79	9.99	177	1	1	0.02%	1.66
2/15/2014	11.34	10.42	154	2	3	0.06%	1.44
2/16/2014	11.98	10.80	174	8	11	0.23%	1.62
2/17/2014	10.87	10.89	178	15	26	0.55%	1.67
2/18/2014	10.21	10.92	162	26	52	1.10%	1.47
2/19/2014	10.99	11.02	152	25	77	1.62%	1.43
2/20/2014	10.72	11.13	136	30	107	2.26%	1.37
2/21/2014	11.01	11.02	112	22	129	2.72%	0.68
2/22/2014	11.19	10.99	105	27	156	3.29%	0.60
2/23/2014	11.38	10.91	100	32	188	3.97%	0.59
2/24/2014	11.62	11.02	95.8	70	258	5.44%	0.48
2/25/2014	11.80	11.24	92.6	15	273	5.76%	0.47
2/26/2014	11.18	11.27	93.5	1	274	5.78%	0.48
2/27/2014	10.56	11.25	415	5	279	5.89%	7.04
2/28/2014	9.74	11.07	382	10	289	6.10%	4.06
3/1/2014	10.22	10.93	481	2	291	6.14%	8.18
3/2/2014	10.19	10.76	357	0	291	6.14%	3.92
3/3/2014	10.13	10.55	593	0	291	6.14%	9.49
¾/2014	11.10	10.45	884	23	314	6.62%	12.27
3/5/2014	11.19	10.45	521	8	322	6.79%	8.61
3/6/2014	11.61	10.60	967	89	411	8.67%	12.27
3/7/2014	11.48	10.85	578	4	415	8.76%	9.39
3/8/2014	11.33	11.00	414	5	420	8.86%	6.93
3/9/2014	10.72	11.08	357	97	517	10.91%	3.92
3/10/2014	11.59	11.29	645	157	674	14.22%	12.27
3/11/2014	10.84	11.25	556	43	717	15.13%	9.07
3/12/2014	10.92	11.21	426	9	726	15.32%	7.67
3/13/2014	11.19	11.15	575	57	783	16.52%	9.36
3/14/2014	11.64	11.18	489	40	823	17.36%	8.26
3/15/2014	12.32	11.32	388	60	883	18.63%	4.09
3/16/2014	12.89	11.63	313	88	971	20.49%	3.72

Date	Max. Temp. (C)	7DADM (C)	Avg. flow (cfs)	Net Passage	Cumulative net passage	Cumulative passage	Limiting Width (ft)
3/17/2014	12.63	11.78	270	236	1207	25.46%	3.33
3/18/2014	12.36	11.99	232	90	1297	27.36%	2.74
3/19/2014	12.36	12.20	222	159	1456	30.72%	2.49
3/20/2014	12.82	12.43	210	140	1596	33.67%	2.03
3/21/2014	12.95	12.62	212	48	1644	34.68%	2.14
3/22/2014	12.92	12.70	205	45	1689	35.63%	1.85
3/23/2014	13.15	12.74	189	94	1783	37.62%	1.69
3/24/2014	13.26	12.83	185	97	1880	39.66%	1.69
3/25/2014	12.52	12.86	205	40	1920	40.51%	1.89
3/26/2014	11.05	12.67	473	108	2028	42.78%	8.10
3/27/2014	11.54	12.48	430	333	2361	49.81%	7.70
3/28/2014	11.08	12.22	257	41	2402	50.68%	3.11
3/29/2014	10.80	11.91	1355	4	2406	50.76%	12.27
3/30/2014	10.28	11.50	1121	138	2544	53.67%	12.27
3/31/2014	9.71	11.00	709	43	2587	54.58%	12.27
4/1/2014	8.99	10.49	629	3	2590	54.64%	12.18
4/2/2014	10.54	10.42	544	15	2605	54.96%	8.85
4/3/2014	10.70	10.30	471	19	2624	55.36%	8.07
4/4/2014	10.30	10.19	445	12	2636	55.61%	7.81
4/5/2014	11.43	10.28	625	9	2645	55.80%	11.72
4/6/2014	12.53	10.60	506	172	2817	59.43%	8.45
4/7/2014	13.45	11.14	456	336	3153	66.52%	7.90
4/8/2014	13.91	11.84	409	107	3260	68.78%	6.34
4/9/2014	14.45	12.40	379	67	3327	70.19%	4.04
4/10/2014	14.88	12.99	333	91	3418	72.11%	3.81
4/11/2014	14.99	13.66	299	42	3460	73.00%	3.65
4/12/2014	15.26	14.21	275	60	3520	74.26%	3.43
4/13/2014	15.38	14.62	254	25	3545	74.79%	3.08
4/14/2014	15.37	14.89	201	71	3616	76.29%	1.74
4/15/2014	15.77	15.16	135	58	3674	77.51%	1.37
4/16/2014	15.88	15.36	137	98	3772	79.58%	1.37
4/17/2014	16.59	15.61	128	103	3875	81.75%	1.36
4/18/2014	16.64	15.84	145	120	3995	84.28%	1.40
4/19/2014	16.76	16.06	126	132	4127	87.07%	1.35
4/20/2014	16.83	16.26	116	41	4168	87.93%	0.72
4/21/2014	16.10	16.37	108	57	4225	89.14%	0.64
4/22/2014	16.23	16.43	110	35	4260	89.87%	0.66
4/23/2014	15.85	16.43	115	31	4291	90.53%	0.71
4/24/2014	15.60	16.29	109	47	4338	91.52%	0.65

Date	Max. Temp. (C)	7DADM (C)	Avg. flow (cfs)	Net Passage	Cumulative net passage	Cumulative passage	Limiting Width (ft)
4/25/2014	15.02	16.05	125	14	4352	91.81%	1.35
4/26/2014	14.16	15.68	137	11	4363	92.05%	1.37
4/27/2014	13.67	15.23	119	16	4379	92.38%	1.22
4/28/2014	15.15	15.10	109	17	4396	92.74%	0.65
4/29/2014	16.18	15.09	98.5	82	4478	94.47%	0.55
4/30/2014	17.07	15.26	91.3	50	4528	95.53%	0.47
5/1/2014	17.37	15.52	86.5	43	4571	96.43%	0.33
5/2/2014	17.59	15.88	82.0	13	4584	96.71%	0.28
5/3/2014	17.59	16.38	75.1	17	4601	97.07%	0.28
5/4/2014	17.03	16.86	70.8	6	4607	97.19%	0.28
5/5/2014	17.04	17.13	70.1	3	4610	97.26%	0.28
5/6/2014	17.16	17.27	74.0	6	4616	97.38%	0.28
5/7/2014	17.07	17.26	68.2	4	4620	97.47%	0.26
5/8/2014	16.61	17.16	67.1	4	4624	97.55%	0.26
5/9/2014	17.45	17.14	80.2	0	4624	97.55%	0.28
5/10/2014	17.17	17.08	77.6	1	4625	97.57%	0.28
5/11/2014	17.14	17.09	71.3	0	4625	97.57%	0.28
5/12/2014	17.89	17.21	67.3	2	4627	97.62%	0.26
5/13/2014	18.33	17.38	64.9	0	4627	97.62%	0.24
5/14/2014	19.07	17.66	54.8	5	4632	97.72%	0.23
5/15/2014	18.97	18.00	49.2	35	4667	98.46%	0.23
5/16/2014	19.32	18.27	54.4	6	4673	98.59%	0.23
5/17/2014	19.23	18.56	53.9	0	4673	98.59%	0.23
5/18/2014	19.48	18.90	53.8	0	4673	98.59%	0.23
5/19/2014	18.96	19.05	54.2	0	4673	98.59%	0.23
5/20/2014	18.49	19.07	57.7	0	4673	98.59%	0.23
5/21/2014	18.91	19.05	88.2	0	4673	98.59%	0.40
5/22/2014	19.79	19.17	69.9	1	4674	98.61%	0.27
5/23/2014	19.70	19.22	64.1	6	4680	98.73%	0.24
5/24/2014	20.19	19.36	63.2	0	4680	98.73%	0.24
5/25/2014	20.81	19.55	60.9	0	4680	98.73%	0.23
5/26/2014	20.82	19.82	58.6	2	4682	98.78%	0.23
5/27/2014	20.54	20.11	56.3	1	4683	98.80%	0.23
5/28/2014	20.01	20.27	58.3	0	4683	98.80%	0.23
5/29/2014	19.77	20.26	60.4	0	4683	98.80%	0.23
5/30/2014	19.97	20.30	59.6	0	4683	98.80%	0.23
5/31/2014	19.80	20.24	58.8	0	4683	98.80%	0.23
6/1/2014	20.37	20.18	58.7	0	4683	98.80%	0.23
6/2/2014	20.55	20.14	57.6	0	4683	98.80%	0.23

Date	Max. Temp. (C)	7DADM (C)	Avg. flow (cfs)	Net Passage	Cumulative net passage	Cumulative passage	Limiting Width (ft)
6/3/2014	20.38	20.12	52.5	0	4683	98.80%	0.23
6/4/2014	21.15	20.28	42.9	0	4683	98.80%	0.20
6/5/2014	21.43	20.52	41.6	6	4689	98.92%	0.19
6/6/2014	21.95	20.80	40.5	7	4696	99.07%	0.19
6/7/2014	22.29	21.16	39.7	0	4696	99.07%	0.17
6/8/2014	22.43	21.45	38.8	44	4740	100.00%	0.15
6/9/2014	22.98	21.80	35.1	-2	4738	99.96%	0.10
6/10/2014	23.04	22.18	32.7	2	4740	100.00%	0.04
6/11/2014	22.64	22.39	36.2	2	4742	100.04%	0.11
6/12/2014	22.12	22.49	35.6	0	4742	100.04%	0.10
6/13/2014	21.82	22.47	33.9	0	4742	100.04%	0.06
6/14/2014	21.50	22.36	33.8	0	4742	100.04%	0.06
6/15/2014	21.37	22.21	31.3	0	4742	100.04%	0.02
6/16/2014	21.21	21.96	28.9	0	4742	100.04%	0.00
6/17/2014	21.10	21.68	27.2	0	4742	100.04%	0.00
6/18/2014	21.41	21.50	30.3	-2	4740	100.00%	0.00
6/19/2014	21.64	21.44	29.1	-1	4739	99.98%	0.00
6/20/2014	22.10	21.48	29.6	0	4739	99.98%	0.00
6/21/2014	22.08	21.56	28.7	-1	4738	99.96%	0.00
6/22/2014	21.95	21.64	26.4	0	4738	99.96%	0.00
6/23/2014	22.32	21.80	25.9	0	4738	99.96%	0.00
6/24/2014	22.64	22.02	25.6	1	4739	99.98%	0.00
6/25/2014	22.46	22.17	27.7	0	4739	99.98%	0.00
6/26/2014	22.09	22.23	29.0	0	4739	99.98%	0.00
6/27/2014	22.62	22.31	30.4	0	4739	99.98%	0.00
6/28/2014	22.96	22.43	32.8	1	4740	100.00%	0.04
6/29/2014	23.25	22.62	30.4	0	4740	100.00%	0.00
6/30/2014	23.48	22.79	29.2	0	4740	100.00%	0.00

Table I-2. 2015 Time Series for the Lahar Site.

Date	Max. Temp. (C)	7DADM (C)	Avg. flow (cfs)	Net Passage	Cumulative net passage	Cumulative passage	Limiting Width (ft)
2/6/2015	10.285		309	0			3.70
2/7/2015	10.568		1426	0			12.27
2/8/2015	10.727		728	0			12.27
2/9/2015	1.2797		1155	0			12.27
2/10/2015	9.763		839	0			12.27
2/11/2015	9.805		612	0			10.63
2/12/2015	10.529	9.0	370	0	0		3.98
2/13/2015	11.109	9.1	330	1	1	0.1%	3.80
2/14/2015	11.494	9.2	299	2	3	0.2%	3.65
2/15/2015	11.052	9.3	280	16	19	1.0%	3.51
2/16/2015	11.157	10.7	264	13	32	1.7%	3.19
2/17/2015	11.18	10.9	252	32	64	3.3%	3.06
2/18/2015	11.04	11.1	242	21	85	4.4%	3.00
2/19/2015	11.048	11.2	233	2	87	4.5%	2.79
2/20/2015	11.517	11.2	227	16	103	5.3%	2.63
2/21/2015	10.769	11.1	221	33	136	7.0%	2.44
2/22/2015	10.65	11.1	216	42	178	9.2%	2.34
2/23/2015	9.682	10.8	207	4	182	9.4%	2.21
2/24/2015	9.127	10.5	198	4	186	9.6%	1.70
2/25/2015	8.966	10.3	194	4	190	9.8%	1.70
2/26/2015	10.087	10.1	191	7	197	10.2%	1.70
2/27/2015	10.511	10.0	182	35	232	12.0%	1.69
2/28/2015	10.484	9.9	183	15	247	12.7%	1.69
3/1/2015	10.24	9.9	179	14	261	13.5%	1.67
3/2/2015	10.318	10.0	175	15	276	14.2%	1.63
3/3/2015	10.299	10.1	174	14	290	15.0%	1.62
3/4/2015	10.041	10.3	170	4	294	15.2%	1.58
3/5/2015	10.355	10.3	167	11	305	15.7%	1.54
3/6/2015	10.775	10.4	165	27	332	17.1%	1.51
3/7/2015	11.14	10.5	162	41	373	19.2%	1.48
3/8/2015	11.654	10.7	157	61	434	22.4%	1.44
3/9/2015	12.213	10.9	153	142	576	29.7%	1.43
3/10/2015	11.746	11.1	149	85	661	34.1%	1.42
3/11/2015	11.467	11.3	151	31	692	35.7%	1.42
3/12/2015	12.83	11.7	161	37	729	37.6%	1.46
3/13/2015	13.459	12.1	150	38	767	39.6%	1.42
3/14/2015	13.469	12.4	145	50	817	42.1%	1.40

Date	Max. Temp. (C)	7DADM (C)	Avg. flow (cfs)	Net Passage	Cumulative net passage	Cumulative passage	Limiting Width (ft)
3/15/2015	13.446	12.7	142	85	902	46.5%	1.38
3/16/2015	12.788	12.7	139	20	922	47.6%	1.38
3/17/2015	14.546	13.1	142	17	939	48.4%	1.38
3/18/2015	14.22	13.5	139	31	970	50.0%	1.38
3/19/2015	14.139	13.7	139	44	1014	52.3%	1.38
3/20/2015	13.563	13.7	133	52	1066	55.0%	1.37
3/21/2015	14.693	13.9	130	48	1114	57.5%	1.36
3/22/2015	14.323	14.0	127	48	1162	59.9%	1.35
3/23/2015	14.066	14.2	153	74	1236	63.7%	1.43
3/24/2015	13.71	14.1	148	30	1266	65.3%	1.41
3/25/2015	14.391	14.1	143	16	1282	66.1%	1.39
3/26/2015	15.13	14.3	136	35	1317	67.9%	1.37
3/27/2015	15.796	14.6	130	61	1378	71.1%	1.36
3/28/2015	16.009	14.8	125	34	1412	72.8%	1.35
3/29/2015	16.065	15.0	122	25	1437	74.1%	1.34
3/30/2015	15.849	15.3	121	22	1459	75.2%	1.34
3/31/2015	15.742	15.6	119	5	1464	75.5%	1.22
4/1/2015	14.733	15.6	117	19	1483	76.5%	0.84
4/2/2015	14.531	15.5	116	5	1488	76.7%	0.72
4/3/2015	14.405	15.3	113	8	1496	77.2%	0.70
4/4/2015	14.076	15.1	108	3	1499	77.3%	0.62
4/5/2015	13.096	14.6	111	4	1503	77.5%	0.67
4/6/2015	12.788	14.2	119	5	1508	77.8%	1.09
4/7/2015	12.023	13.7	135	41	1549	79.9%	1.37
4/8/2015	12.124	13.3	144	7	1556	80.2%	1.40
4/9/2015	12.652	13.0	132	1	1557	80.3%	1.36
4/10/2015	13.521	12.9	126	11	1568	80.9%	1.35
4/11/2015	13.964	12.9	124	9	1577	81.3%	1.35
4/12/2015	14.804	13.1	122	23	1600	82.5%	1.34
4/13/2015	15.02	13.4	110	22	1622	83.7%	0.65
4/14/2015	14.806	13.8	72.8	17	1639	84.5%	0.28
4/15/2015	14.694	14.2	68.6	7	1646	84.9%	0.26
4/16/2015	15.41	14.6	68.9	11	1657	85.5%	0.26
4/17/2015	16.205	15.0	65.2	23	1680	86.6%	0.24
4/18/2015	16.645	15.4	62.2	5	1685	86.9%	0.23
4/19/2015	17.144	15.7	62.1	15	1700	87.7%	0.23
4/20/2015	17.528	16.1	61.4	11	1711	88.2%	0.23
4/21/2015	17.793	16.5	61.1	10	1721	88.8%	0.23

Date	Max. Temp. (C)	7DADM (C)	Avg. flow (cfs)	Net Passage	Cumulative net passage	Cumulative passage	Limiting Width (ft)
4/22/2015	17.864	16.9	55.5	4	1725	89.0%	0.23
4/23/2015	17.903	17.3	41.4	0	1725	89.0%	0.19
4/24/2015	17.243	17.4	36.5	4	1729	89.2%	0.11
4/25/2015	17.235	17.5	50.3	7	1736	89.5%	0.23
4/26/2015	17.416	17.6	63.0	30	1766	91.1%	0.23
4/27/2015	18.175	17.7	62.2	11	1777	91.6%	0.23
4/28/2015	18.633	17.8	58.0	2	1779	91.7%	0.23
4/29/2015	19.021	17.9	55.5	13	1792	92.4%	0.23
4/30/2015	18.522	18.0	54.2	10	1802	92.9%	0.23
5/1/2015	19.301	18.3	52.0	12	1814	93.6%	0.23
5/2/2015	19.347	18.6	44.2	18	1832	94.5%	0.21
5/3/2015	19.15	18.9	35.0	12	1844	95.1%	0.10
5/4/2015	18.893	19.0	31.2	6	1850	95.4%	0.02
5/5/2015	18.542	19.0	29.5	5	1855	95.7%	0.00
5/6/2015	18.615	18.9	27.0	0	1855	95.7%	0.00
5/7/2015	18.101	18.8	24.7	3	1858	95.8%	0.00
5/8/2015	18.137	18.7	25.4	5	1863	96.1%	0.00
5/9/2015	18.583	18.6	23.7	3	1866	96.2%	0.00
5/10/2015	18.58	18.5	25.0	6	1872	96.5%	0.00
5/11/2015	18.629	18.5	24.0	7	1879	96.9%	0.00
5/12/2015	18.118	18.4	22.7	5	1884	97.2%	0.00
5/13/2015	17.855	18.3	23.5	5	1889	97.4%	0.00
5/14/2015	17.57	18.2	24.1	0	1889	97.4%	0.00
5/15/2015	17.495	18.1	23.7	1	1890	97.5%	0.00
5/16/2015	18.597	18.1	24.2	2	1892	97.6%	0.00
5/17/2015	18.264	18.1	25.4	4	1896	97.8%	0.00
5/18/2015	18.631	18.1	25.7	1	1897	97.8%	0.00
5/19/2015	18.597	18.1	25.8	1	1898	97.9%	0.00
5/20/2015	19.056	18.3	28.6	2	1900	98.0%	0.00
5/21/2015	19.135	18.5	27.9	4	1904	98.2%	0.00
5/22/2015	19.424	18.8	25.9	1	1905	98.2%	0.00
5/23/2015	19.684	19.0	27.8	3	1908	98.4%	0.00
5/24/2015	20.037	19.2	26.8	1	1909	98.5%	0.00
5/25/2015	20.141	19.4	19.0	4	1913	98.7%	0.00
5/26/2015	20.356	19.7	15.9	-1	1912	98.6%	0.00
5/27/2015	20.434	19.9	23.5	0	1912	98.6%	0.00
5/28/2015	20.5	20.1	28.5	1	1913	98.7%	0.00
5/29/2015	20.91	20.3	32.3	3	1916	98.8%	0.04

Date	Max. Temp. (C)	7DADM (C)	Avg. flow (cfs)	Net Passage	Cumulative net passage	Cumulative passage	Limiting Width (ft)
5/30/2015	20.733	20.4	55.5	35	1951	100.6%	0.23
5/31/2015	20.43	20.5	55.4	0	1951	100.6%	0.23
6/1/2015	20.744	20.6	52.5	6	1957	100.9%	0.23
6/2/2015	20.873	20.7	46.0	0	1957	100.9%	0.21
6/3/2015	21.14	20.8	19.3	-3	1954	100.8%	0.00
6/4/2015	21.021	20.8	13.1	-5	1949	100.5%	0.00
6/5/2015	21.645	20.9	23.7	-4	1945	100.3%	0.00
6/6/2015	22.739	21.2	19.2	-1	1944	100.3%	0.00
6/7/2015	23.104	21.6	14.2	1	1945	100.3%	0.00
6/8/2015	23.953	22.1	9.4	-6	1939	100.0%	0.00
6/9/2015	23.346	22.4	12.6	0		100.0%	0.00
6/10/2015	22.917	22.7	16.0	0		100.0%	0.00
6/11/2015	23.381	23.0	15.2	0		100.0%	0.00
6/12/2015	24.238	23.4	13.6	0		100.0%	0.00
6/13/2015	24.466	23.6	12.7	0		100.0%	0.00
6/14/2015	24.26	23.8	11.9	0		100.0%	0.00
6/15/2015	24.309	23.8	15.4	0		100.0%	0.00
6/16/2015	24.737	24.0	21.5	0		100.0%	0.00
6/17/2015	24.794	24.3	21.7	0		100.0%	0.00
6/18/2015	24.554	24.5	21.2	0		100.0%	0.00
6/19/2015	24.222	24.5	24.7	0		100.0%	0.00
6/20/2015	24.343	24.5	25.5	0		100.0%	0.00
6/21/2015	23.96	24.4	25.3	0		100.0%	0.00
6/22/2015	23.427	24.3	21.3	0		100.0%	0.00
6/23/2015	23.77	24.2	19.5	0		100.0%	0.00
6/24/2015	23.905	24.0	19.2	0		100.0%	0.00
6/25/2015	25.141	24.1	19.1	0		100.0%	0.00
6/26/2015	25.642	24.3	24.7	0		100.0%	0.00
6/27/2015	25.458	24.5	27.5	0		100.0%	0.00
6/28/2015	24.674	24.6	27.8	0		100.0%	0.00
6/29/2015	25.431	24.9	28.0	0		100.0%	0.00
6/30/2015	25.211	25.1	29.0	0		100.0%	0.00

Appendix J. Sample Froude Number Plots

Figure J-1. Lahar site Froude Number Plot at 120 cfs.

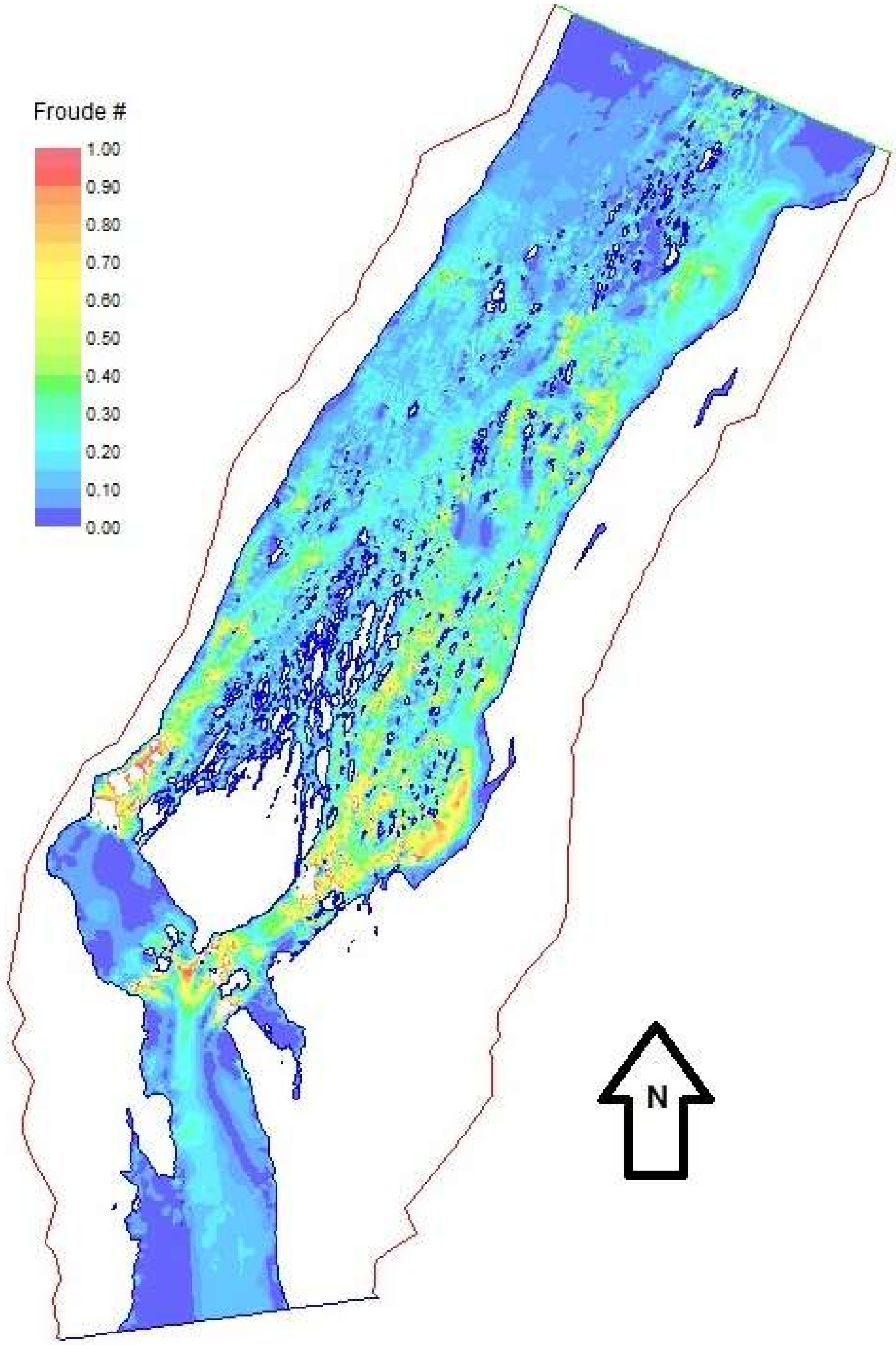


Figure J-2. Riffle 95 Froude Number Plot at 200 cfs.

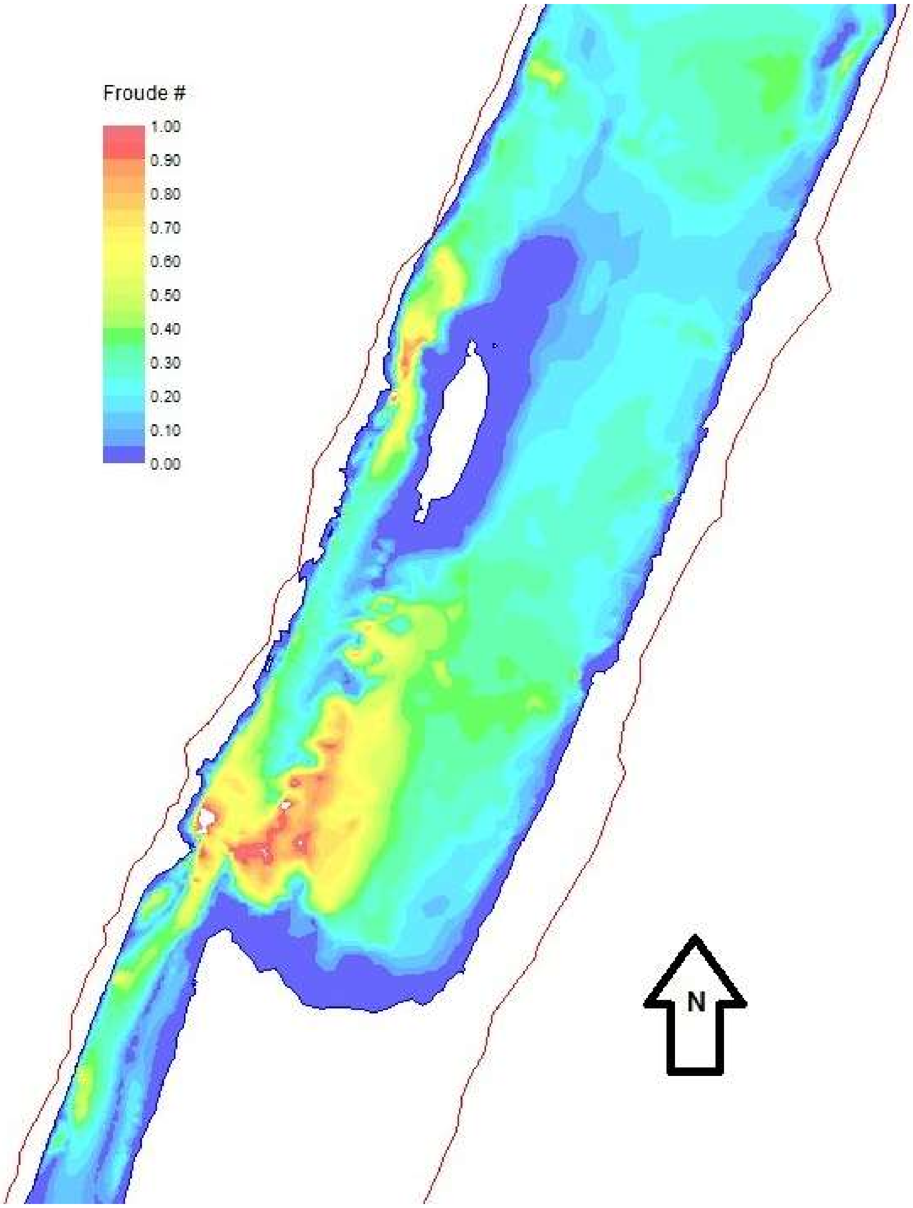


Figure J-3. Riffle 96 Froude Number Plot at 120 cfs.

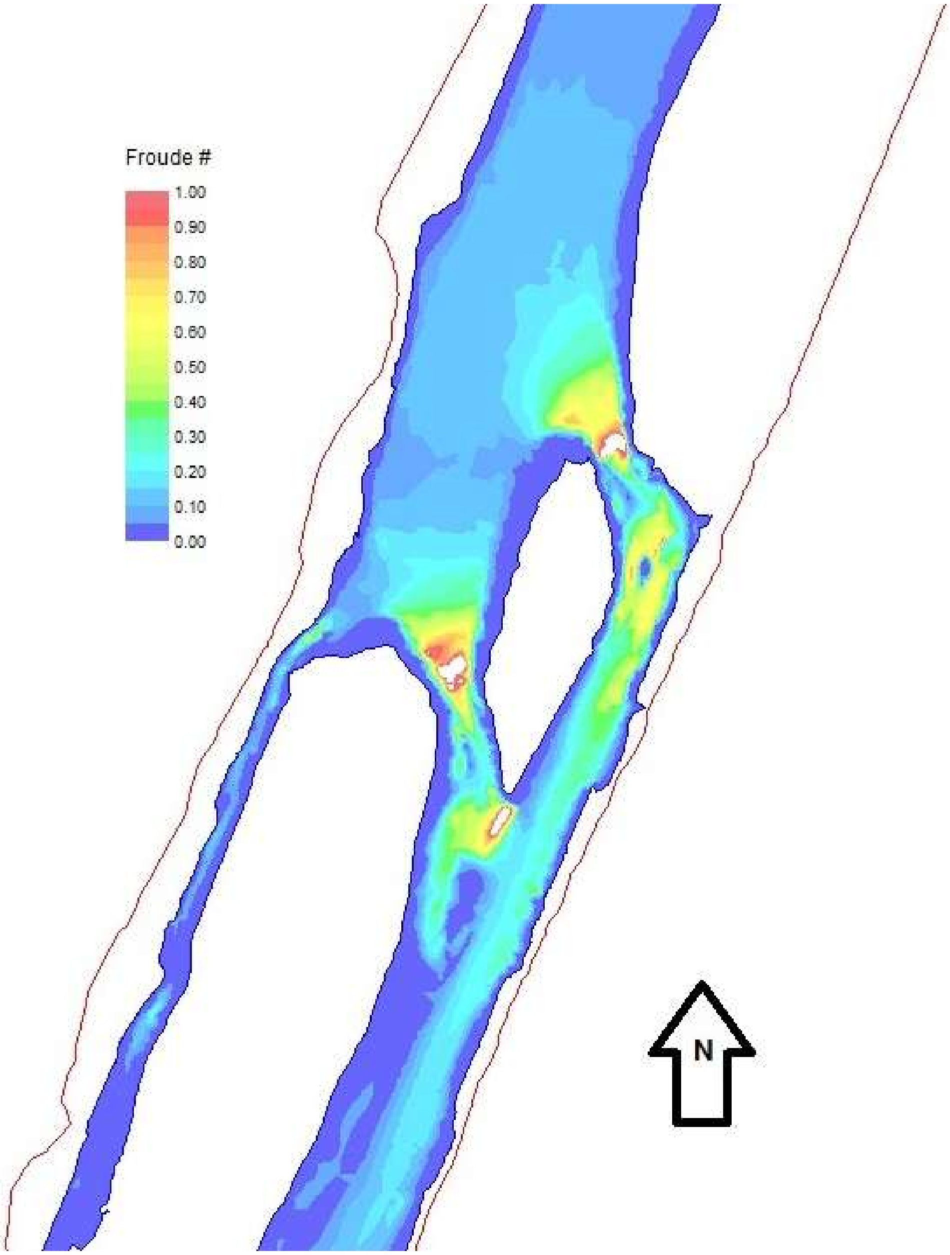
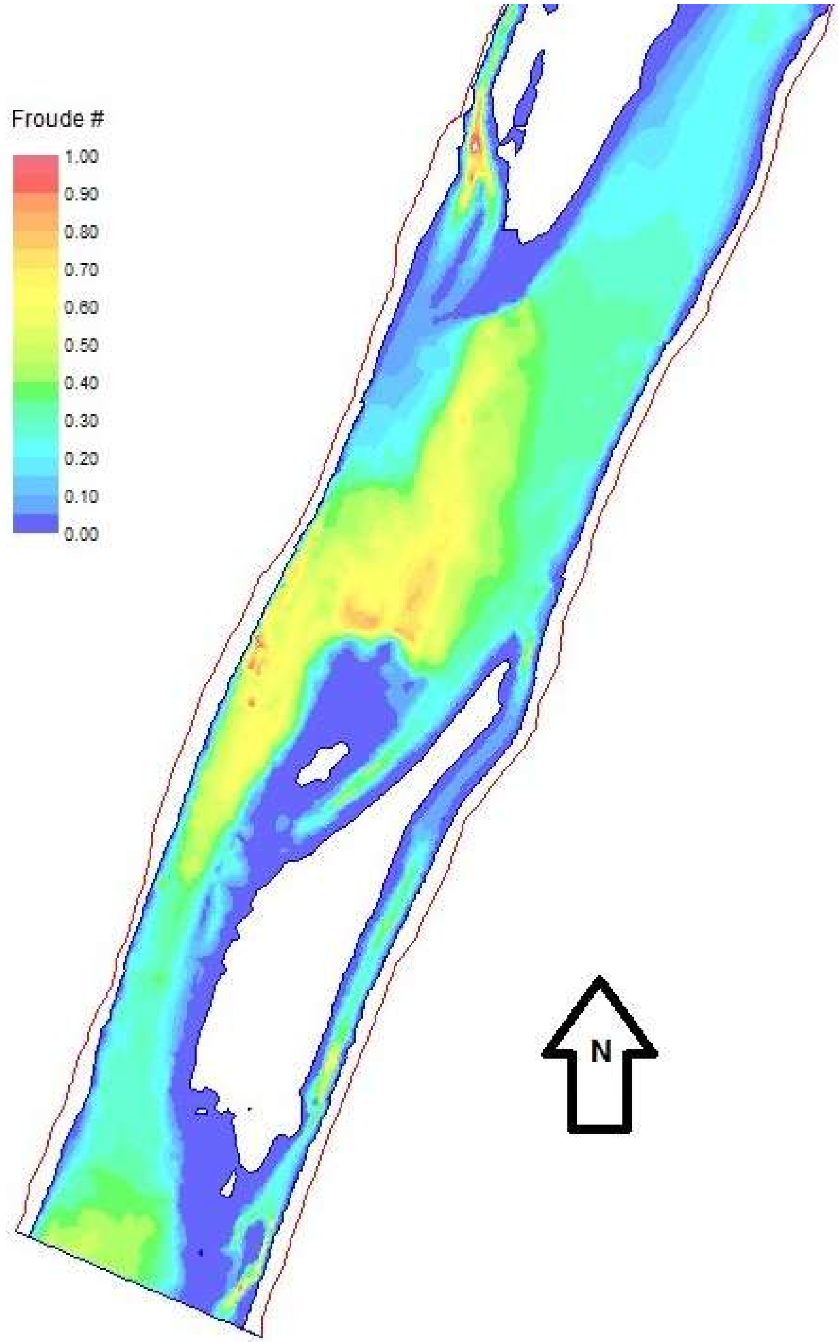


Figure J-4. Riffle 97 Froude Number Plot at 390 cfs.



State of California
Natural Resources Agency
Department of Fish and Wildlife
Water Branch, Instream Flow Program
830 S Street
Sacramento, CA. 95811