

**CHINOOK SALMON POPULATION MODEL
AMENDED STUDY REPORT
DON PEDRO PROJECT
FERC NO. 2299**



Prepared for:
Turlock Irrigation District – Turlock, California
Modesto Irrigation District – Modesto, California

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Chinook Salmon Population Model Amended Study Report

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List of Acronyms

ACEC.....	Area of Critical Environmental Concern
AF	acre-feet
ACOE.....	U.S. Army Corps of Engineers
ADA	Americans with Disabilities Act
ALJ.....	Administrative Law Judge
APE	Area of Potential Effect
ARMR.....	Archaeological Resource Management Report
BA	Biological Assessment
Basin Plan	Water Quality Control Plan for the Sacramento and San Joaquin Rivers
BDCP	Bay-Delta Conservation Plan
BLM.....	U.S. Department of the Interior, Bureau of Land Management
BLM-S	Bureau of Land Management – Sensitive Species
BMI	Benthic macroinvertebrates
BMP	Best Management Practices
BO	Biological Opinion
CalEPPC	California Exotic Pest Plant Council
CalSPA.....	California Sports Fisherman Association
CAS.....	California Academy of Sciences
CCC.....	Criterion Continuous Concentrations
CCIC	Central California Information Center
CCSF.....	City and County of San Francisco
CCVHJV	California Central Valley Habitat Joint Venture
CD	Compact Disc
CDBW.....	California Department of Boating and Waterways
CDEC.....	California Data Exchange Center
CDFA.....	California Department of Food and Agriculture
CDFG.....	California Department of Fish and Game
CDMG.....	California Division of Mines and Geology
CDOF.....	California Department of Finance
CDPH.....	California Department of Public Health
CDPR	California Department of Parks and Recreation

CDSOD	California Division of Safety of Dams
CDWR.....	California Department of Water Resources
CE	California Endangered Species
CEII.....	Critical Energy Infrastructure Information
CEQA.....	California Environmental Quality Act
CESA	California Endangered Species Act
CFR.....	Code of Federal Regulations
cfs.....	cubic feet per second
CGS.....	California Geological Survey
CMAPI	California Monitoring and Assessment Program
CMARP.....	Comprehensive Monitoring, Assessment, and Research Program
CMC.....	Criterion Maximum Concentrations
CNDDB.....	California Natural Diversity Database
CNPS.....	California Native Plant Society
CORP	California Outdoor Recreation Plan
CPUE	Catch Per Unit Effort
CRAM.....	California Rapid Assessment Method
CRLF.....	California Red-Legged Frog
CRRF	California Rivers Restoration Fund
CSAS.....	Central Sierra Audubon Society
CSBP.....	California Stream Bioassessment Procedure
CT	California Threatened Species
CTR.....	California Toxics Rule
CTS	California Tiger Salamander
CVRWQCB	Central Valley Regional Water Quality Control Board
CWA	Clean Water Act
CWHR.....	California Wildlife Habitat Relationship
Districts	Turlock Irrigation District and Modesto Irrigation District
DLA	Draft License Application
DPRA.....	Don Pedro Recreation Agency
DPS	Distinct Population Segment
EA	Environmental Assessment
EC	Electrical Conductivity

EES	EES Consulting, Inc.
EFH	Essential Fish Habitat
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
ESA	Federal Endangered Species Act
ESRCD	East Stanislaus Resource Conservation District
ESU	Evolutionary Significant Unit
EWUA	Effective Weighted Useable Area
FC	Candidate for listing under ESA
FE	Federally listed Endangered Species under ESA
FERC	Federal Energy Regulatory Commission
FFS	Foothills Fault System
FL	Fork length
FLA	Final License Application
FMU	Fire Management Unit
FOT	Friends of the Tuolumne
FPC	Federal Power Commission
FPD	Species Proposed for Delisting under ESA
FPE	Proposed for listing as Endangered under ESA
FPT	Species Proposed to be listed as Threatened under ESA
FT	Federally listed Threatened Species under ESA
ft/mi	feet per mile
FWCA	Fish and Wildlife Coordination Act
FYLF	Foothill Yellow-Legged Frog
GIS	Geographic Information System
GLO	General Land Office
GORP	Great Outdoor Recreation Pages
GPS	Global Positioning System
HCP	Habitat Conservation Plan
HHWP	Hetch Hetchy Water and Power
HORB	Head of Old River Barrier
HPMP	Historic Properties Management Plan

ILP.....	Integrated Licensing Process
ISR	Initial Study Report
ITA.....	Indian Trust Assets
kV.....	kilovolt
m	meters
M&I.....	Municipal and Industrial
MCL.....	Maximum Contaminant Level
mg/kg	milligrams/kilogram
mg/L.....	milligrams per liter
mgd	million gallons per day
MID.....	Modesto Irrigation District
MOU	Memorandum of Understanding
MSCS.....	Multi-Species Conservation Strategy
msl.....	mean sea level
MVA	Megavolt Ampere
MVZ.....	Museum of Vertebrate Zoology
MW	megawatt
MWh	megawatt hour
mya.....	million years ago
NAE	National Academy of Engineering
NAHC	Native American Heritage Commission
NAS.....	National Academy of Sciences
NAWQA	National Water Quality Assessment
NCCP	Natural Community Conservation Plan
NEPA	National Environmental Policy Act
ng/g	nanograms per gram
NGOs	Non-Governmental Organizations
NHI	Natural Heritage Institute
NHPA.....	National Historic Preservation Act
NISC	National Invasive Species Council
NMFS.....	National Marine Fisheries Service
NOAA.....	National Oceanic and Atmospheric Administration
NOI	Notice of Intent

NPS	U.S. Department of the Interior, National Park Service
NRCS	National Resource Conservation Service
NRHP	National Register of Historic Places
NRI.....	Nationwide Rivers Inventory
NTU	Nephelometric Turbidity Unit
NWI.....	National Wetland Inventory
NWIS	National Water Information System
NWR	National Wildlife Refuge
O&M.....	operation and maintenance
OEHHA.....	Office of Environmental Health Hazard Assessment
ORV	Outstanding Remarkable Value
PAD.....	Pre-Application Document
PDO.....	Pacific Decadal Oscillation
PEIR.....	Program Environmental Impact Report
PGA.....	Peak Ground Acceleration
PHG.....	Public Health Goal
PM&E	Protection, Mitigation and Enhancement
PMF.....	Probable Maximum Flood
POAOR.....	Public Opinions and Attitudes in Outdoor Recreation
ppb.....	parts per billion
ppm	parts per million
PSP	Proposed Study Plan
PTL	Project Tracking List
RA	Recreation Area
RBP.....	Rapid Bioassessment Protocol
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
RM	River Mile
RMP	Resource Management Plan
RP.....	Relicensing Participant
RSP	Revised Study Plan
RST	Rotary Screw Trap
RWF.....	Resource-Specific Work Groups
RWG	Resource Work Group

RWQCB	Regional Water Quality Control Board
SC.....	State candidate for listing under CESA
SCD.....	State candidate for delisting under CESA
SCE	State candidate for listing as endangered under CESA
SCT	State candidate for listing as threatened under CESA
SD1	Scoping Document 1
SD2	Scoping Document 2
SE.....	State Endangered Species under CESA
SFP	State Fully Protected Species under CESA
SFPUC	San Francisco Public Utilities Commission
SHPO	State Historic Preservation Office
SJRA	San Joaquin River Agreement
SJRGa	San Joaquin River Group Authority
SNTEMP.....	stream network temperature
SR.....	California Rare Species
SRA.....	State Recreation Area
SRMA	Special Recreation Management Area or Sierra Resource Management Area (as per use)
SRMP	Sierra Resource Management Plan
SRP	Special Run Pools
SSC	State species of special concern
ST.....	California Threatened Species
STORET	Storage and Retrieval
SWAMP.....	Surface Water Ambient Monitoring Program
SWE	Snow-Water Equivalent
SWRCB.....	State Water Resources Control Board
TAF	thousand acre-feet
TAC.....	Technical Advisory Committee
TCP	Traditional Cultural Properties
TDS	Total Dissolved Solids
TID	Turlock Irrigation District
TMDL	Total Maximum Daily Load
TOC.....	Total Organic Carbon

TRT	Tuolumne River Trust
TRTAC	Tuolumne River Technical Advisory Committee
UC	University of California
UUILT.....	Ultimate upper incipient lethal temperature
USDA.....	U.S. Department of Agriculture
USDOC	U.S. Department of Commerce
USDOI	U.S. Department of the Interior
USFS	U.S. Forest Service
USFWS	U.S. Department of the Interior, Fish and Wildlife Service
USGS	U.S. Geological Survey
USR.....	Updated Study Report
VAMP	Vernalis Adaptive Management Plan
VELB	Valley Elderberry Longhorn Beetle
VRM	Visual Resource Management
WPT	Western Pond Turtle
WSA.....	Wilderness Study Area
WSIP	Water System Improvement Program
WWTP	Wastewater Treatment Plant
WY	water year
µS/cm	microSeimens per centimeter

Glossary of Terms and Definitions

Adipose fin	A small fleshy fin with no rays, located between the dorsal and caudal fins. Clipping of adipose fins is used to identify hatchery-raised salmonids.
Age	The number of years of life completed, here indicated by an Arabic numeral, followed by a plus sign if there is any possibility of ambiguity (e.g., age 1, age 1+).
Age composition	Proportion of individuals of different ages in a stock or in the catches.
Age-class	A group of individuals of a certain species that have the same age.
Alevin	The developmental life stage of young salmonids and trout that are between the egg and fry stage. The alevin has not absorbed its yolk sac and has not emerged from the spawning gravels.
Anadromous	Fish that migrate from the sea to spawn in fresh water.
Coded-wire tag (CWT)	A small (0.25mm diameter x 1 mm length) wire etched with a distinctive binary code and implanted in the snout of salmon or steelhead, which, when retrieved, allows for the identification of the origin of the fish bearing the tag.
Cohort	Members of a life-stage that were spawned in the same year.
Density-dependent	Density-dependence in stock-production relationships occurs whenever food or space limitations cause the life-stage specific survival or growth to be related to the numbers of individuals present. Density dependent factors may include spawning habitat area or juvenile rearing area at higher population sizes.
Density Independence	Factors affecting the population regardless of population size, such as temperature, disease, or stranding.
Delta	An alluvial landform composed of sediment at a river mouth that is shaped by river discharge, sediment load, tidal energy, land subsidence, and sea-level changes. The Sacramento and San Joaquin River Delta refers to a complex network of channels east of Suisun Bay (an upper arm of the San Francisco Bay estuary).
Dispersal	A process by which animals move away from their natal population
Escapement	The number of sexually mature adult salmon or steelhead that successfully pass through an ocean fishery to reach the spawning grounds. The total amount of escapement reflects losses resulting from harvest, and does not reflect natural mortality during upmigration such as pre-spawn mortality.
El Niño	A climactic event that begins as a warming episode in the tropical Pacific zone that can result in large scale intrusions of anomalously

	warm marine water northward along the Pacific coastline of North America (also see La Niña).
Estuary	A region where salt water from the ocean is mixed with fresh water from a river or stream (also see Delta). The greater San Francisco Bay estuary includes brackish and salt water habitats from the Golden Gate Bridge in San Francisco Bay and includes Suisun, San Pablo, Honker, Richardson, San Rafael, San Leandro, and Grizzly bays.
Floodplain	The part of a river valley composed of unconsolidated river deposits that periodically floods. Sediment is deposited on the floodplain during floods and through the lateral migration of the river channel across the floodplain.
Fry	Salmonid life stage between the alevin and parr stages. Functionally defined as a size <50–69 mm, fry generally occupy stream margin habitats, feeding on available insect larvae.
Homing	The ability of a salmon or steelhead to correctly identify and return to their natal stream, following maturation at sea.
Hydroelectric	Generation of electricity by conversion of the energy of running water into electric power.
Irrigation	The application of water to land for agricultural crops by means of pumps, pipes, and ditches in order to provide water required by the crops for growth.
Kelts	A spent or exhausted salmon or steelhead after spawning. All species of Pacific salmon, except some steelhead and sea-run cutthroat, die after spawning.
La Niña	A cooling of the surface water of the eastern and central Pacific Ocean, occurring somewhat less frequently than El Niño events but causing similar, generally opposite disruptions to global weather patterns.
Life history	The events that make up the life cycle of an animal, with events for fish including migration, spawning, incubation, and rearing. There is typically a diversity of life history patterns both within and between populations. Life history can refer to one such pattern, or collectively refer to a stylized description of the 'typical' life history of a population.
Life-stage	Temporal stages (or intervals) of an animal's life history that have distinct anatomical, physiological, and/or functional characteristics that contribute to potential differences in use of available habitats.
Macroinvertebrate	Invertebrates visible to the naked eye, such as insect larvae and crayfish generally found in streams and become food for fish.

Osmoregulation	Refers to the physical changes that take place in salmonids as their gills and kidneys adjust from fresh water to salt water as they enter the ocean, and from salt water to fresh water upon their return.
Pacific Decadal Oscillation	A pattern of Pacific climate variability associated with sea surface warming and changes in ocean circulation that shifts phases on at least inter-decadal time scale, usually about 20 to 30 years.
Parr	Life stage of salmon or <i>O. mykiss</i> between the fry and smolt stages. Functionally defined as a size of 50–69 mm at this stage, juvenile fish have distinctive vertical parr marks and are actively feeding in fresh water.
Predator	An animal which feeds on other living animals.
Production	Output from a stock-production model at a particular life-step.
Proximate factor	Stimuli or conditions responsible for animal behavior at ecological time scales (i.e., immediate or short-term responses).
Recruitment	Addition of new fish to a defined life history stage by growth from among smaller size categories. Often used in context of management, where the stage is the point where individuals become vulnerable to fishing gear.
Redd	A nest of fish eggs within the gravel of a stream, typically formed by digging motion performed by an adult female salmon or <i>O. mykiss</i> .
Riffle	A shallow gravel area of a stream that is characterized by increased velocities and gradients, and is the predominant stream area used by salmonids for spawning.
Riparian	Referring to the transition area between aquatic and terrestrial ecosystems. The riparian zone includes the channel migration zone and the vegetation directly adjacent to the water body that influence channel habitat through alteration of microclimate or input of LWD.
River mile	A statute mile measured along the center line of a river. River mile measurements start at the stream mouth (RM 0.0).
Riverine	Referring to the entire river network, including tributaries, side channels, sloughs, intermittent streams, etc.
Rotary Screw Trap	Rotary screw traps (RST) consist of a large perforated cone and live-box that are mounted on a floating platform and facing upstream at a fixed location in the river. Rotary screw traps are used to sample a portion of emigrating juvenile salmonids and other fish as they move downstream to allow estimation of total passage.
Semelparous	A reproductive strategy characterized by a single reproductive episode before death.
Smolt	Salmonid life stage between the parr and adult stages. Functionally defined as a size ≥ 70 mm at this stage, juvenile salmon and steelhead

	actively outmigrate from freshwater habitats and take on the appearance of silver adult fish.
Smoltification	Refers to the physiological changes to allow tolerance to saltwater conditions in the ocean.
Spawn	The act of producing a new generation of fish. The female digs a redd in the river bottom and deposits her eggs into it. The male then covers the eggs with milt to fertilize them.
Spawning grounds	Areas where fish spawn.
Straying	A natural phenomena of adult spawners not returning to their natal stream, but entering and spawning in some other stream.
Stock	Input value required by the stock-production models. It is the first required value entered into the population dynamics model spreadsheets; for example, stock would be the number of fry, for a fry-to-juvenile step.
Superimposition	Superimposition occurs when a redd site is reused by subsequent female spawners before the embryos (see Alevin) of the earlier arriving spawners have had sufficient time to develop and emerge fromn the spawning gravels.
Wild	Salmon or <i>O. mykiss</i> produced by natural spawning in fish habitat from parents that were spawned and reared in fish habitat.
Woody debris	Logs, branches, or sticks that fall or hang into rivers that may become submerged at changing river discharge. This debris gives salmonids places to hide and provides food for insects and plants which fish feed upon.
Yolk sac	A small sac connected to alevin which provides them with protein, sugar, minerals, and vitamins. Alevin live on the yolk sac for a month or so before emerging from the gravel and beginning to forage food for themselves.

1.0 INTRODUCTION

1.1 Background

Turlock Irrigation District (TID) and Modesto Irrigation District (MID) (collectively, the Districts) are the co-licensees of the 168-megawatt (MW) Don Pedro Project (Project) located on the Tuolumne River in western Tuolumne County in the Central Valley region of California. The Don Pedro Dam is located at river mile (RM) 54.8 and the Don Pedro Reservoir has a normal maximum water surface elevation of 830 ft above mean sea level (msl; NGVD 29). At elevation 830 ft, the reservoir stores over 2,000,000 acre-feet (AF) of water and has a surface area slightly less than 13,000 acres (ac). The watershed above Don Pedro Dam is approximately 1,533 square miles (mi²). The Project is designated by the Federal Energy Regulatory Commission (FERC) as project no. 2299.

Both TID and MID are local public agencies authorized under the laws of the State of California to provide water supply for irrigation and municipal and industrial (M&I) uses and to provide retail electric service. The Project serves many purposes including providing water storage for the beneficial use of irrigation of over 200,000 ac of prime Central Valley farmland and for the use of M&I customers in the City of Modesto (population 210,000). Consistent with the requirements of the Raker Act passed by Congress in 1913 and agreements between the Districts and City and County of San Francisco (CCSF), the Project reservoir also includes a “water bank” of up to 570,000 AF of storage. CCSF may use the water bank to more efficiently manage the water supply from its Hetch Hetchy water system while meeting the senior water rights of the Districts. The “water bank” within Don Pedro Reservoir provides significant benefits for CCSF’s 2.6 million customers in the San Francisco Bay Area.

The Project also provides storage for flood management purposes in the Tuolumne and San Joaquin rivers in coordination with the U.S. Army Corps of Engineers (ACOE). Other important uses supported by the Project are recreation, protection of aquatic resources in the lower Tuolumne River, and hydropower generation.

The Project Boundary extends from RM 53.2, which is one mile below the Don Pedro powerhouse, upstream to RM 80.8 at an elevation corresponding to the 845 ft contour (31 FPC 510 [1964]). The Project Boundary encompasses approximately 18,370 ac with 78 percent of the lands owned jointly by the Districts and the remaining 22 percent (approximately 4,000 ac) owned by the United States and managed as a part of the U.S. Bureau of Land Management (BLM) Sierra Resource Management Area.

The primary Project facilities include the 580-foot-high Don Pedro Dam and Reservoir completed in 1971; a four-unit powerhouse situated at the base of the dam; related facilities including the Project spillway, outlet works, and switchyard; four dikes (Gasburg Creek Dike and Dikes A, B, and C); and three developed recreational facilities (Fleming Meadows, Blue Oaks, and Moccasin Point Recreation Areas). The location of the Project and its primary facilities is shown in Figure 1.1-1.

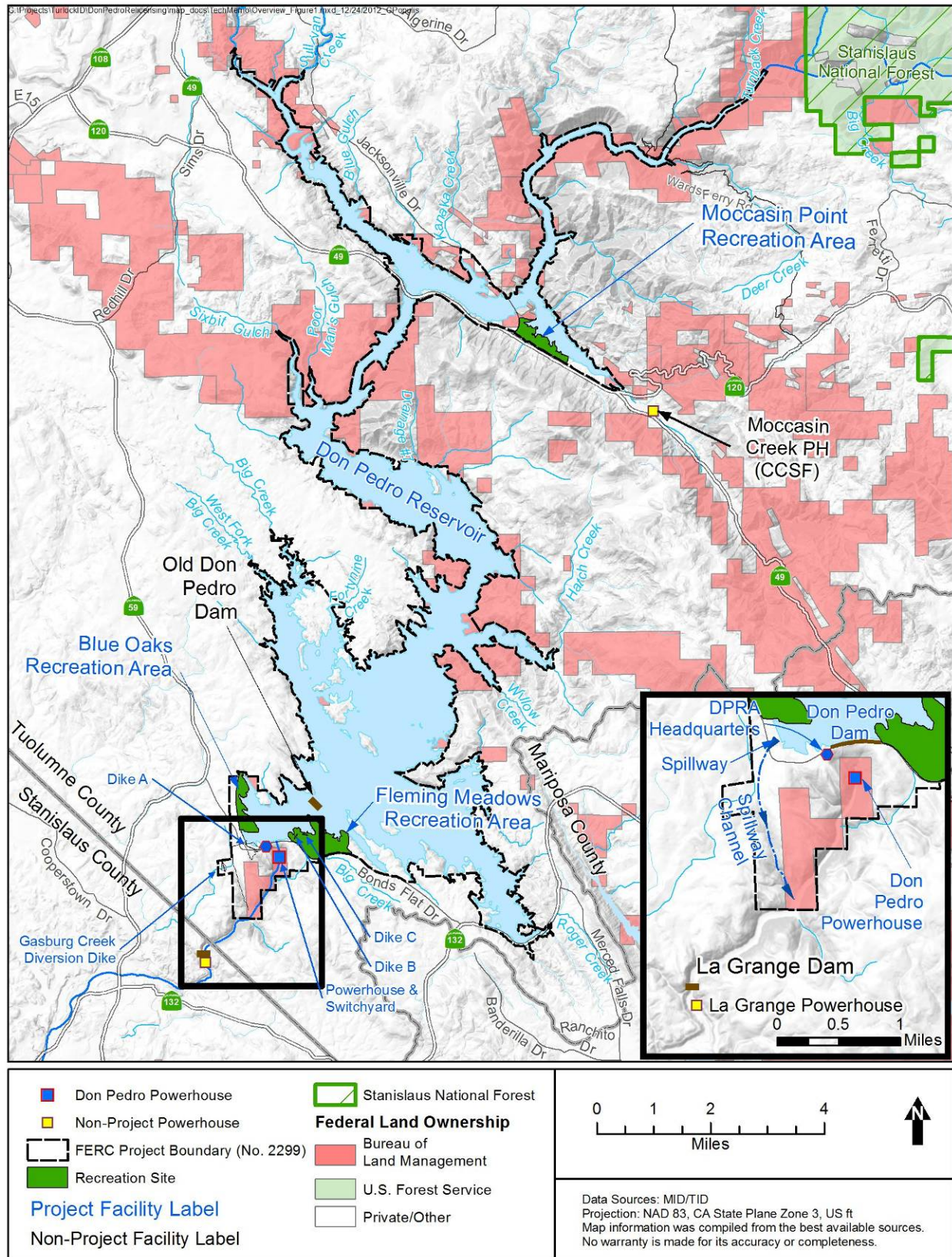


Figure 1.1-1. Don Pedro Project location.

1.2 Relicensing Process

The current FERC license for the Project expires on April 30, 2016, and the Districts will apply for a new license no later than April 30, 2014. The Districts began the relicensing process by filing a Notice of Intent and Pre-Application Document (PAD) with FERC on February 10, 2011, following the regulations governing the Integrated Licensing Process (ILP). The Districts' PAD included descriptions of the Project facilities, operations, license requirements, and Project lands as well as a summary of the extensive existing information available on Project area resources. The PAD also included ten draft study plans describing a subset of the Districts' proposed relicensing studies. The Districts then convened a series of Resource Work Group meetings, engaging agencies and other relicensing participants in a collaborative study plan development process culminating in the Districts' Proposed Study Plan (PSP) and Revised Study Plan (RSP) filings to FERC on July 25, 2011 and November 22, 2011, respectively.

On December 22, 2011, FERC issued its Study Plan Determination (SPD) for the Project, approving, or approving with modifications, 34 studies proposed in the RSP that addressed Cultural and Historical Resources, Recreational Resources, Terrestrial Resources, and Water and Aquatic Resources. In addition, as required by the SPD, the Districts filed three new study plans (W&AR-18, W&AR-19, and W&AR-20) on February 28, 2012 and one modified study plan (W&AR-12) on April 6, 2012. Prior to filing these plans with FERC, the Districts consulted with relicensing participants on drafts of the plans. FERC approved or approved with modifications these four studies on July 25, 2012.

Following the SPD, a total of seven studies (and associated study elements) that were either not adopted in the SPD, or were adopted with modifications, formed the basis of Study Dispute proceedings. In accordance with the ILP, FERC convened a Dispute Resolution Panel on April 17, 2012 and the Panel issued its findings on May 4, 2012. On May 24, 2012, the Director of FERC issued his Formal Study Dispute Determination, with additional clarifications related to the Formal Study Dispute Determination issued on August 17, 2012.

This study report describes the objectives, methods, and results of the *Tuolumne River Chinook Salmon Population Model Study* (W&AR-06) as implemented by the Districts in accordance with FERC's SPD and subsequent study modifications and clarifications. Documents relating to the Project relicensing are publicly available on the Districts' relicensing website at: <http://www.donpedro-relicensing.com/>

1.3 Study Plan

FERC's Scoping Document 2 identified potential effects of the Project on aquatic resources including anadromous fish. The continued operation and maintenance (O&M) of the Project may contribute to cumulative effects on habitat availability and production of in-river life stages of Chinook salmon. The *Chinook Salmon Population Model Study Plan* (W&AR-06) was accepted by FERC in their December 22, 2011 Study Plan Determination (SPD) with the modifications discussed below.

As recommended by FERC Staff in Element No.1 of the SPD for the *Tuolumne River Chinook Salmon Population Model Study* (W&AR-06), the population model includes mechanisms and parameters “that address the association between flows, water temperature, changing habitat conditions, predation, and the population response for specific in-river life-stages including smolts for existing conditions and for potential future conditions.” As recommended in Elements No. 2 through 6, a workshop consultation process was prepared and distributed to relicensing participants on March 20, 2012 that centers upon “Communication” recommendations in the June 2011 *Integrated Life Cycle Models Workshop Report* (Rose et al. 2011), including elements such as a standard glossary of terms and definitions, preparation of presentations and documentation that are tailored to the audience, methods for achieving consensus on key issues between interested participants and the Districts, and applicable conceptual clarifications.

The Districts have held the first of two relicensing participant meetings on November 15, 2012. Workshop No. 1 was held to review preliminary conceptual models developed as part of the interrelated *Salmonid Information Integration and Synthesis Study* (W&AR-05) (“Synthesis Study”) and to present the approaches and parameters to be used in the development of life-stage-specific population models in accordance with the *Tuolumne River Chinook Salmon Population Model Study Plan* (W&AR-06). A meeting agenda was provided to relicensing participants on November 5, 2012 and materials presented at the Workshop—preliminary conceptual models and an accompanying narrative—were provided to relicensing participants on November 15, 2012. At the workshop, relicensing participants and the Districts discussed the model framework and approach for investigating the relative influence of factors identified by the Synthesis Study (W&AR-05). Draft workshop notes were prepared and distributed to relicensing participants on December 13, 2012 and comments were received from CDFW on January 14, 2013. In their filing of the final notes for Workshop No. 1 on March 18, 2013, the Districts responded to comments and provided assurances that the effects of flow and water temperature upon individual life stages would be included in the model.

On August 6, 2013, the Districts held a second workshop with relicensing participants on the Tuolumne River Chinook Salmon Population Model Study Plan (W&AR-06). Consultation Workshop No. 2 was held to: (1) review and discuss the selected modeling approach; (2) present the Tuolumne River Chinook Salmon Population Model (TRCh) calibration and validation results; (3) discuss model parameter sensitivity testing results in the context of initial factors identified as part of the interrelated *Salmonid Information Integration and Synthesis Study* (W&AR-05) (Synthesis Study); and (4) present TRCh modeling results for the base case hydrology from the Tuolumne River Operations Model. A meeting agenda was provided to relicensing participants on July 26, 2013 along with directions to the Don Pedro website where the Draft *Chinook Salmon Population Model Study Report* (model report) was provided for review. At the Workshop, the Districts described model components and relicensing participants were asked to provide initial feedback regarding the TRCh model and model report, additional flow scenario requests, and requests for model distribution and training. Draft notes for Consultation Workshop No. 2 were provided to relicensing participants on August 21, 2013 and comments were received from CDFW, SWRCB, USFWS, and TRT/CSPA on September 20, 2013. In their comments, USFWS made several requests for additional modeling scenarios, including (a) flows to meet the AFRP doubling goal targets for salmon escapement, (b) observed La Grange flows, and (c) percent of unimpaired flows evaluated as part of the Substitute

Environmental Document. In their filing of the final notes for Workshop No. 2 on October 31, 2013, the Districts responded to comments and agreed to discuss details of additional requested flow scenarios with USFWS staff through the relicensing process.

This final report is a revised version of the report draft distributed to relicensing participants on July 26, 2013 in advance of Workshop No. 2. Revisions to the report include: (1) a description of the Workshop No. 2 comments and ongoing consultation process for this study; (2) additional figures showing combined in-channel and overbank habitat availability as requested in comments on the Draft report; and (3) updated TRCh model results for the Base Case included in the July 26, 2013 Draft to reflect a revised calibration of the *Lower Tuolumne River Temperature Model Study* (W&AR-16) in November 2013.

On May 18, 2017, the Districts hosted a Modeling Tools Update Meeting with relicensing participants. At the meeting, the Districts summarized various updates to the Chinook Population Model. A model update has been prepared to provide background on model development, an overview of the model changes, a presentation of expanded model calibration and validation simulations, and simulations of salmonid production under a range of water year types represented in the Base Case (1971–2012) hydrology (Attachment A).

2.0 STUDY GOALS AND OBJECTIVES

The goal of the *Tuolumne River Chinook Salmon Population Model Study* is to provide a quantitative salmon production model to investigate the influences of various factors on the life-stage specific production of Chinook salmon in the Tuolumne River, identify critical life-stages that may represent a life-history “bottleneck,” and compare relative changes in population size between potential alternative management scenarios. Using historical information as well as results of interrelated relicensing studies, the results of this study will be used to assess the extent to which the abundance of juvenile Chinook salmon in the Tuolumne River may be affected by in-river factors.

3.0 STUDY AREA

Figure 3.0-1 provides an overview of the broad geographic range of fall-run Chinook salmon life stages occurring in the Tuolumne River, Delta, and ocean. The study area includes habitat used by in-river life stages (i.e., upmigration, spawning, egg incubation, fry/juvenile rearing, and smolt emigration) along the Tuolumne River from the La Grange Dam (River Mile [RM] 52) downstream to the location of the rotary screw trap at Grayson River Ranch (RM 5) near the San Joaquin River confluence. As discussed in the Synthesis Study (W&AR-05), the average age at return for Chinook salmon upmigrants arriving from the ocean is 2.7 years, with three-, two-, and four-year-old salmon making up the largest proportions of the annual spawning run. Following egg incubation for 2–3 months, juveniles rear for an additional 3–4 months prior to smoltification and emigration. Although Chinook salmon may potentially emigrate as yearlings (i.e., Year 1+ smolts), because the contribution of this life history strategy to juvenile production is very low under current conditions, juvenile Chinook salmon over-summering and yearling emigration is not represented in the current model implementation.

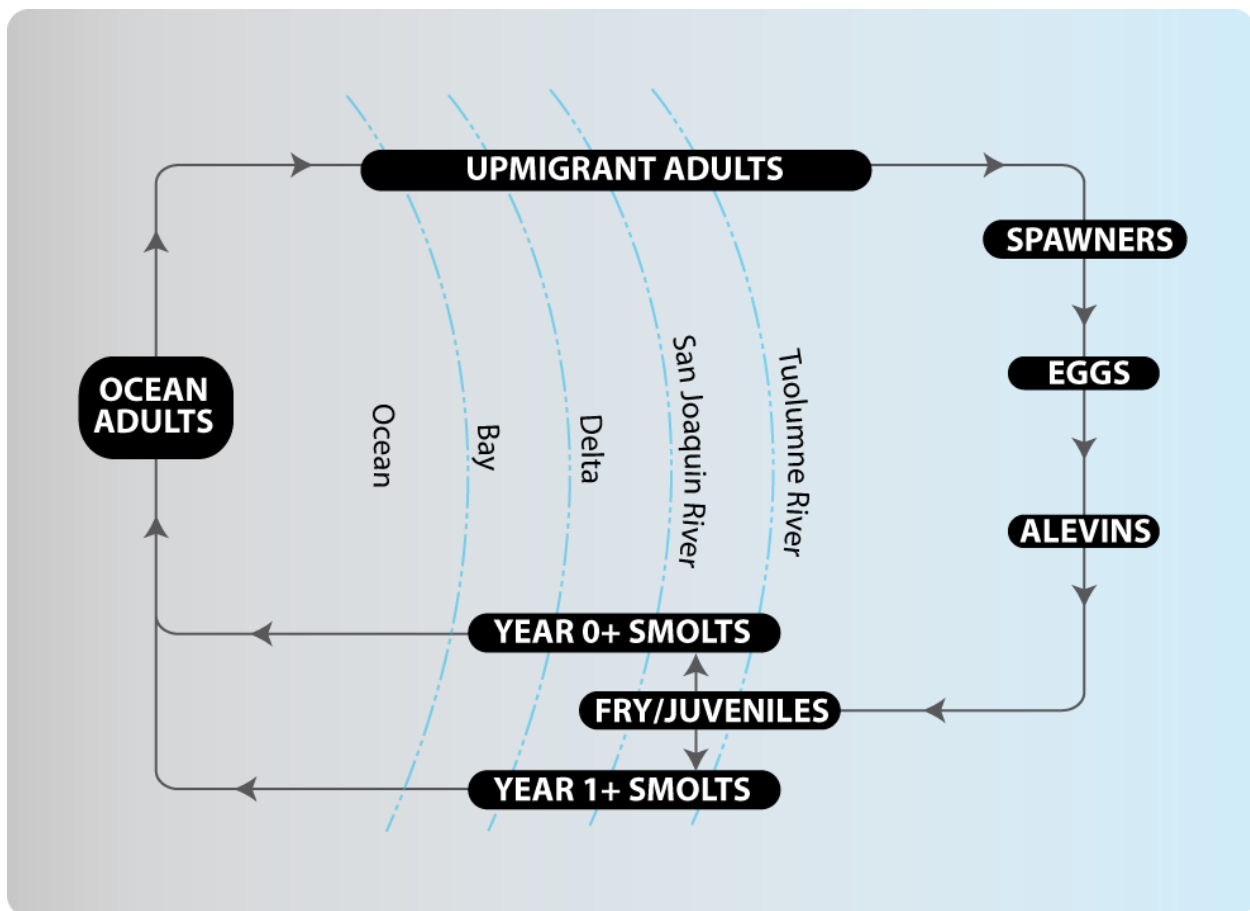


Figure 3.0-1. Generalized life stage distribution of Tuolumne River fall-run Chinook salmon.

4.0 METHODOLOGY

The *Tuolumne River Chinook salmon population modeling study* builds upon existing literature and information identified in the interrelated Synthesis Study (W&AR-05), including monitoring data collected as part of previously conducted Tuolumne River monitoring efforts, more recent data from interrelated relicensing studies, as well as previous population modeling efforts on the Tuolumne River. As detailed further below, the population model development was separated into four steps: (1) Conceptual Model Review and Refinement, (2) Quantitative Model Development, (3) Sensitivity Analyses, and (4) Evaluation of Relative Salmon Production under Current and Potential Future Project Operations.

4.1 Conceptual Model Refinement and Functional Relationships

Potential density-dependent and density-independent factors affecting in-river life-stages of Chinook salmon in the Tuolumne River were identified as part of the initial conceptual model development in the Synthesis Study (W&AR-05). Attachment B provides graphical depictions of primary factors for modeling of in-river Chinook salmon life stages. A workshop was held with relicensing participants on November 15, 2012 to review and discuss conceptual models and to determine the relevant factors and preliminary parameters to be included in the model. The following sections draw upon these sources of information in developing functional relationships to represent the effects of flow upon physical habitat (e.g., areas of suitable depth and velocity) as well as indirect effects of flow and seasonal air temperatures during upmigration and spawning; egg incubation and fry emergence, in-river rearing and emigration.

4.1.1 Adult Upmigration and Spawning

4.1.1.1 Migration Timing and Spawner Movement

Information reviewed as part of the Synthesis Study (W&AR-05) suggests variations in arrival timing of Chinook salmon spawners near La Grange are unrelated to flow conditions in the lower Tuolumne River. Since water temperatures near the San Joaquin River confluence (RM 0) are only weakly related to variations in instream flows during September and October, other factors such as day-length effects or regional meteorology are more likely to affect upmigration timing into the lower Tuolumne River. Based upon this information, a decision was made to represent arrival timing based upon either the empirical distribution of weir passage data at RM 24.5 from 2009–2012 (Figure 4.1-1) or as a fixed spawner population size arriving according to the seasonal distribution of peak live count information collected by CDFW in historical spawner surveys. Comparisons of distribution of weir passage date (Figure 4.1-1) with the distribution of spawning activity based upon CDFW redd count data (Figure 4.1-2) indicates that redd construction typically lags weir passage by approximately two weeks. This is equivalent to 1–2 mi/day assuming no holding prior to spawning, or a faster upmigration in combination with some period of holding prior to spawning. Although little additional information is available to estimate upmigration rates in the Tuolumne River, rates of 4–46 km/d (2–29 mi/d) have been reported in tracking studies on the Klamath River (Strange 2010) as well as Columbia River (Gonia et al 2006).

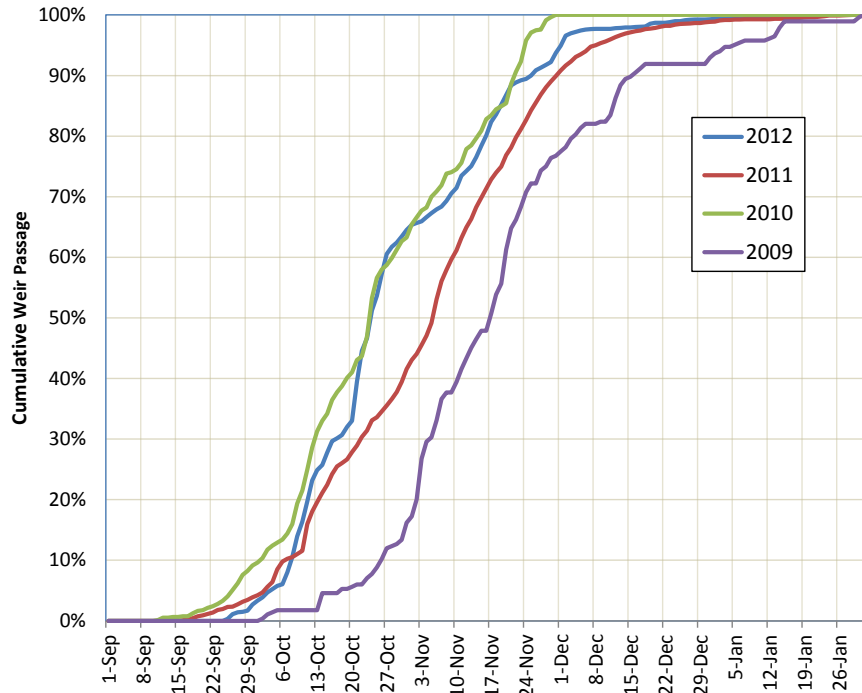


Figure 4.1-1. Distribution of Chinook salmon passage timing at the Tuolumne River weir (RM 24.5) from 2009–2012.

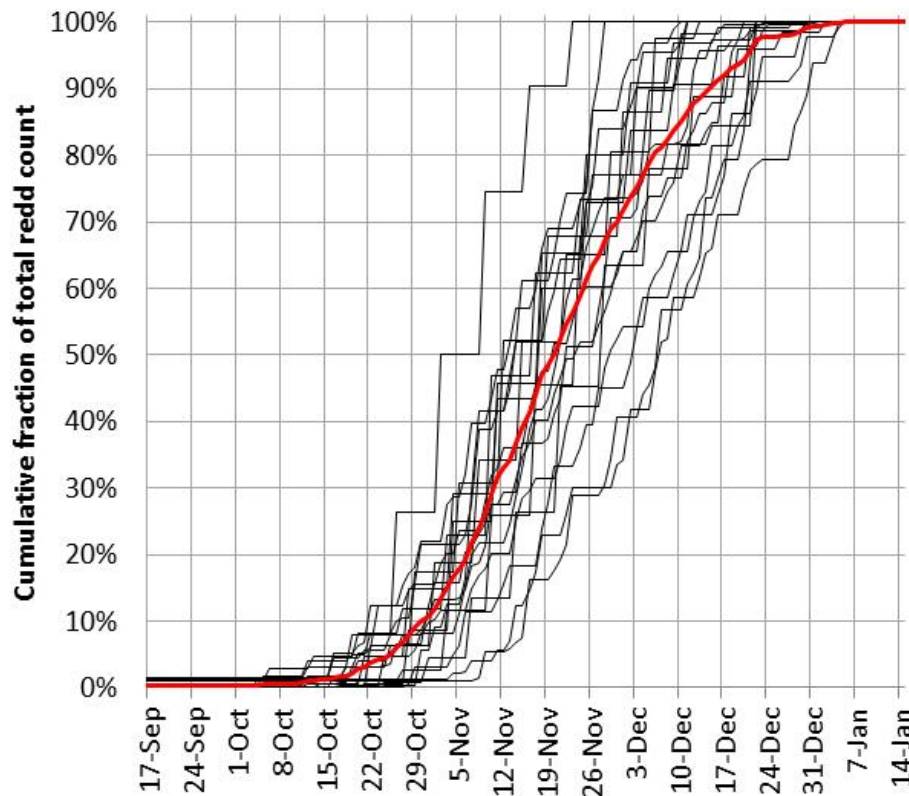


Figure 4.1-2. Distribution of redd construction timing in the Tuolumne River (1992–2010).

4.1.1.2 Spawning Habitat Use

Selection of suitable habitat by spawning female salmon is affected by (1) the availability of suitably-sized spawning gravels, (2) site-specific hydraulic conditions (i.e., depth, velocity, hyporheic flows), and (3) limitations on spawning at locations with suitable water temperatures. Use of PHABSIM modeling for predicting spawning habitat use is based upon studies in the Merced and American Rivers by Gallagher and Gard (1999) who found a significant correlation between weighted usable area (WUA) predictions and the observed density of Chinook salmon redds. On this basis, spawning habitat availability for the model is estimated from mapped areas of suitable gravels in riffle habitats from the *Spawning Gravel Study* (W&AR-04). Using PHABSIM modeling from the *Lower Tuolumne River Instream Flow Study* (Stillwater Sciences 2013), mapped areas of suitable gravels are re-scaled to areas at other flows based upon the relative amounts of WUA occurring within individual reaches of the lower Tuolumne River. Figure 4.1-3 shows the variation of total useable area with discharge as estimated within riffle habitats of various sub-reaches of the lower Tuolumne River.

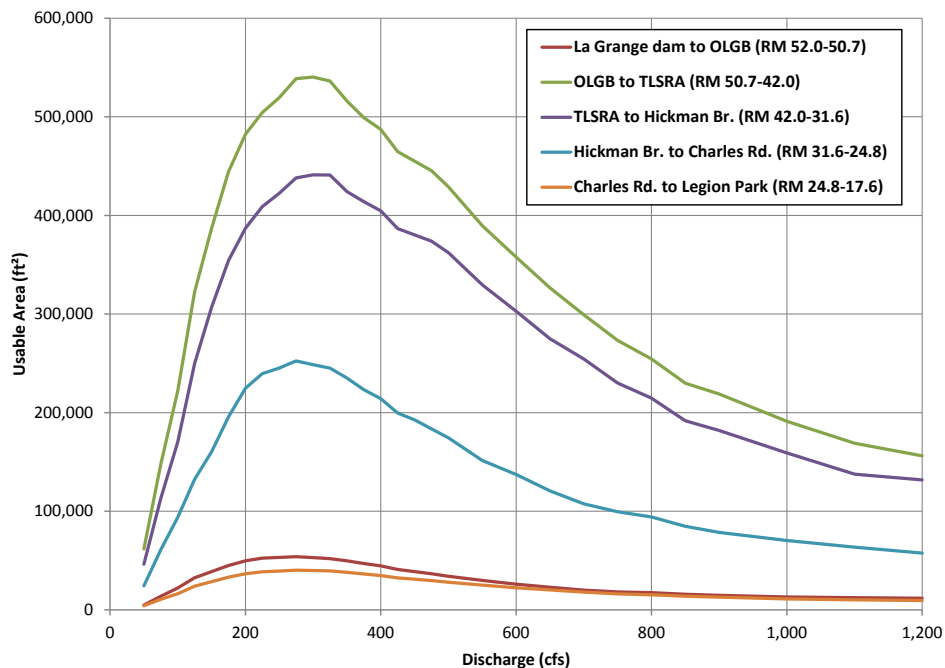


Figure 4.1-3. Variation of usable spawning area estimates with discharge for Chinook salmon in sub-reaches of the lower Tuolumne River.

In order to address potential temperature limits for spawning habitat selection, area estimates provided in Figure 4.1-3 are truncated to exclude sub-reach area contributions occurring downstream of locations exceeding the water temperature threshold for spawning, as determined by historical thermograph records as well as the *Lower Tuolumne River Temperature Model Study* (W&AR-16). Although literature reviews by McCullough (1999) found a maximum temperature of 18.9°C (66°F) for Chinook salmon upmigration and holding, an initial estimate of 16°C (60.4°F) was established as the upper limit for initiation of spawning (Groves and Chandler

1999). Spawners are assumed to avoid locations with water temperature above this threshold with spawning habitat selection limited to upstream (i.e., cooler) locations.

In addition to the effects of hydraulic and water temperature conditions upon spawning habitat selection, historical spawning surveys have long documented that Chinook salmon spawning habitat use is more heavily weighted towards upstream locations nearer to La Grange Dam (RM 52.2). Figure 4.1-4 shows the apparent habitat “preference” on the basis of cumulative gravel availability occurring downstream of mapped redd locations, with approximate locations shown as a secondary (upper) axis. For example, approximately 50% of redds observed between 2010–2012 and mapped as part of the *Salmonid Redd Mapping Study* (W&AR-08) were located within the 85 percent of the spawning gravels mapped downstream of approximately RM 49, with the other 50 percent of spawning occurring within the remaining 15 percent of the spawning gravels occurring between RM 49 and La Grange Dam (RM 52.2). The fitted line in Figure 4.1-4 represents this apparent preference based on the model in Equation 1 below.

$$\begin{aligned}\Phi^{-1}(G(i)) &= b_0 + b_1 \Phi^{-1}(F(i)), \\ \Phi(z) &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^z e^{-t^2/2} dt\end{aligned}\tag{Equation 1}$$

Equation 1 represents the fitted preference line in Figure 4.1-4, where Φ^{-1} is the inverse of the probit transform $\Phi(z)$ above and $F(i)$ is the cumulative fraction of gravel area within and downstream of a mapped riffle number (i) and $G(i)$ is the cumulative fraction of the female spawners expected to spawn within and downstream of riffle number i .

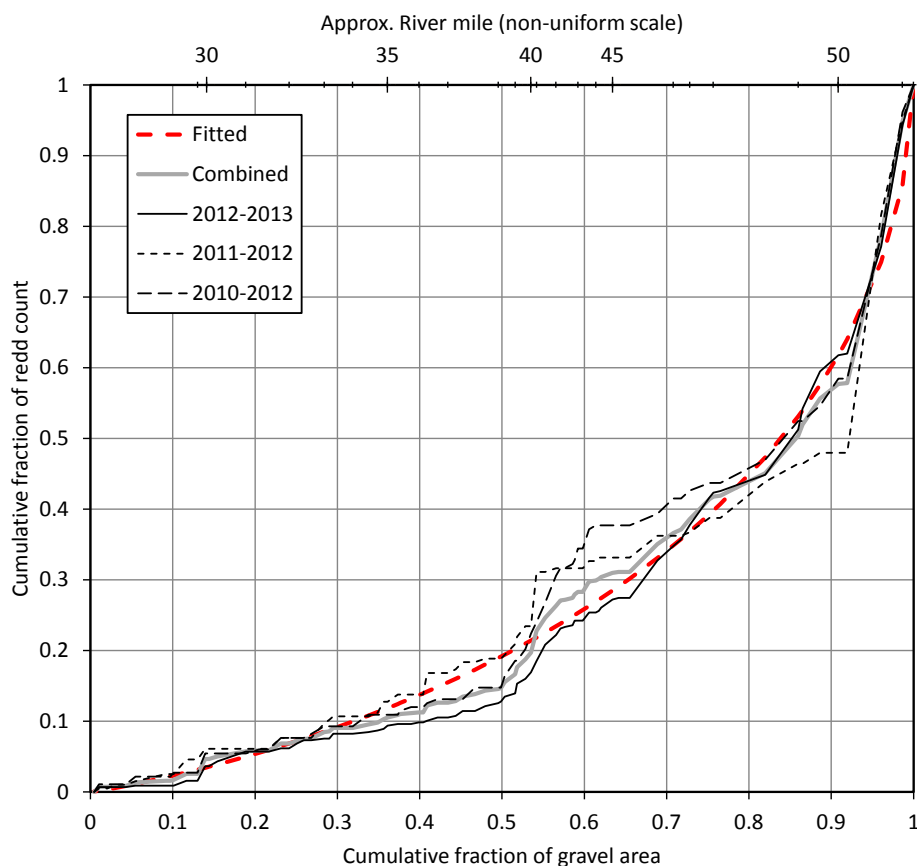


Figure 4.1-4. Cumulative proportion of total Chinook salmon spawning activity (2010–2012) as a function of total spawning gravel areas occurring downstream of mapped redds.

Depending upon the spawner preferences discussed above, adult female Chinook salmon arriving at a particular location will construct redds over a period of several days. Based upon detailed measurements ($n=354$) recorded in 1988–1989 (TID/MID 1992, Appendix 6), the disturbed gravel area that may result in potential redd superimposition is estimated at 4.8 m^2 (52 ft^2). Egg pocket measurements from the *Redd Mapping Study* (W&AR-08) were similar to these historical disturbed areas estimates, averaging 4.0 m^2 (43 ft^2). Spawner fecundity and egg deposition (Equation 2) is estimated based upon fish size and egg count information ($n=48$) collected by examining female spawners caught at the Los Banos Trap (Merced River) during fall 1988 by CDFW (Loudermilk et al 1990 as cited in TID/MID 1992, App 8) along with size information for various age classes (i.e., 2, 3, 4, or 5 yrs) estimated from weir monitoring or historical spawner surveys on the Tuolumne River (e.g., TID/MID 2012, Report 2011-2).

$$\text{Eggs} = 158.45 \times L - 6138.91$$

Equation 2

Based upon observations of redd superimposition summarized as part of the Synthesis Study (W&AR-05), spawning at locations previously occupied by spawning redds are assumed to potentially occur unless it is being actively defended. Typical redd defense times by the spawning female can range from 6–25 days (Neilson and Banford 1983), with a typical range of

7-days observed in the Tuolumne River based upon repeat redd surveys conducted in 1988 and 1989 (TID/MID 1992, App 6; TID/MID 1997, Report 96-6).

4.1.1.3 Mortality during Upmigration and Spawning

Potential sources of pre-spawn mortality during upmigration and arrival on the spawning gravels include exposure of spawning adults to elevated water temperatures with varying probabilities of direct or delayed mortality (e.g., Marine 1992). However, pre-spawn mortality has not been documented on the Tuolumne River and only low levels of pre-spawn mortality (1–4%) was identified on the neighboring Stanislaus River (Guignard 2006), mortality during upmigration and spawning due to elevated water temperature is assumed to be negligible and is not represented in the model. Chinook salmon are semelparous and generally die within a period of days to weeks following spawning due to cessation of feeding and related physiological changes (Dickhoff 1989). Based upon studies of senescence in sockeye salmon (*O. nerka*) by Morbey et al (2005), an upper estimate of 21-days survival for Chinook salmon spawners after arrival on the spawning gravels was selected for use in modeling.

4.1.2 Egg Incubation

4.1.2.1 Embryo Development

Normal Chinook salmon egg development times depend primarily upon water temperature as well as initial egg weight. Conventional degree-day models used in hatchery operations accumulate the exposure time of the eggs as the daily mean water temperature, predicting egg hatch and alevin “swim-up” when some thresholds are reached. After egg deposition, typical hatch times of 60–90 days have been observed, depending upon water temperature (Alderdice and Velson 1978, as cited in Healey 1991). Water temperature degree-day models have been used to successfully predict emergence timing of Chinook salmon fry (TID/MID 2007, Report 2006-7) and has been used in the formulation of a prior population model of the lower Tuolumne River (Jager and Rose 2003). Because incubation times have been shown to also depend upon initial egg weight (Beacham and Murray 1990), we employ a modified degree day model of Rombough (1985) for development time at a fixed temperature as well as initial egg weight. To account for time-varying water temperatures, Equation 3 accumulates “weighted thermal units” (WTU) based upon daily average water temperature, showing that fry hatching occurs D days after fertilization, where D is the smallest number for which:

$$\sum_{i=1}^D WTU_i \geq 1, \text{ where} \quad WTU_i = e^{-5.88 - 0.000513W + 0.152T_i} \quad \text{Equation 3}$$

An estimate of initial egg weight (W) of 246 mg (Std. Dev.=35 mg) was used in Equation 3 based upon egg lot subsample measurements ($n=125$) recorded as part of the 2001 *Tuolumne River Survival to Emergence Study* (TID/MID 2007, Report 2006-7).

4.1.2.2 Embryo Mortality during Incubation

Chinook salmon egg mortality is assumed to occur through redd superimposition, exceedance of laboratory based estimates of water temperature mortality thresholds (e.g., UUILT), or impairment of intra-gravel flow conditions due to excess fines. Information reviewed as part of the Synthesis Study (W&AR-05) suggested that it is unlikely that intragravel water temperature conditions contribute to high rates of egg mortality of Chinook salmon on the Tuolumne River. Geist et al. (2006) suggest that early-stage embryos are more tolerant of warm water, so that Chinook spawning occurring at water column temperatures of 15–16°C may not result in high rates of egg mortality. Nevertheless, to allow evaluation of a broad range of flow and water temperature conditions using the completed model, an initial acute mortality threshold of 14.4°C (58°F) was included based upon a literature review by Rich (2007). This is within the range of 13.9–15.6°C (57–60°F) corresponding to a rapid increase in mortality documented in laboratory experiments by Seymour (1956), which was validated in further experiments by USFWS (1998) in the Sacramento River.

In addition to potential mortality due to water temperature, redd superimposition can be a major mortality factor for eggs and alevins that results in a density-dependent relationship in which subsequent fry production is inversely proportional to spawning escapement size (McNeil 1964). The Districts have conducted a range of studies examining potential egg mortality due to redd superimposition (TID/MID 1992, Appendices 6 and 7; TID/MID 1997, Report 96-7) as well as survival-to-emergence as a function of gravel quality in several studies (TID/MID 1992, Appendix 8; TID/MID 2001, Report 2000-6; TID/MID 2007, Report 2006-7). Estimates of egg survival-to-emergence for the lower Tuolumne River are on the order of 30 percent based upon both bulk gravel quality using the Tappel and Bjornn (1983) model as well as direct emergence trapping (TID/MID 1992, Appendix 8). Because intensive permeability sampling conducted in 1999 at 122 sampling locations across 12 riffles extending from RM 50.8–36.8 (TID/MID 2001, Report 2000-6) did not result in more precise estimates of survival-to-emergence at individual riffle locations, an initial estimate of 32 percent survival was selected based upon the previous emergence trapping results (TID/MID 1992, Appendix 8).

4.1.3 Fry Rearing

4.1.3.1 Fry Habitat Use

After hatching, Chinook salmon alevins remain in the gravel for two to three weeks and absorb their yolk sac before emerging from the gravels into the water column. Following emergence, fry rearing generally occurs in low velocity, shallow water habitat along channel margins (Everest and Chapman 1972) as well as in inundated overbank habitat locations with connectivity to the mainstem channel (Moyle et al 2007). To represent habitat availability for fry in the lower Tuolumne River, PHABSIM modeling conducted for the *Lower Tuolumne River Instream Flow Study* (Stillwater Sciences 2013) is used to estimate the area of suitable habitat at in-channel locations. Fry rearing habitat use has been related to WUA at the site scale in studies by USFWS (1991) and forms the basis of a related Chinook salmon population model (i.e., SALMOD) on the Trinity River (Bartholow et al 1993), a Chinook salmon production model developed by the Oak Ridge Chinook salmon model (ORCM) for the Tuolumne River (Jager et

al 1997) and other population models. Estimates of in-channel fry rearing habitat availability as a function of flow and WUA are shown in Figure 4.1-5, as developed from habitat suitability criteria presented in the *Instream Flow Study* (Stillwater Sciences 2013).

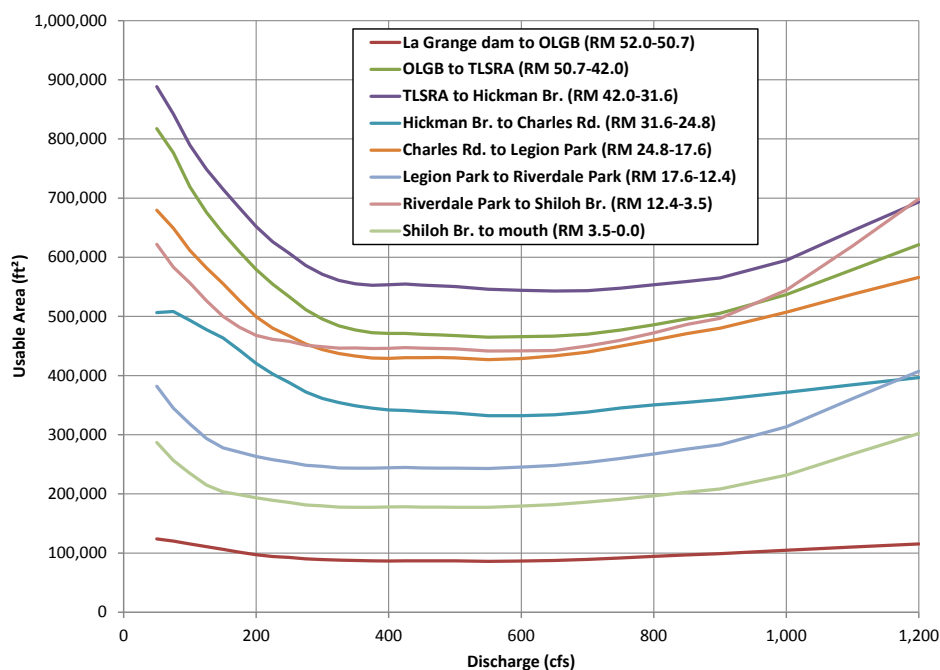


Figure 4.1-5. Variation of usable fry rearing area estimates with discharge for Chinook salmon in sub-reaches of the lower Tuolumne River.

In order to represent fry rearing habitat availability at overbank locations occurring at higher flows, WUA estimates for study sites evaluated using 2D modeling for the *Pulse Flow Study Report* (Stillwater Sciences 2012) were expanded in proportion to overbank inundation occurring on a river-wide basis (Figure 4.1-5) using digitized historical aerial photography collected as part of the Tuolumne River GIS development (TID/MID 1997, Report 96-14). Figures 4.1-6 and 4.1-7 represent the estimate of suitable habitat availability from current information sources.

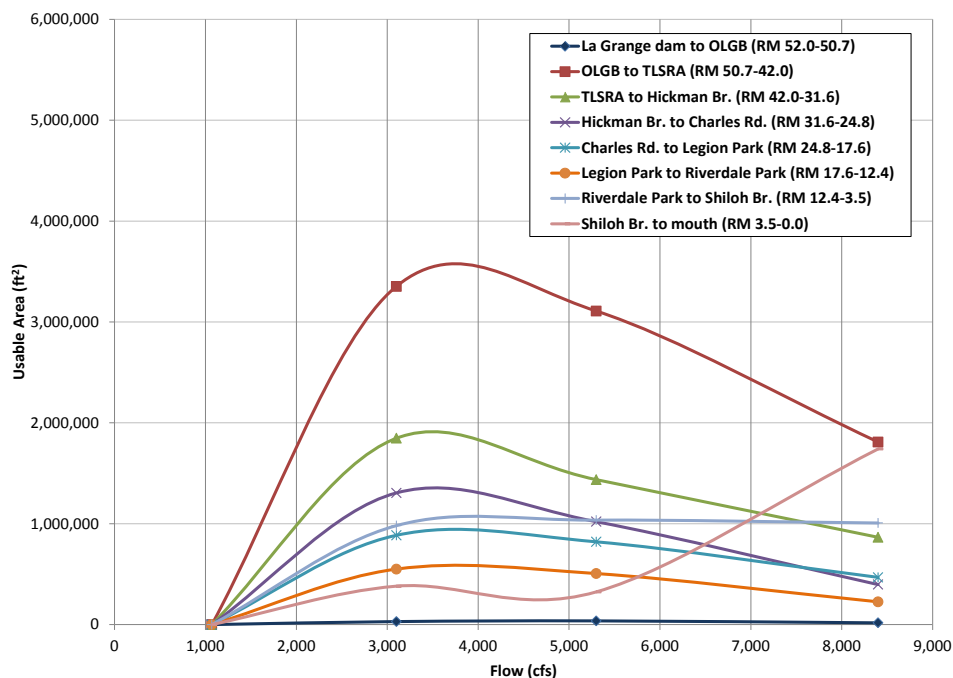


Figure 4.1-6. Estimated total usable overbank habitat for Tuolumne River Chinook salmon fry.

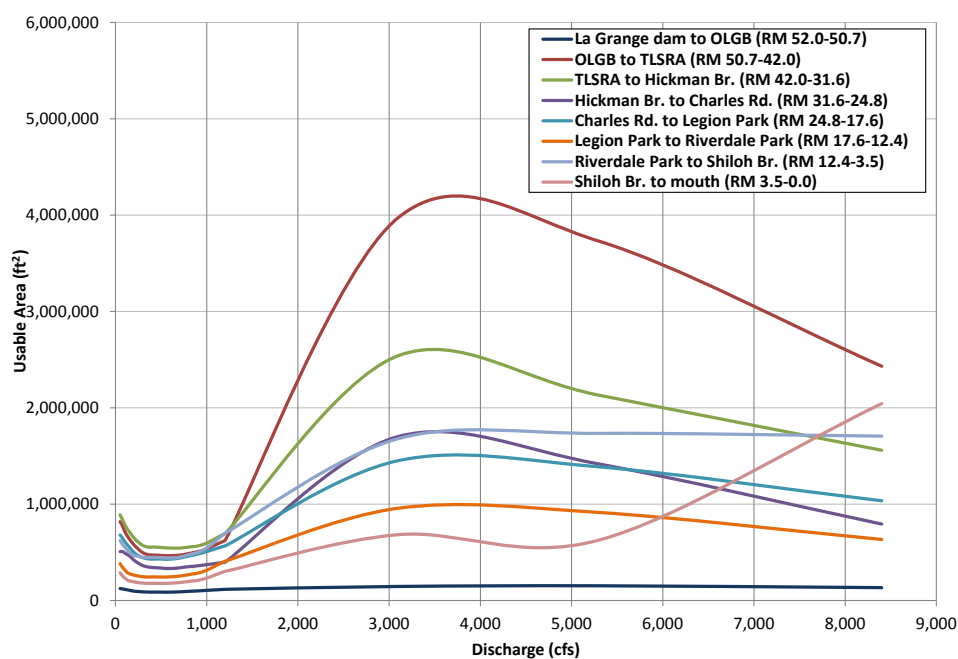


Figure 4.1-7. Estimated total combined usable in-river and overbank habitat for Tuolumne River Chinook salmon fry.

As noted in Stillwater Sciences (2012a), the 2D model-derived estimates of suitable habitat at the site scale may not represent all conditions occurring river-wide. For example, in addition to potential errors related to riverwide expansion of the site-specific data developed from Stillwater Sciences (2012), the estimates for the reach downstream of Shiloh Bridge (RM 3.5) may be

strongly influenced by backwater effects from flood flow conditions occurring in the San Joaquin River at the time that air photos were flown for this analysis. The Districts have developed a study plan to conduct a *Lower Tuolumne River Floodplain Hydraulic Assessment* (W&AR-21) recommended by FERC in the May 21, 2013 Determination on Requests for Study Modifications and New Studies for the Don Pedro Hydroelectric Project. Depending upon the degree to which usable overbank habitat estimates developed as part of this new study differ from those used in Figures 4.1-6 and 4.1-7 as well as whether those results alter model predictions, the results of this study may be updated.

4.1.3.2 Fry Movement

In most years, early fry passage at the Waterford (RM 29.8) and Grayson (RM 5.2) rotary screw traps (RSTs) occurs in January and February, with apparent peaks associated with emergence from the spawning gravels. This is consistent with either flow displacement or active emigration of weakly swimming fry prior to the fry locating low velocity habitats along the channel margins. As discussed in the Synthesis Study (W&AR-05), RST catch data for the Grayson (RM 5.2) location exhibits large numbers of early emigrating fry in years following high escapements (e.g., 1998–2002) as well as in years with moderate escapement levels accompanied by extended flood control releases such as occurred in 2011 (TID/MID 2012, Report 2011-4). Juvenile Chinook salmon density estimates from seine data (1999–2012) provided in Attachment C suggest that fry rearing occurs at upstream locations in drier water year types without flood control releases (e.g., WY 2001–2004, 2007–2010, and 2012). Fry are distributed farther downstream during years with extended high flows (e.g., WY 1999–2000, 2005–2006, and 2011). Taken together, the RST and seining data observations are consistent with the combined mechanisms of flow displacement as well as volitional emigration found in other systems (Healey 1991) and leads to the following movement assumptions in the model. Upon emergence, 30 percent of all fry are assumed to emigrate from the Tuolumne River, with the remainder assumed to be displaced for a period of 30 minutes. To provide an estimate of the displacement distance at varying discharges, the displacement period is multiplied by reach-specific estimates of channel velocity developed using transect-based information from the ongoing IFIM Study (Stillwater Sciences 2013) fitted to a simple hydraulic geometry relationship between velocity (v) and stream discharge (Q) by Leopold and Maddock (1953) shown in Equation 4, with fitted parameters k , and m .

$$v = kQ^m \quad \text{Equation 4}$$

In addition to volitional emigration following emergence, fry movement may be attributed to mechanisms of slower active migration found in other Central Valley Rivers (Williams 2006), as well as due to potential exclusion from nearshore rearing locations due to limited habitat availability. Based upon biweekly seine sampling summarized as part of the Synthesis Study (W&AR-05), seasonal fry movement rates were estimated at approximately 0.2 mi/day from relative changes in seining density vs. river mile in repeated sampling events in non-flood years (WY 2002–2004, 2009, 2012). To account for movement at other flows, these rates were represented as a daily movement probability of 0.05 d^{-1} using the same 2-hr movement period and velocity estimate as applied to newly emergent fry (Equation 4). For areas with fry densities in excess of habitat carrying capacity, defined as the maximum attainable densities under

optimum habitat conditions (e.g., Burns 1971), fry movement is re-initiated using the duration and velocity estimates described above. Although the Synthesis Study (W&AR-05) suggested that it is unlikely that fry rearing habitat is limiting for Chinook salmon in the lower Tuolumne River, the maximum attainable fry density in the Tuolumne River is estimated at 16.1 fry/m² based upon individual seine haul data collected in years following moderately high escapements occurring in 1988, 1998, and 2002. This density is slightly in excess of the 90th percentile estimates of 15.3 fry/m² estimated for the Klamath River by Bartholow and Henriksen (2006) as well as the 15.5 fry/m² found by Grant and Kramer (1990) in studies examining territoriality of stream type salmonids. However, because ocean type fish such as fall-run Chinook salmon generally exhibit reduced site fidelity and territoriality (Taylor 1990) as compared to stream-dwelling salmonids, it is not unexpected that greater rearing densities have been observed on the Tuolumne than for other river systems.

4.1.3.3 Fry Growth

For fry not emigrating from the Tuolumne River, growth is modeled as a function of water temperature and estimated food availability for various sub-reaches of the lower Tuolumne River using a growth model by Stauffer (1973) shown in Equation 5. Stauffer's model for the change in weight (W^+) over a relatively short time interval Δt is represented as an exponential relationship as a function of starting weight W_0 and growth rate (g). The growth rate is estimated as a function of maximum growth rate (G_{MAX}), water temperature T , ration level R as a fraction of maximum food intake (R_{MAX}) at complete satiation, as well as ration for maintenance of body weight (R_{MAINT}).

$$W^+ = W_0 e^{g\Delta t}, \text{ where}$$

$$g = G_{MAX} \sin\left(\frac{\pi}{2} \frac{R - R_{MAINT}}{R_{MAX} - R_{MAINT}}\right) \quad \text{Equation 5}$$

$$G_{MAX} = (a_1 + a_2 T + a_3 T^2 + a_4 T^3 + a_5 T^4)(a_6 W^{-a_7})$$

$$R_{MAINT} = (l_1 10^{l_2 T})(l_3 W^{-l_4})$$

$$R_{MAX} = (-l_5 + l_6 \ln T)(l_7 W^{-l_8})$$

Other model fitting parameters used in Equation 5 (a_{1-7} , l_{1-8}) are included in Stauffer (1973). Weight-length conversions obtained by linear regression of log-weight and log-length of fish from RST sampling (Figure 4.1-8) conducted in the Tuolumne River between 2004–2010 (e.g., TID/MID 2013, Report 2012-4). Ration estimates are developed from historical sampling conducted during the 1980s (TID/MID 1992, Appendix 16). As summarized in the Synthesis Study, during 1983–1987 gastric lavage (i.e., stomach pumping) was conducted on juvenile Chinook salmon. Stomach content samples (n=525) were analyzed to examine invertebrate prey items and provide broad daily ration estimates on a river-wide basis ($R_f \approx 70\%$ of maximum) for the Tuolumne River (TID/MID 1997, Report 96-9). With the exception of samples collected near the San Joaquin River confluence during high flow conditions occurring in 1983 and 1986, ration estimates at locations downstream of Modesto (RM 16.2) were generally lower than those samples collected nearer to La Grange Dam (RM 52.2). Based upon these data, in-channel feeding ration levels were represented as relatively high ($R = 70\%$) from RM 52.2 downstream to

Legion Park (RM 17.2), with a 30 percent ration estimated for the sand bedded reaches nearer the San Joaquin River confluence. Although no direct studies of overbank habitat use or growth have been conducted on the Tuolumne River, because of higher growth rates observed for juvenile Chinook in published floodplain rearing studies (Sommer et al 2001; Jeffres et al 2008), ration levels for any fry rearing in overbank habitat areas are assumed to be at least 70 percent of maximum at all overbank locations.

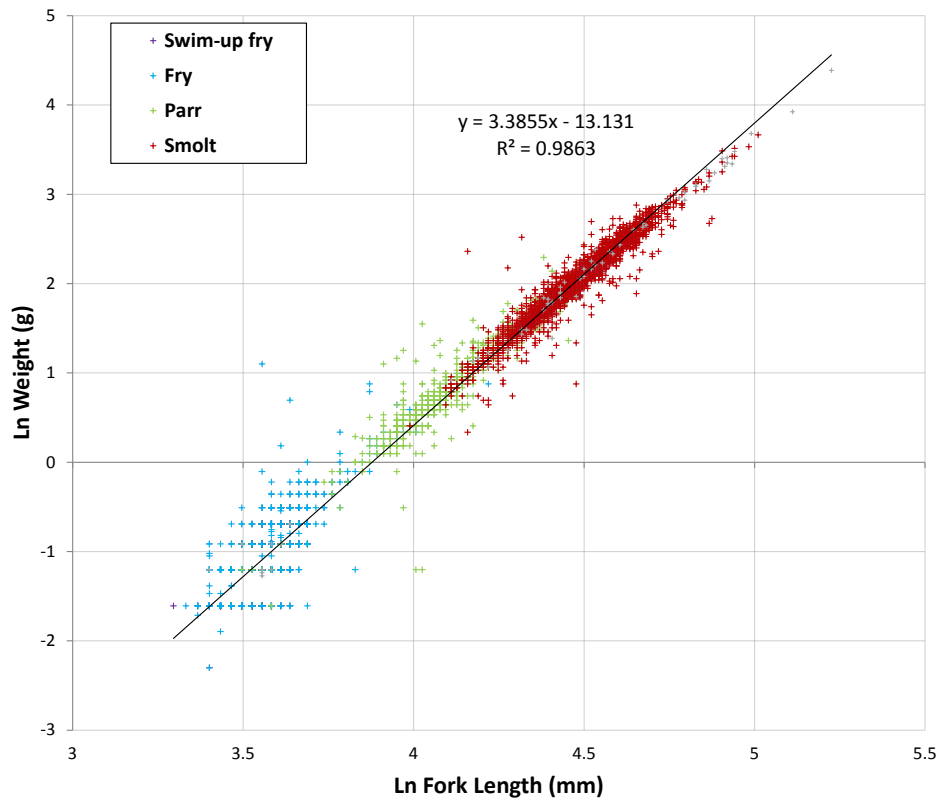


Figure 4.1-8. Length vs. Weight relationship for juvenile Chinook salmon in the Tuolumne River (2004–2010).

4.1.3.4 Fry Mortality

Potential mortality sources to Chinook salmon fry include predation effects due to the relative habitat availability for predators and juvenile salmon. As summarized in the Synthesis Study (W&AR-05), comparison of recovery data and estimated passage at RSTs located downstream of the spawning reach indicates substantial mortality of juvenile Chinook salmon (fry, parr, and smolt) in the approximately 25–26 miles between the upper (RM 29.8) and lower (RM 3.5 and RM 5.2) RSTs. Using whole season estimates of juvenile passage at the upper and lower traps, apparent survival in this reach has averaged 12 percent from 2008–2012, ranging from a low of 4 percent in 2012 to a high of 21 percent during extended flood control releases occurring in 2011 (TID/MID 2012, Report 2012-4). In order to represent mortality for fry rearing in differing locations as well as at differing flows, the apparent mortality across the distance separating the upper and lower RSTs is first converted to mortality per unit time using the estimated channel velocity in Equation 4. Next, the probability of fry survival for any incremental exposure time

from t_1 to t_2 in the main channel where potential predation may occur is modeled as an exponential function of the instantaneous mortality $m(t)dt$ between times t_1 and t_2 shown in Equation 6 below.

$$Survival = e^{-\int_{t_1}^{t_2} m(t)dt} \quad \text{Equation 6}$$

In addition to fry predation mortality, fry emerging during late spring may potentially be subject to water temperature related mortality during periods of hot weather. In laboratory studies, UUILT for Chinook salmon juveniles has been estimated at 25.1°C by Brett (1952) for Chinook salmon from the Pacific northwest that were acclimated at 20–24°C. Orsi (1971) estimated UUILT at 24.9°C for Sacramento River Chinook salmon acclimated at 21.1°C. Based upon this information, an initial mortality threshold of 25°C (77°F) was selected for Chinook salmon fry as a daily average. Although potential water temperature related mortality may occur at higher water temperatures, this is unlikely to affect the majority of fry emerging in January and February of each year.

Lastly, a background mortality rate of 0.002 d⁻¹ is applied to account for the potential for mortality due to other causes that may not be well represented in the model (e.g., disease, stranding, avian predation, and entrainment). Although no data are available to provide an estimate for the Tuolumne River, this rate is within the range as used in modeling conducted on the Klamath River (Bartholow and Henriksen 2006).

4.1.4 Juvenile Rearing

4.1.4.1 Juvenile Habitat Use

As rearing Chinook salmon juveniles progress from fry to the parr life stage, the increased body size is accompanied by increased swimming speeds. At this time broader foraging habitat use is necessary to meet increasing energy requirements (Everest and Chapman 1972). Following the same rationale for using WUA as a predictor of Chinook salmon fry habitat use (Section 4.1.3.1), juvenile salmon rearing from parr to pre-smolt sizes (50–69 mm) is represented using PHABSIM modeling. Estimates of in-channel juvenile rearing habitat availability as a function of flow is shown as WUA in Figure 4.1-9 using habitat suitability criteria presented in the *Lower Tuolumne River Instream Flow Study* (Stillwater Sciences 2013).

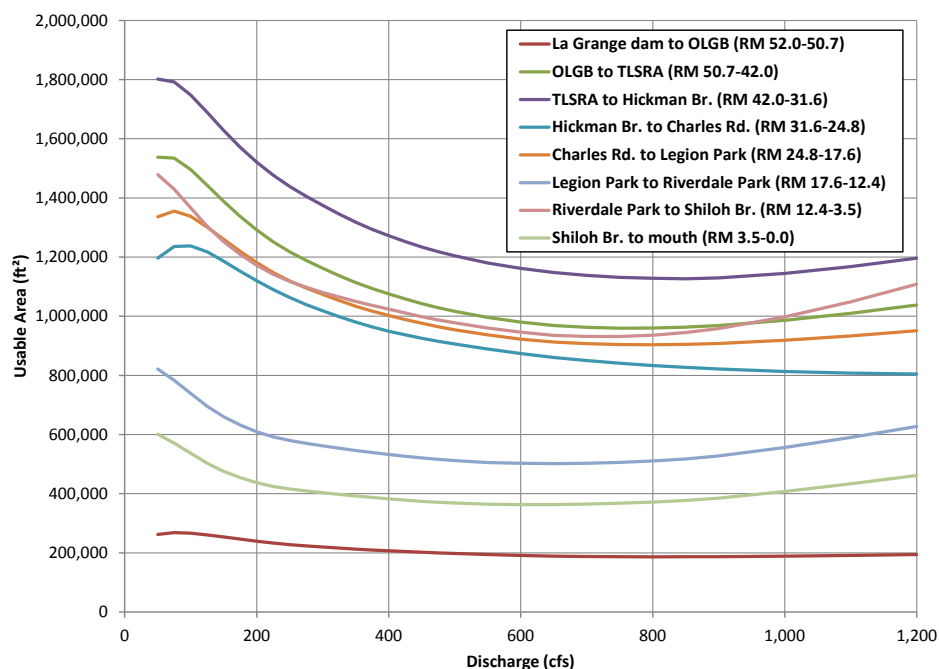


Figure 4.1-9. Variation of usable juvenile rearing area estimates with discharge for Chinook salmon in sub-reaches of the lower Tuolumne River.

In order to represent juvenile rearing habitat use on overbank habitat occurring at higher flows, WUA estimates for study sites evaluated using 2D modeling for the *Pulse Flow Study Report* (Stillwater Sciences 2012) were expanded in proportion to overbank inundation occurring on a river-wide basis (Figures 4.1-10 and 4.1-11) using digitized historical aerial photography (TID/MID 1997, Report 96-14). As noted for fry (Section 4.1.3.1), the 2D model-derived estimates of suitable habitat at the site-scale may not represent all conditions occurring river-wide. For example, estimates for the reach downstream of Shiloh Bridge (RM 3.5) may be strongly influenced by backwater effects from flood flow conditions occurring in the San Joaquin River at the time that air photos were flown for this analysis. The Districts have developed a study plan to conduct a *Lower Tuolumne River Floodplain Hydraulic Assessment* (W&AR-21) recommended by FERC in the May 21, 2013 Determination on Requests for Study Modifications and New Studies for the Don Pedro Hydroelectric Project. Depending upon the degree to which usable overbank habitat estimates developed as part of this new study differ from those used in Figure 4.1-10 and 4.1-11 as well as whether those results alter model predictions, the results of this study may be updated at that time.

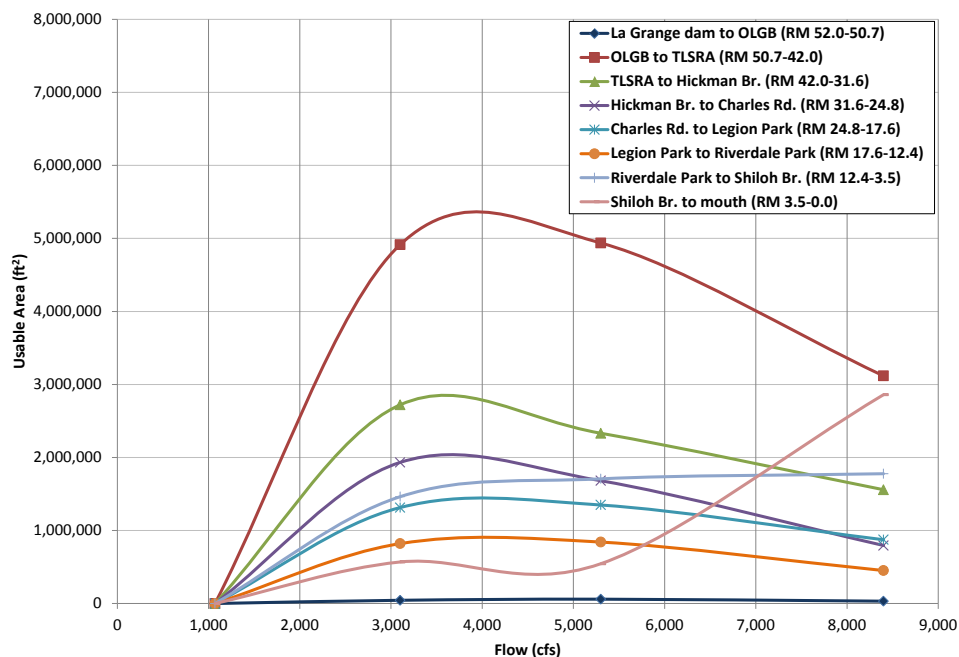


Figure 4.1-10. Estimated total usable overbank habitat for Tuolumne River Chinook salmon juveniles.

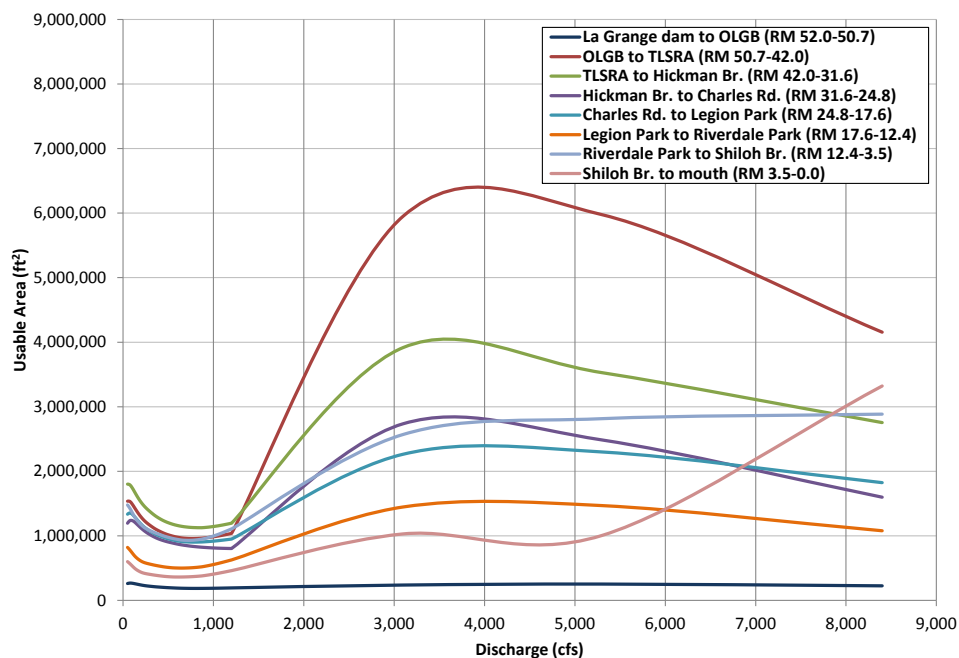


Figure 4.1-11. Estimated total combined usable in-river and overbank habitat for Tuolumne River Chinook salmon juveniles.

4.1.4.2 Juvenile Movement

In contrast to patterns of early Chinook salmon fry emigration found in RST monitoring on the Tuolumne River, juvenile emigration prior to smoltification is not assumed to occur. Movement

during the juvenile rearing period includes the same 0.2 mi/day estimate as applied to fry (Section 4.1.3.2), which was estimated from relative changes in seining density vs. river mile in bi-weekly sampling during non-flood years (WY 2002–2004, 2009, 2012). To account for these seasonal movements at higher flows, movement rates were represented as a daily movement probability initially estimated at 0.01 d^{-1} followed by a movement period of 2 hrs and velocity estimate from Equation 4. For areas with juvenile densities in excess of habitat carrying capacity, juvenile movement is initiated using the same 2 hr movement period and velocity estimates as for daily movements above. Because existing seine data on larger Chinook salmon juveniles is generally collected nearer the channel margins, it may not be representative of habitat utilization nearer the channel thalweg with higher velocities. For this reason, the maximum attainable juvenile density in the Tuolumne River is estimated at 5 juveniles/ m^2 based upon spatially explicit density estimates from long-term snorkel survey monitoring of juvenile habitat use on the Trinity River (USFWS 1991).

4.1.4.3 Juvenile Growth

Juvenile Chinook salmon growth in the lower Tuolumne River is represented in the same manner as for fry. Reach specific estimates of food availability are used in combination with daily water temperature as input variables into the growth model by Stauffer (1973) shown in Equation 5.

4.1.4.4 Juvenile Mortality

Potential mortality sources to Chinook salmon juveniles include predation effects due to the relative habitat availability for predators and juvenile salmon, as well as the potential for water temperature related mortality at higher water temperatures. Predation mortality for juveniles is represented in the same manner as for fry, using Equation 4 to convert from mortality as a function of distance between the upper and lower RSTs to mortality per unit time, and then calculating survival at incremental exposure times for fish at differing locations using Equation 6.

In addition to predation mortality discussed above, water temperature and background mortality for larger juveniles is the same as presented for Chinook salmon fry. Based upon information reviewed for Chinook salmon fry mortality (Brett 1952, Orsi 1971), an initial mortality threshold of 25°C (77°F) was selected for Chinook salmon juveniles as a daily average water temperature. A background mortality rate of 0.002 d^{-1} is also applied to account for the potential for mortality due to other causes that may not be well represented in the model (e.g., disease, stranding, avian predation, and entrainment).

4.1.5 Smolt Emigration

4.1.5.1 Smolt Movement

For juvenile Chinook salmon undergoing the physiological transformation from the parr to emigrant smolt life-stage, variations in the timing of the parr-smolt transition is influenced by genetics (Taylor 1990), fish size (Ewing et al. 1984), flow (Bjornn 1971), water temperature (Myrick and Cech 2001), and other environmental (e.g., lunar cycle, photo-period, turbidity) and

demographic factors discussed by Høgåsen (1998). Smolt emigration timing for fall-run Chinook salmon in the Tuolumne River generally occurs from late April through mid- to late-May (e.g., TID/MID 2013, Report 2012-4), depending upon many of the above factors. Examining smolt emigration under various water year types occurring since the initiation of routine RST monitoring at the Waterford (RM 29.8) and Grayson (RM 5.2) locations in 2006, the dates at which smolts migrate past the traps are quite variable, within years, between years, and between trap locations. There is a general pattern of extended emigration periods in high flow years that is well explained on the basis of size at emigration. Although there is evidence that a portion of annual smolt emigration occurs at sizes as low as 70 mm in all years, in below normal water year types (2007–2009, 2012) Figure 4.1-12 shows that the size-distributions of emigrating smolts at the Waterford (dashed line) and Grayson (solid line) RSTs are normally distributed in each year as illustrated by blue shaded normal curves on each of the tiles along the diagonal. The distributions at the upstream and downstream locations are also very similar in each year as shown by the yellow band showing equality between the two distributions. The below normal water year type size distributions are normally distributed around a mean size near 80–85mm. In above normal water year types (2006, 2010, and 2011), Figure 4.1-13 shows that smolt size at emigration is also normally distributed, with a mean size at emigration peaking at a larger mean size between 90–100 mm. In examining the smolt passage dates, smolts tend to leave later in above normal water years than in below normal years, and this extended period of in-river rearing may explain the larger size at emigration. Extended rearing prior to smoltification has been associated with reduced growth rates and slower development at lower water temperatures in hatchery studies in British Columbia (Rombough 1985).

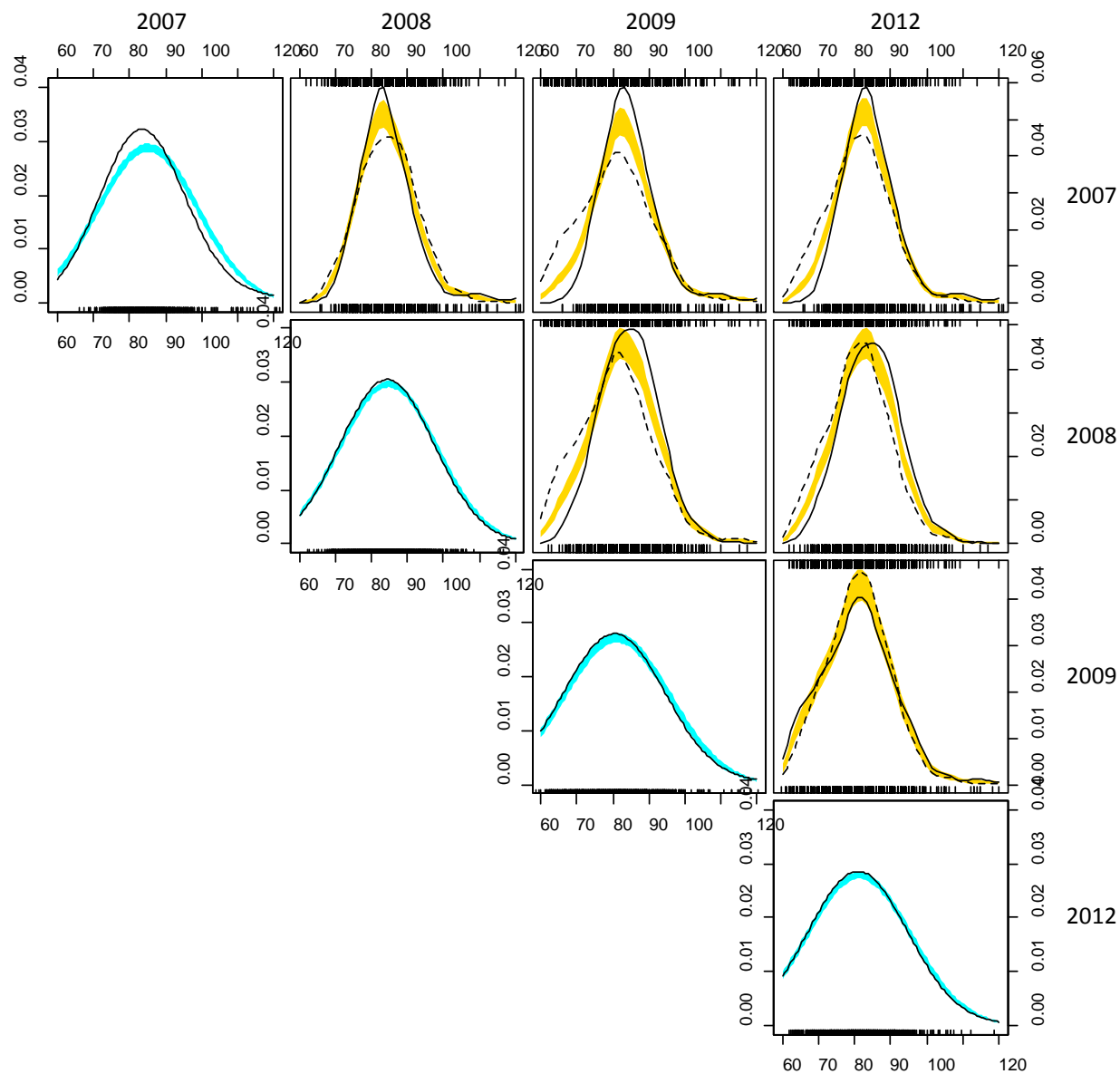


Figure 4.1-12. Comparisons of smolt size at emigration in below average water year types (2007–2009, and 2012) in the Tuolumne River.

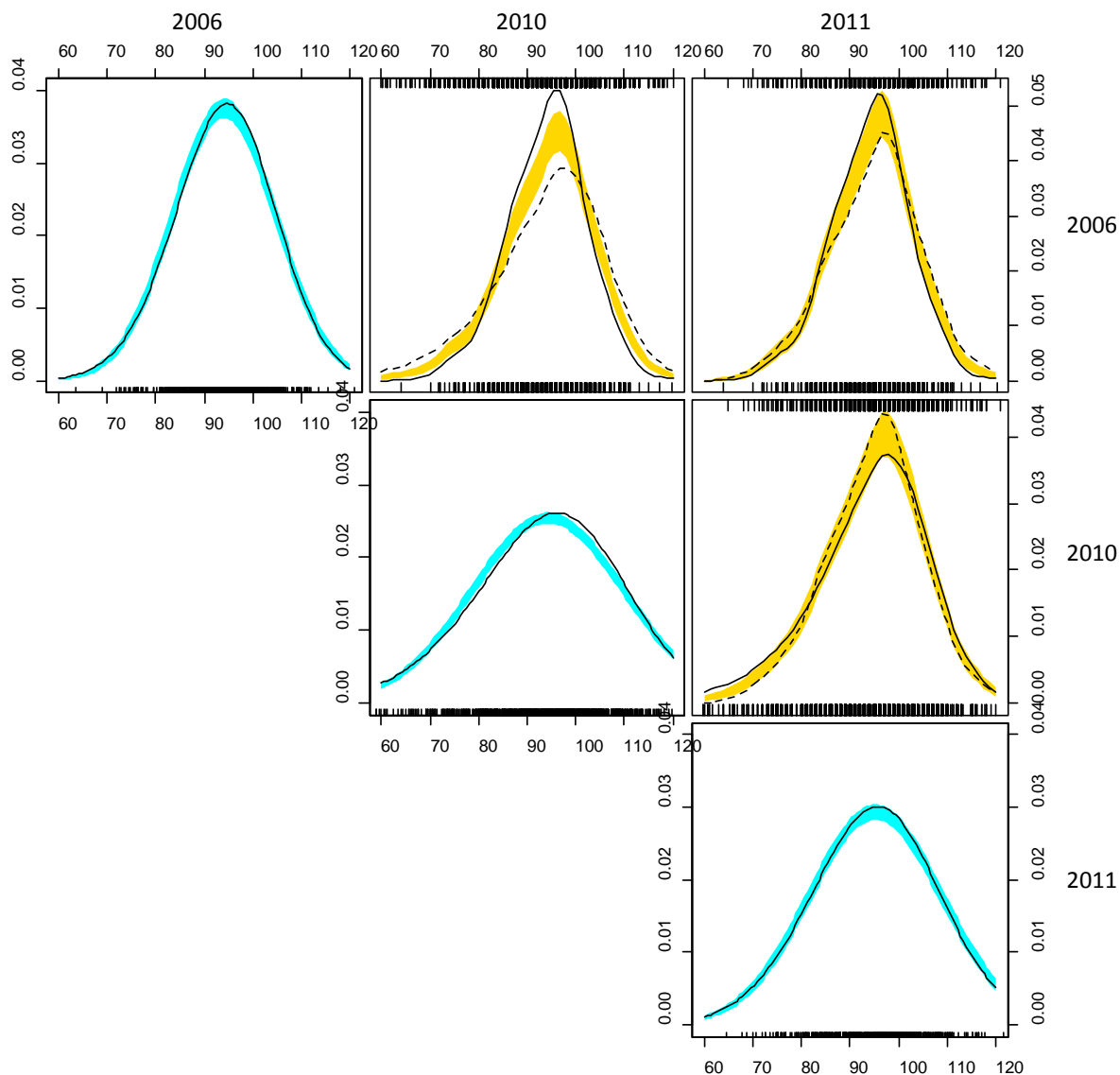


Figure 4.1-13. Comparisons of smolt size at emigration in above average water year types (2006, 2010, and 2011) in the Tuolumne River.

Based upon the observed smolt sizes in the Tuolumne River (Figure 4.1-12 and Figure 4.1-13), smolt movement is modeled on the basis of achieving a length based minimum development threshold to achieve “smolt-ready” status, followed by emigration movement on the basis of a probability distribution around the means sizes discussed above. The minimum threshold selected for smolt-ready status is 70mm, as found in other studies (Ewing and Birks 1982), with individuals emigrating according to the size distributions in above- and below-normal water years based upon their individual exposure history of various discharge levels. Assuming that the daily growth increment ΔL is small in comparison to the length of the individual fish, the probability (P) that an individual will smolt at a length between L and $L+\Delta L$ is shown using a normal distribution around the mean length (μ) in Equation 7 below.

$$P = \frac{\frac{1}{\sqrt{2\pi\sigma^2}} e^{-(L-\mu)^2/2\sigma^2}}{\int_L^\infty \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(\lambda-\mu)^2/2\sigma^2} d\lambda} \frac{\Delta L}{\sigma}. \quad \text{Equation 7}$$

Based upon previous estimates of emigration speeds of up to 46 mi/day in multiple mark recapture smolt survival studies (TID/MID 2001, Report 2000-4), smolt emigration was represented as an outmigration speed of 26 mi/day in addition to reach specific velocity estimates (Equation 4).

In addition to emigration on the basis of size, outmigration pulse flows have been implemented on the Tuolumne River under the current FERC (1996) license to improve conditions for emigrating smolts. Flow has been broadly associated as a factor associated with emigration timing (Bjornn 1971, Sykes et al 2009) and short-term increases in smolt passage following pulse flow reductions has been observed on the Tuolumne River (Attachment D) as well as the neighboring Stanislaus River (Demko and Cramer 1996). However, because of the low sample size used in evaluating flow as a stimulatory cue for smolt emigration from the Tuolumne River as well as the high variability in daily smolt passage on the Tuolumne River outside of the pulse flow periods, flow magnitude or flow change have limited ability to explain the initiation of smolt outmigration (Attachment D). For this reason, no flow related outmigration cues have been included in the initial model development and smolt outmigration timing is based upon the Equation 7 probability function representing the historical observations of size at emigration (Figure 4.1-12 and Figure 4.1-13).

4.1.5.2 Smolt Mortality

As summarized in the Synthesis Study (W&AR-05), extensive smolt survival studies using paired releases of coded wire-tagged (CWT) hatchery salmon have provided only a broad estimate of a flow-survival relationship for the lower Tuolumne River. Higher smolt survival in the Tuolumne River was associated with the two tests occurring at 4,000 cfs and greater, lower survival was associated with tests done at low flows near 600 cfs, and more variable results were obtained at intermediate flows. Because only a limited number of smolt survival estimates were used in the development of the Tuolumne River Technical Advisory Committee (TRTAC) smolt survival relationship (TID/MID 2005a, Report 2004-7), estimation of smolt survival at intermediate and high flows is not feasible. Further, survival of wild smolts may not be well represented by experimental results on large releases of hatchery reared fish. In addition to the behavioral differences between hatchery and wild counterparts (Berejikian and Ford 2004), other concerns regarding representing smolt survival from the existing TRTAC smolt survival relationship are related to biases from the “swamping” effects that large numbers of CWT fish may have on predation and the resulting survival estimates (Fritts and Pearsons 2008).

Because season wide estimates of outmigration survival in recent RST reports (2008–2012) are on the order of 4–21 percent (TID/MID 2013, Report 2012-4), well below that suggested by the TRTAC smolt survival relationship, additional examination of RST passage at Waterford (RM 29.8) and Grayson (RM 5.2) was conducted to further evaluate apparent smolt survival relationships with flow (Attachment D). Overall, the analysis indicates lower survival than the TRTAC smolt survival relationship over a range of flows, consistent with patterns in lower

relative smolt passage between the upstream and downstream traps exhibited in RST monitoring reports. To provide consistency with RST data used in model fitting, a linear flow-survival relationship fitted to RST data (Equation 8) was selected for modeling smolt outmigration survival (Attachment D). In order to represent predation mortality of outmigrant smolts emigrating from different portions of the lower Tuolumne River, discharge-specific survival (S_{RST}) between the RST locations (RM 29.8 to RM 5.2) as a function of flow (Equation 8) was converted to a survival estimate per unit distance (S_D) travelled (Equation 9).

$$S_{RST} = \min(0.03287 + 2.347 \times 10^{-5} \times Q_{LaGrange}, 1) \quad \text{Equation 8}$$

$$S_D = e^{-mD}, \text{ where } m = -\frac{\log S_{RST}}{29.8-5.2} \quad \text{Equation 9}$$

In addition to predation mortality discussed above, water temperature related mortality for Chinook salmon smolts is the same as presented for Chinook salmon juveniles above (Section 4.1.4.4). Based upon information reviewed for Chinook salmon juvenile mortality (Brett 1952), an initial mortality threshold of 25°C (77°F) was selected for Chinook salmon smolts as a daily average water temperature.

4.2 Model Implementation

The Tuolumne River Chinook population model is implemented within the publicly available “R” statistical software package (R Development Core Team 2013) with data and parameter inputs as well as outputs formatted as MS Excel spreadsheets. The model uses a generalized multi-stage stock production approach (Baker 2009) in which starting numbers of a particular life-stage (stock) are mathematically modeled to predict how the numbers change as the cohort goes through subsequent life stages. Each life stage is represented in the stock-production model as a data frame, with one record per individual, having attribute fields as presented in Table E-1 (Attachment E). However, because the numbers of individuals within the fry, juvenile, and smolt life stages are very large, it is not computationally practical to model every individual. In these cases, a large random sample of typical individuals is drawn from the population, and these are tracked; their outcomes are then extrapolated to the entire population of the subsequent life stage. The size of this sample is selectable as a user-provided parameter, independent of the population size; the default values used for the results presented in this document are 50,000 swim-up fry, 10,000 parr, and 5,000 smolts.

The stock-production models developed for each life stage are discussed in the following sections, with parameters in the form of discrete numbers or ranges that are dependent upon the attributes of an individual within the larger population. For example, fecundity may be dependent upon the age of an individual spawner. The model also includes random elements for many mechanisms affecting life history progression, relying on probability distributions for events such as upmigration timing, individual spawner age, spawning locations, fry and juvenile movements, predation related mortality, as well as size at emigration. Each stock production model also makes use of temporally and spatially varying environmental conditions while determining the progression of individuals within their respective life stages and promotion into the next life stage. For example, depending upon the spatial and temporal resolution of the discharge and water temperature time series data provided (e.g., discharge and water temperature data, output from *Operations Model*, output from *Water Temperature Model*), an interpolation

module is employed to provide discharge and water temperature estimates at more specific locations and times through interpolation. As the simulation for each modeled individual progresses through time, the stock-production model queries the discharge and water temperature module to help define environmental conditions within a certain area on any given day. Several of the stock-production models also gather information from a “habitat generator” module (output defined in Attachment E, Table E-2), a set of flow-dependent habitat suitability models (which also retrieve information from the discharge and water temperature module). All input data for these environmental modules can be linked to historical environmental data records to provide opportunities for model validation. In addition, synthetic historical data from the *Project Operations/Water Balance Model* (W&AR-02) as well as the *Lower Tuolumne River Temperature Model* (W&AR-16) may be used to examine the potential effects of various operational scenarios. Below, individual stock production models are described along with their associated model parameters.

4.2.1 Adult Upmigration and Spawning

The adult upmigration and spawning stock-production model essentially follows the progression of a spawner life stage into a redd life stage and a carcass life stage. This model draws upon information from the following sources:

- (1) spawner population data,
- (2) the spawning habitat generator,
- (3) the discharge and water temperature module, and
- (4) a list of parameters (Table 4.2-1)

Table 4.2-1. Parameters and associated references for upmigration and spawning.

Parameter		Range (selected value)	Description	Reference
migration.rate		2–30 mi/day (1 mi/day)	rate at which adults move upstream from the weir to spawning gravels	Weir passage (TID/MID 2013, Rpt. 2012-7), redd counts (TID/MID 2011, Rpt. 2010-1), Strange 2010; Goniea et al 2006
fecundity	age 2	3425 eggs	number of fertile eggs produced by a successful female spawner	TID/MID 1992, App 1; Loudermilk et al 1990 as cited in TID/MID 1992, App 8
	age 3	5964 eggs		
	age 4	7524 eggs		
	age 5	7963 eggs		
male.surv.time		7–21 days (21 days)	time from arrival at spawning gravels to death	Sockeye salmon (Morbey et al 2005)
female.surv.time		7–21 days (21 days)	time from arrival at spawning gravels to death, unless able to construct a redd	Sockeye salmon (Morbey et al 2005)
spawn.wtemp.max		16–18.9°C (16°C)	maximum temperature at which spawning habitat will be considered usable by spawners	Groves and Chandler 1999, McCullough 1999
redd.disturb.area		24–172 ft ² (52 ft ²)	area of region excavated by a spawning female	TID/MID 1992, App 6; Burner 1951; Chapman 1943; W&AR-08
redd.defense.area		96–688 ft ² (214 ft ²)	defended area excluding later arriving spawners (~ 4x redd disturbance area)	Burner, 1951

Parameter	Range (selected value)	Description	Reference
redd.defense.time	7–25 days (7 days)	time female will prevent other spawners from disturbing her redd	Neilson and Banford 1983; TID/MID 1992, App 6; TID/MID 1997, Report 96-6

The model must be provided with a “spawning run”, represented by a table having one row per spawner and specifying such things as the date and river mile at which each spawner is considered to enter the population, gender, and age or size. This table can be based on data from the counting weir (RM 24.5) or synthesized from summary statistics such as the total run size, age composition, fraction of females, and the mean and standard deviation of arrival times.

The spawning habitat generator defines the suitability of spawning habitat at a specific location and time. Using functional relationships described in Section 4.1.1.1, the spawning habitat sub-model calculates temporally and spatially varying availability of suitable spawning gravels and assigns spawner usage probability based upon an MS Excel table of gravel feature areas, gravel quality, and spawner preferences by river mile and discharge. It also queries the discharge and water temperature module to obtain discharge and water temperature. Each spawner is assigned to a discrete gravel feature on the basis of the area and preference value for the feature at the time the spawner enters the population. Migration rates are provided in Table 4.2-1. Mortality during migration to the assigned feature is assumed to be negligible (Section 4.1.1.3), and spawning preferences are assumed not to change significantly on the time-scale of the migration.

Once an upmigrant spawner reaches its assigned feature, it is assumed to stay there. Males are assumed to die a fixed number of days after arrival, and females are assumed to die a fixed number of days after arrival only if they are unable to find room to construct a spawning redd. A female which is able to construct a redd is assumed to die after a fixed number of days defending the redd. If a female dies before spawning, her eggs are assigned to her carcass for tracking purposes, otherwise the eggs are assigned to her redd according to the spawner size at age (Table 4.2-1). The associated numbers of redds and carcasses produced by the model allow for validation or calibration from corresponding redd and carcass surveys.

The model keeps track of the gravel occupancy by spawners and redds over the course of a spawning season. Whenever a new spawner arrives or a redd location becomes undefended, the area of usable gravel for each feature is updated. Pending spawners are then allowed to build redds as long as there is room to accommodate them, and larger spawners are given priority. When a new redd is constructed in a gravel feature, it is assumed to disrupt a fraction of the undefended gravels in the feature, and destroy this same fraction of the eggs in undefended redds (TID/MID 1992, Appendix 6).

4.2.2 Egg Incubation and Fry Emergence

The Egg Incubation and Fry Emergence stock-production model follows the progression of a redd life stage into a swim-up life stage. This model draws upon information from the following sources:

- (1) the adult upmigration and spawning stock-production model output,
- (2) the discharge and water temperature module,
- (3) results of the spawning habitat generator, and
- (4) a list of parameters (Table 4.2-2)

Table 4.2-2. Parameters and associated references for egg incubation and fry emergence.

Parameter	Range (selected value)	Description	Reference
gravel.qual	0–100% (32%)	egg survival to fry emergence due to gravel quality effects upon intra-gravel conditions	TID/MID 1992, Appendix 8; Jensen et al 2009
embryo.uuilt	13.9–15.6°C (14.4 °C)	temperature at which mortality increases from 0% to 100%	Seymour 1956; USFWS 1998; Rich 2007

From these data sources, the model predicts the dates of alevin swim-up on the basis of fertilization dates (i.e. redd construction dates) provided by the adult upmigration and spawning stock-production model and water temperatures from the discharge and water temperature module. Using relationships described in Section 4.1.2, the model tracks development of individual eggs as a function of temperature as well as tracking egg and alevin mortality attributable to excessive temperatures, gravel quality, and redd superimposition. An individual becomes a “swim-up fry” once it successfully emerges from the gravels.

4.2.3 Fry Rearing

The Fry Rearing stock-production model follows the progression of a swim-up life stage into a parr life stage or a dead fry life stage. Additionally, it tracks the movement of fry past landmarks using the passage fry life stage. This stock-production model draws upon information from the following sources:

- (1) the egg incubation and fry emergence stock-production model,
- (2) the discharge and water temperature module,
- (3) the fry habitat generator, and
- (4) a list of parameters (Table 4.2-3)

Table 4.2-3. Parameters and associated references for fry rearing.

Parameter	Range (selected value)	Description	Reference
length.swimup	32–38 mm (33 mm)	fork-length at swim-up	TID/MID 2007, Report 2006-7
fry.emigrate.p	0.3	fraction of swim-ups assumed to leave the river entirely	Fitted to RST data by date (TID/MID unpublished)
fry.displace.rate	0.05 days ⁻¹	instantaneous rate at which fish will become displaced	Fitted to seine/RST data (TID/MID unpublished) by RM/date
fry.displace.time.mean	0.0208 days	mean interval between time a fish is displaced and time it becomes re-established	
fry.displace.time.CV	1	coefficient of variation of displacement time	

Parameter	Range (selected value)	Description	Reference
fry.density	1.496 ft ⁻²	maximum fry rearing density	Historical maximum from seine haul data (1989, 1999, 2003) (TID/MID unpublished)
Rf	0.7, 0.3	feeding ration fraction as proportion of maximum	TID/MID 1997, Report 96-9, Sommer et al 2001, Jeffres et al 2008
fry.migr.mrate	5.408 days ⁻¹	mortality rate applied to fry moving downstream	Fitted to RST passage data (TID/MID unpublished)
fry.mrate	0.002 days ⁻¹	mortality rate applied to all fry	Bartholow and Henriksen 2006
fry.uuilt	24–25°C (25°C)	temperature at which mortality increases from 0% to 100%	Brett 1952; Orsi 1971; McCullough 1999
length.parr	50 mm	fork-length at parr	Operational size class (TID/MID 2013, Report 2012-4)

Following the emergence of swim-up fry, as simulated by the egg incubation and fry emergence stock-production model, this stock-production predicts the dates of parr promotion (attainment of a given fork length) on the basis of emergence dates, water temperatures, and feeding rations in various locations along the lower Tuolumne River. The fry habitat generator defines daily in-channel and floodplain habitat suitability based upon discharge and water temperature. It draws upon a user-provided table of reach-specific estimates of mortality rates, feeding ration levels, fry densities, and flow-dependent velocities and useable habitat areas. It receives discharge and water temperature values from the discharge and water temperature module. Using relationships discussed in Section 4.1.4, the model simulates fry growth at a daily times step as a function of its current fork length, the water temperature at its current location, and a measure of food availability in its current reach.

The model tracks the redistribution of fry from the spawning gravels to downstream habitat (in some cases out of the system), on the basis of discharge and habitat usage. Upon emergence from the gravels, some fraction of the new swim-ups is assumed to emigrate from the river entirely. This fraction is given by the parameter “p.emigrate.” As the model progresses through time, the remaining swim-ups and any rearing fry in excess of the current carrying capacity of the reach they are in (defined as exceedance of the user-defined reach density within usable habitat areas for the reach), are assumed to be displaced. These fry are carried downstream for a random length of time, implemented as a lognormal deviate whose mean and coefficient of variation are provided by the user (as parameters “displace.time.mean” and “displace.time.CV”, respectively). All fry (both “emigrant” and “temporarily displaced”) are subjected to “migration mortality” for as long as they are in motion. This is intended to represent predation. In addition, all fry are subjected to “background mortality”, intended to account for things like disease or avian predation and to immediate death if temperatures exceed a critical value. The model reports the passage of weir-specified landmarks, such as, the RSTs of Waterford (RM 29.8) and Grayson (RM 5.2) as the pseudo-life stage of “passage fry”, and exit from the mouth of the Tuolumne River as the lifestage “emigrant fry.” In addition to water temperature (Table 4.2-3),

reach-specific estimates of mortality probability per unit time are based upon estimates from juvenile passage at the upstream and downstream RSTs (Section 4.1.3.4). Fry which die or leave the Tuolumne River before attaining parr status are labeled as a dead fry and are passed into the dead fry life stage.

4.2.4 Juvenile Rearing

The Juvenile Rearing stock-production model follows the progression of a parr life stage into a smolt-ready life stage or a dead parr life stage. It also tracks the movement of juvenile Chinook past landmarks with the passage juvenile life stage. The juvenile rearing model is very similar to the fry rearing model, but it is represented as a separate life stage because juveniles have somewhat different habitat requirements from fry. Juveniles are strong swimmers, already established in rearing habitat, so dispersal is modeled as a less important a mechanism. This stock-production model draws upon information from the following sources:

- (1) results of the Fry Rearing stock-production model,
- (2) the discharge and water temperature module,
- (3) the juvenile habitat generator, and
- (4) a list of parameters (Table 4.2-4).

Table 4.2-4. Parameters and associated references for juvenile rearing.

Parameter	Value	Description	Reference
juv.displace.rate	0.01 days ⁻¹	instantaneous rate at which fish will become displaced	Fitted to seine/RST data by RM/date (TID/MID unpublished) by RM/date
juv.displace.time.mean	0.0833 days	mean interval between time a fish is displaced and time it becomes re-established	
juv.displace.time.CV	1	coefficient of variation of displacement time	
juv.density	0.465 ft ⁻²	Maximum fry rearing density	USFWS (1991) Trinity River snorkel data
Rf	0.7, 0.3	feeding ration fraction as a proportion of maximum	TID/MID 1997, Report 96-9, Sommer et al 2001, Jeffres et al 2008
juv.migr.mrate	0.1386 days ⁻¹	aquatic predation rate due to downstream movement	Fitted to RST passage data (TID/MID unpublished)
juv.mrate	0.002 days ⁻¹	background mortality rate due to disease, stranding, avian predation, and entrainment	Bartholow and Henriksen 2006
smolt.fraction	0.9	proportion of juveniles becoming smolts	Approximation based upon summer rearing population estimates (Stillwater Sciences 2008, 2009, 2011, 2012)
smolt.promotion.jday	151 days	last day (from 1 January) that smolting can occur in the spring	Operational threshold (not used)

Parameter	Value	Description	Reference
length.smoltmin	70 mm	minimum size threshold for smolting	Operational size class (TID/MID 2013, Report 2012-4)
length.smoltmu	83.46 mm	Median size of smolts passing RSTs	Size distributions from 2006–2012 RST data (TID/MID unpublished)
	0.0018 mm/cfs	Estimated size increase by flow	
length.smoltsd	7.63 mm	coefficient of variation of smolt size	
length.smoltmax	120 mm	maximum size threshold before smolting	Upper estimate in RST reports (e.g., TID/MID 2013, Report 2012-4)
juvenile.uuilt	24–25°C (25°C)	temperature at which mortality increases from 0% to 100%	Brett 1952; Orsi 1971; McCullough 1999

This stock-production model tracks groups of Chinook juveniles from their promotion to parr status until they emigrate out of the system, attain smolt status, or die, all the while making note of landmark passages such as the RSTs at Waterford (RM 29.8) or Grayson (RM 5.2). The juvenile habitat generator defines daily in-channel and floodplain habitat suitability based upon discharge and water temperature. It draws upon a user-provided table of mortality rates, feeding ration levels, maximum fry and juvenile densities, as well as flow-dependent useable habitat areas by reach. It receives discharge and water temperature values from the discharge and water temperature module. The model predicts the dates of smolt-ready promotion (attainment of a given fork length) using growth relationships on the basis of parr promotion dates, and growth estimated from water temperatures and feeding rations (Section 4.1.4.3). During each time step (one day), each juvenile grows by an increment determined from its current fork length, the water temperature at its current location, and a measure of food availability in its current reach.

The model tracks the redistribution of juveniles on the basis of discharge and habitat usage, as well as juvenile emigration. The model tracks individuals as they pass any of a number of user-specified landmarks such as the RSTs. Mortality during any movements or redistribution is estimated by exposure to predation and excessive temperatures. As the model simulation progresses through time, juveniles in excess of the current carrying capacity of the reach they are in (defined as exceedance of the user-defined reach density), are assumed to be displaced. These juveniles are carried downstream for a random length of time, implemented as a lognormal deviate whose mean and coefficient of variation are provided by the user (as parameters “displace.time.mean” and “displace.time.CV”, respectively). In addition to water temperature (Table 4.2-4), reach-specific estimates of mortality probability per unit time are based upon estimates from juvenile passage at the upstream and downstream RSTs (Section 4.1.4.4). Juveniles which die or leave the Tuolumne River before attaining smolt status are labeled as a dead juvenile and are passed into the dead juvenile life stage.

Smoltification of rearing juveniles is based upon attainment of a minimum size threshold (parameter “length.smoltmin”) with the probability that a smolt-ready individual will smolt based upon fish size relative to typical distributions of size at emigration developed in Section 4.1.5.1. The model uses a truncation of the tails of the size distribution, with any fish reaching the maximum size (“length.smoltmax”) being automatically promoted to smolts. Rather than applying temperature limits for smoltification, the model assumes a fixed proportion of smolt-ready individuals (“smolt.fraction”) will continue rearing (i.e., over-summer) to become yearling smolts in the following year.

4.2.5 Smolt Emigration

The Smolt Emigration stock-production model follows the outmigration of a smolt life stage from the Tuolumne River, tracking movements of smolts past landmarks. This stock-production model draws upon information from the following sources:

- (1) results of the Juvenile Rearing stock-production model,
- (2) the discharge and water temperature module, and
- (3) a list of parameters (Table 4.2-5)

Table 4.2-5. Parameters and associated references for smolt emigration.

Parameter	Value	Description	Reference
smolt.uuilt	24–25°C (25°C)	temperature at which mortality increases from 0% to 100%	Brett 1952; Myrick and Cech 2001, McCullough 1999
smolt.surv.rstreach.byq	0.00002347/cfs	fitted slope of survival from Waterford (RM 29.8) to Grayson (RM 5.2)	RST data (e.g., TID/MID 2013, Report 2012-4) estimates of flow vs. survival (Attachment D)
	0.03287	fitted intercept of survival at zero flow	

Mortality during smolt emigration is estimated by exposure to predation and excessive temperatures. In addition to water temperature mortality thresholds (Table 4.2-5), reach-specific estimates of mortality probability per unit distance and discharge are based upon estimates from juvenile passage at the upstream and downstream RSTs (Section 4.1.5.2).

4.3 Model Calibration and Validation

As described in the Study Plan, calibration and validation was conducted by comparisons of modeling results of fry and/or smolt production with annual production estimates available from RST sampling conducted in the lower Tuolumne River. Some model mechanisms and functional relationships discussed in Section 4.2 have been studied in detail, under controlled conditions, and the appropriate values for the relevant model parameters (Section 4.2) are constrained by experimental data. Other relationships are purely empirical, or based on simple models, and use parameter values constrained only loosely by “common sense” arguments. The calibration and validation phase of the model has two purposes: (1) to fine-tune the less well constrained parameter values in order to maximize the agreement between the model and monitoring data, and (2) to examine the degree to which the modeled mechanisms account for the year-to-year variability in these data. Two sources of data were used, RST sampling as well as river-wide seining data.

4.3.1 Calibration to Recent RST Data

The most recent RST data collected in the Tuolumne River were used as the primary data source to calibrate the model, including the 2010, 2011, and 2012 sampling seasons. The rationale for using data from these years is that they overlap the period of operation for the counting weir (RM 24.5) as well as recent mapping efforts conducted as part of the *Redd Mapping Study* (W&AR-08). For these years, weir passage data were reviewed to ensure the adult upmigration

and spawning stock-production model (Section 4.2.1) was provided with well constrained numbers, sizes, arrival dates of spawners, as well as spawning dates. Subsequent stock-production models for egg incubation through juvenile rearing and emigration allow prediction of fork-lengths, and passage dates of fish passing the RST monitoring locations as fry, juveniles, and smolts. These model quantities correspond precisely to the data collected in annual RST monitoring reports. A data quality review for RST passage data (Attachment D) was used to re-estimate juvenile Chinook salmon passage for the period 2007–2012 to ensure the best available data were available for model calibration. Using parameter estimates for upmigration, spawning, egg incubation, and fry rearing (Table 4.2-1 through 4.2-3), fry passage at Waterford (RM 29.8) and Grayson (RM 5.2) was fit through adjustment of movement related parameters (fry.emigrate.p, fry.displace.rate, fry.displace.time) as well as mortality (fry.mrate and fry.migration.mrate). Because downstream movement of juveniles is assumed to be slower than for fry, smolt passage was fit through adjustment of juvenile mortality related parameters only (juv.mrate and juv.migration.mrate). Smolt survival parameters (smolt.surv.rstreach.byq) developed from the updated flow survival relationship in Attachment D were not adjusted during calibration.

4.3.2 Validation to Historical RST Data not used in Model Calibration

Following calibration to recent RST data, model validation was conducted by comparing modeling results for other years of paired RST operations that were not included in the calibration. As discussed in the Synthesis Study (W&AR-05), paired RST monitoring has been conducted at the Waterford (RM 29.8) and Grayson (RM 5.2) locations since 2006 with only partial sampling of the Grayson location occurring in 2007. Although no upstream passage information exists prior to installation of the RM 24.5 counting weir in September 2009, CDFW spawner count information for escapement years 2005–2008 was used in the model to estimate juvenile production for the corresponding outmigration years (2006–2009) and compared to RST production estimates.

4.3.3 Validation using Historical Seining Data

Because existing RST data only provide direct information at two locations (RM 29.8, RM 5.2), and only for fish in motion, model validation was conducted using seining data corresponding to the outmigration occurring in the combined calibration and validation period (2007–2012). The model predicts the dates and locations at which fish are promoted from one life stage to another, for example, the dates and locations at which fry emerge from spawning redds, the dates and locations at which fry are promoted to parr status (FL >50mm), and the dates and locations at which smolt-ready juveniles (FL >70mm) undergo smoltification. These model results may be used to examine spatial and temporal patterns in the distributions of non-migrating fish rearing at various locations in the lower Tuolumne River—patterns that are observable in the historical seining data (Attachment C) and are primarily used to confirm assumptions and parameters affecting development rates (hence temporal patterns) as well as those related to movement and emigration rules (hence spatial patterns).

4.4 Sensitivity Analyses

Using hydrology for WY 2009 (Dry) and WY 2011 (Wet) and corresponding water temperature data, variations in juvenile production was examined using sensitivity testing by varying parameter values in the validated model. The sensitivity analysis consisted of making a large number of model runs, varying one parameter at a time. For each change in a particular parameter value, the model was used to recalculate the estimated juvenile production, holding all other values constant. Table 4.4-1 shows the thirty parameters that were selected for examination along with the calibrated value and the parameter range tested (i.e., Min, Max). Parameters excluded from sensitivity testing were of two types. First, some parameters have very subtle effects: for example, the model has a parameter representing the number of days a male will survive after it reaches the spawning grounds (male.surv.time), but this number has no effect at all on the rest of the life history (the model assumes that there are always enough males around to fertilize any redds constructed), and so is omitted from the sensitivity analysis. Second, some collections of parameters function together in such a way that it would be redundant to consider them all separately. For example, the number of eggs per spawner and the survival of embryos from fertilization to alevin swim-up are separate parameters, but only the product of the two has visible consequences, and so only the latter is varied in the analysis.

Table 4.4-1. Model parameters selected for sensitivity testing.

Model Parameter	Description	Calibrated Value	Min Tested	Max Tested
Upmigration and Spawning				
spawn.wtemp.max	maximum temperature for spawning (C)	16	14	18
redd.disturb.area	area reworked by redd construction (ft2)	52	13	208
redd.defense.time	redd defense time (d)	7	4	14
Egg Incubation and Fry Emergence				
embryo.development	number of “weighted thermal units” from fertilization to swim-up	1	0.5	1.5
embryo.survival	egg survival-to-emergence	0.32	0.16	0.64
embryo.uuilt	upper incipient lethal temperature for egg/alevin (C)	14.44	12	16
Fry Rearing				
fry.emigrate.p	fraction of fry emigrating at swim-up	0.3	0.2	0.4
fry.displace.time.mean	mean duration of fry displacement (d)	0.02	0.01	0.04
fry.ration (in-channel)	fry in-channel feeding ration levels (% max)	0.7	0.4	1
fry.ration (floodplain)	fry floodplain feeding ration levels (% max)	0.7	0.4	1
fry.density (in-channel)	fry in-channel rearing densities (#/ft2)	1.496	0.374	5.984
fry.density (floodplain)	fry floodplain rearing densities (#/ft2)	1.496	0.374	5.984
fry.uuilt	upper incipient lethal temperature for fry (C)	25	17	25
fry.mrate (in-channel)	fry in-channel background mortality rates (1/day)	0.002	0.001	0.004
fry.mrate (floodplain)	fry floodplain background mortality rates (1/day)	0.002	0.001	0.004
fry.migr.mrate	fry migration mortality rates (1/day)	2.704	1.352	5.408
Juvenile Rearing				
juv.displace.time.mean	mean duration of juvenile displacement (d)	0.0833	0.04165	0.1666
juv.ration (in-channel)	juvenile in-channel feeding ration levels (% max)	0.7	0.4	1
juv.ration (floodplain)	juvenile floodplain feeding ration levels (% max)	0.7	0.4	1
juv.density (in-channel)	juvenile in-channel rearing densities (#/ft2)	0.464	0.116	1.856

Model Parameter	Description	Calibrated Value	Min Tested	Max Tested
juv.density (floodplain)	juvenile floodplain rearing densities (#/ft ²)	0.464	0.116	1.856
juvenile.uuilt	upper incipient lethal temperature for juveniles (C)	25	17	25
juv.mrate (in-channel)	juvenile in-channel background mortality rates (1/day)	0.002	0.001	0.004
juv.mrate (floodplain)	juvenile floodplain background mortality rates (1/day)	0.002	0.001	0.004
juv.migr.mrate	juvenile migration mortality rates (1/day)	0.1386	0.0693	0.2772
length.smoltmu (intercept)	size at smoltification (zero discharge) (mm)	83.46362	75	90
length.smoltmu (slope)	size at smoltification as a function of flow (mm/cfs)	0.001833	0.001	0.003
Smolt Emigration				
smolt.uuilt	upper incipient lethal temperature for smolts (C)	25	17	25
smolt.surv.byq (intercept)	smolt survival between RM 29.5 and RM 5.2 RSTs at zero discharge (dimensionless)	0.03287	0	0.1
smolt.surv.byq (slope)	smolt survival between RM 29.5 and RM 5.2 as a function of flow (1/cfs)	2.35E-05	1.17E-05	4.69E-05

Parameters ranges shown in Table 4.4-1 may be varied as a proportion as shown in the Study Plan (e.g., $\pm 25\%$ of initial value) or may be varied across a typical range. For sensitivity testing, the typical range approach was used for most parameters (e.g., UUILT), but the proportionate approach was used when a typical range could not be identified from existing Tuolumne River data or the literature (e.g., fry.mrate, fry.migr.mrate, juv.mrate, juv.migr.mrate). Lastly, although key model input variables are not directly assessed through sensitivity testing (e.g., flow, spawning population size), sensitivity testing was conducted using the WY 2009 (Dry) and WY 2011 (Wet) hydrology and over two run sizes representing low (200 females) and high (10,000 females) escapement.

4.5 Evaluation of Juvenile Chinook Salmon Production under Current and Potential Future Project Operations Scenarios

Using the parameterized and validated model, juvenile Chinook salmon production was estimated under “base case” conditions contained in the *Project Operations/Water Balance Model Study* (W&AR-02). The “base case” depicts the operation of the Project in accordance with the current FERC license, ACOE flood management guidelines, and the Districts’ irrigation and M&I water management practices since completion of Don Pedro Dam in 1971. For the purposes of this study, the base case hydrology represents instream flow conditions downstream of La Grange Dam for Chinook salmon spawners arriving from the fall of 1971 through juvenile outmigration occurring in the spring of 2009, with accompanying water temperature estimates provided by the *Reservoir Temperature Model* (W&AR-03) and *Lower Tuolumne River Temperature Model* (W&AR-16) studies. The base case provides a thirty seven year time series of varying hydrology and meteorology to examine variations in juvenile salmon production under a variety of water year types as well as to provide a basis of comparison for any alternative operating scenarios.

For the base case hydrology and water temperature data, juvenile Chinook salmon production was estimated at three levels of spawning escapement: 200 female spawners (Low), 2,000 females (Medium), and 10,000 females (High). Using long-term averages of run timing, run composition (age, sex ratio), and spawner fecundity, variations in juvenile Chinook salmon production metrics were evaluated for the simulation period. Production metrics include river-wide fry passage at the San Joaquin River confluence (RM 0.0), as well as smolt passage at RM 0.0 divided by the number of female spawners.

5.0 RESULTS

5.1 Model Calibration

Model calibration was conducted using RST data collected in the 2010, 2011, and 2012 sampling seasons. Modeled fry and smolt passage for each of the outmigration years above are plotted in Figure 5.1-1 through Figure 5.1-3, respectively, along with daily juvenile passage estimates from the RSTs. Since the absolute number of fry or smolts passing Waterford (RM 29.8) should primarily reflect production of fry or smolts upstream of this location, patterns in seasonal passage were used to assess the adequacy of the model growth, rearing, and survival mechanisms. That is, temporal patterns of fry and smolt passage at Waterford (RM 29.8) should primarily reflect growth rates, parameters and criteria used to simulate promotion from one life stage to the next. For the three years used in calibration, modeled fry passage timing occurred earlier in 2010 than corresponding RST passage estimates (Figure 5.1-1), with greater overlap in model- and RST-based estimates occurring in 2011 (Figure 5.1-2) and 2012 (Figure 5.1-3). Model estimates of smolt passage timing at Waterford (RM 29.8) and Grayson (RM 5.2) corresponded to estimates of RST passage at these locations in all three years. Annual smolt passage at the two trap locations over the three years used for calibration (2010–2012) is shown in Table 5.1-1 below along with corresponding model estimates. Although the three year sample size is too small to apply goodness-of-fit statistics, model predictions were close to RST passage estimates for emigrant fry and smolts at Grayson (RM 5.2), fry at Waterford (RM 29.8), but did not match smolt passage well at the Waterford location.

Table 5.1-1. Estimated Chinook salmon fry and smolt passage at Waterford (RM 29.8) and Grayson (RM 5.2) for 2010–2012.

Outmigration Year	Waterford (RM 39.8)				Grayson (RM 5.2)			
	Fry		Smolt		Fry		Smolt	
	Model	RST	Model	RST	Model	RST	Model	RST
2010	12,220	10,595	5,325	62,876	874	92	811	1,964
2011	320,762	284,444	4,535	74,494	51,923	71,071	21,863	21,955
2012	50,185	29,907	44,349	24,601	1,494	72	3,976	2,186

The temporal patterns of fry and smolt passage at Waterford (RM 29.8) should primarily reflect growth rates, parameters and criteria used to simulate promotion from one life stage to the next. These patterns can therefore be used qualitatively to assess the adequacy of the model mechanisms for growth and development, and quantitatively to adjust the parameters used in these mechanisms. Although the lack of model fit for smolt passage at Waterford may be due to model assumptions regarding the fry movement and rearing locations, because the model predictions matched RST passage estimates for both fry and smolts at Grayson (RM 5.2) over a broad flow range, model calibration was accepted and a broader validation was conducted using data from outmigration years 2007–2009.

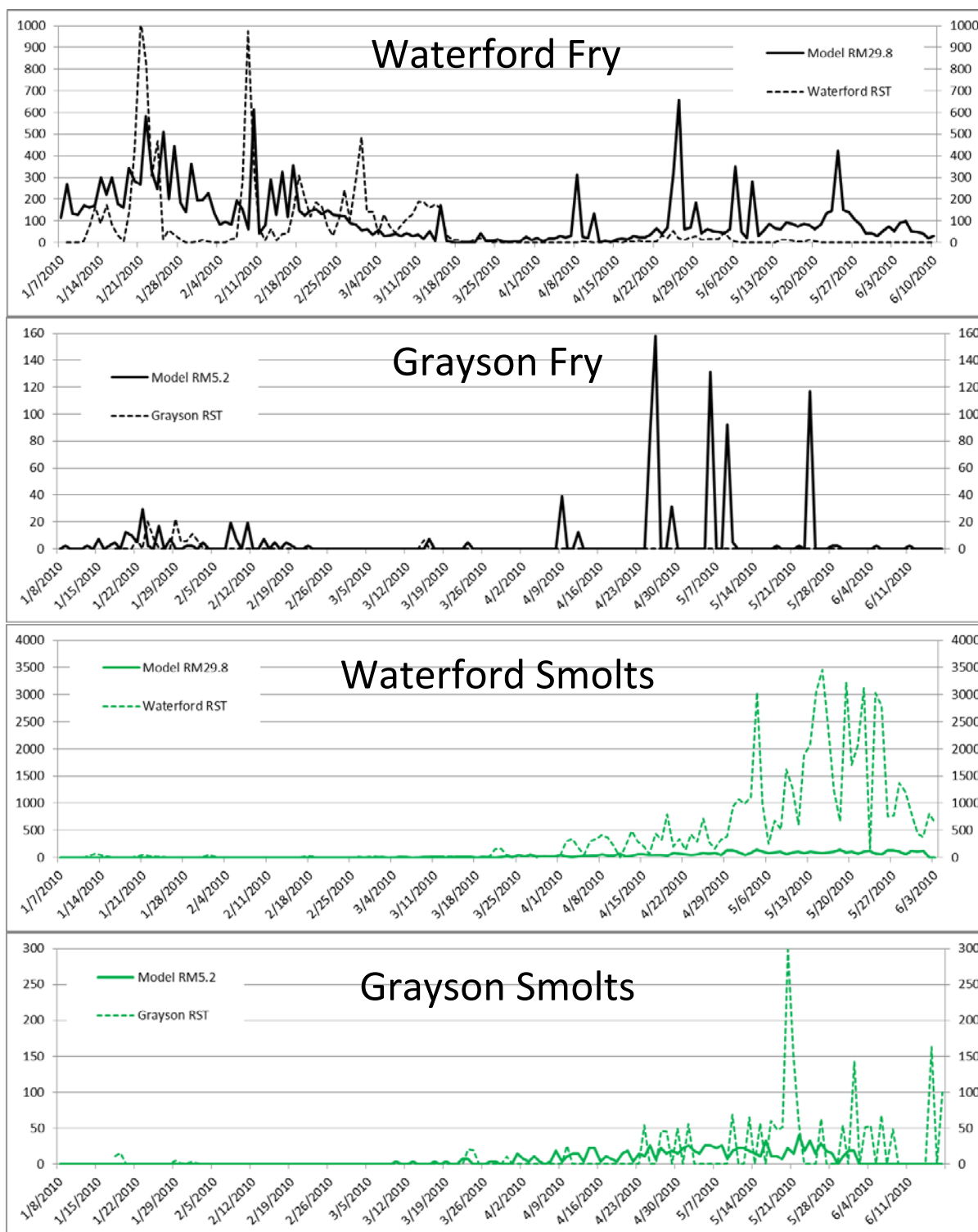


Figure 5.1-1. Model-based and RST based passage of Chinook salmon fry (upper panels) and smolts (lower panels) in the Tuolumne River during 2010.

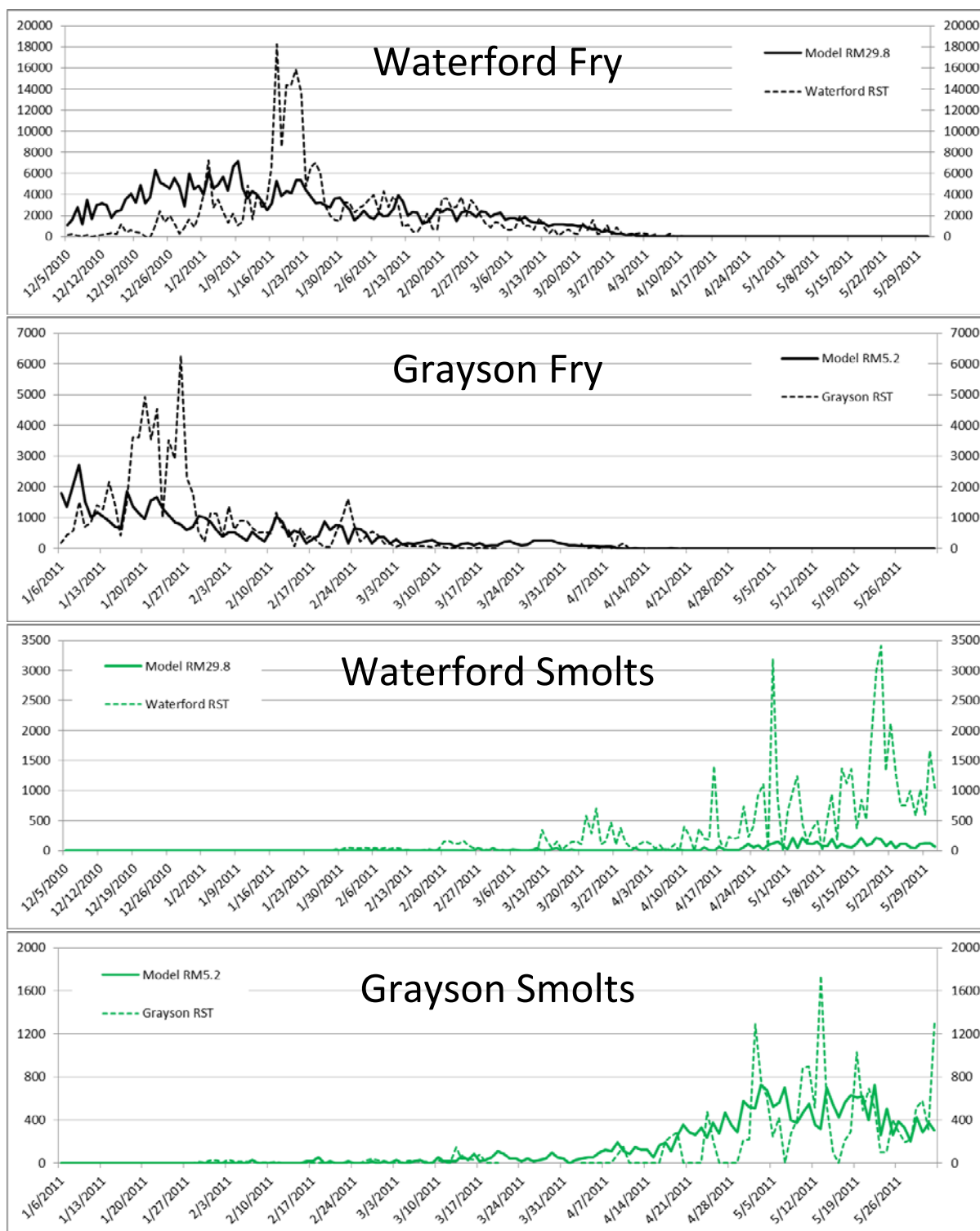


Figure 5.1-2. Model-based and RST based passage of Chinook salmon fry (upper panels) and smolts (lower panels) in the Tuolumne River during 2011.

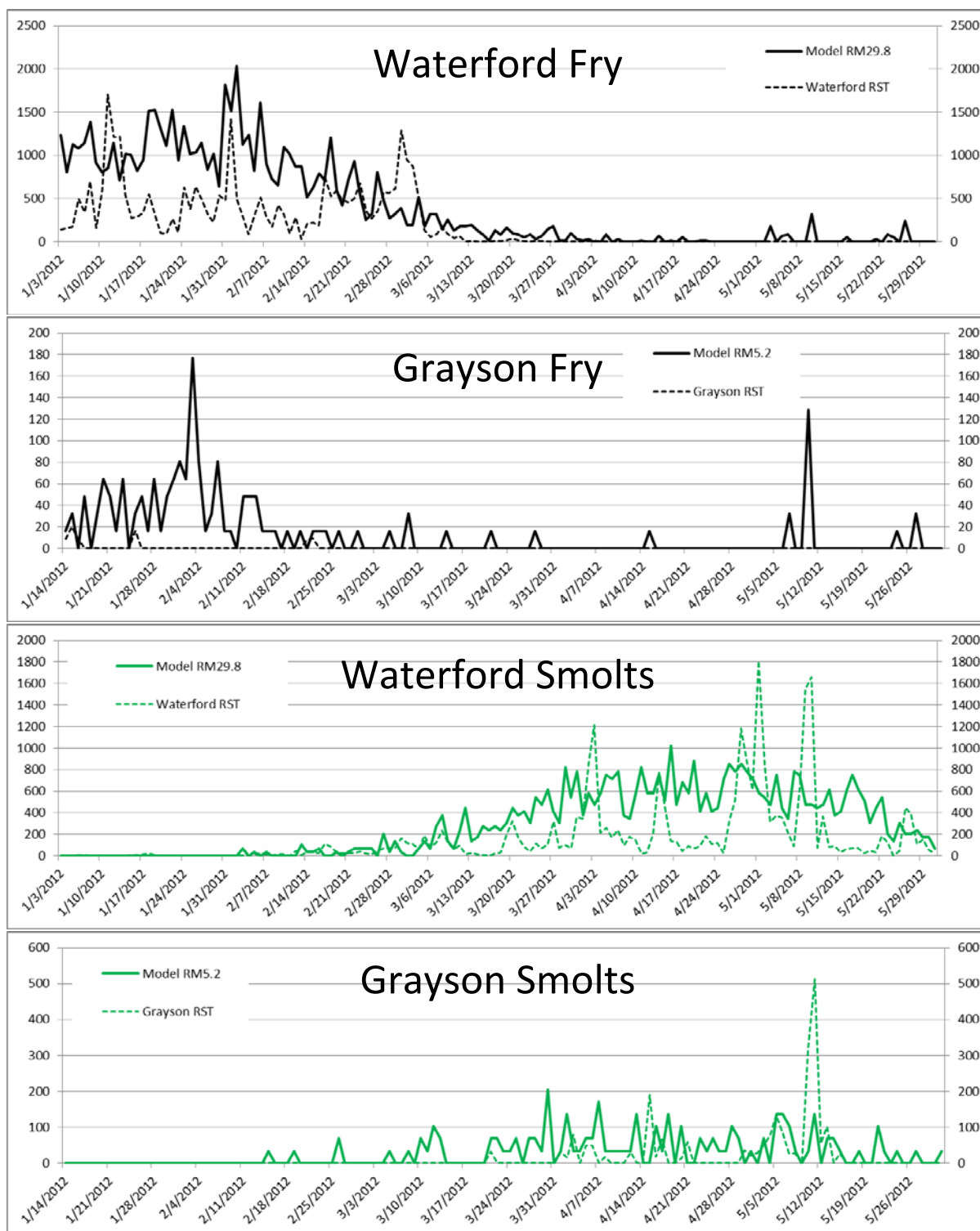


Figure 5.1-3. Model-based and RST based passage of Chinook salmon fry (upper panels) and smolts (lower panels) in the Tuolumne River during 2012.

5.2 Model Validation

Model validation was conducted using RST data collected in the 2007, 2008, and 2009 sampling seasons. Seasonal total fry and smolt passage estimates for the combined calibration and validation period (2007–2012) are in Figure 5.2-1 and Figure 5.2-2, respectively. For the validation period (2007–2009), instead of weir passage estimates at RM 24.5, upmigrant arrival timing at the spawning grounds was estimated from CDFW carcass survey data (Figure 4.1-2). Because fry passage estimates at the Grayson (RM 5.2) RST are low in all years except for the high flow conditions occurring in 2011, Figure 5.2-1 shows an expected model fit across the combined calibration and validation periods (2008–2012). For smolts, Figure 5.2-2 shows greater variation occurring in years using redd count information and timing (i.e., 2008–2009 plus additional 2010 estimate from spawning survey data) than years using weir count information (2010–2012). A second estimate is also provided for 2010 that reflects a higher percent female estimate at the counting weir (TID/MID 2010, Report 2009-8) than those found in the CDFW spawning survey report (TID/MID 2011, Report 2010-1). Although the model represents variations in fry and smolt passage at Grayson well, the corresponding model fit ($r^2=0.95$) primarily reflects the influence of high passage estimates corresponding to extended high flow conditions during 2011, the 10th wettest year since 1901.

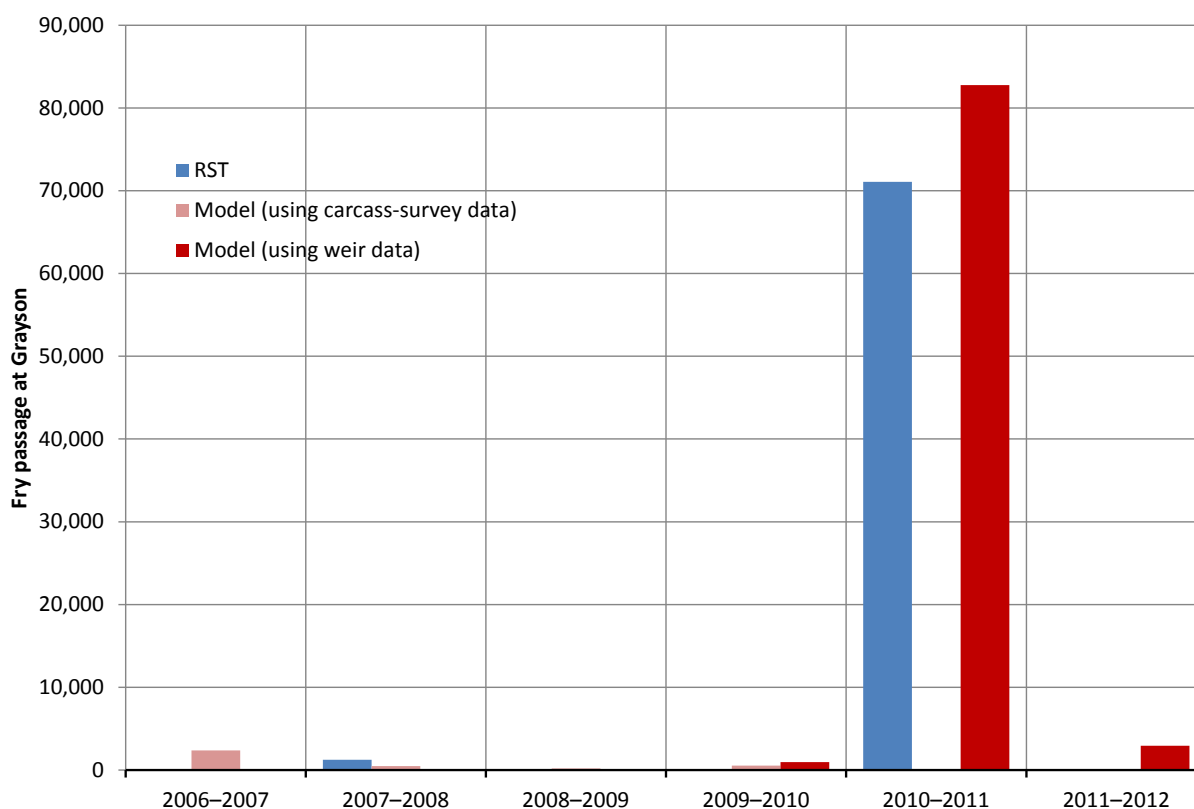


Figure 5.2-1. Seasonal Chinook salmon fry passage at Grayson (RM 5.2) using model-based and RST-based estimates (2007–2012).

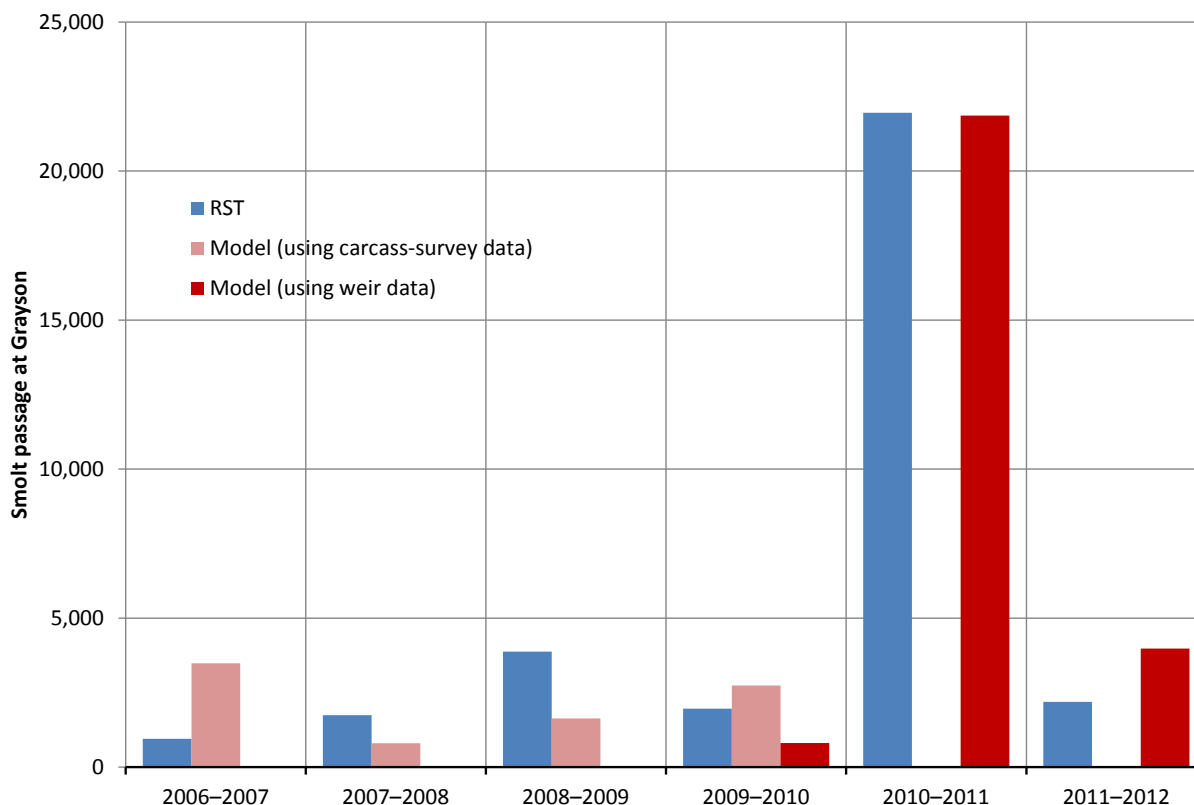


Figure 5.2-2. Seasonal Chinook salmon smolt passage at Grayson (RM 5.2) using model-based and RST-based estimates (2007–2012).

Based upon calibration and validation comparisons with RST data, additional validation was conducted by comparison of the spatial-temporal patterns predicted by the model with those found in historical seining data. Attachment C provides plots of seining density and fork lengths of Chinook salmon by location and date using seining data collected over eight survey sites along the river, sampled at two-week intervals (e.g., TID/MID 2013, Report 2012-3). Using modeled years representing lower and higher seasonal discharge corresponding to water year types occurring in 2008 (Dry) and 2011 (Wet), Figure 5.2-3 and Figure 5.2-4 show the seasonal distribution of juvenile Chinook salmon as swim-up fry (33 mm), parr (50 mm), and smolts (70 mm). Although not directly comparable to plots showing seine density in Attachment C (Figures C-11 and C-13), model results are consistent with upstream rearing in drier water years (Figure 5.2-3) and downstream displacement during wetter water year types (Figure 5.2-4).

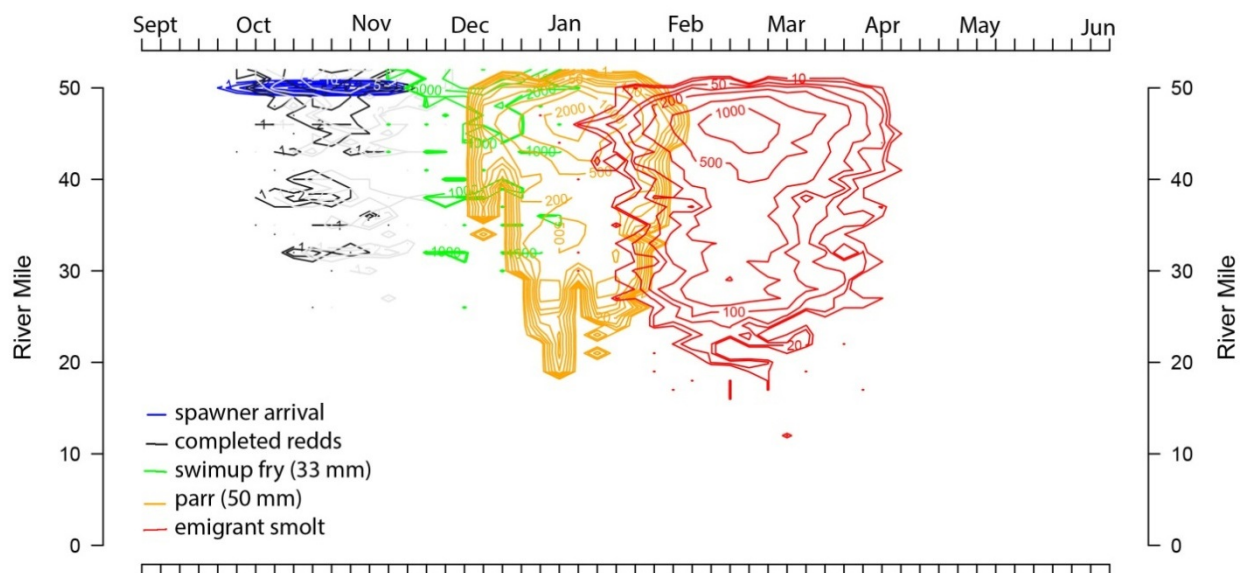


Figure 5.2-3. Modeled locations of swim-up fry (33 mm FL), parr (FL = 50 mm), and emigrant smolts in the Tuolumne River during WY 2009.

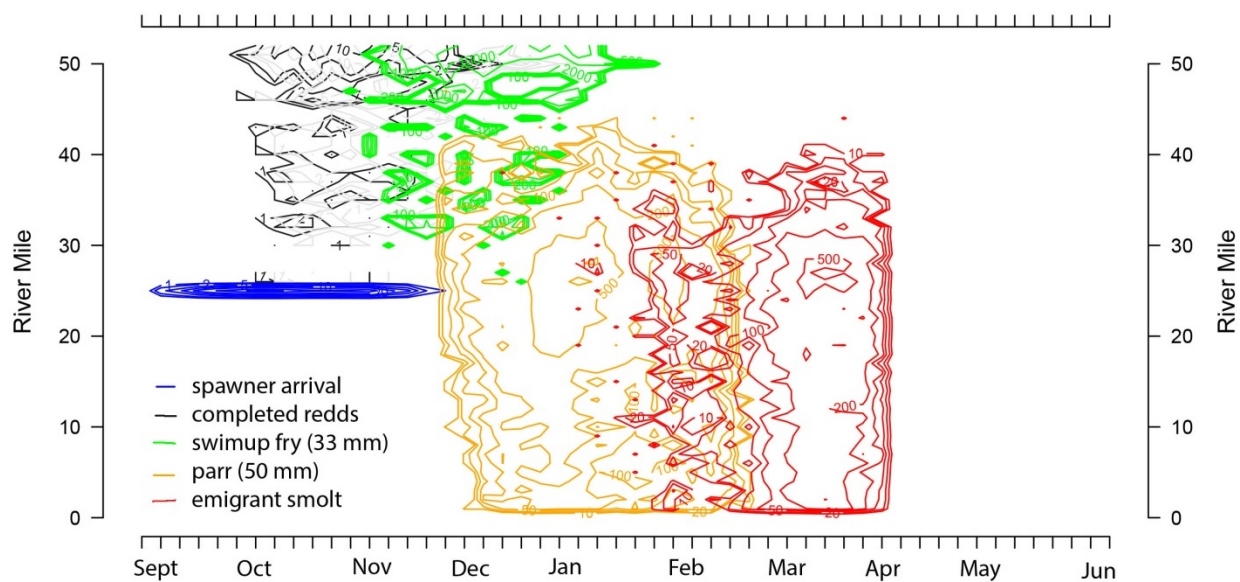


Figure 5.2-4. Modeled locations of swim-up fry (33 mm FL), parr (FL = 50 mm), and emigrant smolts in the Tuolumne River during WY 2011.

5.3 Sensitivity Analyses

Model sensitivity testing was conducted using the calibrated parameter values and ranges shown in Table 4.4-1. Four combinations of run size and hydrologic conditions were explored: a low escapement, dry year (200 female spawners, WY 2009 flows and water temperatures); a low escapement, wet year (200 female spawners, WY 2011 hydrology); a high escapement, dry year (10,000 females, WY 2009 hydrology); and a high escapement, wet year (10,000 females, WY 2011 hydrology). For each of these sixteen scenarios, and each of the thirty parameters, a model run was made at four parameter values across the ranges shown in Table 4.4-1. In all, 1,920 model simulations were performed. The metric used in the sensitivity tests was smolt productivity per spawner calculated as the ratio of the total number of smolts predicted to pass the mouth of the Tuolumne River (RM 0) divided by the contributing number of female spawners. Figure 5.3-1 shows the sensitivity test results as this smolt/spawner “productivity” metric shown with the calibration value for each parameter as a vertical black line and the results for each sensitivity test (i.e., alternate parameter value, WY and spawner scenario) connected by a horizontal or sloping colored line. Parameters exerting greater influence over the resulting variation in smolt productivity are shown with a greater slope above or below horizontal. For many of the parameters, however, the productivity line for each scenario is roughly horizontal, showing that the model is fairly insensitive to the exact value of the parameter selected across the ranges in Table 4.4-1.

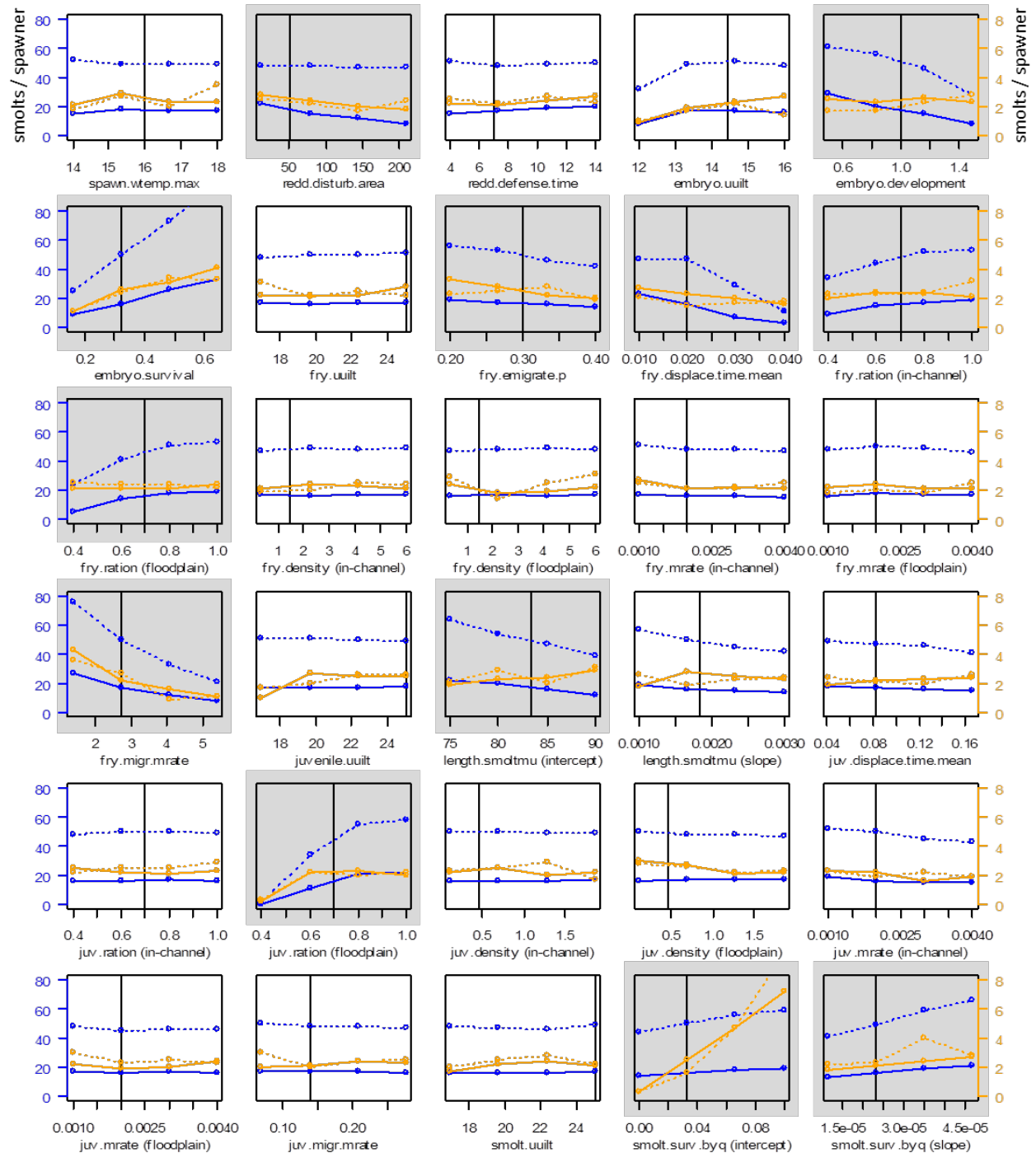


Figure 5.3-1. Model sensitivity to parameter variations expressed as smolts passing the San Joaquin River confluence (RM 0) divided by the number of female spawners.

Notes:

1. Results shown for low escapement (200 females, dashed lines) and high escapement (10,000 females, solid lines) under Dry (WY 2009, orange lines) and Wet (WY 2011, blue lines) water year hydrology.
2. Sensitive parameters (shaded tiles) shown by larger variation in smolt productivity across modeled range.
3. Parameter units provided in Table 4.4-1.

In addition to identifying individual model parameter sensitivity, parameters that are shown to result in greater changes in smolt productivity (Figure 5.3-1) may also be used to indicate potential factors controlling overall population levels. Within the overall life-history framework (Figure 3.0-1), juvenile Chinook salmon production is represented in the model as a series of independent sub-models linking a parent stock of a given life stage with production into the subsequent life stage, for example the number of spawners leads directly to the number of deposited eggs, and so on. This approach, first used by Reeves et al (1989) to identify habitat needs for Coho salmon (*O. kisutch*), assumes that when habitat or other issues limit the progression of an individual life stage cohort (e.g., growth, survival), subsequent life stages and long-term populations may also be affected. In the sections below, the relative sensitivity of model parameters shown in Figure 5.3-1 is discussed in the context of potential issues affecting life stage progression identified as part of literature reviews conducted for the Synthesis Study (W&AR-05).

5.3.1 Adult Upmigration and Spawning

Of the parameters used to represent the influences of spawning success upon juvenile production, redd disturbance area (redd.disturb.area) is shown to exert a strong influence on smolt productivity at the highest escapement levels (Figure 5.3-1). Increasing this parameter is functionally equivalent to decreasing the amount of spawning habitat; thus the model finds smolt productivity is sensitive to spawning habitat availability at only high escapement levels for wet water year conditions such as 2011, but at both low and high escapement levels under dry year conditions such as 2009. As documented in the Synthesis Study (W&AR-05), the potential for redd superimposition, is low under current escapement levels but may result in increased density dependent mortality of deposited eggs at higher escapement levels. Prior redd superimposition studies (TID/MID 1992, Appendix 6) as well as the current *Redd Mapping Study* (W&AR-08) have shown that redd superimposition occurs to some degree at all escapement levels, exerting a greater influence on juvenile production as escapement increases.

5.3.2 Egg Incubation and Fry Emergence

Of the parameters used to represent conditions affecting egg incubation, incubation rates (embryo.development) as well as egg survival-to-emergence (embryo.survival) are shown to exert a strong influence upon smolt productivity (Figure 5.3-1). Although egg development rates are well constrained by laboratory studies (Equation 3), increases in the embryo.development parameter can be used to indicate the effect of longer development times, with the effect on smolt productivity decreasing in Figure 5.3-1 due to longer incubation times and increased risk due to redd superimposition and delayed smoltification. Although gravel quality was not considered of greater importance than other issues discussed in the Synthesis Study (W&AR-05), the effect of gravel quality upon egg survival-to-emergence (embryo.survival) is shown for all flow scenarios and escapement levels (Figure 5.3-1). This suggests that potential measures to improve gravel quality (e.g., gravel augmentation, gravel cleaning) would result in proportionate increases in juvenile Chinook salmon production. The remaining parameter evaluated in the sensitivity testing, embryo.uuilt, was not shown to be sensitive within the 13.9–15.6°C (57–60°F) typical range identified by laboratory studies (Seymour 1956, USFWS 1998). This is consistent with the majority of spawning occurring at upstream locations (Figure 4.1-4) or later

in the season (Figure 4.1-2) when water temperatures are unlikely to affect incubation conditions or subsequent juvenile production.

5.3.3 Fry Rearing

Of the parameters used to represent fry rearing, parameters related to fry movement (p.emigrate, fry.displace.time), mortality due to predation (fry.migr.mrate), as well as food availability at overbank locations (fry.ration [floodplain]) were shown to affect the resulting smolt productivity (Figure 5.3-1). The proportion of fry emigrating upon emergence (p.emigrate) directly affect subsequent smolt production, with lower resulting smolt productivity from the Tuolumne River, many of these fish may potentially rear at downstream locations in the San Joaquin River and Delta. For fry remaining to rear in the Tuolumne River, predation related parameters (fry.displace.time, fry.migr.mrate) are shown to exert a strong influence on smolt productivity. Because these parameters were estimated through model fitting, more direct estimates of fry survival as a function of flow may be required to assess model uncertainty. For example, marked fry releases in conjunction with paired RST monitoring at Waterford (RM 39.5) and Grayson (RM 5.2) may be used to develop a fry survival relationship similar to the analysis conducted in Attachment D. For the parameter related to food availability at overbank locations (fry.ration [floodplain]), increases in the assumed ration for overbank locations are not accompanied with an increase in smolt productivity (Figure 5.3-1). However, lower ration levels than those assumed ($R_f = 0.7$) could result in lower juvenile production and the corresponding smolt productivity. Food availability at in-channel locations (fry.ration [in-channel]) was not shown to affect smolt productivity (Figure 5.3-1) and given the increased attention to improved food availability at overbank locations relative to in-channel locations (Sommer et al 2001, Jeffres et al 2008), food availability is unlikely to be limiting fry rearing during high flows resulting in extended floodplain inundation. As suggested in the Synthesis Study (W&AR-05), juvenile production was shown to be insensitive to changes in fry rearing habitat availability as expressed by maximum rearing density (fry.density [in-channel, floodplain]). Lastly, smolt productivity was also shown to be insensitive to the water temperature mortality threshold for fry (fry.uuilt) (Figure 5.3-1). This is consistent with fry rearing occurring at low water temperatures during winter and early spring.

5.3.4 Juvenile Rearing

Of the parameters used to represent juvenile rearing, parameters related to food availability at overbank locations (juv.ration [floodplain]) were shown to affect smolt productivity (Figure 5.3-1). The number of smolts/spawner was insensitive to variations in the movement related mortality (juv.migr.mrate) attributed to predation. For the very high discharge levels associated with WY 2011 hydrology, increases in the parameter affecting downstream movement rates (juv.displacement.time) is shown to initially increase smolt productivity, with decreases at the longest displacement times. This is possibly due to changes in the primary rearing location to areas with large increases in overbank habitat, such as that shown for the reach between Shiloh Bridge (RM 3.4) and the San Joaquin River confluence (RM 0)(Figure 4.1-9). At the highest displacement times, however, the predicted smolt productivity is shown to decrease, which is consistent with early juvenile emigration effects on the number of potential smolts remaining as well as increased exposure to predation related mortality due to these movements.

As found for fry rearing, food availability at overbank locations (juv.ration [floodplain]) at levels below those assumed in the model ($R_f = 0.7$) could result in lower juvenile production and the corresponding smolt productivity (Figure 5.3-1). As suggested in the Synthesis Study (W&AR-05), juvenile production was shown to be insensitive to changes in juvenile rearing habitat availability as expressed by maximum rearing density (juv.density [in-channel, floodplain]). The size at smoltification, as represented by parameterization of Equation 7 as a function of flow (length.smoltmu [intercept, slope]), was shown to directly affect smolt production and the resulting smolt productivity (Figure 5.3-1). This reflects that extended rearing periods in the Tuolumne River would result in increased numbers of juveniles oversummering rather than emigrating. Lastly, smolt productivity was shown to be insensitive to the water temperature mortality threshold for juveniles (juv.uuilt) for most of the range tested (Figure 5.3-1), but assuming lethal mortality occurs at temperatures as low as 18°C would hypothetically result in decreased productivity.

5.3.5 Smolt Emigration

Of the parameters used to represent smolt emigration, smolt survival as a function of flow (smolt.surv.by.q [intercept, slope]) is shown to be proportionate to smolt productivity (Figure 4.1-8) with some sensitivity to the length at smoltification. As discussed in the Synthesis Study (W&AR-05), high levels of predation related mortality have been documented in direct surveys by the Districts, in multi-year smolt survival tests, and by comparisons of upstream and downstream smolt passage at rotary screw traps (Attachment D). The model sensitivity to parameter values is reflective of the strong effect of predation upon juvenile production and suggests that identified uncertainties in the smolt survival relationship (Attachment D) may affect predictions of smolt passage in any given year. Interestingly, the non-flow-dependent intercept of the smolt survival relationship (smolt.surv.byq [intercept]) is shown to exert a greater influence on smolt productivity than the flow related parameter (smolt.surv.byq [intercept])(Figure 5.3-1). This suggests that additional non flow factors may affect smolt survival separately from flow. Since smolt productivity was shown to be insensitive to the water temperature mortality threshold for smolts (smolt.uuilt) (Figure 5.3-1), this suggests that predation effects have a flow based component (e.g., exposure time, spatial separation at high velocities) as well as a non-flow component (e.g., predator abundance). For example, multiple mark recapture smolt survival studies conducted in 2000 suggested lower survival in reaches with greater pool habitat frequency resulting from historical in-channel mining (TID/MID 2001, Report 2000-4). Planned predation studies in 2014 may provide additional information regarding reach-specific survival.

5.4 Evaluation of Relative Salmon Production under Current and Potential Future Project Operations

Using long-term averages of run timing, run composition (age, sex ratio), and spawner fecundity, variations in juvenile Chinook salmon production metrics were evaluated for the base case simulation period (1971–2009). For the base case hydrology and water temperature data, the ratio of smolt passage at the San Joaquin River confluence (RM 0) to female spawners is presented in Figure 5.4-1 for three “reference” runs of 200, 2,000, and 10,000 female spawners. It should be noted that the model simulation is restarted in each year with the same reference

runs, and the results do not reflect year-to-year variations in out of basin factors that may affect adult recruitment and subsequent escapement. Nevertheless, the general pattern shown in Figure 5.4-1 is consistent with variations in the historical adult escapement record, including lower productivity occurring during periods of extended droughts as well as higher productivity in years with extended flood control releases.

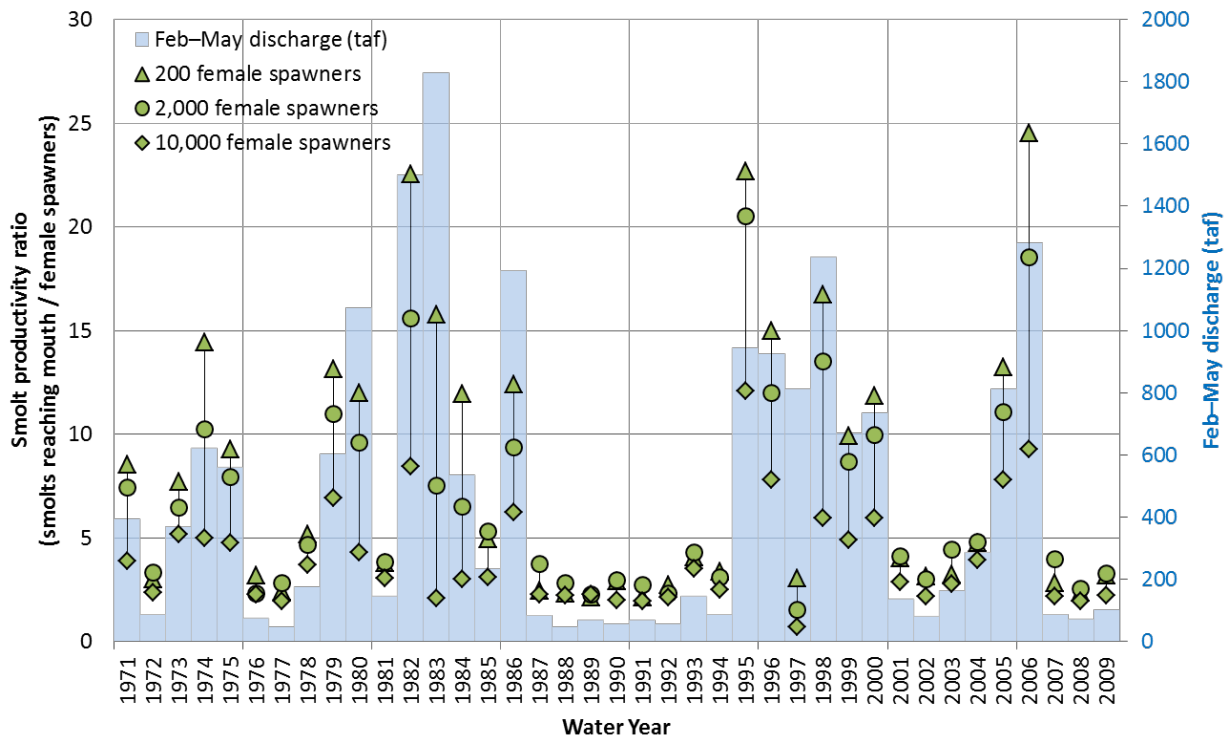


Figure 5.4-1. Modeled Chinook salmon smolt productivity for the base case (1971–2009) plotted with La Grange discharge (February–May) for three reference runs.

The smolt productivity results for the base case are grouped by water year type and plotted by decreasing La Grange discharge from February–May (TAF) in Figure 5.4-2. For the broad range in hydrologic conditions evaluated, Figure 5.4-2 shows that smolt productivity occurring in Above Normal and Wet water year types is consistently higher than those for Below Normal and drier types. Exceptions to this pattern relate to the occurrence of flood control releases in several years. For example, no flood control releases occurred in WY 1978 and WY 1993, which corresponded to reservoir filling following Critical water year conditions in the prior drought years. As another example, record flood flows occurring in January 1997 were followed by the cessation of flood control releases by mid-March due to below normal precipitation during later winter and spring months.

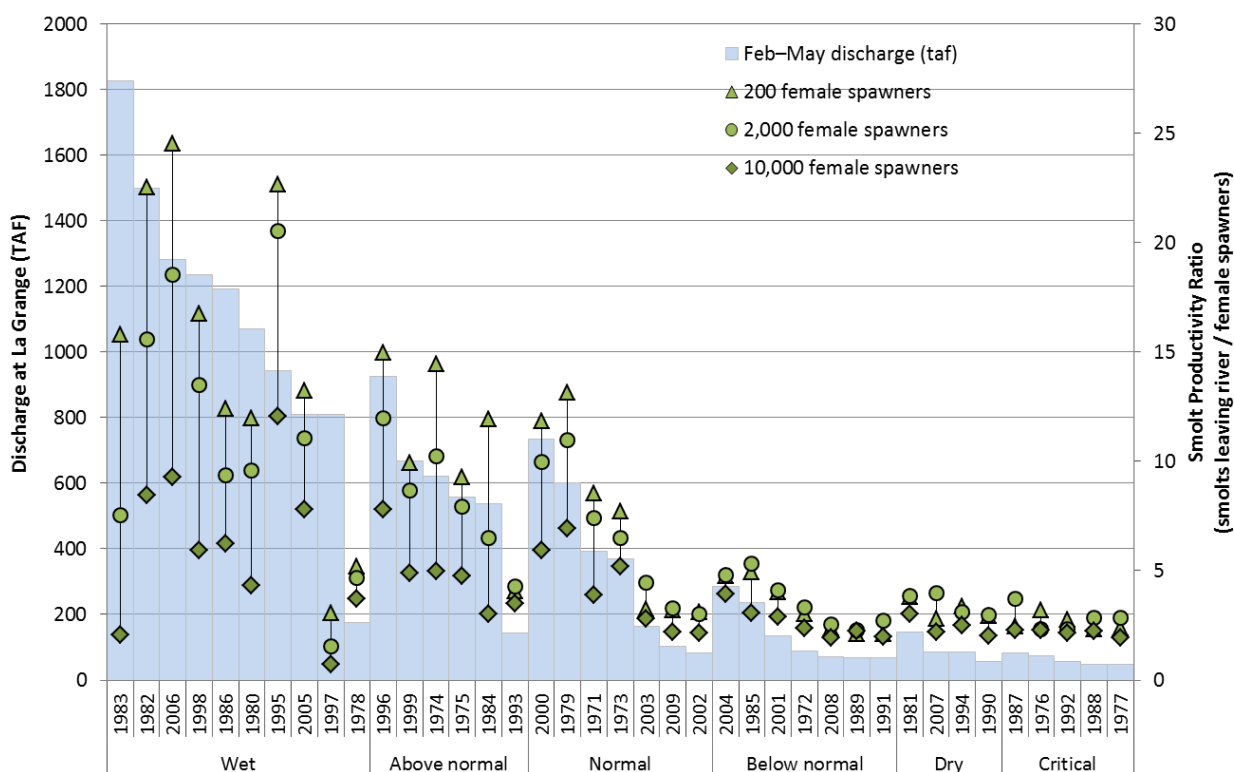


Figure 5.4-2. Modeled Chinook salmon smolt productivity for the base case (1971–2009) sorted by La Grange discharge (February–May) and water year type for three reference runs.

For smolts, the increased smolt productivity with increasing La Grange discharge generally reflects increased survival at higher flows (Equations 9 and 10; Attachment D). As discussed in the Synthesis Study, these results are generally consistent with historical observations of increased juvenile passage at the Grayson (RM 5.2) RST in years with larger flood control releases as well as increased spawning escapement observed 3 years later. Although the two wettest years shown in Figure 5.4-2 (WY 1997, WY 1983) appear to have lower productivity than some other wet years, potentially due to displacement of many fry out of the river in high flows, the general pattern of increasing productivity with La Grange discharge is retained for all water year types.

To provide a basis of comparison of the base case results above to additional scenarios to be developed with relicensing participants at Workshop No. 2 in August 2013, Table 5.4-1 and Table 5.4-2 show the geometric mean productivity for fry and smolts passing the Tuolumne River confluence with the San Joaquin River (RM 0), respectively, separated by water year types occurring during the simulation period (1971–2009). When separated in this manner, the results generally show the expected increase in productivity with increased runoff and discharge, but also show variations that may be reflective of the numbers of years represented in each water year type as well as the influences of seasonal flow patterns occurring within individual years.

Table 5.4-1. Chinook salmon productivity as Tuolumne River fry emigrants per spawner by water year type and escapement level for the base case (1971–2009).

Water Year type	years	Geometric mean productivity (fry/spawner) for three constant reference runs		
		200 females	2,000 females	10,000 females
WET	10	48.05	54.57	45.69
ABOVE NORMAL	6	34.47	37.42	30.24
NORMAL	7	4.00	6.39	5.08
BELOW NORMAL	7	1.23	1.88	1.76
DRY	4	1.42	1.97	1.57
CRITICAL	5	1.07	1.41	1.28
All	39	6.47	8.51	7.21

Table 5.4-2. Chinook salmon productivity as Tuolumne River smolt emigrants per spawner by water year type and escapement level for the base case (1971–2009).

Water Year type	years	Geometric mean productivity (smolts/spawner) for three constant reference runs		
		200 females	2,000 females	10,000 females
WET	10	12.63	9.23	4.70
ABOVE NORMAL	6	9.94	8.04	4.55
NORMAL	7	6.16	5.76	3.85
BELOW NORMAL	7	3.14	3.46	2.62
DRY	4	3.20	3.32	2.31
CRITICAL	5	2.61	2.83	2.49
All	39	5.92	5.39	3.48

In addition to the effects of increasing discharge on smolt productivity (Figure 5.4-2), the results also suggest decreased productivity with increases in escapement size (Table 5.4-2). These results are consistent with redd superimposition effects suggested in by the sensitivity analyses (Figure 5.3-1), which results in a range of effects identified in the Synthesis Study (W&AR-05), including exclusion from preferred spawning locations, egg/alevin mortality due to redd superimposition, as well as later emigration for emergent fry. Interestingly, Table 5.4-2 shows higher smolt productivity at intermediate escapement sizes (i.e., 2,000 spawners simulated) in Normal water years and all other drier water year types. For these drier water year types with lower La Grange discharge, the apparent increase in productivity at intermediate run sizes appear to be related to subtle interactions between emigration periods and pulse flow timing. As escapement levels rise, increasing rates of superimposition has the effect of shifting fry emergence timing by several days later in the season. This in turn leads to later rearing periods and later emigration of smolts. Depending upon emigration timing, greater or lesser proportions of emigrant smolts may leave the river within the pulse flow period assumed for the base case (i.e., April 15th through May 15th).

Because of the higher smolt survival expected at higher flow rates (Equations 9 and 10), pulse flow timing is shown to affect smolt productivity, suggesting that variable pulse flow timing or duration by water year type or other means (e.g., real-time monitoring of fish sizes) could be used to optimize productivity. For example, in drier water year types smolt emigration can be expected to occur earlier due to faster juvenile growth rates at higher water temperatures (Sections 4.1.3.3 and 4.1.4.3) and an increased tendency to emigrate at a smaller size (Section 4.1.5.1). In contrast, smolt emigration can be expected to occur later in wetter water years due to

slower growth at lower water temperatures and an increased tendency to emigrate at a larger size. Figure 5.4-3 shows modeled dates of smolt emigration occurring for the base case (1971–2009) at an assumed escapement size of 2,000 female spawners and fixed spawning timing. The center (green) portions of the bars represent the timing window for 50 percent of the smolt emigration, whereas the outer (white) bars represent emigration of 80 percent of the smolts. For the base case, considerable year-to-year variability in the model results is apparent extending both earlier and later than the pulse flow period (April 15th to May 15th). There is also a pattern of earlier and later emigration in dry and wet WY types, respectively. Year-to-year variations in spawning timing may also affect subsequent smolt emigration timing, suggesting that peaks in smolt emigration may not always coincide with the pulse flow period. Although spawning run size may affect emigration timing as well (i.e., larger spawning runs resulting in later emigration), it should be emphasized that this superimposition effect is subtle and should affect timing of the overall peak emigration period by only a few days.

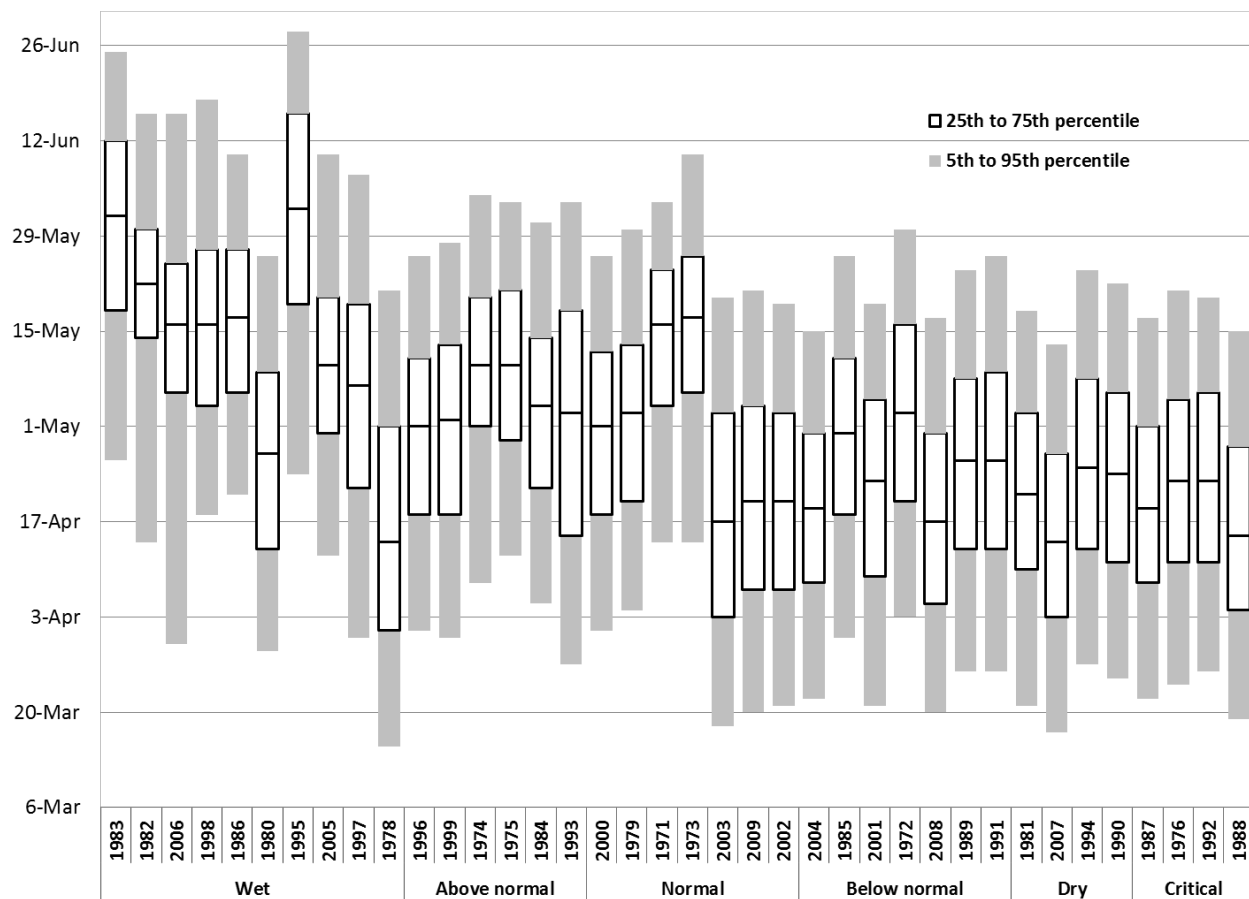


Figure 5.4-3. Modeled smolt emigration timing quantiles from 2,000 spawners for the base case (1971–2009) sorted by water year type and decreasing La Grange discharge (February–May).

6.0 DISCUSSION AND FINDINGS

As recommended in the June 2011 Integrated Life Cycle Models Workshop Report (Rose et al. 2011), this *Tuolumne River Chinook Salmon Population Model Study* was developed to predict juvenile Chinook salmon production within the Tuolumne River for different water year types, drawing upon existing literature and additional information identified in the Synthesis Study (W&AR-05), including previously conducted Tuolumne River studies and interrelated relicensing studies. Independent life-stage specific sub-models were developed using a series of functional relationships and associated parameters to predict life history progression from upmigration through spawning, egg incubation, fry and juvenile rearing, to smolt emigration. The calibrated model may be used to examine the relative influences of various factors on the life-stage specific production of Chinook salmon in the Tuolumne River, identify critical life-stages that may represent a life-history “bottleneck,” as well as to compare relative changes in juvenile production between alternative management scenarios.

6.1 Model Calibration and Validation

Using recent spawning estimates from counting weir operations at RM 24.5 along with recorded river discharge and water temperature data, model calibration was carried out by comparisons of modeling results of fry and/or smolt passage with annual estimates from RST sampling in the lower Tuolumne River (RM 29.8, RM 5.2) for the period 2010–2012. Model validation was conducted by comparison of simulated and observed RST passage for the period 2007–2009 using data from the fall CDFW spawning surveys along with recorded river discharge and water temperature data. Overall, model results matched both fry and smolt passage estimates at the Grayson RST location (RM 5.2) for the combined calibration and validation period (2007–2012). In comparisons to patterns in bi-weekly seining data (Attachment C), model results also represented variations in river-wide distribution as well as seasonal rearing patterns documented under representative “dry” (2009) and “wet” (2011) water year hydrology.

6.2 Model Scenario Results

Using the validated model, juvenile Chinook salmon smolt productivity was evaluated for the base case simulation period (1971–2009). The base case provides a thirty seven year time series of varying hydrology and meteorology to examine variations in juvenile salmon production under a variety of water year types as well as to provide a basis of comparison for any alternative operating scenarios. Using water temperature estimates provided by the *Reservoir Temperature Model* (W&AR-03) and *Lower Tuolumne River Temperature Model* (W&AR-16) studies, juvenile Chinook salmon production was estimated at three reference levels of spawning escapement: 200 female spawners (Low), 2,000 females (Medium), and 10,000 females (High). Modeling results showed that the ratio of smolt passage at the San Joaquin River confluence (RM 0) to female spawners during “wet” water year scenarios was consistently higher than for “dry” water year scenarios. The increased smolt productivity generally reflects increased smolt survival during emigration at higher flows. As discussed in the Synthesis Study (W&AR-05), these results are generally consistent with historical information showing increased juvenile passage at the Grayson (RM 5.2) RST in years with larger flood control releases as well as observations of increased spawning escapement 3 years later. In addition to the results of the

base case hydrology presented here and discussed at Workshop No. 2 held on August 6, 2013, alternative scenarios will be developed with relicensing as part of the relicensing process.

As discussed in the sections below, the identified model sensitivity to particular parameters suggests that some non-flow measures could potentially influence overall juvenile production (e.g., gravel additions, gravel cleaning, spawning barriers, predator removal, predator suppression, etc.). Evaluation of such potential measures using the model could be discussed with relicensing participants along with any potential flow scenarios developed as part of Workshop No. 2. Along with information developed in the Synthesis Study (W&AR-05) as well as interrelated relicensing studies, the results of these scenario evaluations will be included in the Draft License Application to inform the effectiveness of any potential management measures.

6.3 Evaluation of Factors Affecting Chinook Salmon Production

Model sensitivity testing was used to identify model parameters affecting juvenile production and overall population levels. Using an overall productivity metric of smolts/spawner, parameters related to the following life stage processes were shown to exert the greatest influence on subsequent juvenile production in the calibrated model.

- **Upmigration and spawning**
 - Sensitivity to parameters related to redd disturbance suggest modeled smolt productivity is affected by spawning habitat availability.
- **Egg incubation and fry emergence**
 - Sensitivity to parameters related to redd disturbance suggest modeled smolt productivity is affected by spawning habitat availability (i.e., area of suitable gravel).
 - Sensitivity to parameters related to egg development rates suggest modeled smolt productivity is affected by egg survival-to-emergence (e.g., gravel quality, intra-gravel flow, etc.).
- **Fry rearing**
 - Sensitivity to parameters related to fry movement suggests modeled smolt productivity is affected by predation related mortality.
 - Sensitivity to lower ration parameter estimates suggests fry growth and modeled smolt productivity may only be affected by variations in food availability below those used in the model calibration.
- **Juvenile rearing**
 - Sensitivity to lower ration parameter estimates suggests juvenile growth and modeled smolt productivity may only be affected by variations in food availability below those used in the model calibration.

▪ Smolt emigration

- Sensitivity to parameters related to smolt survival suggests modeled smolt productivity is affected by predation related mortality and flow.

Below we discuss the results of the sensitivity testing results and base case scenario results in the context of issues identified in the Synthesis Study (W&AR-05).

6.3.1 Spawning Habitat Availability

Modeling results to date show reduced density dependence of smolt productivity with increasing escapement. Model results are consistent with redd superimposition effects suggested by the sensitivity analyses conducted for this study as well as the results of Tuolumne River spawning habitat investigations summarized as part of the Synthesis Study (W&AR-05). Redd superimposition effects are shown in Figure 5.4-1 and Figure 5.4-2-10 by the distance between the smolt productivity estimates for each of the three reference run sizes (200, 2,000, 10,000 females) evaluated for the base case. Because usable spawning habitat for Chinook salmon spawning (Figure 4.1-3) is near optimal based upon results of the *Lower Tuolumne River Instream Flow Study* (Stillwater Sciences 2013), increases in spawning flows may be expected to result in only minor increases in available spawning habitat. The *Spawning Gravel Study* (W&AR-04) indicates relatively little change in available spawning areas as compared to historical estimates. Potential non-flow measures that could be evaluated with the model to increase spawning habitat improvements include gravel augmentation projects at upstream locations of the lower Tuolumne River (McBain & Trush, 2000, 2004) as well as the use of movable spawning barriers to force increased use of downstream spawning areas (TID/MID 1992, Volume 2). In addition, gravel cleaning identified in previous studies (TID/MID 1992, Appendix 9; McBain & Trush 2004) may potentially improve gravel quality conditions by reducing fine sediment intrusion, thereby increasing intragravel flow, egg survival-to-emergence, and subsequent smolt productivity.

6.3.2 Juvenile Rearing Habitat Availability

Modeling results to date show that rearing habitat is not limiting smolt productivity under current conditions, consistent with findings of the Synthesis Study (W&AR-05). Sensitivity testing conducted for this study show that reductions in fry and juvenile rearing density parameters used in the calibrated model are not accompanied by reductions in subsequent smolt productivity. For the highest run sizes evaluated (10,000 female spawners), the resulting fry and juvenile production is shown to be insufficient to fully saturate available rearing habitat under current conditions. The implication of the low sensitivity to fry and juvenile rearing density is that changes in in-channel rearing habitat area through measures recommended to improve access to potential floodplain rearing areas, such as floodplain recontouring (McBain & Trush 2000) as well as extended high flows to maintain floodplain inundation (Mesick 2009), will not result in large increases in subsequent smolt productivity on the basis of relieving any rearing habitat limitation. Although food availability can be shown to reduce modeled smolt productivity at levels below those used in the calibrated model, increases in assumed food availability at in-channel and overbank locations are not accompanied by increased smolt productivity. This is consistent with materials reviewed as part of the Synthesis Study (W&AR-05) which found

adequate food resources supporting juvenile rearing of Chinook salmon were present in the lower Tuolumne River.

6.3.3 Flow Effects

Modeling results for the base case show that smolt productivity is consistently higher in model years with increased La Grange discharge during spring. Figure 5.3-1 and Figure 5.4-1 show smolt productivity model results combined with the summation of flows by water year for the period from February to May inclusive. Flow variations affect all life stages to some degree, affecting water temperatures, habitat area and suitability, as well as movement related mortality due to predation on fry and juveniles. However, sensitivity testing shows that smolt productivity is strongly influenced by parameters of the smolt survival vs. flow relationship (Equation 8). This is consistent with information reviewed as part of the Synthesis Study (W&AR-05) which showed a relationship between springtime flows and subsequent adult escapement (TID/MID 1992, Volume 2; Speed 1993; TID/MID 1997, Report 96-5; Mesick and Marston 2007; Mesick et al. 2008) as well as in variations of annual smolt passage (Mesick et al. 2008). The modeled patterns of increasing smolt productivity and subsequent adult escapement with discharge are consistent with predation as a primary mortality source, with effects upon long-term population levels.

In addition to the direct effects of increasing discharge on smolt productivity (i.e., smolt survival with flow), model results show changes in smolt emigration timing due to water temperature effects upon development rates, as found in monitoring of other river systems (e.g., Rombough 1985, Roper and Scarnecchia 1999). These and other modeled effects upon life history timing (e.g., spawning timing, run sizes) produce results with greater or lower overlap with the scheduled pulse flow period (April 15th through May 15th). Because of the higher smolt survival expected at higher flow rates, pulse flow timing is shown to affect smolt productivity, suggesting that variable pulse flow timing or duration by water year type or other means (e.g., real-time monitoring of fish sizes, shaped pulse flows) could be used to optimize water use and smolt productivity.

6.3.4 Water Temperature

Model sensitivity testing indicates that water temperature is not currently limiting smolt productivity under current conditions, consistent with findings of the Synthesis Study (W&AR-05). Because water temperatures are generally suitable for all in-river life stages in the lower Tuolumne River under both drier and wetter water year types evaluated in sensitivity testing, reductions in mortality threshold parameters (i.e., UUILT) did not result in corresponding changes in smolt productivity. Although water temperature is an important factor controlling egg incubation rates as well as fry and juvenile growth rates, with the exception of issues related to the timing of smoltification and emigration discussed in Section 6.3.3 above, smolt productivity is unaffected by normal seasonal variations in air and water temperatures. More specifically, since the majority of spawning takes place under suitable temperature conditions, modeled egg mortality effects due to potentially unsuitable water temperatures for early arriving spawners during late summer or early fall do not appear to affect subsequent smolt productivity. Further, the majority of smolt emigration occurs prior to periods of potentially

unsuitable water temperature occurring in late spring. For this reason, sensitivity to variations in the selected mortality threshold parameter (i.e., UUILT) was low and was not accompanied by large changes in smolt productivity.

6.4 Potential Information Needs

The identified model sensitivity to particular parameters may be used to guide further refinement of the selected parameter values on the basis of future monitoring. For example, simplifying assumptions have been made in the model implementation regarding the uniformity of food resource distribution as well as predator distribution along the river. Although we have used the best available information in making these assumptions, promoting conditions that lead to rearing in particular areas with greater or lower food resources or mortality risks may lead to greater or lower predicted smolt productivity than we have shown in the current model implementation. In order to improve our understanding of the mechanisms represented in the model as well as to confirm the assumptions made in the model implementation, potential information needs are discussed below.

6.4.1 Fry and Juvenile Movement Data

In modeling of fry and juvenile movement rates, temporal patterns of historical RST passage data as well as seining density were used to fit parameters to describe movement rates for fry (Section 4.1.3.2) and for juveniles (Section 4.1.4.2). Because smolt productivity is shown to be highly sensitive to these parameter estimates, additional movement data could be used to refine fitted parameters and improve the resulting juvenile passage estimates. Movement data could be collected using dye marked fish with existing seine and RST monitoring efforts, or by use of implanted passive integrated transponder (PIT) tags with passage monitoring by deployment of antenna loops at particular locations.

6.4.2 Floodplain Water Temperature

In modeling of growth rates in overbank locations, floodplain water temperatures are assumed to be the same as at nearby in-channel locations on the basis of temperature monitoring conducted during 2011 as part of the *Pulse Flow Study* (Stillwater Sciences 2012). Monitoring data collected for the pulse flow study showed that average water temperatures at in-channel sites were actually slightly above the nearby overbank sites during winter/spring, with overbank sites exhibiting both higher daily maximum and lower daily minimum water temperatures, respectively. Since water temperatures affect growth rates promoting conditions that lead to rearing in particular areas with greater or lower access to in-channel and floodplain habitats may lead to greater or lower smolt productivity than we have shown under the current model implementation. Additional water temperature monitoring at paired overbank and in-channel sites during high flow periods would help confirm use of this assumption in the population model.

6.4.3 Predation

For fry, juvenile, and smolt life stages, the model currently attributes changes in relative passage between the two RST locations at Waterford (RM 29.5) and Grayson (RM 5.2) to predation related mortality. Although the current model implementation is capable of representing differing rates of mortality probability to various sub-reaches in the lower Tuolumne River, parameter fitting in the calibrated model has assumed a uniform distribution of predation risk. Additional *Predation Study* (W&AR-07) experiments in 2014 may help identify particular reaches with greater and lower smolt survival due to mining pits or flow variability. Additional data on this issue (e.g., predator abundance, smolt survival) would be combined with the existing RST based estimates to develop reach-by-reach variations in juvenile survival/mortality, with additional fitting of model parameters to achieve model calibration. For any future smolt-survival experiments conducted during pulse flows, marked smolts should be used to estimate daily capture efficiencies for each RST site during each pulse flow period. Additional RST efficiency experiments on marked releases of smaller life-stages would also help improve resulting passage estimates that could be used to either refine fitted parameters for fry and juvenile mortality or to develop direct survival relationships with flow for these life stages.

6.4.4 Smolt Emigration Cues

Early RST monitoring conducted in the lower Tuolumne River (1998–2000) at multiple locations from RM 42–24.7 identified several potential emigration cues for smolt-sized fish (TID/MID 2005b). In particular, abrupt flow changes appeared to be associated with peaks in smolt emigration, as were releases of large numbers of hatchery-reared CWT salmon in smolt survival studies.

The possibility that flow pulses actively stimulate or concentrate emigration, rather than simply supporting the survival of migrating fish, has implications for the design of spring flows—in particular, for the duration (and perhaps frequency) of flow pulses. Accordingly, exploratory analyses were conducted into the temporal response of emigration to the onset of a spring pulse (Attachment D). Out of six years examined (2007–2012), daily passage was estimated for three years (2007, 2009, and 2012)¹ in which pulse flows were scheduled following steady antecedent flows. Based upon the limited data evaluations to date, emigration cues resulting from pulse flows are suggested, with a greater proportion of fish moving on the first day following flow changes than on subsequent days (Attachment D).

These results suggest that in addition to the overall developmental patterns of smoltification and emigration with broad environmental patterns (e.g., temperature, photo-period), smolt emigration may be temporarily stimulated through the use of variable pulse flows. Because of the increased smolt survival with discharge found in prior smolt-survival tests as well as in the historical RST data record, overall smolt productivity may be expected to increase for years in which emigration timing is closely matched with scheduled pulse flows. Additional study of pulse flow shaping (e.g., multiple steps, flow increases, flow decreases) using marked fish may confirm if this effect is large enough to be meaningful with regards to promoting smolt emigration during periods while higher flow and survival conditions are being maintained.

¹ Although flow conditions were suitable to evaluate smolt passage during the spring pulse of 2008, a data gap in the RST sampling occurred on the second day of the pulse because of the trap shifted out of the channel thalweg.

7.0 STUDY VARIANCES AND MODIFICATIONS

There are no study variances for W&AR-06.

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STUDY REPORT W&AR-06
CHINOOK SALMON POPULATION MODEL STUDY

ATTACHMENT A

**ADDENDUM TO THE TUOLUMNE RIVER CHINOOK SALMON
POPULATION MODEL**

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**ADDENDUM TO THE TUOLUMNE RIVER
CHINOOK SALMON POPULATION MODEL
STUDY REPORT
DON PEDRO PROJECT
FERC NO. 2299**



Prepared for:
Turlock Irrigation District – Turlock, California
Modesto Irrigation District – Modesto, California

Prepared by:
Stillwater Sciences

September 2017

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Addendum to the Tuolumne River Chinook Salmon Population Model Study Report

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List of Acronyms

°C	degrees celsius
cfs	cubic feet per second
Districts	Turlock Irrigation District and Modesto Irrigation District
FERC.....	Federal Energy Regulatory Commission
FL	fork length
GIS	Geographic Information System
IFIM	instream flow incremental methodology
LGDD	La Grange Diversion Dam
MID.....	Modesto Irrigation District
mm	millimeter
OLGB.....	Old La Grange Bridge
PHABSIM.....	Physical Habitat Simulation Model
RM	River Mile
RST	Rotary Screw Trap
SJR	San Joaquin River
TID	Turlock Irrigation District
TLSRA.....	Turlock Lake State Recreation Area
TRTAC	Tuolumne River Technical Advisory Committee
USFWS	U.S. Department of the Interior, Fish and Wildlife Service
USGS	U.S. Geological Survey
WUA.....	weighted usable area
WY	water year

Glossary of Terms and Definitions

Adipose fin	A small fleshy fin with no rays, located between the dorsal and caudal fins. Clipping of adipose fins is used to identify hatchery-raised salmonids.
Age	The number of years of life completed, here indicated by an Arabic numeral, followed by a plus sign if there is any possibility of ambiguity (e.g., age 1, age 1+).
Age composition	Proportion of individuals of different ages in a stock or in the catches.
Age-class	A group of individuals of a certain species that have the same age.
Alevin	The developmental life stage of young salmonids and trout that are between the egg and fry stage. The alevin has not absorbed its yolk sac and has not emerged from the spawning gravels.
Anadromous	Fish that migrate from the sea to spawn in fresh water.
Coded-wire tag (CWT)	A small (0.25 mm diameter x 1 mm length) wire etched with a distinctive binary code and implanted in the snout of salmon or steelhead, which, when retrieved, allows for the identification of the origin of the fish bearing the tag.
Cohort	Members of a life-stage that were spawned in the same year.
Density-dependent	Density-dependence in stock-production relationships occurs whenever food or space limitations cause the life-stage specific survival or growth to be related to the numbers of individuals present. Density dependent factors may include spawning habitat area or juvenile rearing area at higher population sizes.
Density Independence	Factors affecting the population regardless of population size, such as temperature, disease, or stranding.
Delta	An alluvial landform composed of sediment at a river mouth that is shaped by river discharge, sediment load, tidal energy, land subsidence, and sea-level changes. The Sacramento and San Joaquin River Delta refers to a complex network of channels east of Suisun Bay (an upper arm of the San Francisco Bay estuary).
Dispersal	A process by which animals move away from their natal population
Escapement	The number of sexually mature adult salmon or steelhead that successfully passes through an ocean fishery to reach the spawning grounds. The total amount of escapement reflects losses resulting from harvest, and does not reflect natural mortality during upmigration such as pre-spawn mortality.
El Niño	A climactic event that begins as a warming episode in the tropical Pacific zone that can result in large scale intrusions of anomalously

	warm marine water northward along the Pacific coastline of North America (also see La Niña).
Estuary	A region where salt water from the ocean is mixed with fresh water from a river or stream (also see Delta). The greater San Francisco Bay estuary includes brackish and salt water habitats from the Golden Gate Bridge in San Francisco Bay and includes Suisun, San Pablo, Honker, Richardson, San Rafael, San Leandro, and Grizzly bays.
Floodplain	The part of a river valley composed of unconsolidated river deposits that periodically floods. Sediment is deposited on the floodplain during floods and through the lateral migration of the river channel across the floodplain.
Fry	Salmonid life stage between the alevin and parr stages. Functionally defined as a size <50–69 mm, fry generally occupy stream margin habitats, feeding on available insect larvae.
Homing	The ability of a salmon or steelhead to correctly identify and return to their natal stream, following maturation at sea.
Hydroelectric	Generation of electricity by conversion of the energy of running water into electric power.
Irrigation	The application of water to land for agricultural crops by means of pumps, pipes, and ditches in order to provide water required by the crops for growth.
Kelts	A spent or exhausted salmon or steelhead after spawning. All species of Pacific salmon, except some steelhead and sea-run cutthroat, die after spawning.
La Niña	A cooling of the surface water of the eastern and central Pacific Ocean, occurring somewhat less frequently than El Niño events but causing similar, generally opposite disruptions to global weather patterns.
Life history	The events that make up the life cycle of an animal, with events for fish including migration, spawning, incubation, and rearing. There is typically a diversity of life history patterns both within and between populations. Life history can refer to one such pattern, or collectively refer to a stylized description of the 'typical' life history of a population.
Life-stage	Temporal stages (or intervals) of an animal's life history that have distinct anatomical, physiological, and/or functional characteristics that contribute to potential differences in use of available habitats.
Macroinvertebrate	Invertebrates visible to the naked eye, such as insect larvae and crayfish generally found in streams and become food for fish.

Osmoregulation	Refers to the physical changes that take place in salmonids as their gills and kidneys adjust from fresh water to salt water as they enter the ocean, and from salt water to fresh water upon their return.
Pacific Decadal Oscillation	A pattern of Pacific climate variability associated with sea surface warming and changes in ocean circulation that shifts phases on at least inter-decadal time scale, usually about 20 to 30 years.
Parr	Life stage of salmon or <i>O. mykiss</i> between the fry and smolt stages. Functionally defined as a size of 50–69 mm at this stage, juvenile fish have distinctive vertical parr marks and are actively feeding in fresh water.
Predator	An animal that feeds on other living animals.
Production	Output from a stock-production model at a particular life-step.
Proximate factor	Stimuli or conditions responsible for animal behavior at ecological time scales (i.e., immediate or short-term responses).
Recruitment	Addition of new fish to a defined life history stage by growth from among smaller size categories. Often used in context of management, where the stage is the point where individuals become vulnerable to fishing gear.
Redd	A nest of fish eggs within the gravel of a stream, typically formed by digging motion performed by an adult female salmon or <i>O. mykiss</i> .
Riffle	A shallow gravel area of a stream that is characterized by increased velocities and gradients, and is the predominant stream area used by salmonids for spawning.
Riparian	Referring to the transition area between aquatic and terrestrial ecosystems. The riparian zone includes the channel migration zone and the vegetation directly adjacent to the water body that influence channel habitat through alteration of microclimate or input of LWD.
River mile	A statute mile measured along the center line of a river. River mile measurements start at the stream mouth (RM 0.0).
Riverine	Referring to the entire river network, including tributaries, side channels, sloughs, intermittent streams, etc.
Rotary Screw Trap	Rotary screw traps (RST) consist of a large perforated cone and live-box that are mounted on a floating platform and facing upstream at a fixed location in the river. Rotary screw traps are used to sample a portion of emigrating juvenile salmonids and other fish as they move downstream to allow estimation of total passage.
Semelparous	A reproductive strategy characterized by a single reproductive episode before death.
Smolt	Salmonid life stage between the parr and adult stages. Functionally defined as a size ≥ 70 mm at this stage, juvenile salmon and steelhead

	actively outmigrate from freshwater habitats and take on the appearance of silver adult fish.
Smoltification	Refers to the physiological changes to allow tolerance to saltwater conditions in the ocean.
Spawn	The act of producing a new generation of fish. The female digs a redd in the river bottom and deposits her eggs into it. The male then covers the eggs with milt to fertilize them.
Spawning grounds	Areas where fish spawn.
Straying	A natural phenomena of adult spawners not returning to their natal stream, but entering and spawning in some other stream.
Stock	Input value required by the stock-production models. It is the first required value entered into the population dynamics model spreadsheets; for example, stock would be the number of fry, for a fry-to-juvenile step.
Superimposition	Superimposition occurs when a redd site is reused by subsequent female spawners before the embryos (see Alevin) of the earlier arriving spawners have had sufficient time to develop and emerge from the spawning gravels.
Wild	Salmon or <i>O. mykiss</i> produced by natural spawning in fish habitat from parents that were spawned and reared in fish habitat.
Woody debris	Logs, branches, or sticks that fall or hang into rivers that may become submerged at changing river discharge. This debris gives salmonids places to hide and provides food for insects and plants that fish feed upon.
Yolk sac	A small sac connected to alevin that provides them with protein, sugar, minerals, and vitamins. Alevin live on the yolk sac for a month or so before emerging from the gravel and beginning to forage food for themselves.

1.0 INTRODUCTION

As part of the Federal Energy Regulatory Commission (FERC) relicensing process for the Don Pedro Project, the Modesto Irrigation District (MID) and Turlock Irrigation District (TID) (collectively, the Districts) completed an extensive literature and information review [Salmonid Population Information Integration and Synthesis (Synthesis Study)] of factors affecting population dynamics of Tuolumne River salmonids (TID/MID 2013b). Information from the Synthesis Study was used to inform the development of a numerical population model simulating riverine life stages of Central Valley fall-run Chinook salmon (*Oncorhynchus tshawytscha*) in the Tuolumne River.

The Tuolumne River Chinook salmon population model (TRCh model) is a spatially-explicit (1-dimensional) model that uses an individual-based framework to represent the major processes of fall run Chinook Salmon spawning, egg incubation, as well as juvenile growth, movement and mortality to provide estimates of juvenile production as a function of habitat under varying flows and water temperatures in the lower Tuolumne River (TID/MID 2017a). Based upon updates since the publication of the TRCh model study report (TID/MID 2017a), several model enhancements have been made to improve its use in comparing the effectiveness of alternative flow and non-flow measures for the lower Tuolumne River.

On May 18, 2017, the Districts hosted a Modeling Tools Update Meeting with relicensing participants. At the meeting, the Districts summarized various updates to the TRCh model. This addendum to the final study report (TID/MID 2017a) provides an overview of the model changes, presentation of expanded model calibration and validation simulations, as well as simulations of salmonid production under a range of water year types represented in the Base Case (1971–2012) hydrology.

2.0 UPDATES TO THE TUOLUMNE RIVER CHINOOK SALMON POPULATION MODEL

As an update to the final study reports and code of the TRCh model (TID/MID 2017a), this technical memorandum documents the following updates to the models:

- Section 2.1 describes improved representation of overbank habitat at high flows using 2-D modeling tools from the lower Tuolumne River Floodplain Hydraulic Assessment Study Report (TID/MID 2017b).
- Section 2.2 describes reach-specific scaling of movement-related juvenile mortality based on relative predator abundance estimates of predatory fish species from long-term seine and snorkel data. In addition, flow-dependent scaling of movement-related juvenile mortality of Chinook salmon was included to account for floodplain inundation at high flows.
- Section 2.3 presents recalibration of the TRCh model using more typical water year types, updated movement and mortality parameters, as well as updated estimates of overbank habitat.
- Section 2.4 presents additional TRCh model validation results based upon available rotary screw trap (RST) monitoring data collected since 1999, as well as more recent seining data.

As with the 2013 study report, the updated TRCh model has been calibrated and validated to reproduce abundance estimates and life history timing patterns from historical monitoring data. Juvenile production estimates were validated at a range of historical flows downstream of La Grange Diversion Dam (USGS 11289650) and at Modesto (USGS 11290000) as well as accompanying temperatures provided by a thermograph monitoring network maintained by TID (TID/MID 2017a). For simulation purposes, model inputs for discharge are provided by the Tuolumne River Operations Model (Operations Model) (TID/MID 2013d); water temperature inputs are provided by the Don Pedro Reservoir Temperature Model (Reservoir Temperature Model) (TID/MID 2017e) and the Lower Tuolumne River Temperature Model (River Model) (TID/MID 2017c). These external models are integrated to provide river- and reservoir-specific inputs and to describe “Base Case” conditions (i.e., existing baseline as defined by FERC) as well as for evaluation of alternative Project operational scenarios. In the sections below, we describe updated analyses and model changes listed above, as well as updated model calibration and validation results.

2.1 Updated Estimates of Usable In-Channel and Overbank Habitat

Previous estimates of usable habitat within particular habitat types (e.g., riffle, run, pool) as well as reach-specific in-channel weighted usable area (WUA) estimates were developed as a function of discharge in the IFIM Study (Stillwater Sciences 2013). Using flow simulations from the Operations Model (TID/MID 2013d), 2D hydraulic modeling was used as part of the Lower Tuolumne River Floodplain Hydraulic Assessment (TID/MID 2017b) to update estimates of usable floodplain habitat as a function of daily discharge for in-river life stages of Chinook salmon in the lower Tuolumne River from the La Grange Diversion Dam at RM 52.2 to the confluence with the San Joaquin River (RM 0).

Using recent data on floodplain topography and in-channel hydraulic controls that were not included in either the 2012 Pulse Flow Study (Stillwater Sciences 2012) or floodplain geographic information system (GIS) analysis conducted by the U.S. Fish and Wildlife Service (USFWS 2008), the TUFLOW Classic model (TUFLOW) (BMT Group Ltd. 2013; version TUFLOW.2013-12-AC-w64) was selected to expand the modeling domain and flow ranges evaluated by these previous modeling efforts. For the purpose of the TRCh model, the calibrated TUFLOW model was used to estimate total wetted area as well as usable habitat area within in-channel and floodplain habitats for juvenile life stages of Chinook salmon as a function of flow from 1,000 cfs to 9,000 cfs. Estimates of usable floodplain habitat area for rearing fry and juvenile life stages of Chinook salmon were conducted using joint habitat suitability indices (i.e., 0–100 percent) from the Stillwater Sciences (2013) IFIM Study along with TUFLOW model predictions of depth and velocity within floodplain areas. As with in-channel estimates of usable habitat for rearing life stages, estimates of usable rearing habitat were accumulated as look-up tables within each of the sub-reaches used in the salmonid models over flow increments of 250 cfs (1,000–3,000 cfs), and 500 cfs (3,000–9,000 cfs)

Reach-specific estimates of total combined usable in-channel and overbank habitat for Chinook salmon fry as a function of flow are shown in Figure 2.1-1 representing the summation of usable habitat within each cell to provide reach-specific estimates of usable overbank habitat and total usable habitat availability, respectively. Although Physical Habitat Simulation Model (PHABSIM) representation of longitudinal habitat variation is limited to the distribution and lengths of various habitat types, the contributing transect-based data provide valuable information about lateral variation of rearing habitat. For this reason, estimates of usable habitat area within the flow ranges considered by the IFIM Study (Stillwater Sciences 2013) (0–1,000 cfs) were used to represent in-channel habitat area availability for fry rearing.

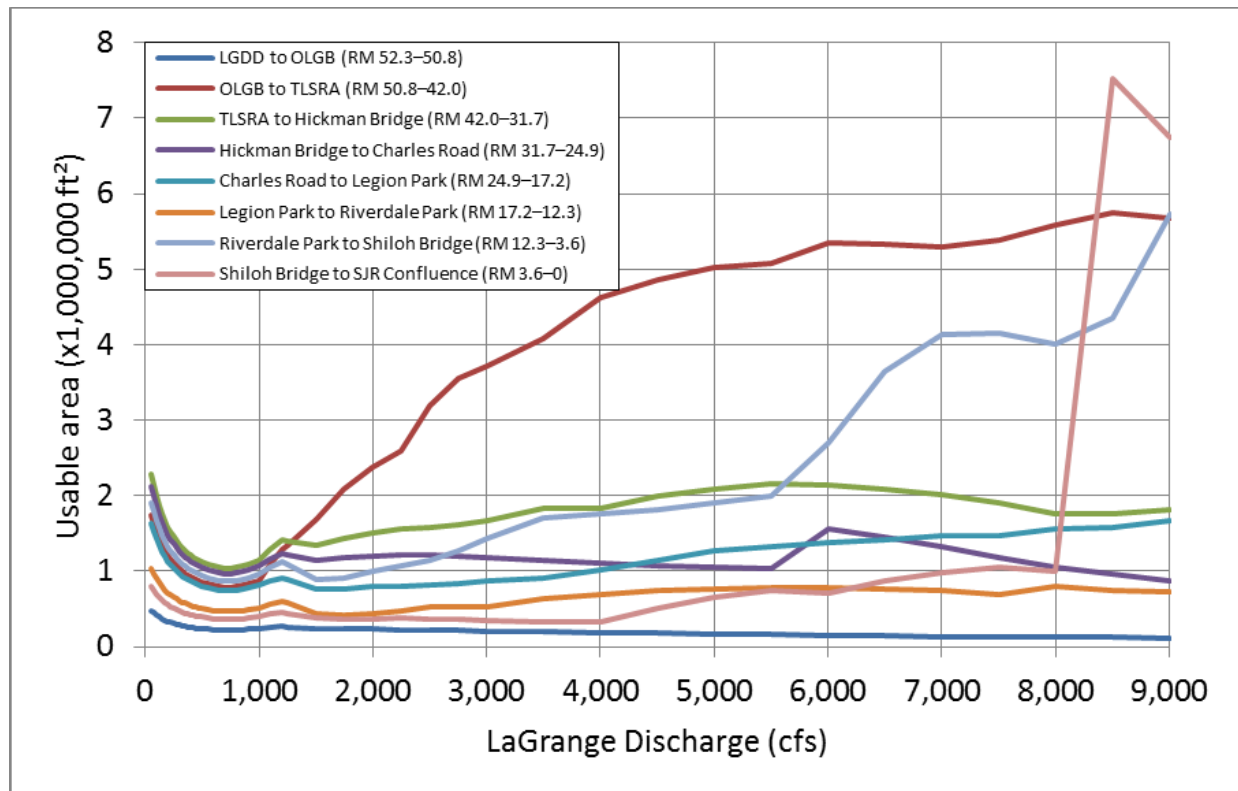


Figure 2.1-1. Estimated total combined usable in-river and overbank habitat for Tuolumne River Chinook salmon fry.

Following the same rationale for estimating in-channel fry rearing habitat availability as a function of flow, usable habitat area estimates at in-channel locations for juvenile rearing were made for each model reach in the IFIM Study (Stillwater Sciences 2013). Rearing habitat availability at overbank locations was estimated as a function of discharge from wetted area, velocity, and depth predictions resulting from 2D modeling conducted as part of the Lower Tuolumne River Floodplain Hydraulic Assessment (TID/MID 2017b). These estimates were later combined with existing habitat suitability criteria from the IFIM Study (Stillwater Sciences 2013) in GIS to calculate the useable fraction of each model cell. Figure 2.1-2 represents the summation of usable habitat within each cell to provide reach-specific estimates of total usable habitat availability for Chinook salmon.

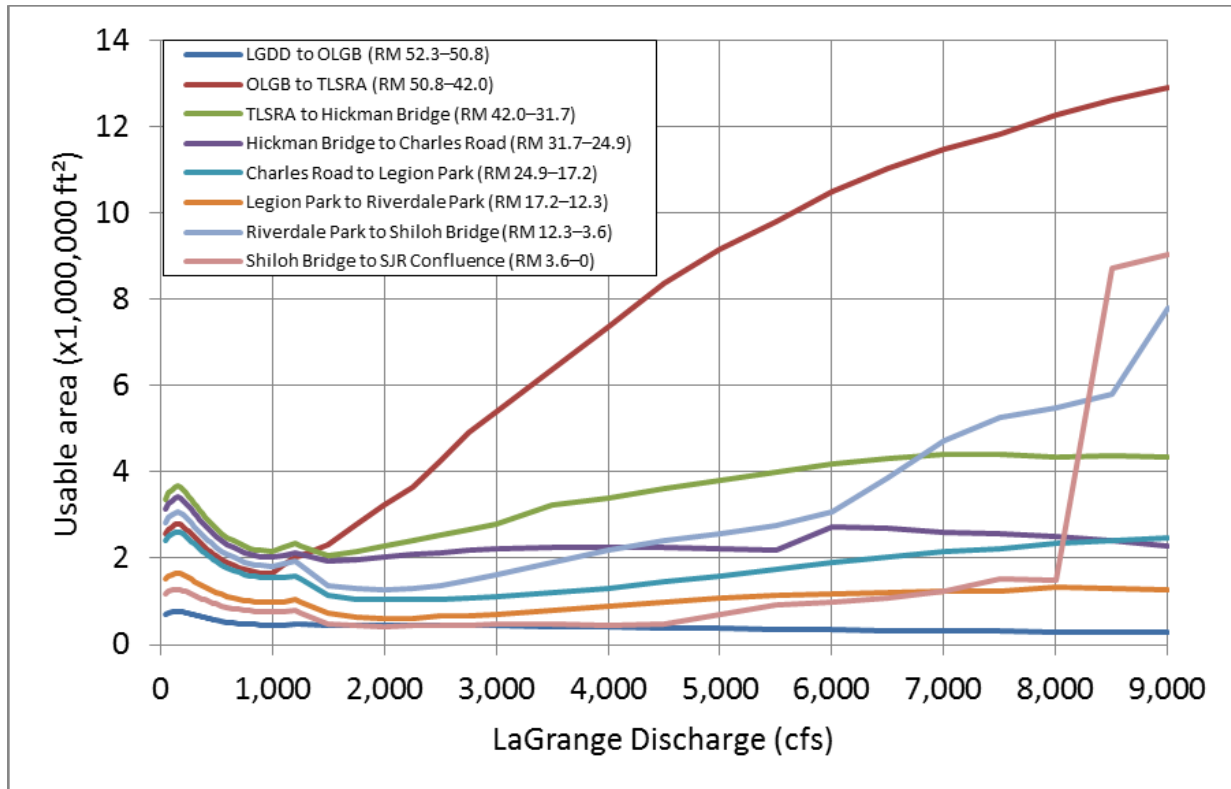


Figure 2.1-2. Estimated total combined usable in-river and overbank habitat for Tuolumne River Chinook salmon juveniles.

2.2 Updated Estimates of Reach Specific Predation Related Mortality

Information reviewed in the Synthesis Study (TID/MID 2013b) suggests that aquatic predation is the primary mechanism of juvenile Chinook salmon mortality, while other sources such as disease, stranding, entrainment, and avian predation are less significant. Accordingly, the model represents predation as the primary mechanism of mortality for the three juvenile life stages of Chinook salmon (fry, juvenile, smolt), although it does represent water temperature-related mortality and background mortality from other sources as well.

High levels of predation-related mortality have been documented in direct surveys by the Districts, in multi-year smolt survival tests and by comparisons of juvenile passage at upstream and downstream rotary screw trap monitoring locations. Reach-specific estimates of relative abundance of predators and species composition were derived from Tuolumne River snorkel and seine survey data from 1997–2014 (TID/MID 2015). Combined with recent results on predator diet and predation rates from the Predation Study (TID/MID 2013a), predation-related mortality risk factors can be used to apportion river wide juvenile salmonid mortality estimates to specific river reaches. For the TRCh model, the combined representation of juvenile mortality is based on several assumptions: (1) predation risk is proportional to the probability of a predator-prey interaction as indicated by the historical monitoring data; (2) some predators are more effective than others; (3) the probability of a predator-prey interaction decreases with increasing flow due to increased wetted areas; and (4) predators feed more effectively in-channel compared to channel margin or overbank habitat.

From the information above, predation risk in the TRCh model is calculated for each modeled reach based on the relative abundance of different predators (black bass and striped bass), weighted according to their relative predation efficiency. Abundance of predators was determined by a combination of snorkel and seine surveys conducted in the Tuolumne River from 1997–2014. Reach-wide mean abundance estimates for each predator type were derived from curves of predator density by river mile (Figures 2.2-1 and 2.2-2). These were then weighted by relative predator efficiency, defined as the relative quantity of Chinook juveniles observed in the gut contents of each predator type. The data sets from the seine and snorkel surveys were combined into a single set by standardizing all reaches to the TLSRA-to-Hickman reach where the curves were most closely aligned, providing relative measures of predation risk by reach. These values were then re-scaled so that river-wide predation risk was equal to 1.

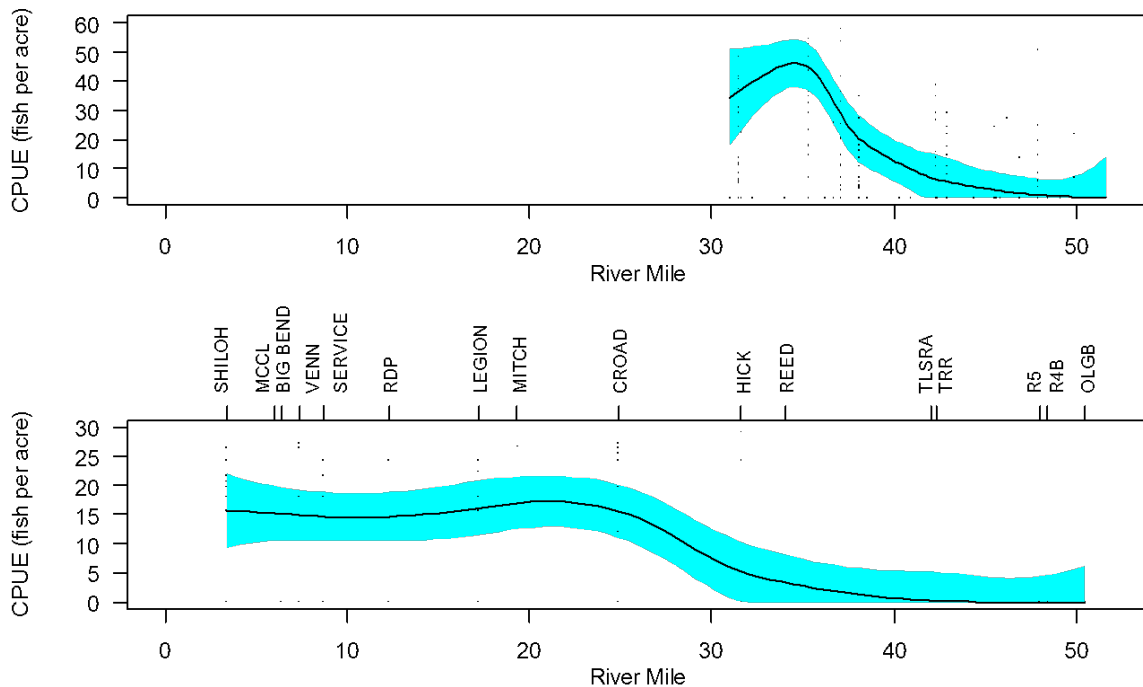


Figure 2.2-1. Relative abundance of black bass (*Micropterus spp.*) in the lower Tuolumne River (1997–2014) as indicated by snorkel observations (top) and seine recoveries (bottom).

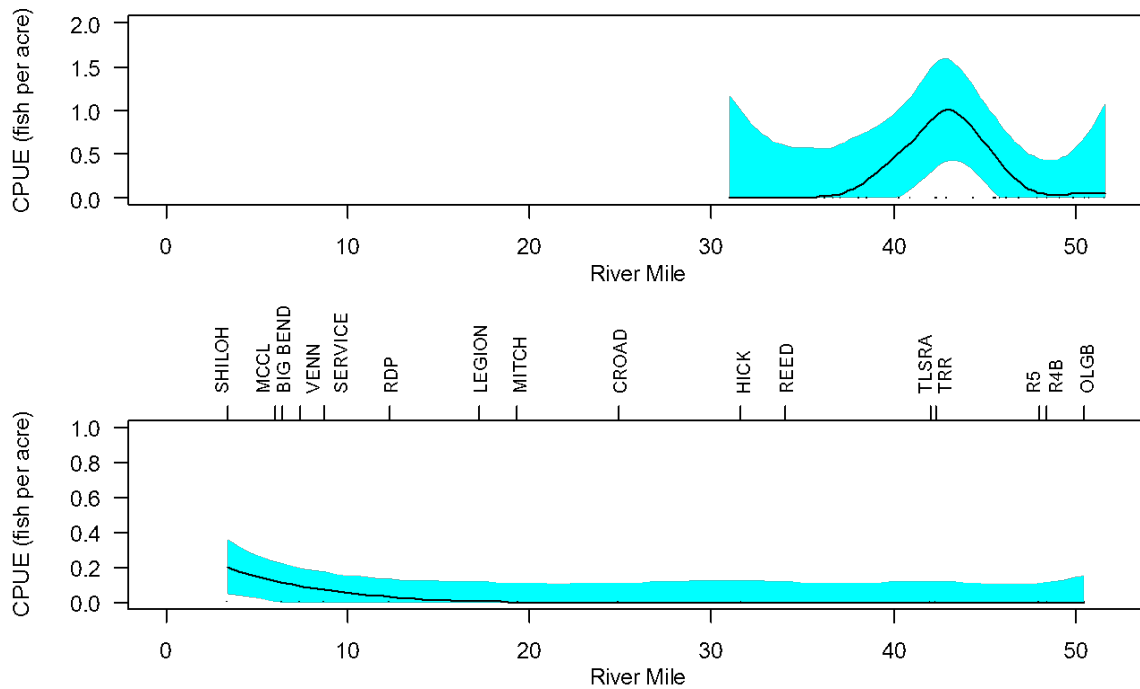


Figure 2.2-2. Relative abundance of Striped Bass (*Morone saxatilis*) in the lower Tuolumne River (1997–2014) as indicated by snorkel observations (top) and seine recoveries (bottom).

Equation 1 represents the probability of survival of fry and juvenile Chinook salmon as an exponential function of the instantaneous mortality rate $m(t)dt$ between times t_1 and t_2 . To better define predation-related mortality within specific reaches, this mortality rate was assumed to be proportional to the relative abundance of predatory fish species documented in historical seine and snorkel surveys discussed above (Figures 2.2-1 and 2.2-2). To account for the large increase in potential habitat at overbank locations, predation risk was assumed to be inversely proportional to wetted area at flows above 1,000 cfs. This was based on the assumption that increasing habitat area decreases the probability of encounter between predator and prey. The model uses a mortality multiplier that is inversely proportional to wetted width within each reach. The flow-dependent mortality is scaled to equal 1.0 at 1,000 cfs discharge.

$$Survival = e^{-\int_{t_1}^{t_2} m(t)dt} \quad \text{Equation 1}$$

Because season wide estimates of outmigration survival in recent RST reports (2008–2012) are on the order of 4–21 percent (FISHBIO 2013), well below that suggested by the Tuolumne River Technical Advisory Committee (TRTAC) smolt survival relationship, additional examination of RST passage at Waterford (RM 29.8) and Grayson (RM 5.2) was conducted to further evaluate apparent smolt survival relationships with flow (Robichaud and English 2017). The analysis indicated lower survival than the TRTAC smolt survival relationship over a range of flows, consistent with patterns in lower relative smolt passage between the upstream and downstream traps exhibited in RST monitoring reports. To provide consistency with RST data used in model fitting, a linear flow-survival relationship fitted to RST data (Equation 2) was selected for

modeling smolt outmigration survival. Discharge-specific survival (S_{RST}) between the RST locations (RM 29.8 to RM 5.2) as a function of flow (Equation 2) was converted to a survival estimate per unit distance (S_D) travelled (Equation 3). In order to account for reach-specific differences in predation risk, Equation 3 was scaled in proportion to the relative abundance of predatory fish species (Section 2.1). The reach-specific mortality multiplier is scaled such that the river-wide average predator density is equal to 1.0. Because equations 2 and 3 include flow as an explanatory variable, discharge-related scaling of the predator-related smolt mortality multiplier was not included.

$$S_{RST} = \min(0.03287 + 2.347 \times 10^{-5} \times Q_{LaGrange}, 1) \quad \text{Equation 2}$$

$$S_D = e^{-mD}, \text{ where } m = -\frac{\log S_{RST}}{29.8-5.2} \quad \text{Equation 3}$$

2.3 Updated TRCh Model Calibration

As with the 2013 study report, updated TRCh model calibration was accomplished through adjustment of movement and mortality rate parameters of fry and juvenile life stages. Many modeled mechanisms and functional relationships affecting other life stages have been studied in detail, under controlled conditions, and the relevant model parameter values are well constrained by experimental data. Other relationships are purely empirical, or based on simple models, and use parameter values constrained only loosely by theoretical arguments regarding movement, habitat use, and mortality. For example, because no site-specific data were available to parameterize spawner upmigration rates after arrival in the river, this value was calibrated to match estimates of spawning timing derived from recent redd survey data (TID/MID 2013c). The upmigration rate was established as a constant 1mi/d, understanding that spawners alternate between periods of faster movement and periods of holding. Because thermal development and mortality relationships in the Egg Incubation and Fry Emergence submodel are well constrained by empirical laboratory results, no calibration of this submodel was necessary. Because smolt survival parameters were developed from the updated flow-survival relationship using RST data, and are thus better constrained than those for fry and juveniles, no calibration of smolt life stage survival parameters from the 2013 study report were conducted.

2.3.1 Initial Conditions

Initial conditions for spawner population, timing, as well as flow and temperature ranges used in TRCh model calibration are shown in Table 2.3-1. Adult spawner escapement and arrival timing in the Tuolumne River are user input values, either derived from weir counts at RM 24.5 (e.g., TID/MID 2015), carcass surveys (e.g., TID/MID 2015), or input as a fixed population size and composition arriving according to an average historical distribution. No exceedance of the embryo temperature mortality threshold (16°C) occurred in the egg incubation period (Nov–Feb) over the calibration period (Water Year [WY] 2010–2013). Temperature exceeded the fry, juvenile, and smolt mortality threshold (25°C) for one day in late April of WY 2012 and for one day in mid-May of WY 2013 at the confluence of the lower Tuolumne and San Joaquin Rivers but was not exceeded for parr/smolt life stages potentially emigrating from upstream locations.

Table 2.3-1. Summary of initial conditions input to the TRCh model for calibration runs, including initial population input as well as flow and temperature by life stage.

Initial Conditions (WY)		2010	2011	2012	2013
Arrival timing ¹		19-Nov	24-Oct	6-Nov	24-Oct
Escapement ²		100	423	748	868
Spawning/incubation flow (cfs) ³ (Nov–Feb)	min	222	359	325	166
	max	259	5,350	369	185
Spawning/incubation temp (°C) ³ (Nov–Feb)	min	8.2	9.3	9.4	7.5
	max	13.4	13.2	13.2	13.7
Rearing flow (cfs) ⁴ (Mar–Apr)	min	217	2,680	168	166
	max	2,229	8,998	622	1,012
Rearing temp (°C) ⁴ (Mar–Apr)	min	10.0	9.1	9.7	10.4
	max	18.5	12.5	25.3	20.4
Smolt emigration flow (cfs) ⁴ (Apr–May)	min	447	3,100	168	162
	max	3,329	8,380	2,120	1,211
Smolt emigration temp (°C) ⁴ (Apr–May)	min	10.0	9.4	10.7	10.5
	max	16.8	14.3	25.3	25.1

¹ Median date from counting weir (RM 24.5), survey seasons vary by year.

² Female escapement from counting weir (RM 24.5), survey seasons vary by year.

³ Based on daily flow and temperature estimates upstream of Robert's Ferry Bridge (RM 39.5).

⁴ Based on daily river-wide flow and temperature estimates.

2.3.2 Calibration of Grayson smolt passage from fry and juvenile movement and mortality rates

The Fry and Juvenile Rearing submodels, which rely on functional relationships of movement and mortality detailed in the 2013 Study report, were used for whole-model calibration. RST data from 2010–2013 (Robichaud and English 2017) and seine survey data from 1999–2012 (FISHBIO 2013) were used to estimate the seasonal rate of downstream movement of fry and juvenile populations. Additionally, these surveys allowed for estimation of seasonal changes in population sizes, and, therefore, estimates of mortality rates. These calculations provided estimates of fry and juvenile movement and mortality rates that enabled us to develop biologically reasonable ranges of parameters to evaluate for whole-model calibration. Smolt emigration timing and passage at the Grayson (RM 5.2) RSTs for water years 2010–2013 were used as the field-based data to which the model was calibrated. Because fry and juvenile movement- and mortality-related parameters are not well constrained, they were ideal candidates for adjustment parameters in the whole-model calibration. Using the ranges identified from RST and seine data, systematic adjustments of parameter combinations of fry and juvenile displacement rates (fry.displace.rate, juv.displace.rate) and migration-related mortality rates (fry.migr.mrate, juv.migr.mrate) were made for each model run. Throughout these adjustments, the ratio of the fry displacement rate (fry.displace.rate) to the juvenile displacement rate (juv.displace.rate) was fixed at 10:1, based on the assumption that fry are weaker swimmers than juveniles and are thus displaced at a higher rate from preferred rearing territories. The parameter range for TRCh calibration was identified as $0.05 < \text{fry.displace.rate} < 0.25$ and $1 < \text{fry.migr.mrate.mult} < 50$, with values representing daily rates. Figure 2.3-1 shows contour plots representing model responses (smolt production) to parameter combinations. Each tile shows the 660 parameter combinations run. Red lines represent target values (observed value) for the response variable (smolt production), when in range (e.g., not visible in 2013).

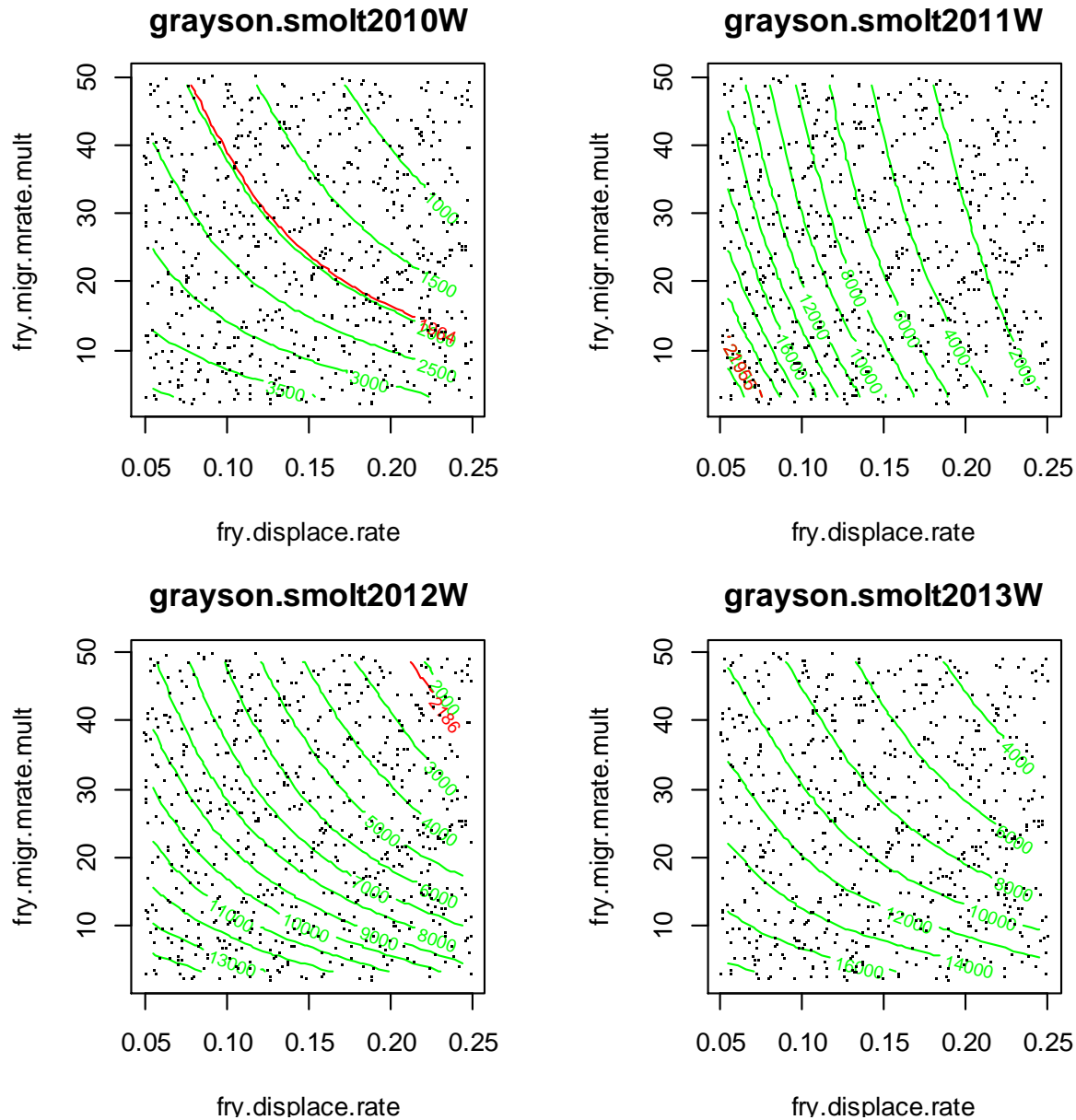


Figure 2.3-1. Modeled seasonal smolt RST passage at Grayson (RM 5.2) as a function of movement and mortality fitting parameters for the water years used for model calibration (2010–2013).

For each model run with different parameter combinations, estimates of smolt productivity (defined as the number of emigrant smolts passing the Grayson RST, RM 5.2) were compared to RST estimates. We considered three principal metrics for model performance: the slope and intercept of linear regressions of observed versus predicted smolt productivity (emigrant smolts per female spawner) across the four calibration years, and the mean of these four productivities. A perfect calibration would result in a slope equal to 1:1 and an intercept equal to zero. However, because optimizing to multiple variables presents a considerable challenge, the slope of the regression line representing modeled vs. observed smolt production was selected as the initial optimization criterion. Figure 2.3-2 shows the three primary calibration metrics as

functions of the parameters adjusted for calibration. Red lines represent target values for calibration.

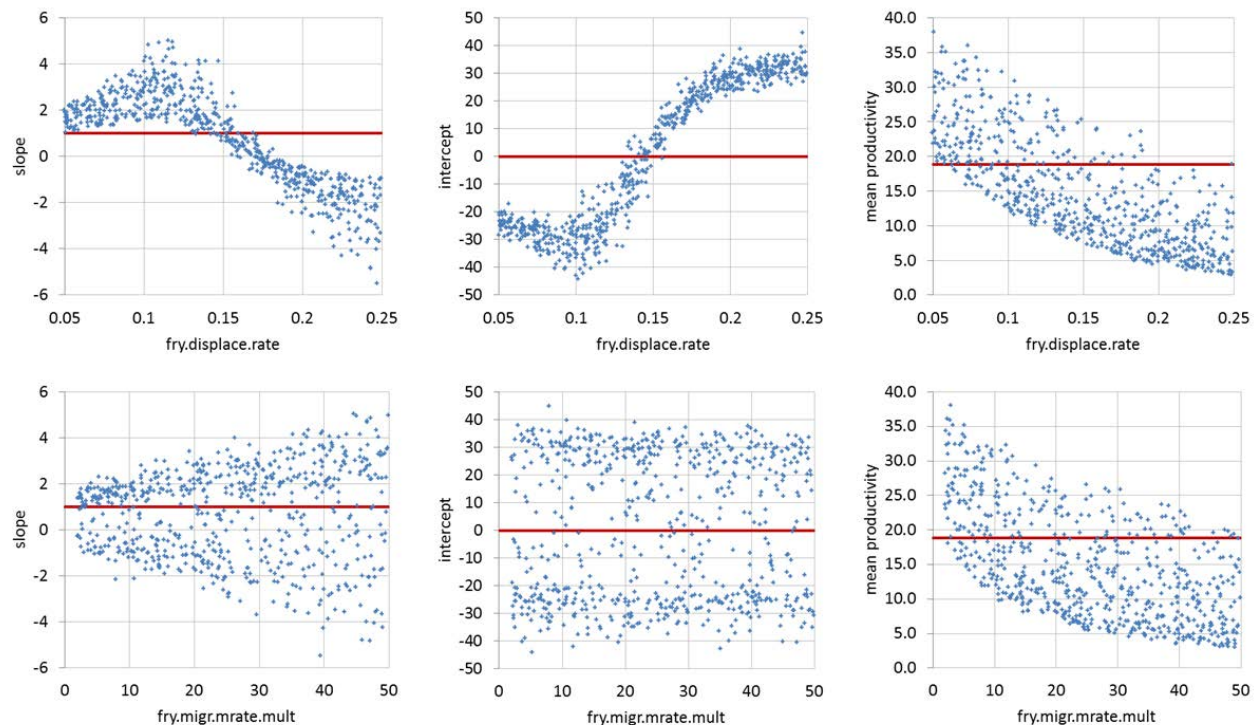


Figure 2.3-2. Calibration process to fit the slope (left) and intercept (middle) of the modeled vs. observed smolt productivity relationship, as well as the mean modeled productivity (right) as a function of fry displacement rate (top) and mortality rate (bottom).

Figure 2.3-2 shows that the calibration metrics are much more sensitive to displacement rate than mortality rate. Accordingly, a value for fry.displace.rate was selected where the slope was closest to one. Using this value for displacement rate, calibration of fry migration mortality could then be constrained by the mean productivity metric, and a narrow range of fry.migr.mrate.mult values corresponding to the target mean productivity was selected. Within this range, the value that maximized the r^2 of the relationship between modeled and observed productivities across the entire validation period was selected.

2.4 Updated TRCh Model Validation

Updates to the TRCh model validation in the 2013 study report was conducted to assess the degree to which predictions from the recalibrated model agreed with available field-based data. Following calibration to recent RST data at Grayson (RM 5.2), model results were compared to other years of paired RST data that were not included in the calibration. As discussed in the Synthesis Study (TID/MID 2013b), paired RST monitoring has been conducted at the Waterford (RM 29.8) and Grayson (RM 5.2) locations since 2006 with only partial sampling of the Grayson location occurring in 2007 (Robichaud and English 2017). As with TRCh model calibration, initial conditions for spawner populations, timing, as well as flow and temperature ranges used in

TRCh model validation are shown in Table 2.4-1. Water temperature did not exceed the temperature mortality threshold for embryos (16°C) during the embryo development period (Nov–Feb) over the validation years (WY 1999–2009). Water temperature did exceed the temperature mortality threshold for smolt emigration below RM 3.5 in late May during WY 2001–2003.

Although no upstream passage information exists prior to installation of the RM 24.5 counting weir in September 2009, data from CDFW carcass surveys were used as model input for escapement in all prior years to estimate smolt production for the corresponding outmigration years. Spawning arrival timing for these years was calculated from a normal distribution derived from redd count surveys in 2005–2009. Timing in years prior to 2005 is represented by a generic composite distribution based on the timing of CDFW carcass surveys in those years. Counting weir estimates of escapement and arrival timing were used as model inputs to estimate smolt production in years 2010–2013. Yearly estimates of smolt passage at the Grayson RST (RM 5.2) from model output were compared to RST data (Figure 2.4-1). Because escapement estimates from the carcass survey and the counting weir for year 2010 differ, model estimates of smolt production vary accordingly. Model estimates of weekly smolt and pre-smolt passage at both Grayson and Waterford RSTs were compared to RST data (Figure 2.4-2). Figure 2.4-3 shows yearly estimates of smolt production, defined as emigrant smolts (i.e., smolts passing Grayson RST, RM 5.2) produced per female spawner, based on the three different methods of estimated spawner arrival timing.

Because existing RST data only provide direct information at two locations (RM 29.8, RM 5.2), and only for fish in motion, model validation was also conducted with seining data (2007–2013) to compare model estimates of the spatial and temporal distribution of juvenile Chinook salmon. The TRCh model predicts the dates and locations at which fish are promoted from one life stage to another, for example, the dates and locations at which fry emerge from spawning redds, the dates and locations at which fry are promoted to juvenile status (fork length [FL] >50mm), and the dates and locations at which smolt-ready juveniles (FL >70mm) undergo smoltification. These results were used to compare modeled spatial and temporal patterns in the distributions of fish rearing at various locations in the lower Tuolumne River to patterns that are observable in the historical seining data (Figure 2.4-4). This validation primarily serves to confirm assumptions and parameters affecting temporal patterns in development as well as patterns of spatial distribution.

Table 2.4-1. Summary of initial conditions input to the TRCh model for validation runs, including initial population input as well as flow and temperature by life stage.

Initial Conditions (WY)		1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Arrival timing ¹		16-Nov	16-Nov	15-Nov	16-Nov	17-Nov	16-Nov	15-Nov	16-Nov	16-Nov	24-Nov	9-Nov
Escapement ²		4,356	3,931	8,626	4,236	3,502	1,031	953	307	274	79	216
Spawning/incubation flow (cfs) ³ (Nov–Feb)	min	271	307	309	169	177	215	172	355	341	162	154
	max	7,580	4,410	3,400	212	220	254	3,230	7,710	410	187	170
Spawning/incubation temp (°C) ³ (Nov–Feb)	min	8.9	9.9	9.4	8.5	8.5	8.8	7.7	9.0	8.5	7.6	8.1
	max	12.9	13.2	12.8	14.2	12.9	12.8	12.3	12.8	13.2	13.6	14.2
Rearing flow (cfs) ⁴ (Mar–Apr)	min	1,050	398	243	160	173	242	3,020	2,880	308	166	165
	max	5,032	7,729	2,844	1,342	1,474	2,851	7,211	10,985	1,015	1,313	784
Rearing temp (°C) ⁴ (Mar–Apr)	min	9.4	9.8	10.1	9.8	10.5	10.5	9.9	9.4	10.3	10.0	8.5
	max	16.0	17.7	20.0	21.9	19.6	20.9	13.8	13.3	20.8	21.6	23.5
Smolt emigration flow (cfs) ⁴ (Apr–May)	min	335	322	138	170	180	173	3,020	3,610	208	143	166
	max	3,620	4,369	1,526	1,342	1,474	1,673	7,211	10,985	1,015	1,338	1,004
Smolt emigration temp (°C) ⁴ (Apr–May)	min	9.3	9.8	10.1	10.3	10.6	10.6	9.9	9.6	10.4	10.0	10.1
	max	23.3	23.4	26.9	27.1	26.2	24.6	14.7	14.3	24.7	22.5	24.0

¹ Median date from CDFW carcass surveys.² Female escapement from CDFW surveys.³ Based on daily flow and temperature estimates upstream of Robert's Ferry Bridge (RM 39.5).⁴ Based on daily river-wide flow and temperature estimates.

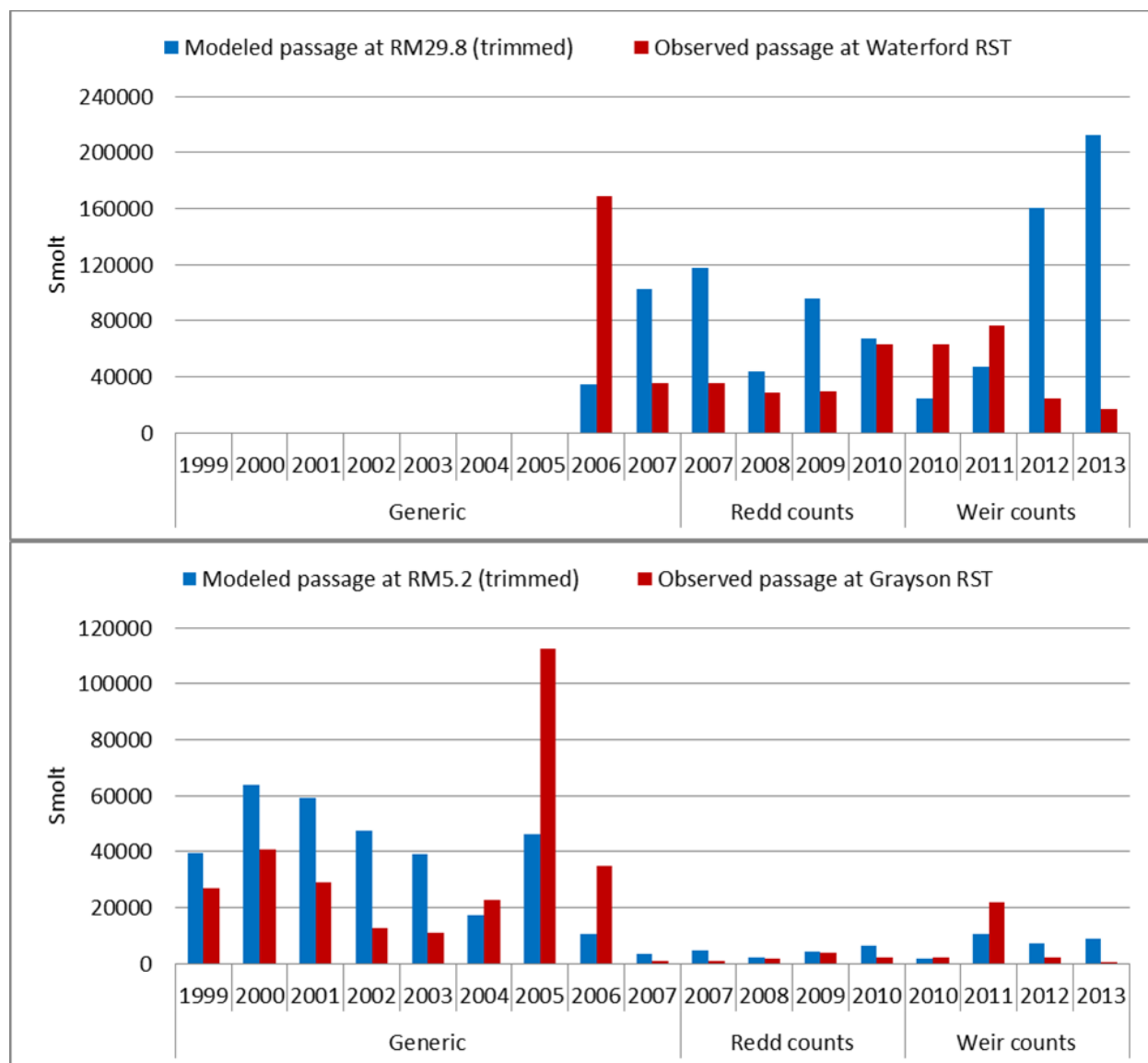


Figure 2.4-1. Modeled vs. observed passage estimates of smolts at the Waterford RST (RM 29.8) (top) and Grayson RST (RM 5.2) (bottom).

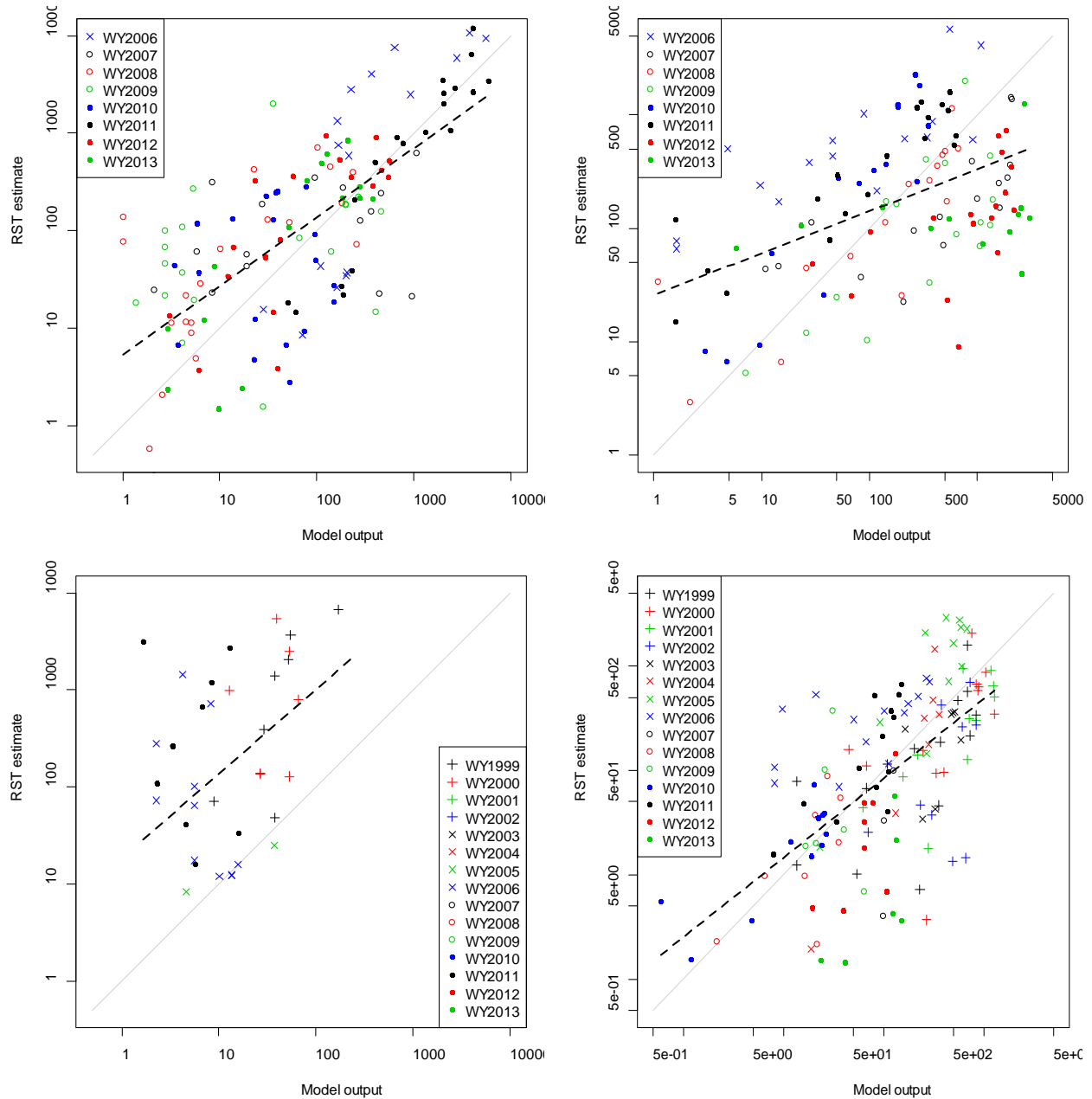


Figure 2.4-2. Modeled vs. observed weekly passage of pre-smolt (juveniles and fry, left) and smolts (right) past the Waterford (top) and Grayson (bottom) RSTs.

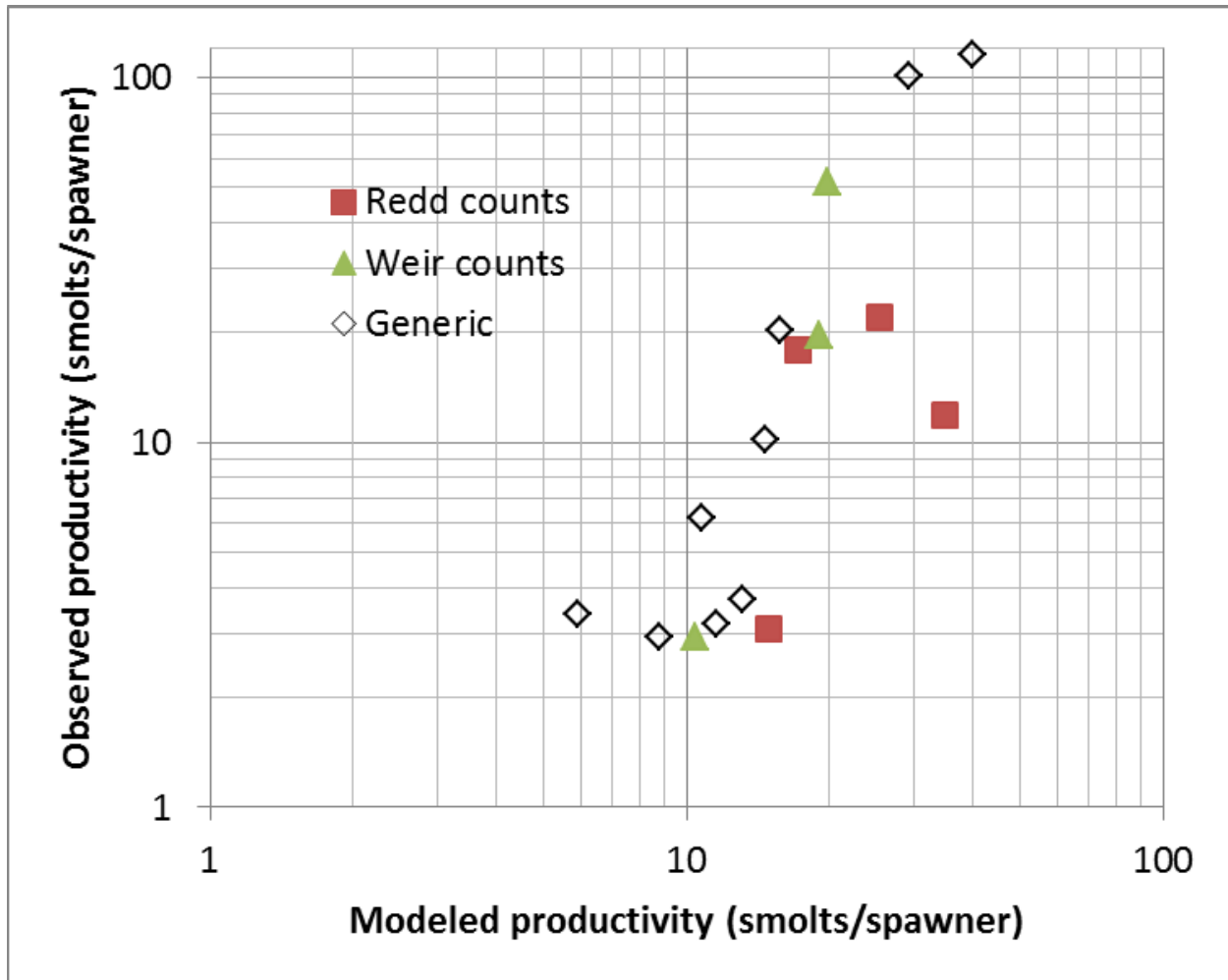


Figure 2.4-3. Modeled vs. observed estimates of smolt production at Grayson RST (RM 5.2), defined as emigrant smolts per female spawner, for three different estimates of run timing.

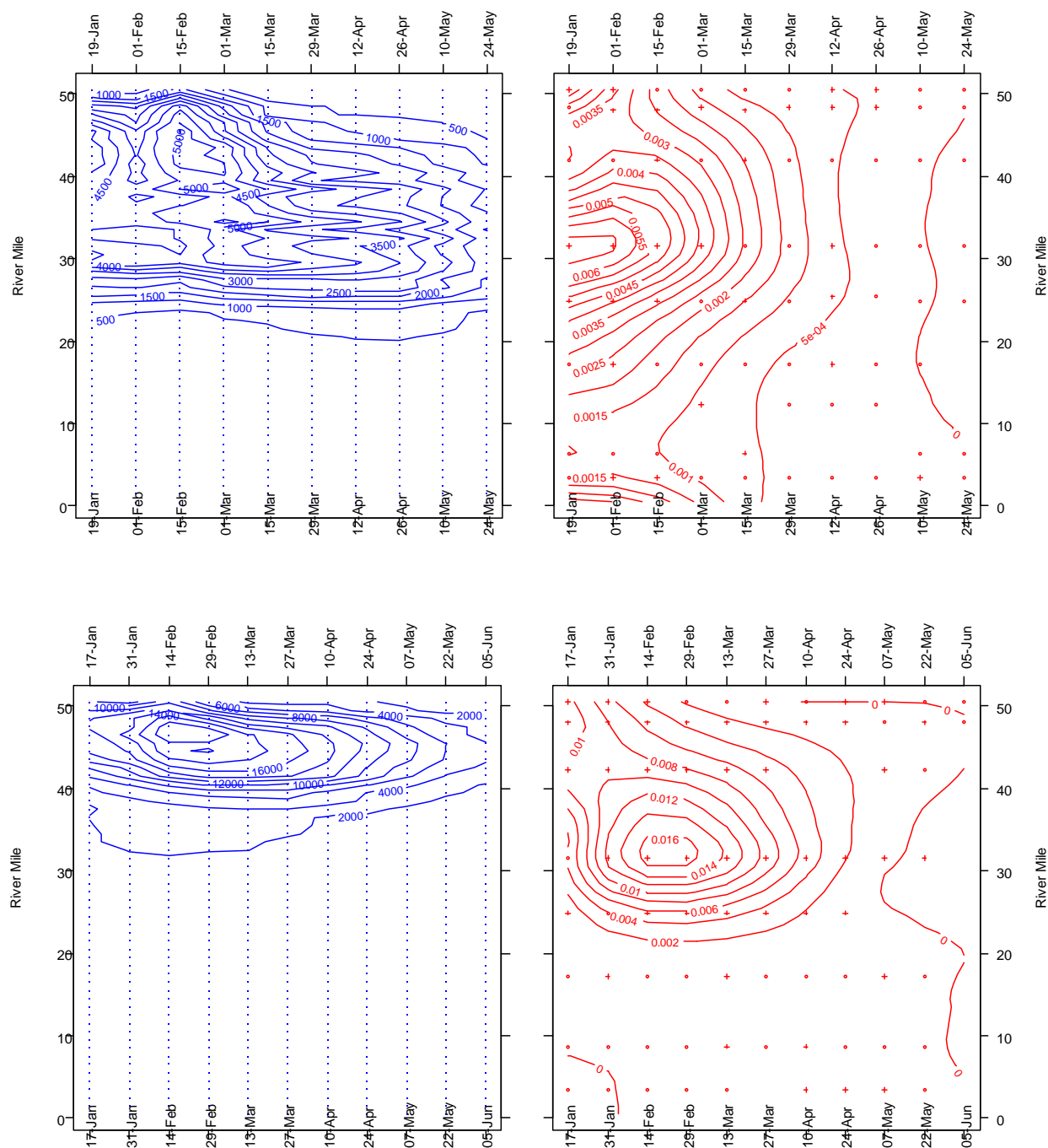


Figure 2.4-4. Comparison of modeled (blue) and observed (red) distribution of rearing Chinook salmon along the lower Tuolumne River during wet (WY 2011 shown, top) and dry (WY 2012 shown, bottom) water year types.

3.0 UPDATED STUDY RESULTS

Using the calibrated and validated TRCh model, juvenile salmonid production has been estimated under Base Case conditions. Using daily flow estimates from the Operations Model (TID/MID 2013d) along with accompanying water temperature estimates provided by the Reservoir Temperature Model (TID/MID 2017e) and Lower Tuolumne River Model (TID/MID 2017c), the Base Case depicts the operation of the Project in accordance with the current FERC license, U.S. Army Corps of Engineers flood management guidelines, and the Districts' irrigation and M&I water management practices since completion of Don Pedro Dam in 1971. In total, the base case provides a thirty-nine-year time series of varying hydrology and meteorology to examine variations in juvenile salmon production under a variety of water year types as well as to provide a basis of comparison for any alternative operating scenarios. Although other scenarios may be evaluated with the TRCh model have been included in the Amendment to the Final License Application, the Base Case scenario results presented in the sections below are intended to illustrate model functionality.

3.1 TRCh Model Base Case Scenario Results

Using long-term averages of fall run Chinook salmon run timing to the lower Tuolumne River, run composition (age, sex ratio), and spawner fecundity, variations in juvenile salmon production metrics were evaluated for the base case simulation period (1971–2012) for three “reference” runs of 2,000, and 10,000 female spawners. For the base case hydrology and water temperature data, the ratio of smolt passage at the San Joaquin River confluence (RM 0) to female spawners (“smolt productivity”) is grouped by water year type and plotted by decreasing La Grange discharge from October-June (TAF) in Figure 3.1-1.

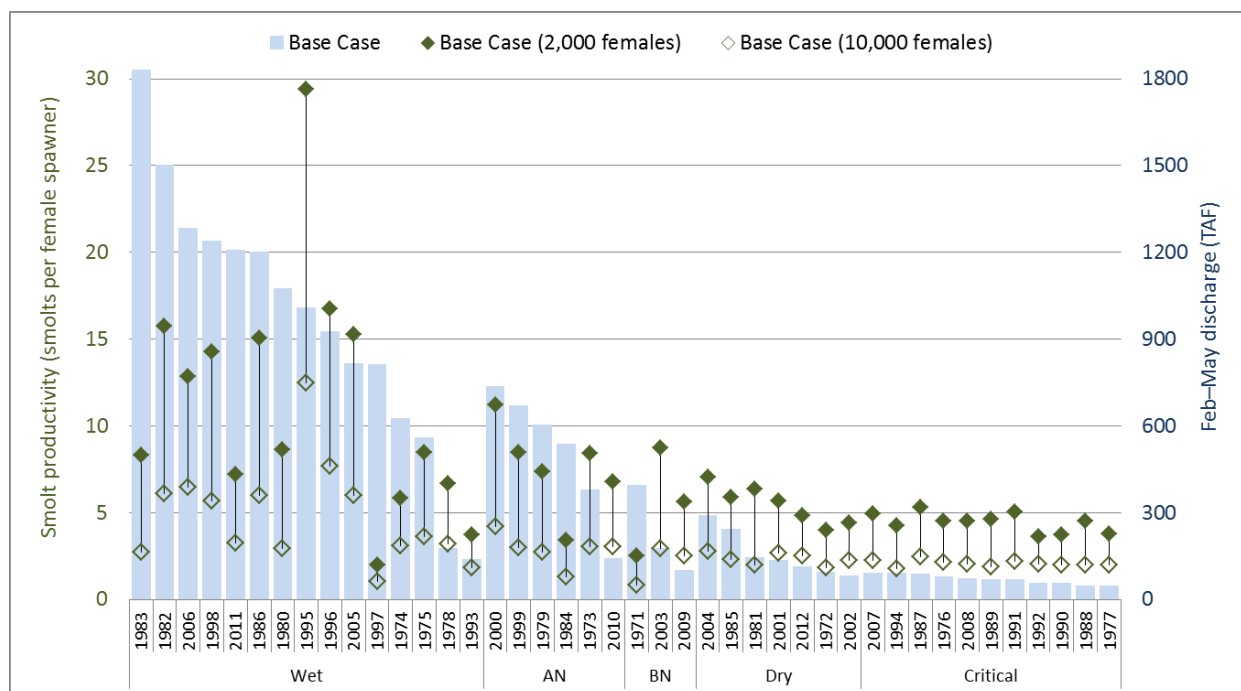


Figure 3.1-1. Modeled yearly (1971–2012) Chinook salmon smolt productivity for the base case sorted by La Grange discharge (Feb–May) and water year type for two reference runs.

For the broad range in hydrologic conditions evaluated, Figure 3.1-1 shows that smolt productivity occurring in Above Normal and Wet water year types is consistently higher than those for Below Normal and drier types. Exceptions to this pattern relate to the occurrence of flood control releases in several years. For example, no flood control releases occurred in WY 1978 and WY 1993, which corresponded to reservoir filling following Critical water year conditions in the prior drought years. As another example, record flood flows occurring in January 1997 were followed by the cessation of flood control releases by mid-March due to below normal precipitation during later winter and spring months. Lastly, it should be noted that the model simulation is restarted in each year with the same reference runs, and the results do not reflect year-to-year variations in out of basin factors that may affect adult recruitment and subsequent escapement.

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ATTACHMENT B

**CONCEPTUAL MODELS FOR IN-RIVER LIFE STAGES OF CHINOOK
SALMON IN THE TUOLUMNE RIVER**

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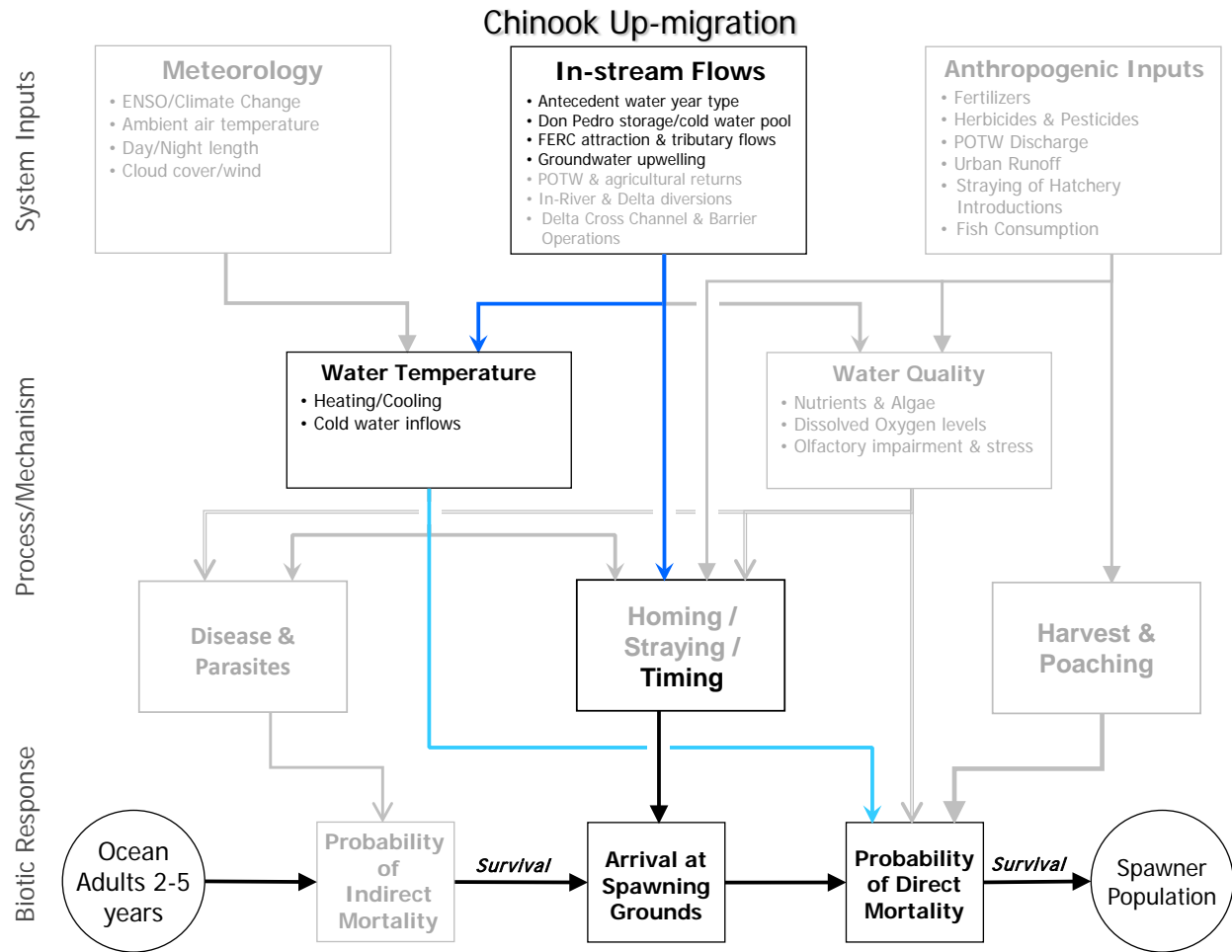


Figure B-1.

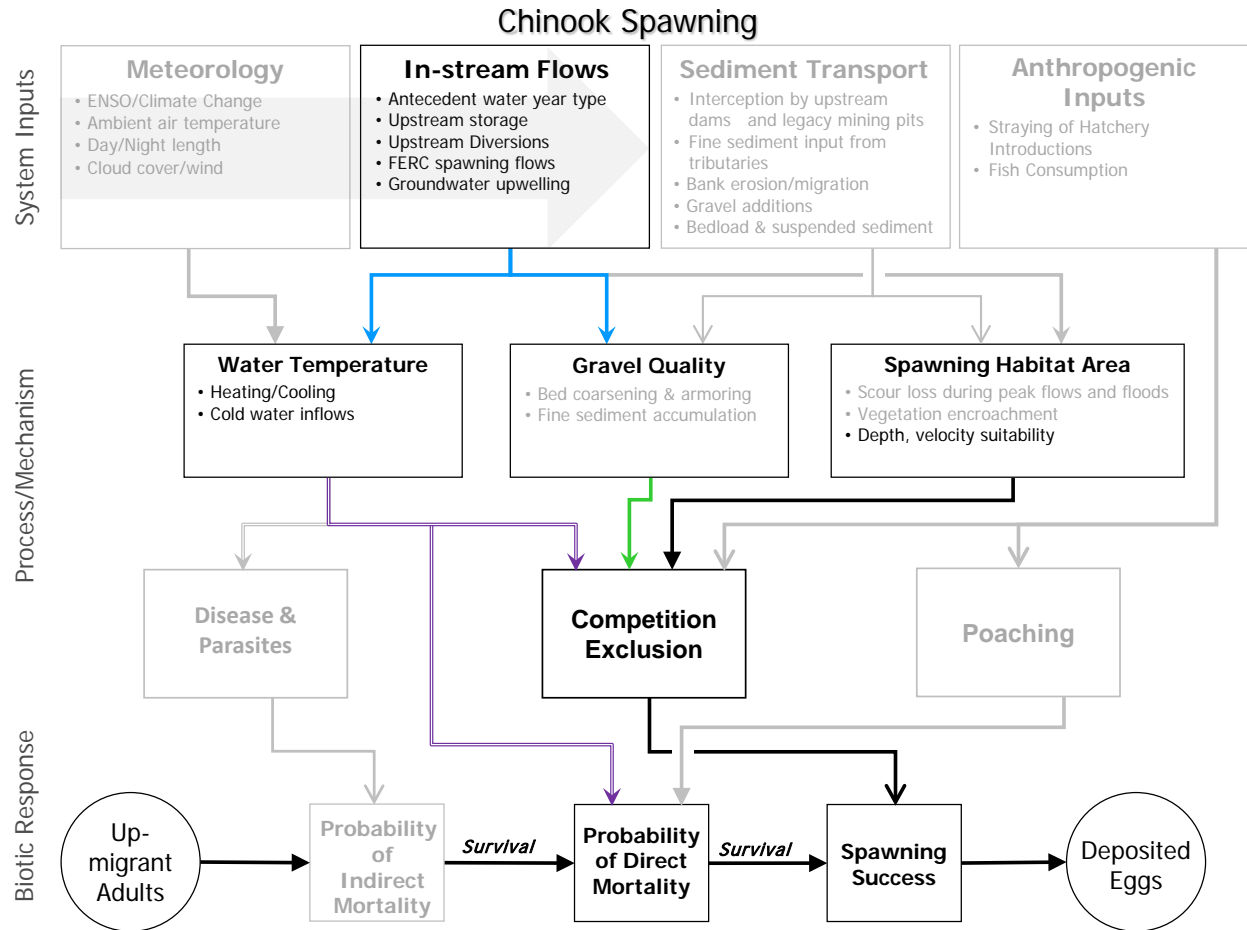


Figure B-2.

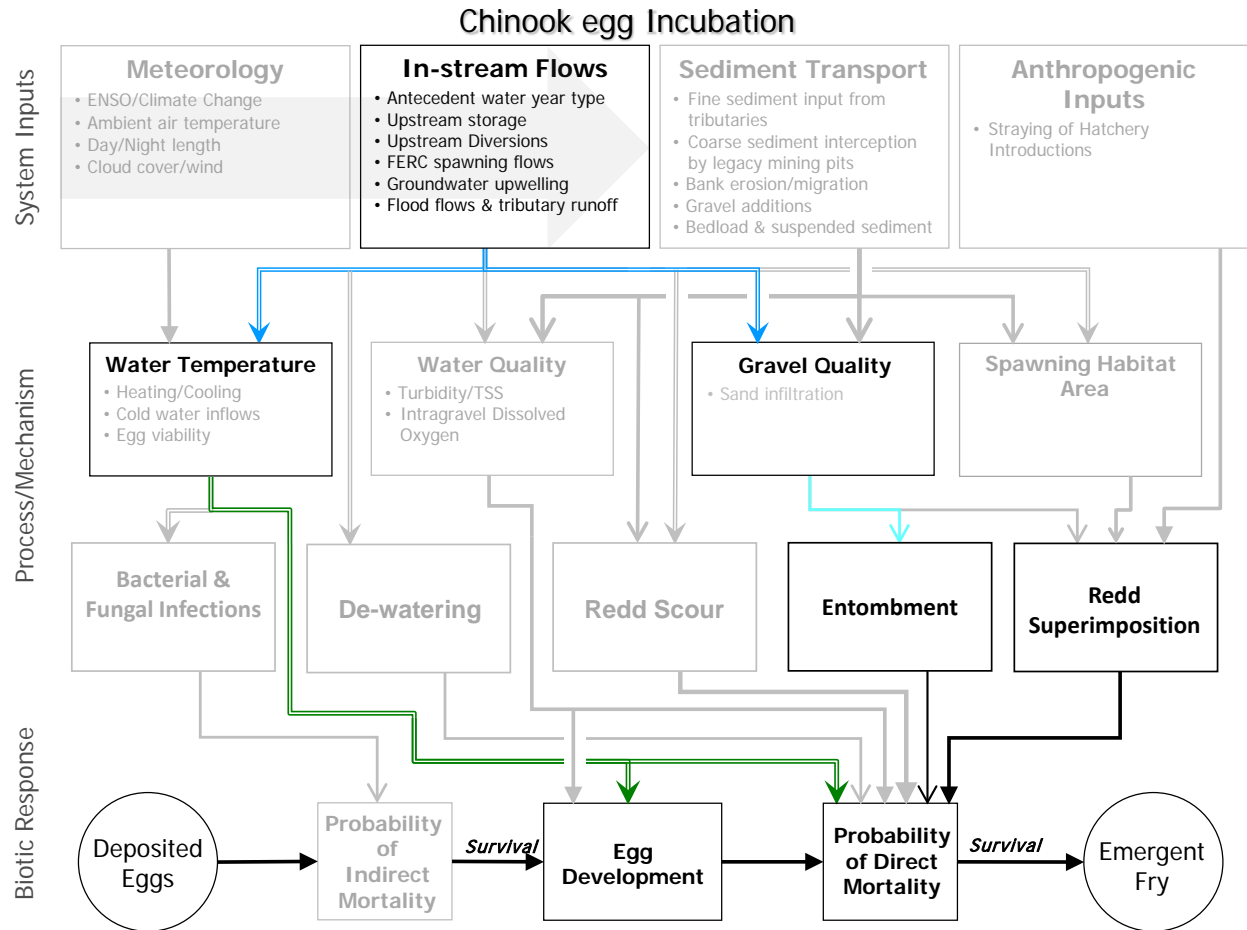


Figure B-3.

Chinook In-River Rearing/Outmigration

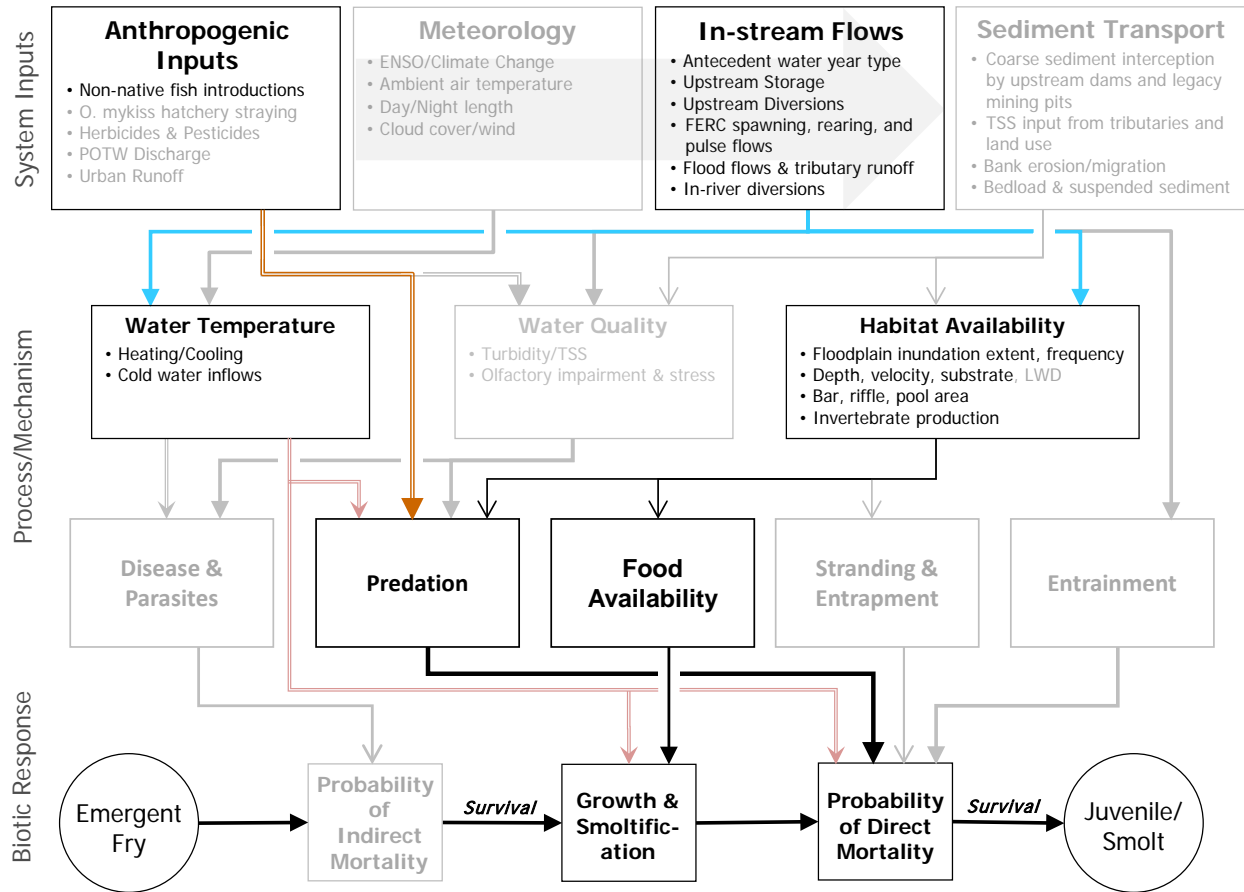


Figure B-4.

**STUDY REPORT W&AR-06
CHINOOK SALMON POPULATION MODEL STUDY**

ATTACHMENT C

**JUVENILE CHINOOK SALMON SEINING DENSITY IN THE
TUOLUMNE RIVER
(1999–2012)**

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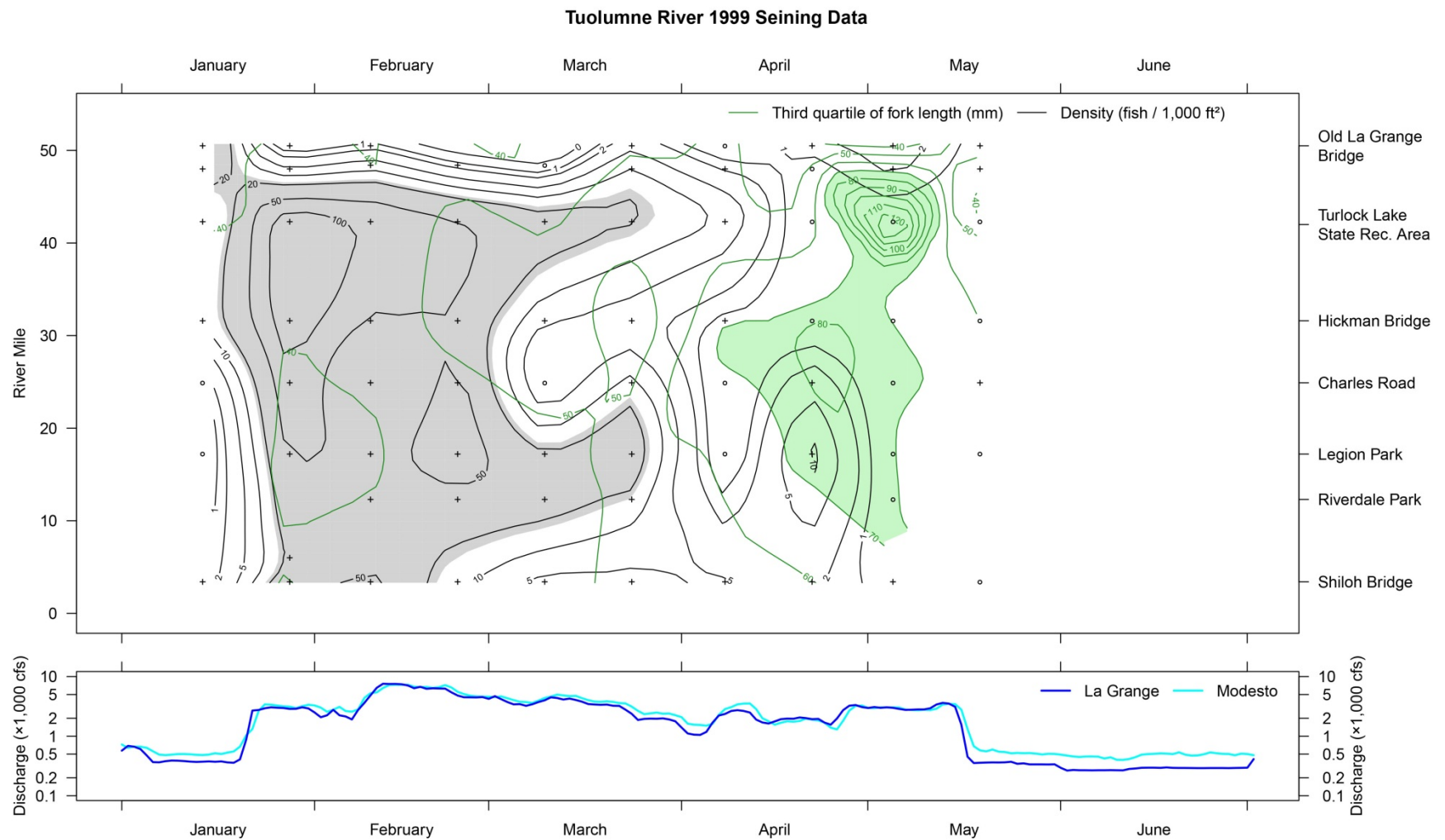


Figure C-1. 1999 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
 (Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

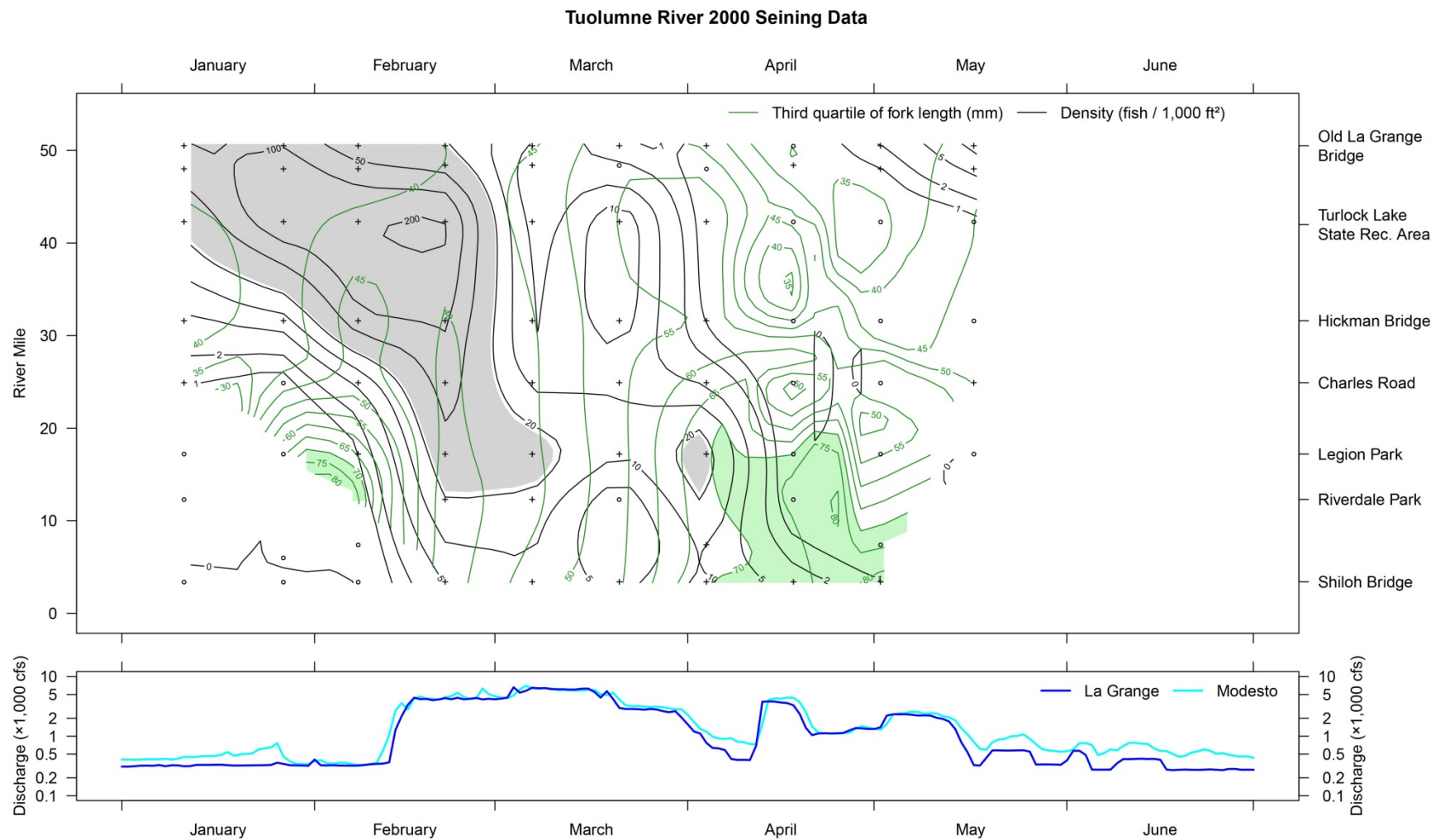


Figure C-2. 2000 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
 (Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

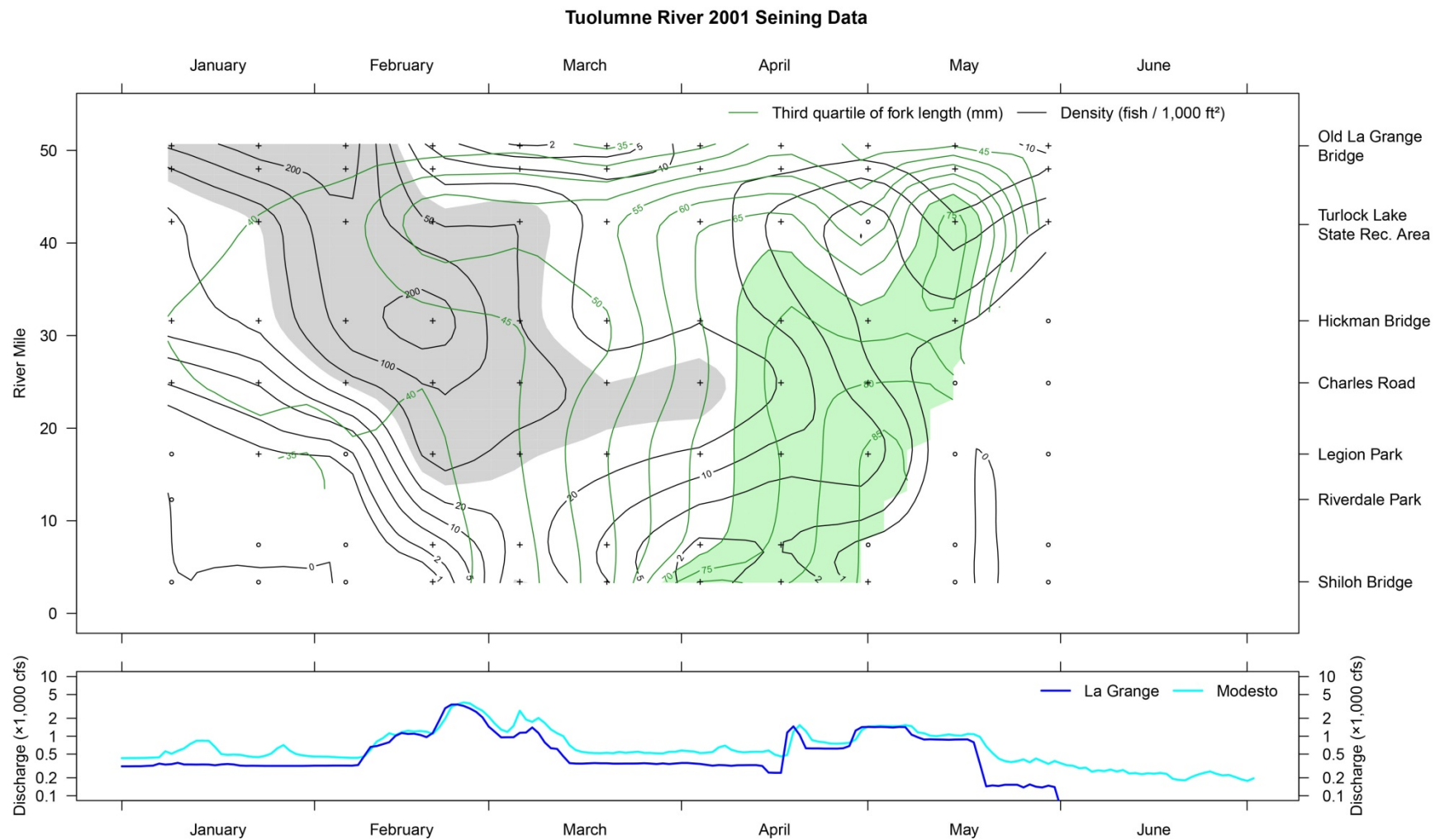


Figure C-3. 2001 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
(Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

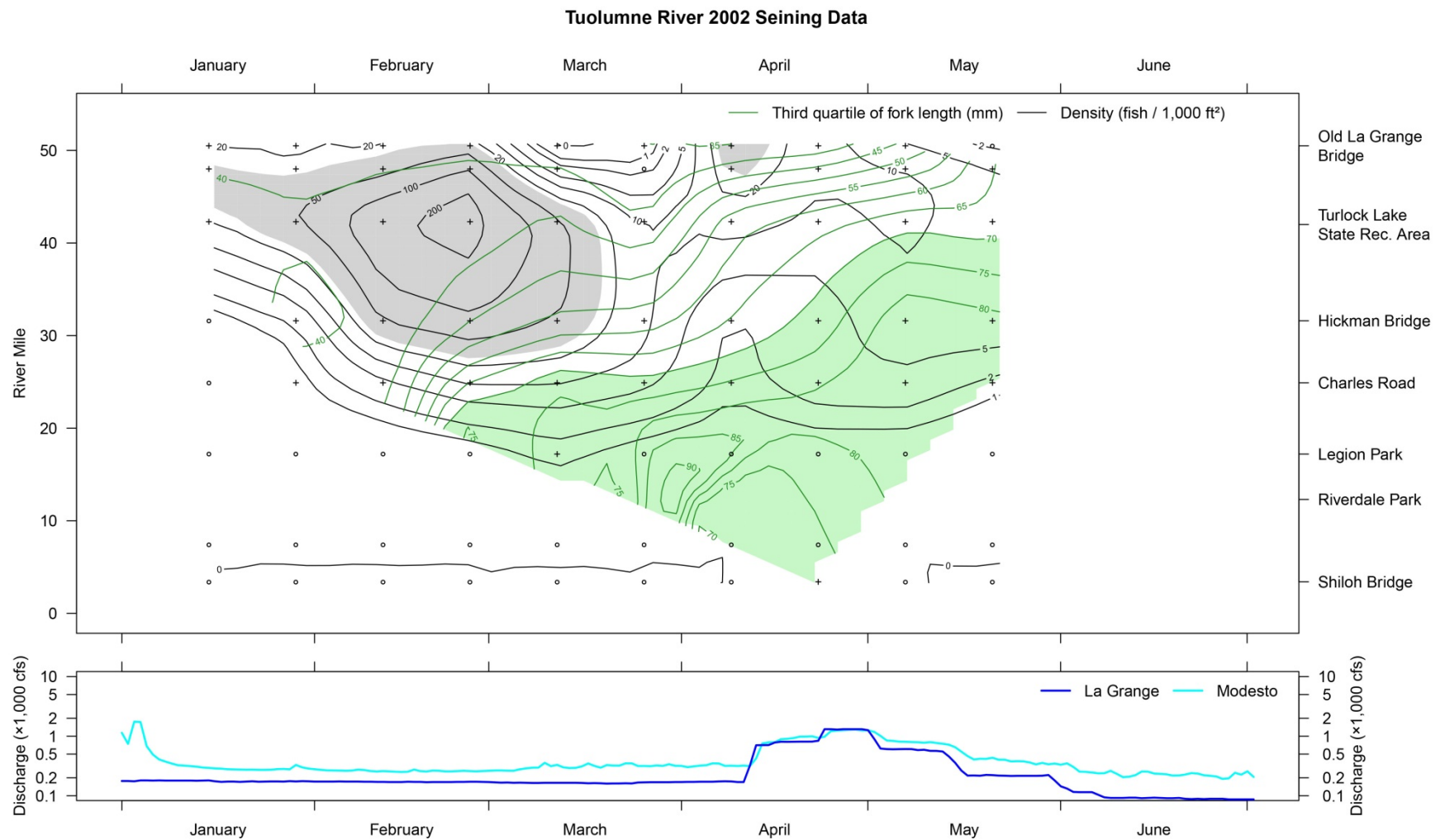


Figure C-4. 2002 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
 (Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

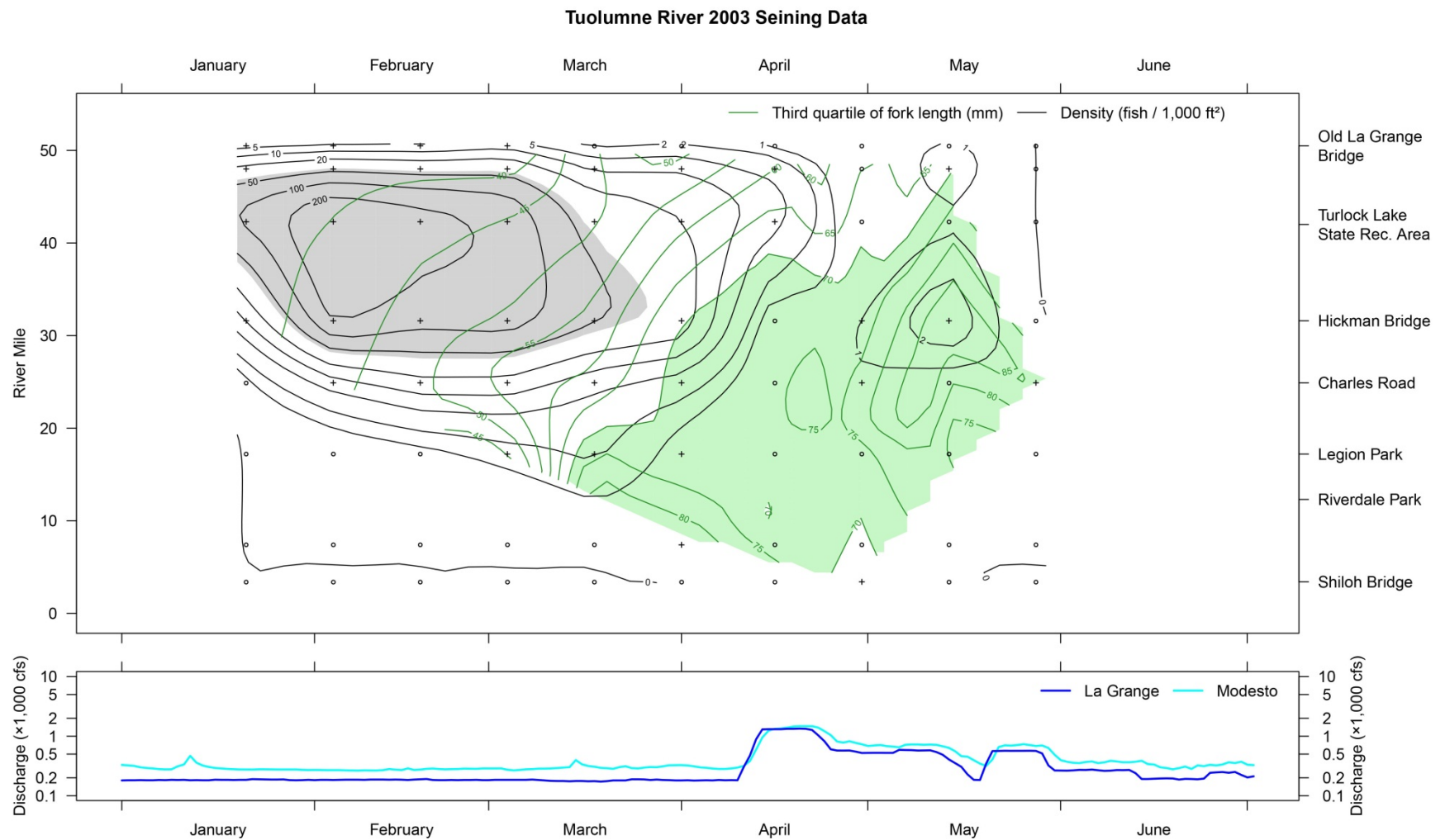


Figure C-5. 2003 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
(Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

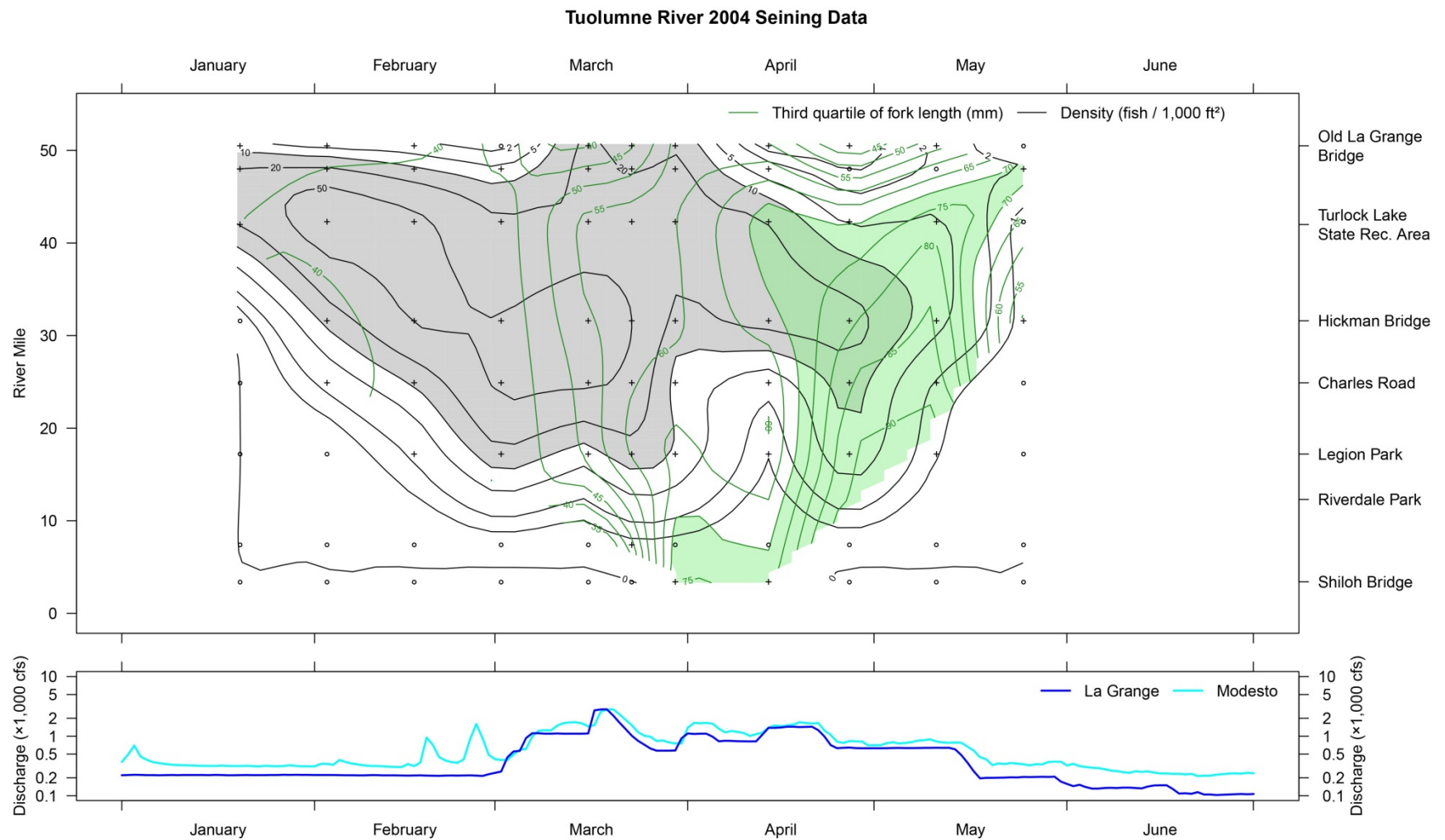


Figure C-6. 2004 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
(Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

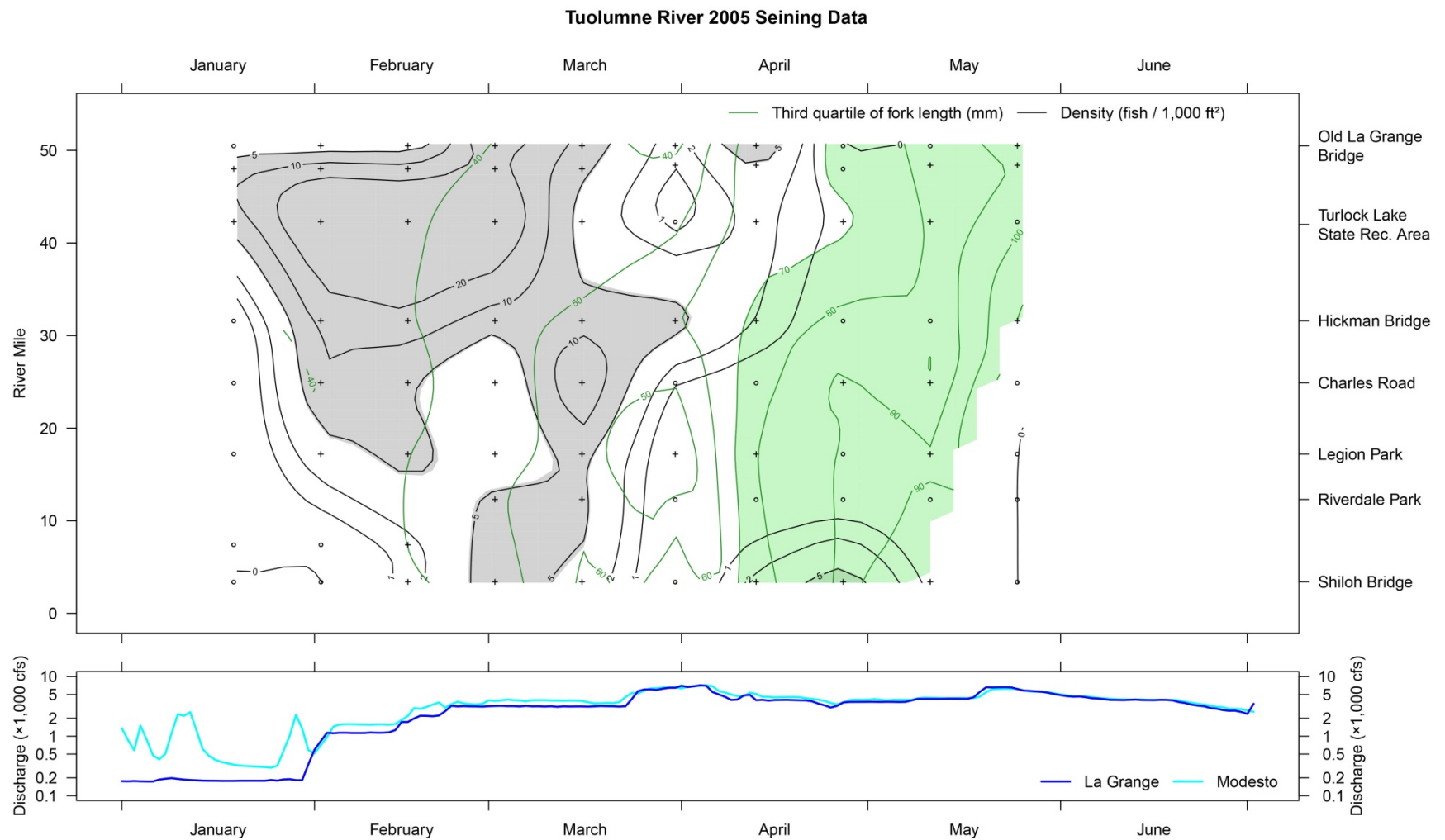


Figure C-7. 2005 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
 (Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

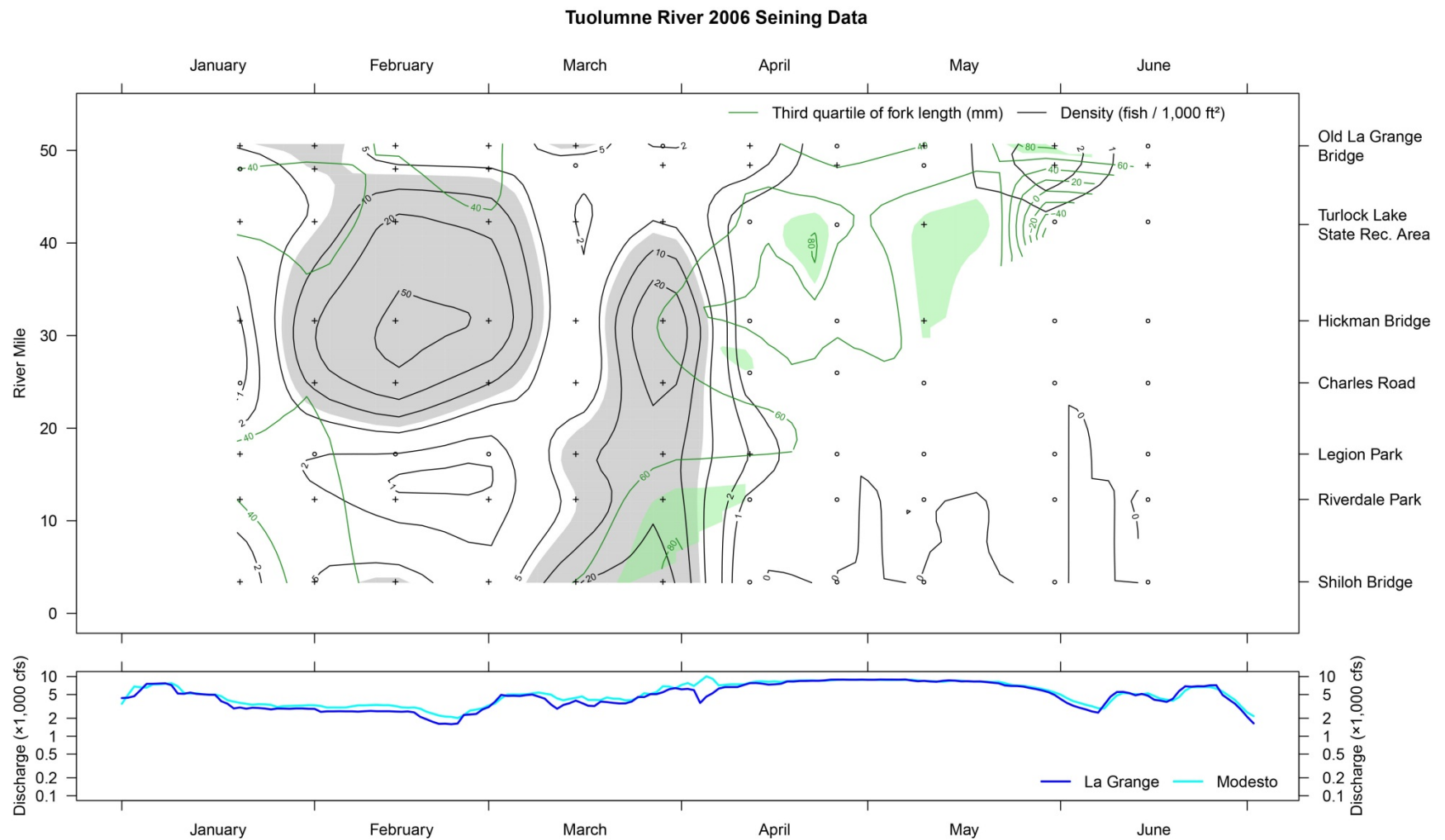


Figure C-8. 2006 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
(Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

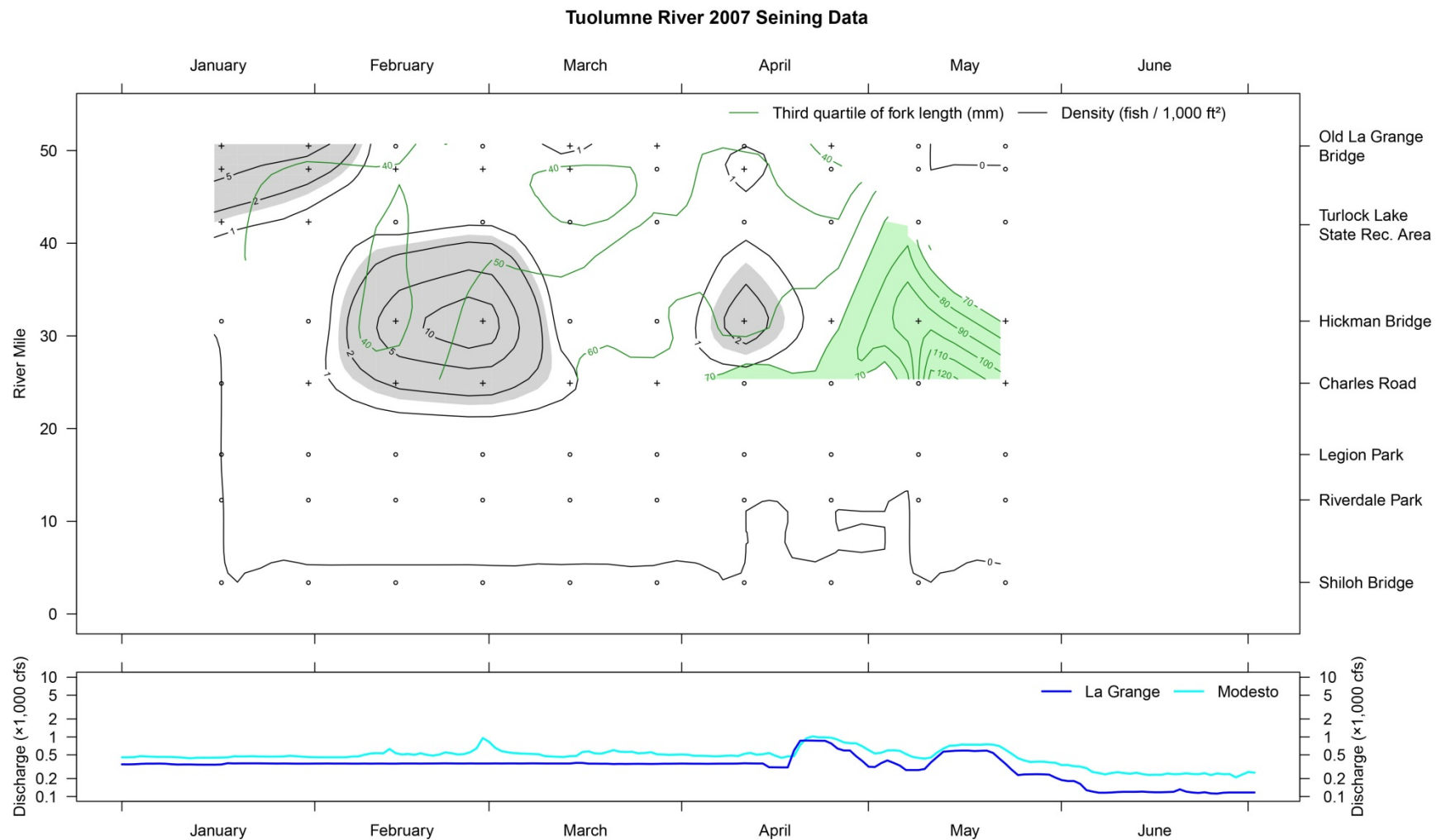


Figure C-9. 2007 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
(Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

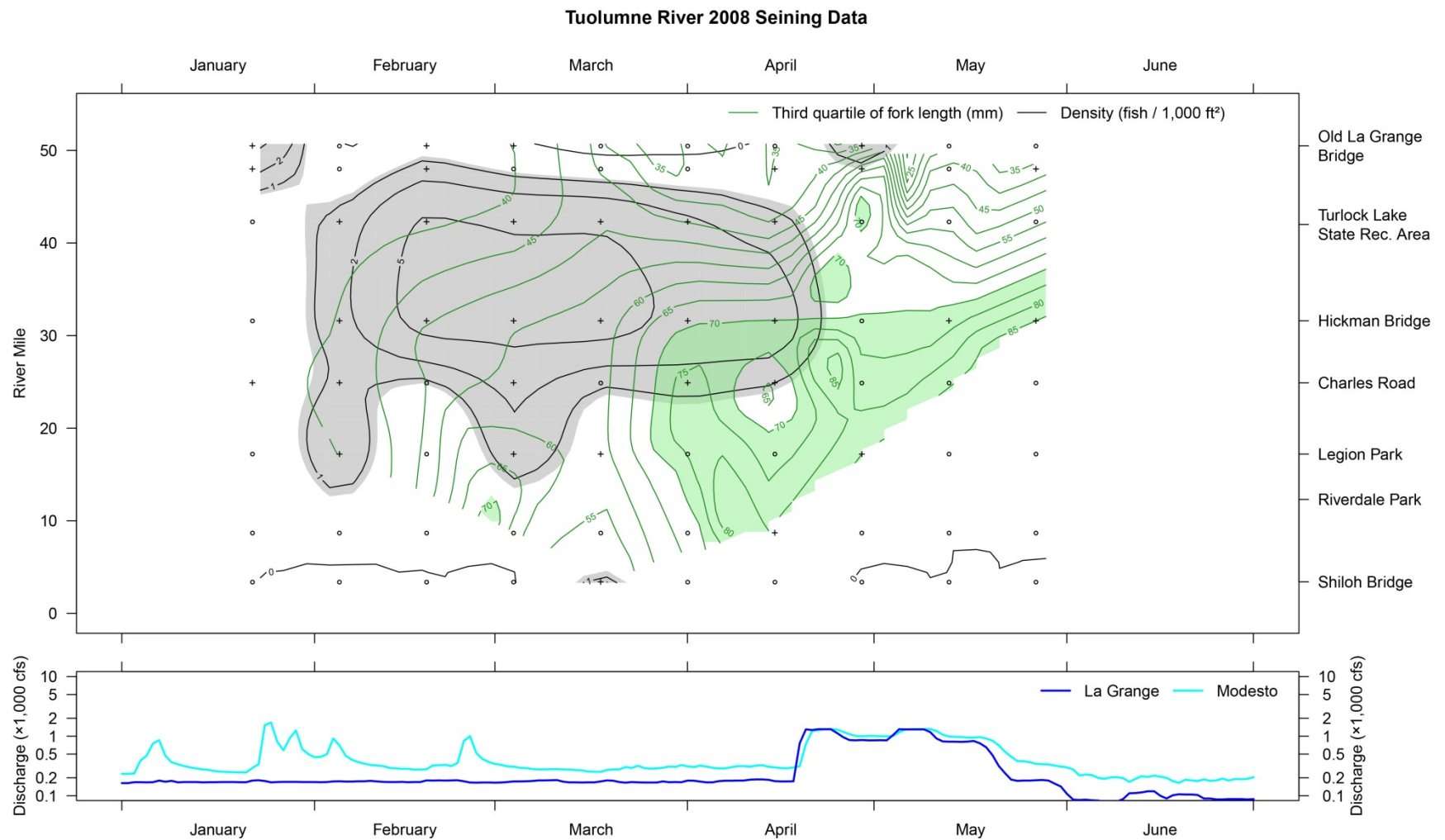


Figure C-10. 2008 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
(Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

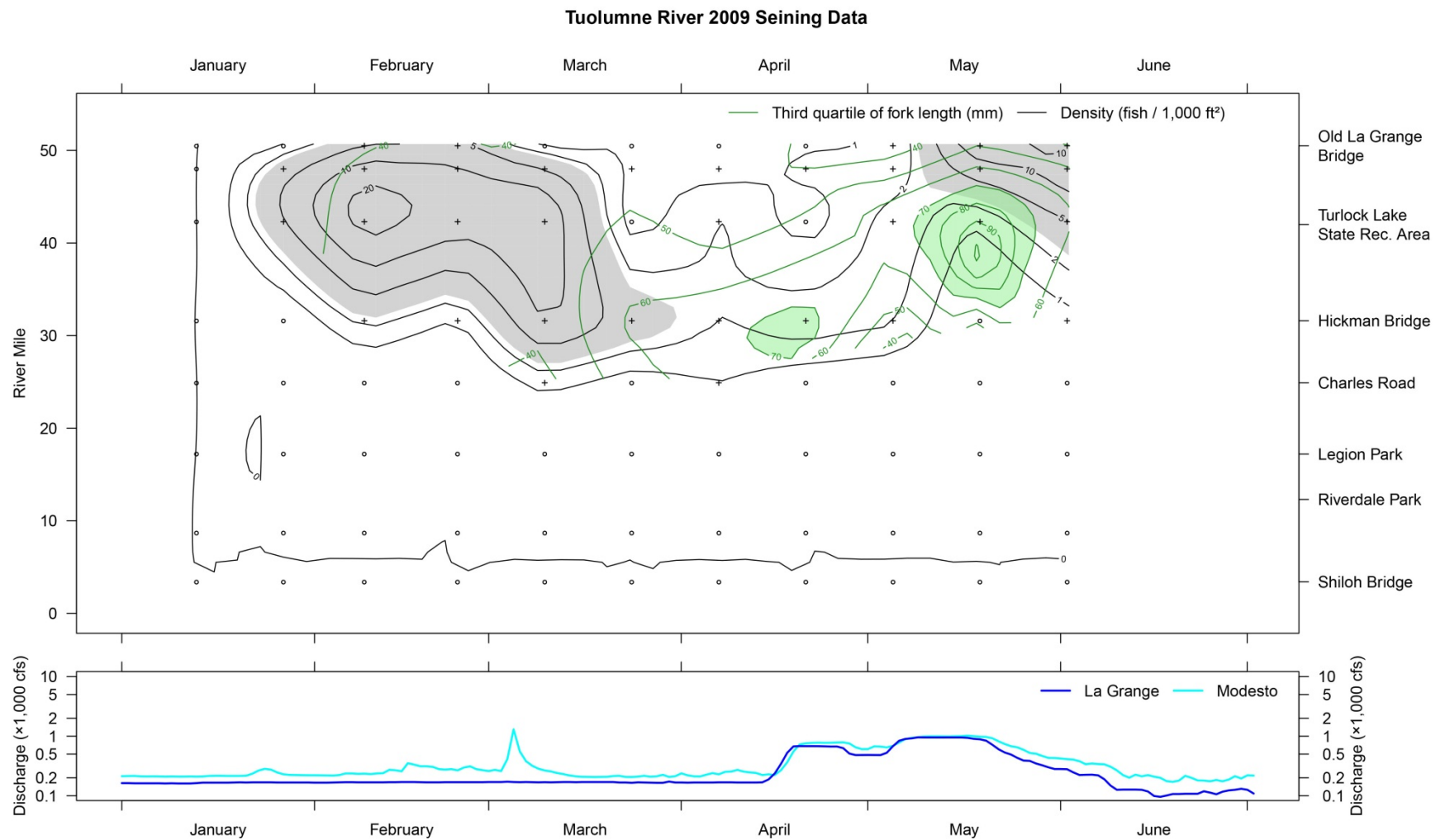


Figure C-11. 2009 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
(Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

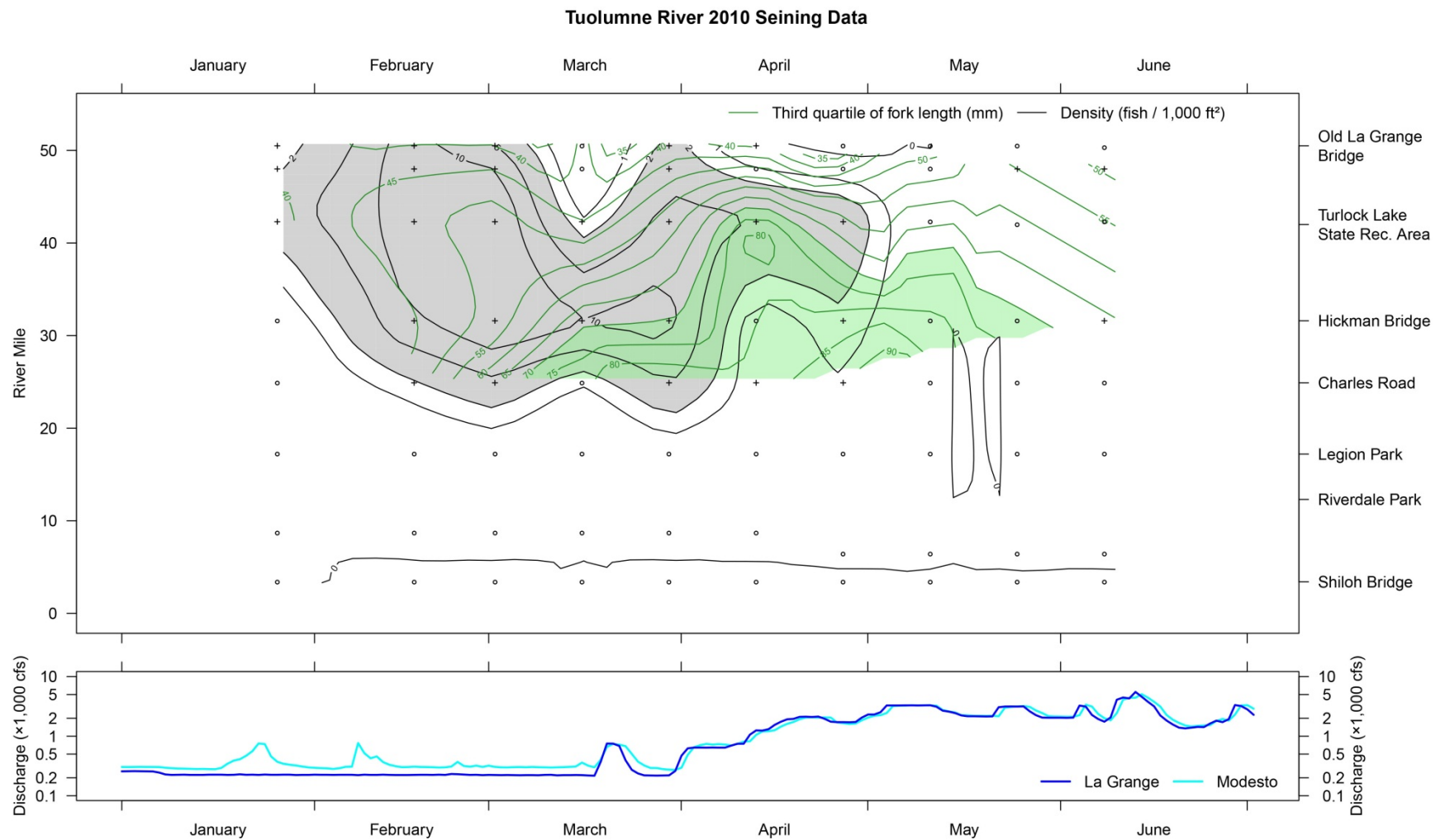


Figure C-12. 2010 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
(Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

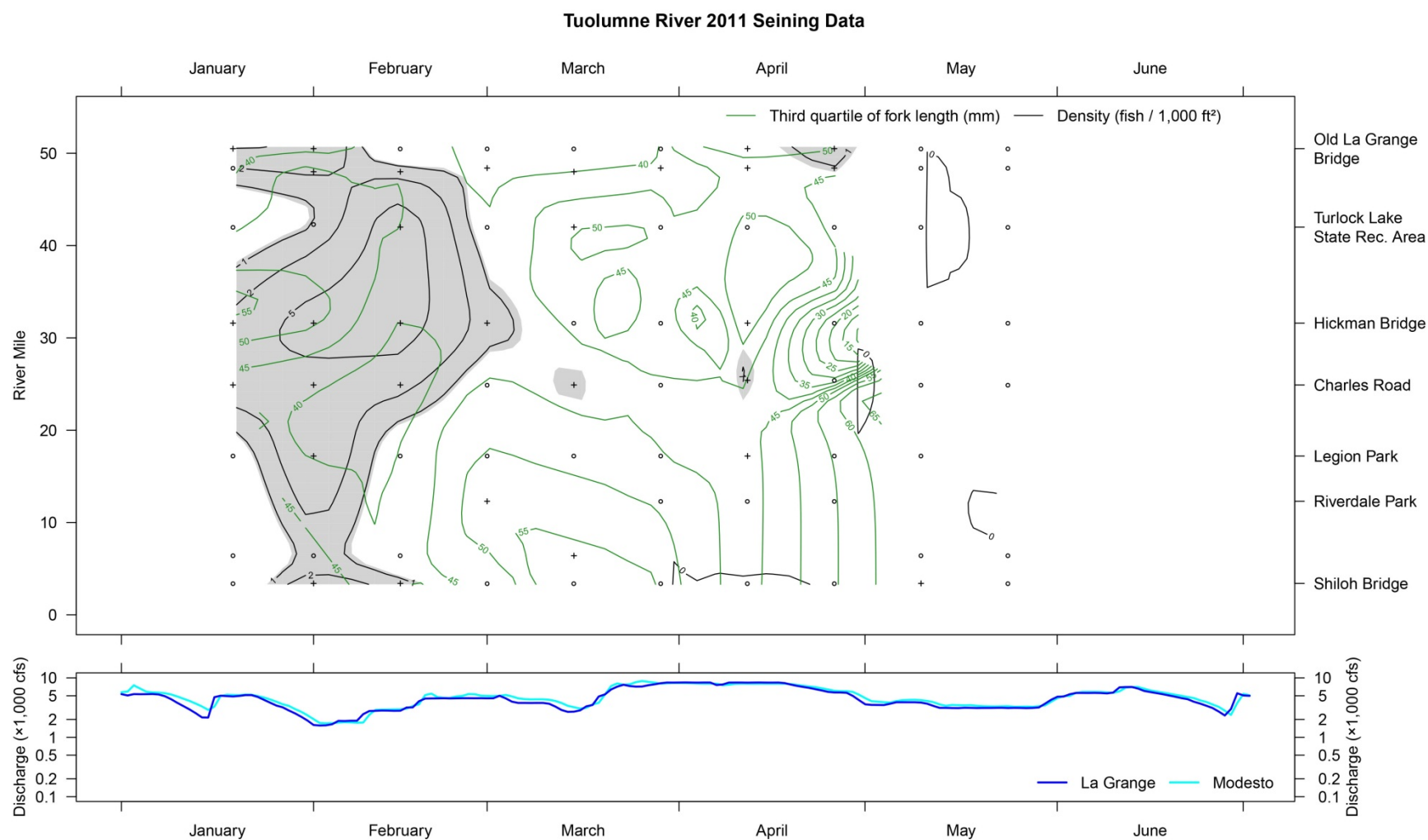


Figure C-13. 2011 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
(Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

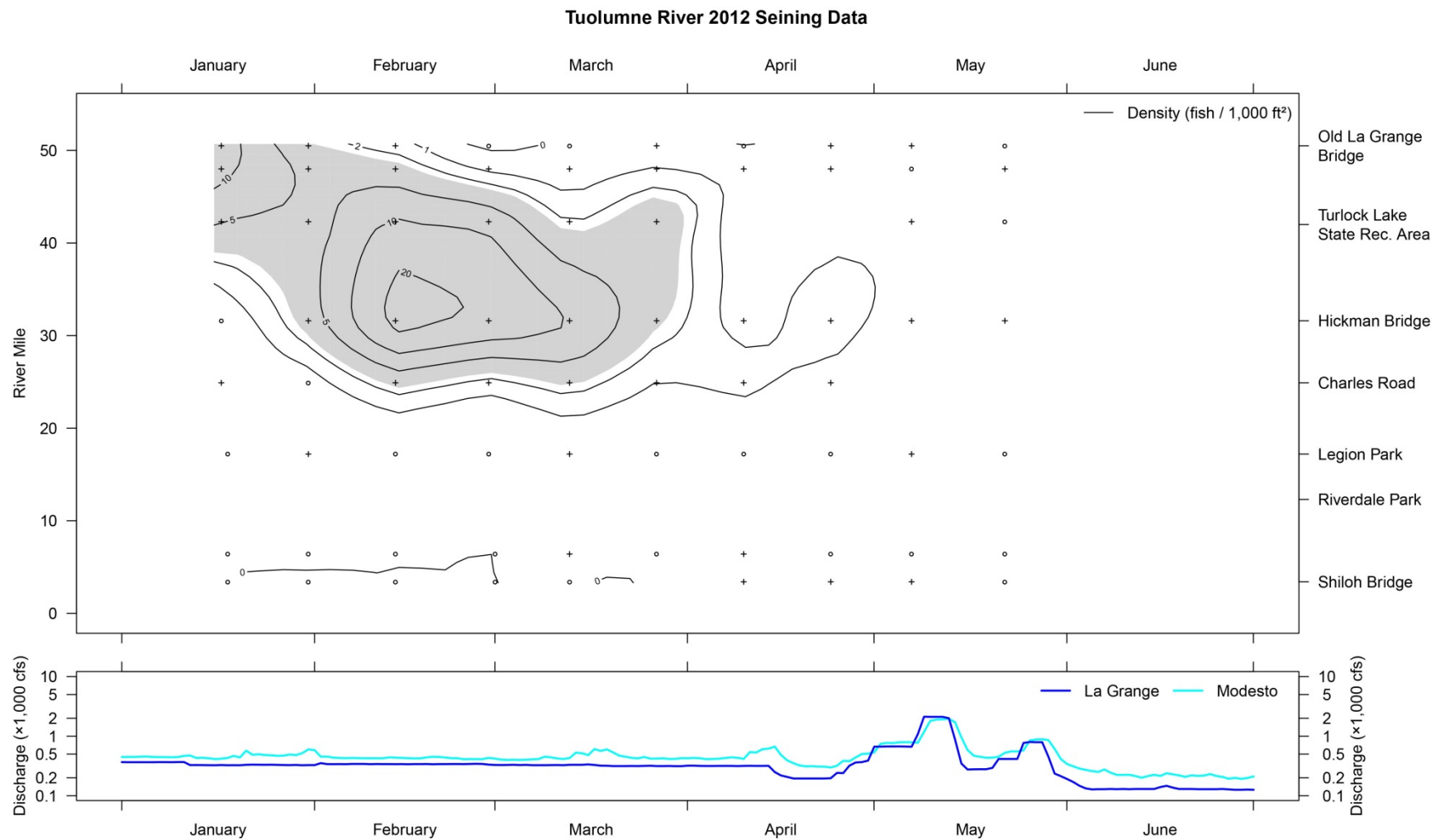


Figure C-14. 2012 Seining Density and Fork Lengths of Chinook Salmon by location and Date with Discharge in the Tuolumne River
(Note: Upper quartiles shaded for juvenile density [grey] and fork length [green])

**STUDY REPORT W&AR-06
CHINOOK SALMON POPULATION MODEL STUDY**

ATTACHMENT D

**ANALYSIS OF TUOLUMNE RIVER ROTARY SCREW TRAP DATA TO
EXAMINE THE RELATIONSHIP BETWEEN RIVER FLOW AND
SURVIVAL RATES FOR SMOLTS MIGRATING BETWEEN
WATERFORD AND GRAYSON (2006-2012)**

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Analysis of Tuolumne River Rotary Screw Trap Data to examine the relationship between river flow and survival rates for Chinook smolts migrating between Waterford and Grayson (2006-12)

Prepared by

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Introduction

The completion of the *Chinook Salmon Population Model Study* for the Tuolumne River requires an estimate of the survival rate for Chinook salmon smolts as they migrate from upstream rearing areas to the mouth of the Tuolumne River. A preliminary examination of the Waterford and Grayson rotary screw trap (RST) catch and river flow data suggested a more detailed data review and analysis should be conducted to examine seasonal passage estimates as well as to provide a RST-based relationship between apparent smolt survival and river flow. The following data were provided to LGL for these analyses:

- 1) The number of Chinook fry, parr and smolts caught each day by the Waterford (2006-2012) and Grayson (1999-2012) RSTs;
- 2) Daily estimates of the river flow at Waterford and Grayson in cubic feet per second (cfs);
- 3) Daily instantaneous river velocity measurements at Waterford and Grayson in feet per second;
- 4) Daily estimates of the % of flow sampled by each trap at Waterford (n=1) and Grayson (n=2);
- 5) All available mark-recapture estimates of trap efficiency and % flow sampled for the Waterford and Grayson RSTs; and
- 6) Daily instantaneous turbidity measurements and daily average water temperatures at the Waterford and Grayson RST locations.

All of these data were provided by FISHBIO (Andrea Fuller, FISHBIO, pers. comm.). The methods used to collect these data are described in annual reports prepared by FISHBIO (e.g., Sonke and Fuller 2013).

Methods

Catchability vs. Flow Relationships

From 1999 to 2012, 159 separate mark-and-recapture trials were conducted, including 81 at Waterford and 78 at Grayson (Appendix Tables 1 and 2). In each trial, Chinook salmon fry, parr, and smolts were

collected from the RSTs or obtained from Merced River Hatchery, and were marked and released upstream of the rotary screw trap. The total numbers of marked fish released were adjusted for dye retention rates to produce an estimate of the effective number of marks released that would be available for recapture in the RSTs. The catch in the trap was examined for several subsequent days, and all marked individuals were counted and at least a sub-sample were measured.

Daily average flow values for the Tuolumne River at La Grange were obtained from a USGS website¹, and were used to represent river flow at the Waterford RST. Daily average flow data for the Tuolumne River at Modesto were obtained from another USGS website², and were used to represent river flow at the Grayson RSTs. The Modesto flow station was below Dry Creek, the largest seasonal tributary entering the river downstream of La Grange Dam. As a result, that site includes flow associated with major winter runoff events.

For each experimental trial, the mean fish length at release and recapture were calculated. For each trial (i) at each trap (t), the percent of flow sampled (Φ_{ti}) was calculated as the ratio of flow through the RST ($F_{RST_{ti}}$) to that of whole-river flow ($F_{RIVER_{ti}}$):

$$(\Phi_{ti}) = F_{RST_{ti}} / F_{RIVER_{ti}} . \quad (\text{Eq. 1})$$

Flow through each RST was calculated by multiplying the water velocity at the RST by the surface area of the trap. Catchability was calculated as the proportion of the total adjusted number of individuals released that were recaptured. The mean length at release was used to separate the trials into those that indicated catchability of fry (mean length at release < 50 mm), parr (50 ≥ length < 65 mm) or smolts (≥ 65 mm). Length thresholds were determined by plotting the polymodal distribution of mean lengths over the 159 trials, and selecting break-points where natural breaks (i.e., ‘troughs’) occurred in the distribution. A decision was made to use 65 mm as the threshold for the ‘parr to smolt’ transition instead of the more typical size threshold of 70 mm because few migrants occurred in the 65-70 mm size class interval, and because use of the 70 mm threshold would have limited the number of smolt experimental trials by 1 at Waterford, and by 8 at Grayson.

For each life stage (s) at each trap (t), if sample-size sufficed, catchability (C_{tsi}) was regressed against percent of flow sampled (Φ_{ti}) during trial i . Both linear and non-linear curve-fitting procedures were used. Linear regression was used to estimate the slope of the line (m_{ts}), with the intercept forced through 0, as

$$C_{tsi} = (m_{ts} \cdot \Phi_{ti}) . \quad (\text{Eq. 2})$$

For non-linear fitting procedures, cumulative Weibull curves,

$$C_{tsi} = 1 - e^{-\left(\frac{\Phi_{ti}}{\lambda_{ts}}\right)^{k_{ts}}} , \quad (\text{Eq. 3})$$

were fit to the data by estimating the parameters λ_{ts} (scale) and k_{ts} (shape) using an iterative least squares algorithm. For each life stage at each trap, ANOVA was used to compare the residual sum of squares between linear and non-linear model fits. Alternative analyses were performed to examine the effects of flow or turbidity on catchability, but these analyses were not further pursued since some non-linear fits failed to converge, and some independent variable distributions were highly skewed.

¹ http://waterdata.usgs.gov/ca/nwis/dv/?site_no=11265000&agency_cd=USGS

² http://waterdata.usgs.gov/ca/nwis/dv/?site_no=11290000&agency_cd=USGS

Passage Estimation

During 2006 and from 2008 to 2012, RSTs were operated at Waterford and Grayson from at least January 29 through May 29, and in many years sampling extended earlier or later. During 2007, sampling at Waterford began in January, but was not initiated at Grayson until March. Daily counts of fry, parr, and smolts were tallied at each trap for all days sampled in each year. The percent of the flow sampled was estimated for each day at each trap as described above. Missing velocity observations were interpolated from adjacent values (except during two long data gaps in 2010: linear regressions were performed on the available 2010 data to estimate missing velocity values from flow). Instantaneous measurements of turbidity were also recorded daily at the traps, and daily average water temperatures were obtained from hourly recording thermographs deployed at or near each trap site.

On any given day, catchability was not expected to be 100%, and fish certainly passed the traps without being counted. Life-stage-specific catchability was to be used to calculate total passage from the numbers counted, but scaling was not possible when zero catches were recorded on a particular day. Since catchability was relatively low throughout the study, zero catches of certain life stages were not uncommon. Moreover, total catch could not be taken at face value, as each life stage was expected to have differing catchability.

To account for varying catchability, a four-stage process was used to estimate total fish passage (N) from catch numbers, as follows. First, proportional catch contributions (ρ_{jw}) were calculated for the three life stages for each week (w) as:

$$\rho_{tsw} = \frac{A_{tsw}}{\sum_s^3 A_{tsw}} \quad (\text{Eq. 4})$$

where

$$A_{tsw} = \frac{\sum_d^7 O_{tswd}}{\left(m_{ts} \cdot \frac{\sum_d^7 \Phi_{twd}}{7} \right)} \quad (\text{Eq. 5})$$

and where O_{tswd} was the observed catch of life stage s at trap t on day d in week w , and Φ_{twd} was the percent flow sampled by trap t on day d in week w . Then, average catchability was calculated for each day at each trap, weighted by the proportional life-stage-specific catch contributions, as:

$$\overline{C}_{twd} = \sum_s^3 [\rho_{tsw} \cdot (m_{ts} \cdot \Phi_{td})] . \quad (\text{Eq. 6})$$

Third, daily total Chinook passage was calculated by dividing total observed catch (of all life stages combined) by the weighted average catchability:

$$N_{twd} = \frac{\sum_s^3 O_{tswd}}{\overline{C}_{twd}} . \quad (\text{Eq. 7})$$

Lastly, the daily total Chinook passage was partitioned into the three life stages, based on the proportional catch rates from Equation 4:

$$N_{tswd} = N_{twd} \cdot \rho_{tsw} . \quad (\text{Eq. 8})$$

If total fish passage on a given day was below the level of measurement error (i.e., the inverse of catchability for that day), this method produced passage estimates of zero fish.

Smolt Survival Estimation

Using daily smolt passage estimates, as calculated above, the proportion of smolts that passed Waterford and subsequently survived to pass Grayson were used to provide RST-based smolt survival estimates. The 2006 data were excluded because of a substantial gap in sampling at Waterford near the peak of the smolt migration period (12-21 April). The 2010 and 2011 data were included to allow construction of survival estimates across a broader flow range. However, since substantial numbers of fry appeared to rear at locations downstream of Waterford, the resulting survival estimates may be biased high by smolts originating in the Waterford to Grayson reach. Based upon the relative timing of apparent peaks in daily smolt counts at the two traps, the Grayson data were lagged by two days to account for the timing of fish passing Waterford that are expected at Grayson. Total smolts at Grayson were then divided by the number that passed Waterford to calculate survival in that stretch of river.

To analyze the apparent smolt survival as a function of flow, daily average flow data from each year were plotted, and changes in flow rate were used to divide each year into periods of relatively uniform flow (Figure 1). During each flow period, the total number of smolts passing each trap site was calculated. Flow periods prior to March were excluded because the sample sizes for these periods were very small and the smolts migrating downstream during these periods were often much larger than those migrating during the primary migration period of April- May. During each flow period, the average turbidity, and average flow at LaGrange were calculated.

Survival was modeled as a function of average flow using several different methods. Linear regressions were performed on the untransformed and on arcsine transformed survival data. The data were also fitted with general linear models (GLMs) that assume a binomial error structure and that use a logit link function (Crawley 2007). The S-shaped curves that are fit by GLM and the arcsine transformed linear model are desirable since survival values are bounded by 0 and 1. Also, since each fish could either survive or not survive, the binomial error structure was the most appropriate for the GLM. We originally proposed to use the methods described in Schnute and Richards (1990) for fitting survival data to a family of six curves. However, further examination of the data showed that there was not sufficient range in the survival and flow estimates to distinguish among the six alternative survival curves.

Multivariate general linear models with binomial error structure and logit link function were used to fit survival as a function of flow (from LaGrange), temperature and turbidity (both from Waterford), and abundance (numbers of smolts estimated past Waterford).

Passage During First Pulse Flow Event

Changes in flow in the Tuolumne River have been hypothesized to provide an environmental cue to initiate downstream movement of salmon smolts. Regulated flows may include 'pulse flow events' where flows increase suddenly and are sustained at an elevated level over several days to stimulate downstream movements. To examine whether there were consistent numbers of fish travelling throughout each pulse flow event or whether the majority passed at the start of the pulse, we calculated fish responses to pulse flows. For this analysis, the first pulse flow event that occurred during the smolt emigration period of each year was examined. Figure 1 shows that there were identifiable pulse flows in 2007 (Flow Period b), 2008 (Period d), 2009 (Period c) and 2012 (Period g). Data from

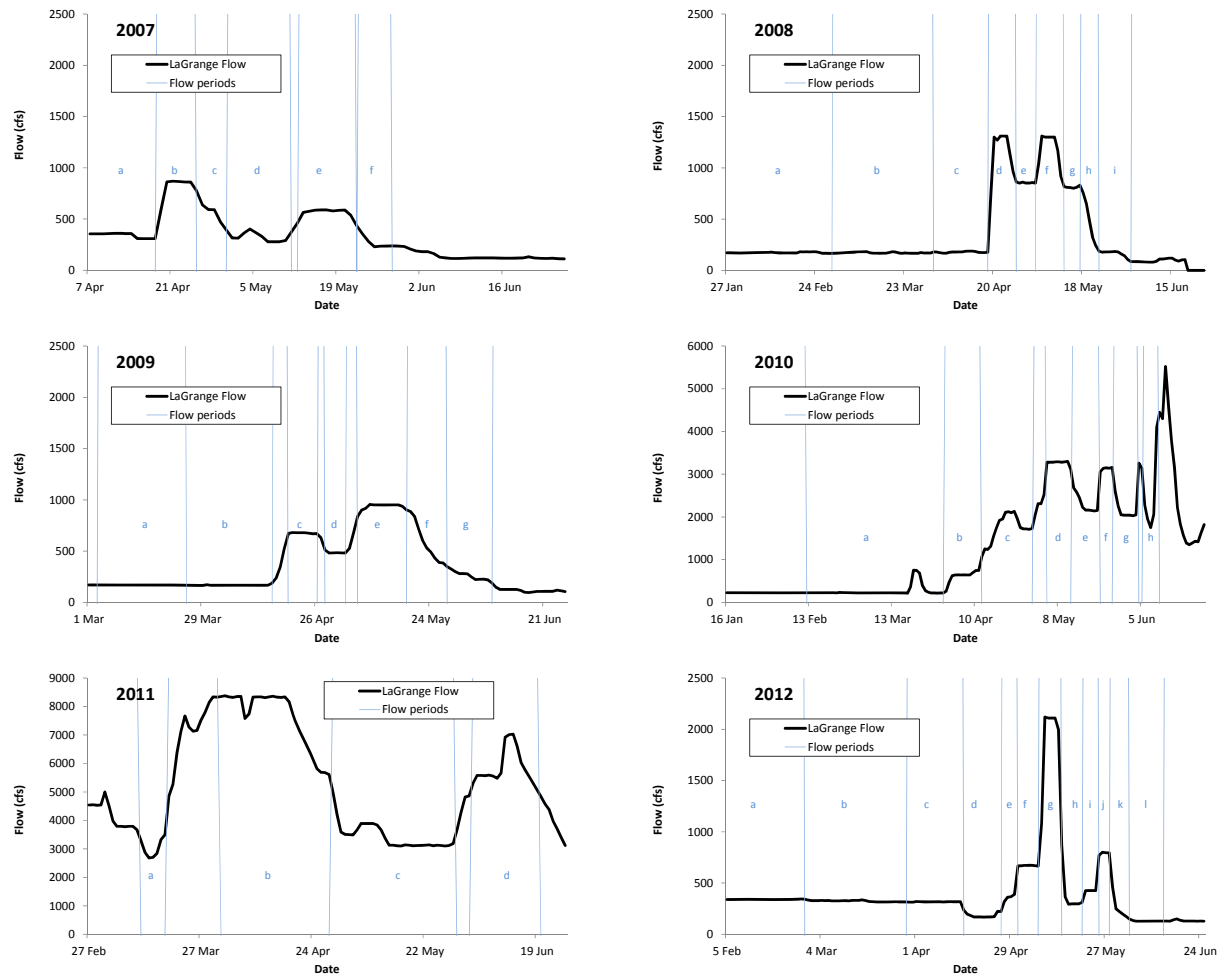


Figure 1. Daily Flow (cfs) measured at LaGrange during the smolting periods in 2007-2012. Each study year has been divided into periods (labelled with letters) based on flow characteristics. Data periods without labels were not included in the analyses. The X and Y axis scales vary among figure panels.

other years were excluded from the analysis. The numbers of fish that passed Waterford on each day from the start of the pulse flow event until the end of the pulse event were tallied. The daily percent of total-event-passage was calculated for each pulse, and presented as daily cumulative proportions.

Statistical Methods

For GLMs, data were considered overdispersed when the residual deviance was much greater than the degrees of freedom. In such cases, GLMs were recalculated, using the 'quasibinomial' error distribution, which fits an additional 'dispersion' parameter, allowing for more accurate model output. R^2 approximations were calculated for GLMs as the squared correlation between the predicted and observed values. All statistical analyses were carried out using R (R Core Team 2013).

Results

Catchability vs. Percent Flow Relationships

The total number of experimental trials for which percent flow and catchability could be calculated was 143 (Appendix Tables 1 and 2). This included 60 fry, 3 parr, and 17 smolt trials at Waterford, and 15 fry, 8 parr, and 40 smolt trials at Grayson. Sample sizes for parr were considered inadequate for robust curve fitting

Curve fits and parameter estimates for each trap, life stage and model are shown in Figure 2 and Table 1, respectively. In no case was there a significant difference between linear and non-linear model fits, thus the simpler (linear) model was selected as the more parsimonious (slopes for parr were set as the mean of those of fry and smolts). Despite the two curves being very similar within the observed range data (Figure 2), the predicted values differed more widely at higher percent flows. Thus, blind extrapolation of these curves beyond the range of the currently available percent flow data is not advisable; and more work will be needed to determine the shape of the curves in high percent flow conditions.

Table 1. Parameter estimates from linear and non-linear models fitting fry and smolt catchability to percent flow at two RST sites (Waterford and Grayson). For each site and life stage, ANOVA (df = 1) was used to compare residual sum of squares between the two model fits. See text for parameter definitions.

Rotary Screw Trap, <i>t</i>	Chinook Life Stage, <i>s</i>	Non-linear Model Parameters		Linear Model Parameter	ANOVA (Non- linear vs. Linear)	
		k_{ts}	λ_{ts}	m_{ts}	F	P
Waterford	Fry	0.68	4.37	0.60	1.65	0.204
	Smolt	0.75	9.72	0.28	0.32	0.578
Grayson	Fry	0.40	78.65	0.53	4.18	0.062
	Smolt	1.31	1.77	0.28	1.26	0.270

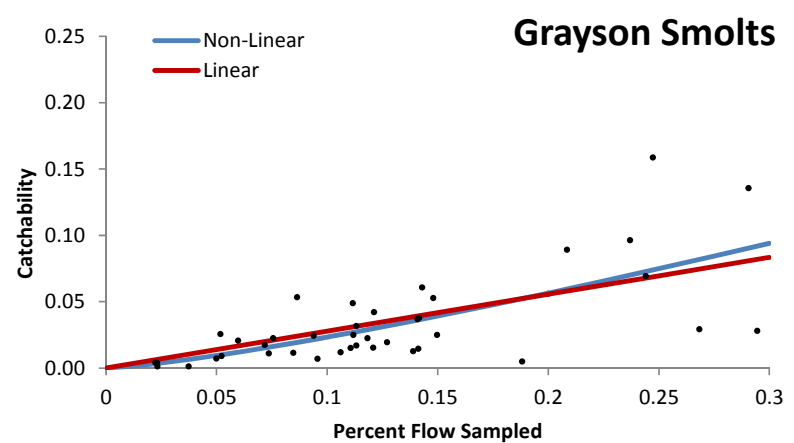
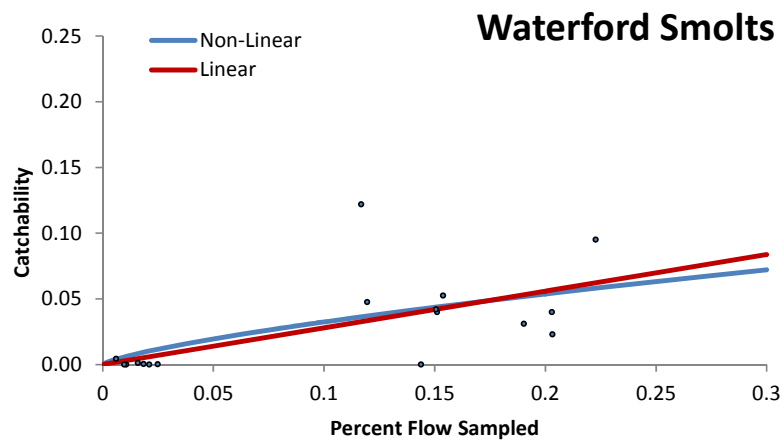
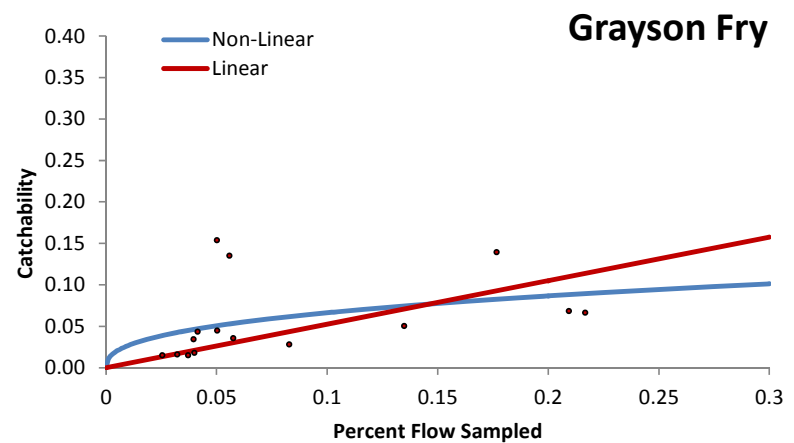
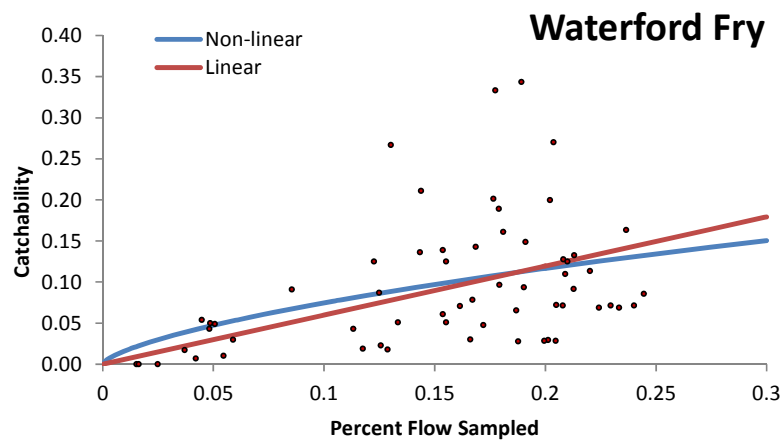


Figure 2. Fry and smolt catchability as a function of the percent flow sampled at two RST sites (Waterford and Grayson). Linear (no intercept) and non-linear (cumulative Weibull) models were fit to each of the datasets. The Y axis scale varies among the figure panels.

Estimated Passage

Daily total numbers of fry, parr and smolts that were estimated to have passed Waterford and Grayson from 2006 to 2012 are shown in Figure 3 to Figure 8. Total annual passage tallies are shown in Table 2. Daily and annual tallies differ from those presented previously (e.g., Sonke and Fuller 2013) primarily due to differences in the methods used to estimate catchability from the available data.

Table 2. Annual passage estimates for fry, parr and smolts at Waterford and Grayson (survey periods varied among traps years and between traps).

	Waterford				Grayson			
Year	Survey Period	Fry	Parr	Smolts	Survey Period	Fry	Parr	Smolts
2007	1/12 - 6/5	11,090	4,911	34,572	3/24 - 5/29	0	0	952
2008	1/8 - 6/2	17,806	1,921	29,800	1/29 - 6/4	1,251	25	1,744
2009	1/7 - 6/9	17,492	7,306	29,719	1/8 - 6/11	57	138	3,877
2010	1/5 - 6/10	10,595	1,049	62,876	1/6 - 6/17	92	0	1,964
2011	12/4/'10 - 6/30	284,444	5,689	74,494	1/6 - 6/30	71,071	2,130	21,955
2012	1/3 - 6/15	29,907	7,568	24,601	1/3 - 6/15	72	10	2,186

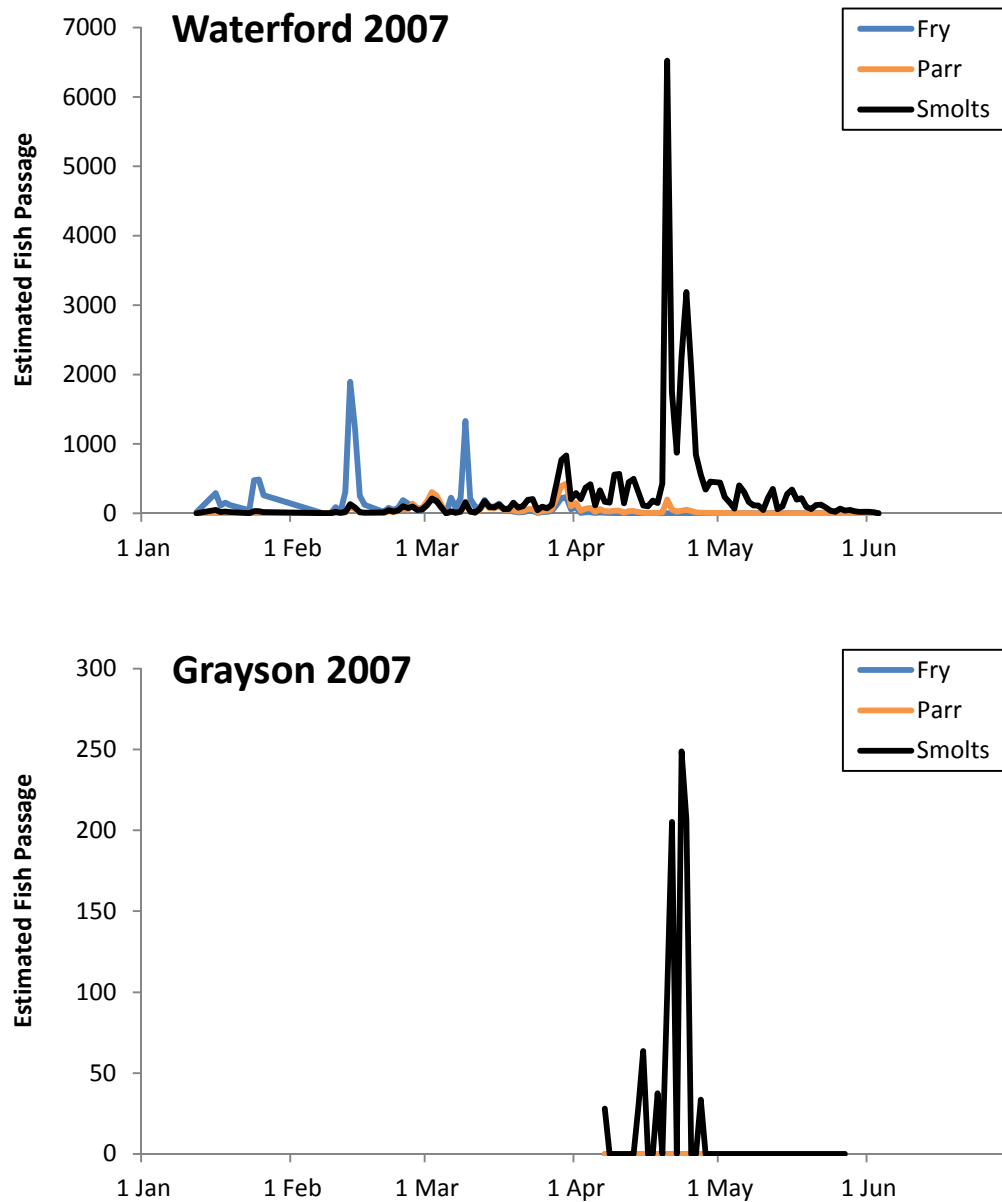


Figure 3. Estimates of daily passage numbers for fry, parr and smolts at Waterford and Grayson in 2007. Grayson data are lagged by two days.

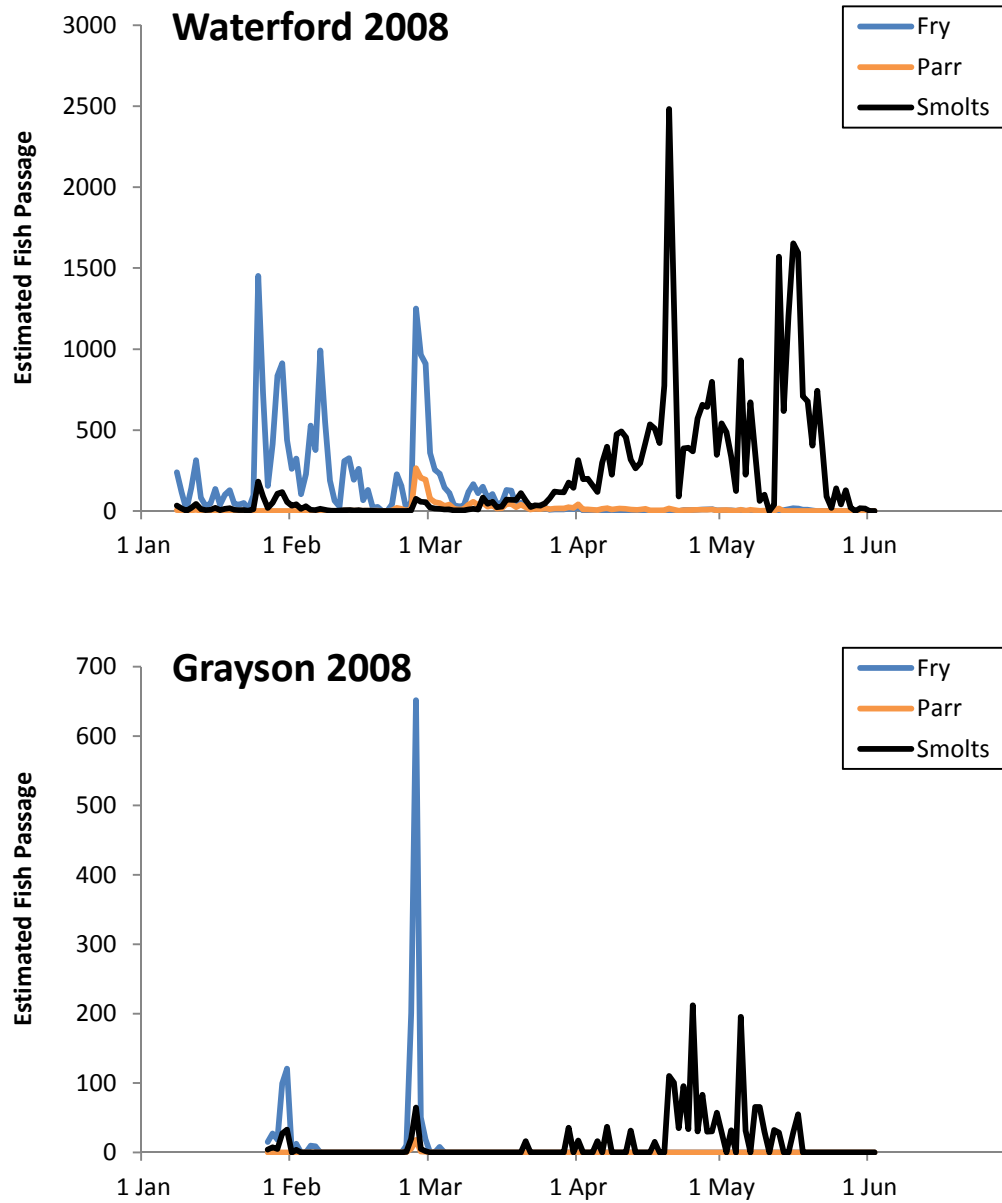


Figure 4. Estimates of daily passage numbers for fry, parr and smolts at Waterford and Grayson in 2008. Grayson data are lagged by two days.

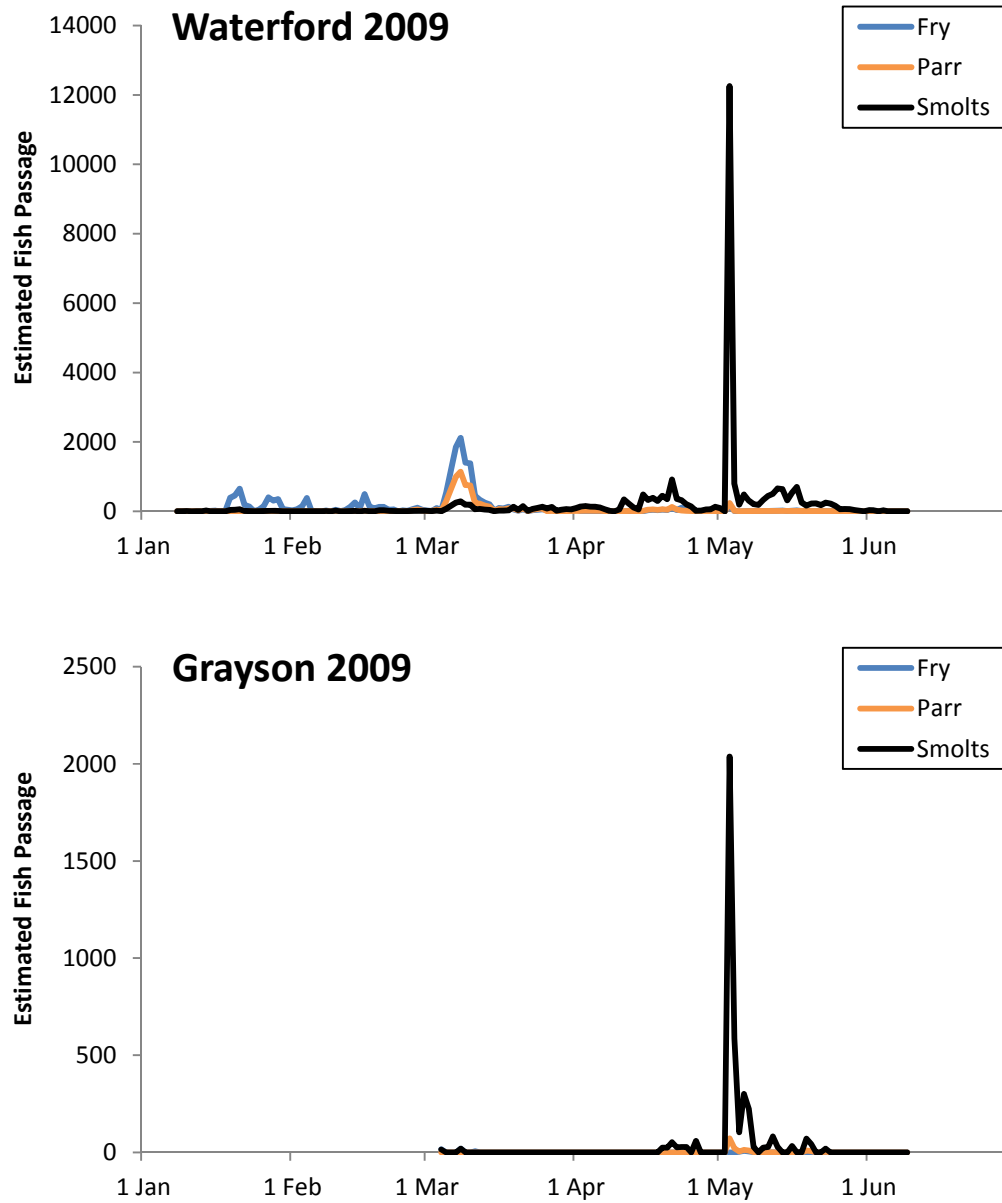


Figure 5. Estimates of daily passage numbers for fry, parr and smolts at Waterford and Grayson in 2009. Grayson data are lagged by two days.

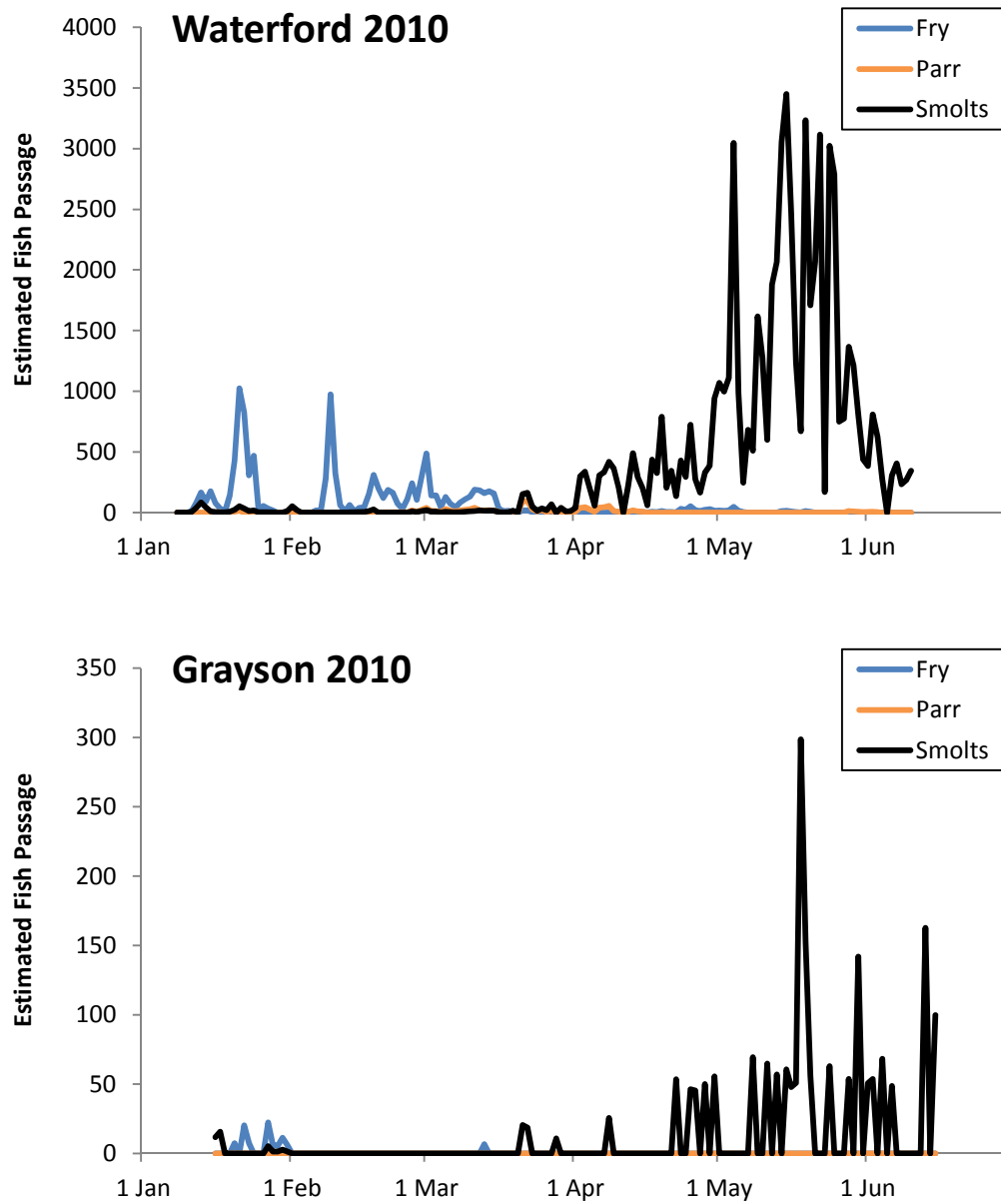


Figure 6. Estimates of daily passage numbers for fry, parr and smolts at Waterford and Grayson in 2010. Grayson data are lagged by two days.

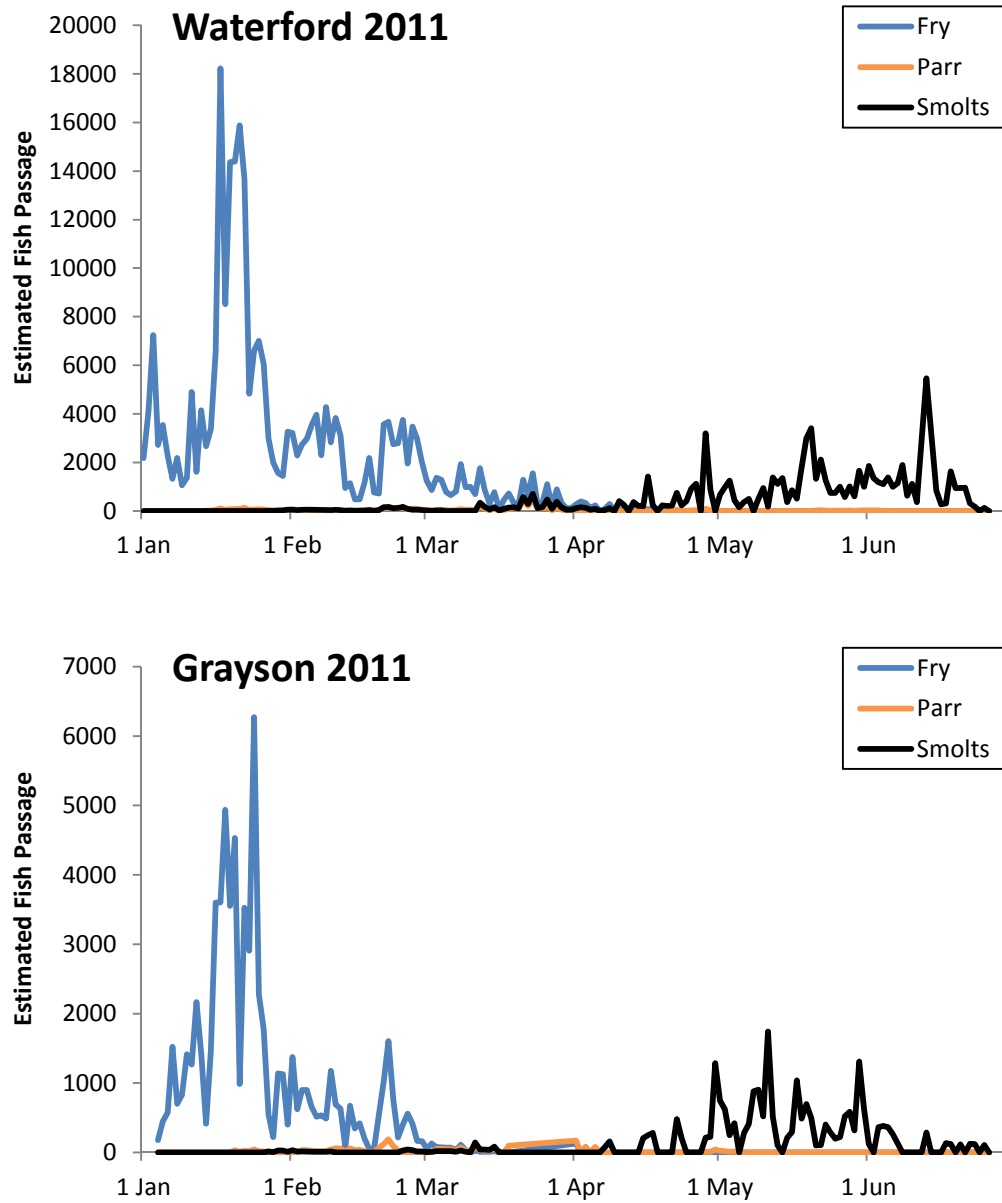


Figure 7. Estimates of daily passage numbers for fry, parr and smolts at Waterford and Grayson in 2011. Grayson data are lagged by two days.

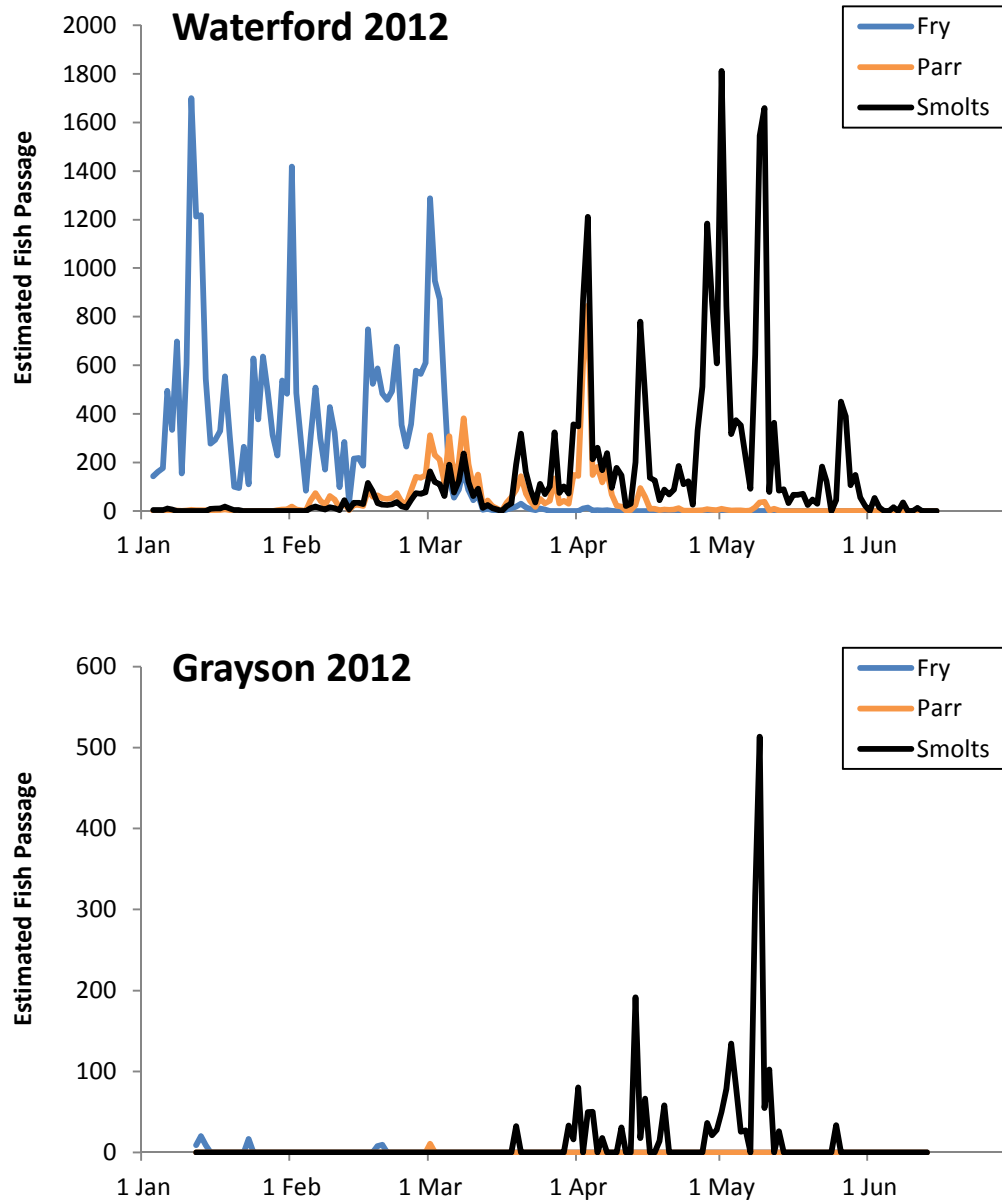


Figure 8. Estimates of daily passage numbers for fry, parr and smolts at Waterford and Grayson in 2012. Grayson data are lagged by two days.

Smolt Survival Estimation

Table 3 shows the total number of smolts that passed each trap, along with estimated survival from Waterford to Grayson, and mean flow, water temperature, and turbidity during each of the flow periods in 2007 to 2012. Survival ranged from 0% during many of the flow periods, to a high of 49.4% at a flow of 3,435 cfs during 29 April to 29 May 2011 (Table 3).

The linear relationship between survival and mean flow had a slope of 2.38×10^{-5} ($P = 0.002$; $R^2 = 0.20$). The slope of the arcsine-transformed model was (in transformed units) 4.90×10^{-5} ($P = 0.001$; approximate $R^2 = 0.16$). For the univariate GLM, the survival data were originally fitted to the mean flow data using a binomial error structure. However, the data were overdispersed, so the GLMs were recalculated using a 'quasibinomial' fit. The univariate GLM showed that flow was a statistically significant factor predicting survival ($P = 0.015$; Figure 9). The predictive equation for the univariate GLM was

$$Survival = \frac{1}{1 + e^{-(-2.551 + (0.000229 \cdot Mean\ Flow))}} \quad (Eq. 10)$$

The approximate R^2 of the univariate model was 0.16. The effect of the exclusion of the single highest survival point (49.4% in 2011) resulted in improved fits (linear $R^2 = 0.21$; arcsine approximate $R^2 = 0.19$; GLM approximate $R^2 = 0.20$) and shallower slopes (i.e., lower predicted survival values; linear slope = 1.66×10^{-5} ; arcsine slope = 4.00×10^{-5} ; GLM coefficients: -2.96 and 0.000148).

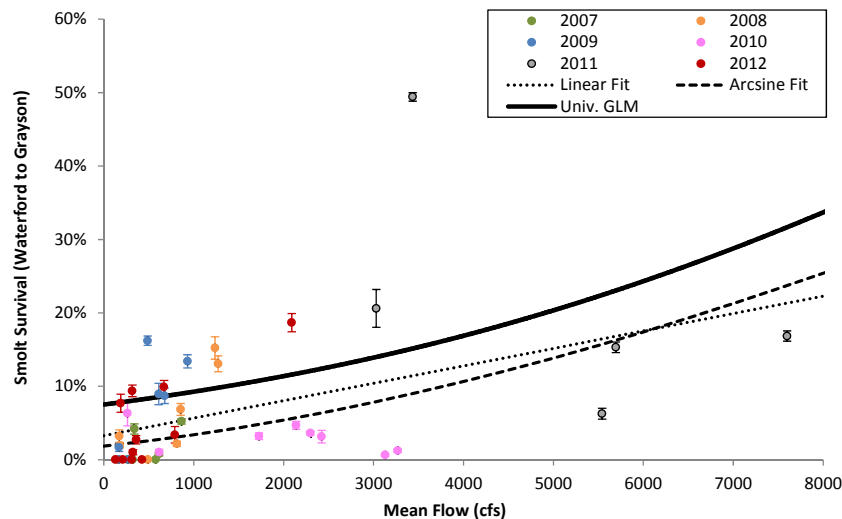


Figure 9. Survival from Waterford to Grayson, as a function of mean flow (discharge measured at LaGrange). Linear regressions on the raw ($R^2 = 0.20$) and arcsine transformed (approximate $R^2 = 0.16$) survival data are shown, along with the results of the univariate quasibinomial general linear model, with approximate $R^2 = 0.16$.

The multivariate quasibinomial GLM showed that abundance was the most important factor ($P < 0.0001$) predicting survival. No other predictors improved the model (turbidity: $P = 0.18$; flow: $P = 0.56$; temperature: $P = 0.84$). The predictive equation for the final GLM was

$$Survival = \frac{1}{1 + e^{-(3.51 + (0.000107 \cdot Smolt\ Abundance))}} \quad (Eq. 11)$$

The approximate R^2 of the multivariate model was 0.49. However, this model fit was highly sensitive to one data-point with very high abundance and very high survival (Figure 10). With that point removed, abundance was no longer a significant factor ($P = 0.10$), discharge ($P < 0.001$) and turbidity ($P < 0.001$) were statistically significant, and temperature was not ($P = 0.68$). Figure 11 shows the 3-D plane of the fitted relationship between flow, turbidity and survival (with the high abundance data-point removed). The approximate R^2 of the fitted plane was 0.30.

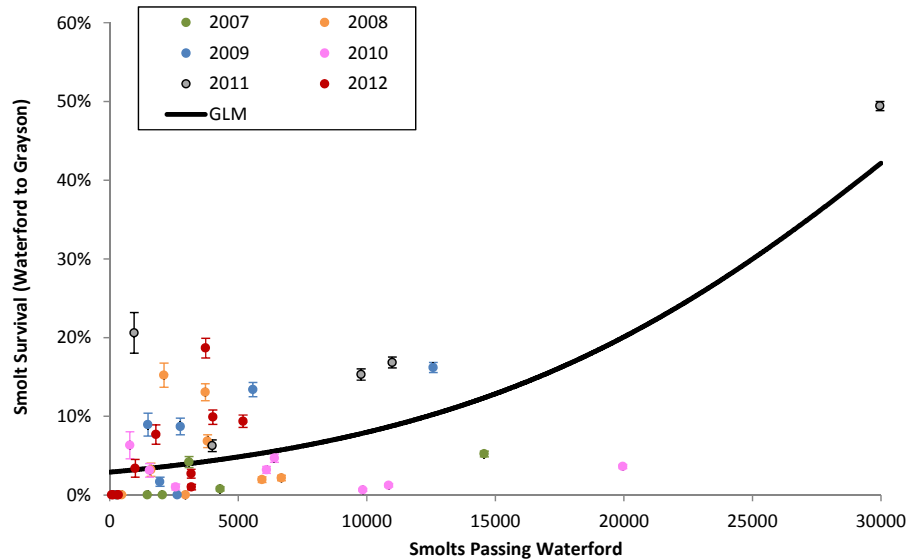


Figure 10. Survival from Waterford to Grayson, as a function of abundance (number of smolts passing Waterford). Line is the fit from a quasibinomial general linear model, with approximate $R^2 = 0.49$.

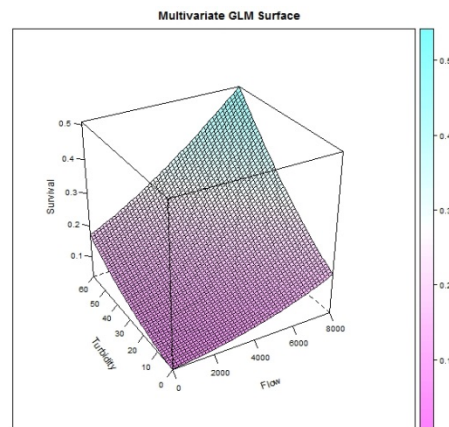


Figure 11. Survival from Waterford to Grayson, as a function of mean flow (discharge measured in cfs at LaGrange) and turbidity (NTU), as fitted by a multivariate quasibinomial general linear model. One data point with high leverage was removed before fitting this model.

Table 3. Total number of smolts estimated to have passed each RST (Waterford and Grayson), survival between the RSTs (with 95% Confidence Intervals), and mean flow, temperature and turbidity during each of the flow periods from 2007 to 2012.

Interval	Interval Dates (at Waterford)		Estimated Smolt Passage		Survival (estimate)	Survival (95 % Confidence Interval)		Mean discharge at La Grange (cfs)	St Dev (discharge)	Mean Temperature		Mean Turbidity	
	Start	End	Waterford	Grayson		Lower	Upper			Waterford (°F)	Grayson (°F)	Waterford (NTU)	Grayson (NTU)
2007a	7 Apr	18 Apr	3085	129	4.2%	3.5%	4.9%	339.8	24.7	58.7	59.3	0.8	2.8
2007b	20 Apr	24 Apr	14570	760	5.2%	4.9%	5.6%	864.0	3.5	54.8	57.0	1.6	3.1
2007c	25 Apr	29 Apr	4294	33	0.8%	0.5%	1.0%	613.4	108.4	58.4	63.4	1.0	1.9
2007d	1 May	10 May	2049	0	0.0%	0.0%	0.0%	321.7	43.8	60.9	64.2	0.7	2.0
2007e	13 May	21 May	1469	0	0.0%	0.0%	0.0%	577.2	16.7	60.0	64.4	1.0	2.2
2007f	23 May	27 May	252	0	0.0%	0.0%	0.0%	266.8	52.5	64.8	69.6	0.7	1.3
2008b	1 Mar	31 Mar	1606	52	3.2%	2.3%	4.1%	172.0	5.4	58.1	61.2	2.7	4.4
2008c	1 Apr	18 Apr	5923	116	2.0%	1.6%	2.3%	178.8	5.5	61.5	65.4	2.6	4.5
2008d	20 Apr	25 Apr	3719	486	13.1%	12.0%	14.1%	1272.0	79.5	53.8	58.2	2.4	4.2
2008e	27 Apr	3 May	3806	260	6.8%	6.0%	7.6%	854.9	4.9	56.1	61.2	1.4	3.7
2008f	4 May	10 May	2110	321	15.2%	13.7%	16.7%	1236.7	110.0	56.1	61.6	1.4	2.6
2008g	12 May	17 May	6680	144	2.2%	1.8%	2.5%	812.8	9.7	58.4	67.6	1.3	2.4
2008h	18 May	22 May	2945	0	0.0%	0.0%	0.0%	489.8	217.4	60.5	66.1	1.3	3.9
2008i	23 May	2 Jun	465	0	0.0%	0.0%	0.0%	160.6	34.5	65.3	69.6	1.5	3.1
2009a	4 Mar	24 Mar	1953	33	1.7%	1.1%	2.3%	169.1	1.5	57.9	60.5	9.9	16.4
2009b	25 Mar	15 Apr	2627	0	0.0%	0.0%	0.0%	168.2	4.7	60.9	63.9	2.6	5.4
2009c	19 Apr	26 Apr	2746	239	8.7%	7.6%	9.8%	676.3	4.3	57.5	63.5	2.4	7.1
2009d	28 Apr	3 May	12583	2038	16.2%	15.6%	16.8%	487.3	11.1	56.6	62.4	55.4	39.0
2009e	6 May	18 May	5569	746	13.4%	12.5%	14.3%	931.2	34.1	58.1	64.8	3.9	6.7
2009f	19 May	26 May	1486	133	8.9%	7.5%	10.4%	610.9	185.3	60.7	67.9	1.9	4.3
2009g	27 May	8 Jun	266	0	0.0%	0.0%	0.0%	271.5	57.2	66.0	71.8	2.7	6.6
2010a	12 Feb	30 Mar	784	50	6.3%	4.6%	8.0%	263.4	127.6	55.5	57.8	3.0	8.5
2010b	31 Mar	11 Apr	2567	26	1.0%	0.6%	1.4%	616.8	132.0	54.5	56.5	1.1	3.7
2010c	12 Apr	29 Apr	6104	195	3.2%	2.8%	3.6%	1726.7	330.8	53.5	56.3	2.0	3.6
2010d	4 May	12 May	10850	134	1.2%	1.0%	1.4%	3267.8	55.9	53.2	55.4	1.2	1.9
2010e	13 May	21 May	19960	723	3.6%	3.4%	3.9%	2298.9	211.3	54.3	56.5	0.6	1.9
2010f	22 May	26 May	9847	63	0.6%	0.5%	0.8%	3130.0	40.0	53.4	55.7	1.2	2.4
2010g	27 May	3 Jun	6406	300	4.7%	4.2%	5.2%	2138.8	204.0	55.3	60.0	0.5	1.4
2010h	6 Jun	10 Jun	1551	49	3.1%	2.3%	4.0%	2422.0	951.4	56.7	58.9	0.6	3.0
2011a	12 Mar	18 Mar	950	196	20.6%	18.0%	23.2%	3030.0	332.3	50.8	51.5	2.6	3.6
2011b	1 Apr	28 Apr	10991	1850	16.8%	16.1%	17.5%	7600.4	1011.5	51.3	52.3	2.5	3.0
2011c	29 Apr	29 May	29962	14807	49.4%	48.9%	50.0%	3435.5	437.5	52.9	55.2	1.3	2.3
2011d	3 Jun	11 Jun	9778	1497	15.3%	14.6%	16.0%	5695.6	470.0	53.3	55.7	1.5	1.9
2011e	15 Jun	19 Jun	3990	250	6.3%	5.5%	7.0%	5542.0	379.6	54.6	57.2	0.6	2.1
2012b	28 Feb	29 Mar	3181	32	1.0%	0.7%	1.4%	324.6	7.4	55.1	57.6	1.6	3.6
2012c	30 Mar	14 Apr	5186	486	9.4%	8.6%	10.2%	316.8	1.6	57.7	60.8	2.1	5.7
2012d	15 Apr	26 Apr	1798	138	7.7%	6.5%	8.9%	187.2	25.5	66.1	70.6	2.0	4.1
2012e	27 Apr	30 Apr	3168	86	2.7%	2.1%	3.3%	359.5	28.8	62.6	69.6	2.2	4.5
2012f	1 May	7 May	4012	397	9.9%	9.0%	10.8%	669.6	3.0	59.6	65.2	2.7	4.5
2012g	9 May	13 May	3730	696	18.7%	17.4%	19.9%	2090.0	50.5	56.7	60.5	2.2	2.7
2012h	15 May	20 May	307	0	0.0%	0.0%	0.0%	309.8	27.3	64.7	70.6	1.6	4.3
2012i	21 May	24 May	335	0	0.0%	0.00%	0.00%	426.5	0.6	65.0	68.7	1.8	3.2
2012j	25 May	28 May	991	34	3.4%	2.26%	4.51%	790.3	12.4	59.2	65.3	1.5	3.0
2012k	30 May	2 Jun	130	0	0.0%	0.00%	0.00%	210.8	32.4	69.1	74.0	1.4	4.1
2012l	3 Jun	13 Jun	76	0	0.0%	0.00%	0.00%	130.8	6.3	71.9	73.2	1.5	3.3

Passage During First Pulse Flow Event

Four years of data were initially selected for this analysis, however, the first pulse flow peak in 2008 had a data gap on the second day of the pulse (the Waterford RST had shifted out of the thalweg and only fished 424 revs; Andrea Fuller, FISHBIO, pers. comm.), and was excluded. Figure 12 shows the cumulative proportion of fish passing on each day of the first pulse flow event in 2007, 2009 and 2012. On average, 35% of the fish passed on the first day of the event (45% in 2007 and 2012, 16% in 2009). By day three, an average of 66% of the fish had passed (63% in 2007, 62% in 2009, and 74% in 2012). Sample sizes were very limiting for this analysis (i.e., $n=3$), and results should be interpreted with caution.

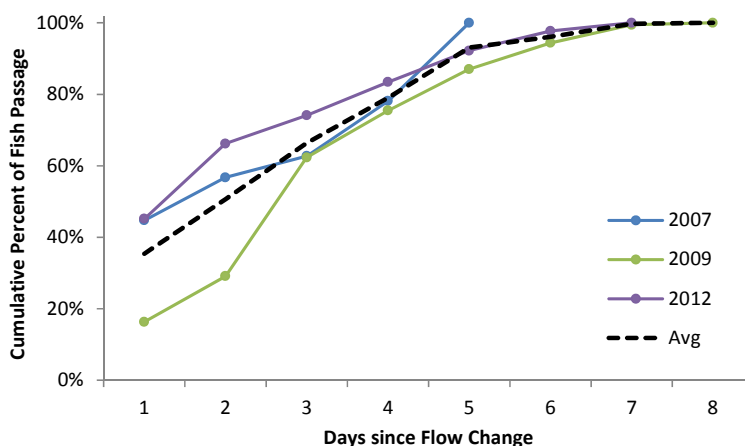


Figure 12. Cumulative proportion of smolts that passed on each day of the first pulse flow event in 2007, 2009 and 2012, relative to the total number of smolts that passed during the pulse flow event.

Conclusions

- A. There were no significant differences between the linear and non-linear relationships between catchability and % flow, so we used the linear relationship to convert daily estimates of the % flow sampled into daily estimates of RST catchability for each RST site.
- B. The relationships between smolt catchability and % flow were very consistent for the Waterford and Grayson RSTs. Catchability of smolts was less than that of fry at all % flow levels, and the effect was more pronounced when greater portions of the total flow were sampled (i.e., the slopes for the smolt relationships (0.28) were lower than those for fry (0.60 at Waterford; 0.53 at Grayson)).
- C. There was a positive and significant relationship between survival from Waterford to Grayson and river flow, although the exact relationships were sensitive to outlier values. Abundance of smolts and turbidity also appear to impact survival. Other possible factors, for which we lack adequate data to test, include predator abundance and predation rate.
- D. On average, 35% of the fish moved during the first day of increased flows, and 66% moved within the first three days.

Recommendations

1. Further experimentation with flows between 1300 cfs and 8000 cfs (especially between 3500 and 8000 cfs) should be conducted to better define the shape of the 'survival vs flow' relationship above 1300 cfs.
2. To derive more meaningful estimates of the survival rates for pulse flows, additional data are required. To obtain additional survival data, experimental pulse flows should be maintained for 4 days. The available data suggested that, for the first pulse flow event, the daily increment in smolt migration is relatively low after the first 3 to 4 days of elevated flow.
3. For any future smolt-survival experiments conducted during pulse flows, marked smolts should be used to estimate daily capture efficiencies for each RST site during each pulse flow period.
4. Once additional survival estimates have been obtained for periods with flows above 1300 cfs, the curve fitting approach described in Schnute and Richards (1990) may be applied to select between alternative curve forms that best describe the resulting survival versus flow relationship.

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Appendix Table 1. Release and recapture data recorded for each of the 81 catch efficiency experiments conducted at Waterford between 2006 and 2012, along with flow and turbidity data. Experiments with missing %flow data were excluded from analyses.

Release Date	Origin	Size Class	Adjusted Number Released	Number Recaptured	% Recaptured	Length at Release (mm)	Length at Recapture (mm)	Flow (cfs)	% Flow Sampled	Turbidity (NTU)
31 Jan 2006	Wild	Fry	240	13	0.054	35	35	3171	0.045	3.38
8 Feb 2006	Wild	Fry	225	11	0.049	35	35	2940	0.051	2.56
10 Feb 2006	Wild	Fry	120	6	0.050	35	35	3027	0.049	2.29
17 Feb 2006	Wild	Fry	163	7	0.043	34	34	2892	0.048	2.18
6 May 2006	Hatchery	Smolts	778	0	0.000	73	.	8870	0.011	1.35
13 May 2006	Hatchery	Smolts	1581	0	0.000	78	.	8480	0.010	1.31
17 May 2006	Hatchery	Smolts	2442	11	0.005	83	83	8360	0.006	1.67
26 May 2006	Hatchery	Smolts	2326	3	0.001	86	74	6780	0.016	1.41
3 Jun 2006	Hatchery	Smolts	2948	1	0.000	79	80	3243	0.025	1.30
9 Jun 2006	Hatchery	Smolts	2731	0	0.000	85	.	4623	0.021	1.34
15 Jun 2006	Hatchery	Smolts	2163	1	0.000	98	75	4793	0.018	0.59
13 Feb 2007	Wild	Fry	35	1	0.029	35	37	356	0.205	5.13
14 Feb 2007	Wild	Fry	238	23	0.097	35	33	356	0.179	1.48
3 Mar 2007	Wild	Fry	98	7	0.071	46	49	358	0.229	1.41
5 Mar 2007	Wild	Parr	75	3	0.040	56	60	359	0.231	0.62
10 Mar 2007	Wild	Fry	180	13	0.072	38	37	358	0.205	0.35
15 Mar 2007	Wild	Fry	61	4	0.066	36	36	367	0.187	0.75
29 Mar 2007	Wild	Parr	48	3	0.063	57	60	355	0.181	2.88
31 Mar 2007	Wild	Parr	75	3	0.040	58	47	356	0.203	0.52
5 Apr 2007	Wild	Smolts	50	2	0.040	76	75	354	0.203	1.48
11 Apr 2007	Wild	Smolts	63	6	0.095	81	80	361	0.223	0.70
24 Apr 2007	Wild	Smolts	63	3	0.048	82	80	860	0.119	1.42
26 Apr 2007	Wild	Smolts	171	9	0.053	80	79	637	0.154	2.26
13 Jan 2008	Wild	Fry	32	11	0.344	37	37	170	0.189	3.86
26 Jan 2008	Wild	Fry	132	15	0.114	36	36	170	0.220	75.20
27 Jan 2008	Wild	Fry	98	13	0.133	37	37	171	0.213	18.60
31 Jan 2008	Wild	Fry	131	12	0.092	37	38	170	0.213	15.70
1 Feb 2008	Wild	Fry	55	9	0.164	37	37	170	0.236	9.33
6 Feb 2008	Wild	Fry	64	6	0.094	37	37	173	0.190	14.00
13 Feb 2008	Wild	Fry	33	11	0.333	37	37	170	0.177	.
28 Feb 2008	Wild	Fry	140	20	0.143	38	38	167	0.168	13.00
16 May 2008	Wild	Smolts	41	5	0.122	88	88	811	0.117	0.67
20 Jan 2009	Wild	Fry	42	2	0.048	43	35	168	0.172	0.69
22 Jan 2009	Wild	Fry	70	5	0.071	36	36	168	0.208	1.28
28 Jan 2009	Wild	Fry	47	7	0.149	35	35	167	0.191	1.89
30 Jan 2009	Wild	Fry	37	7	0.189	37	36	167	0.179	1.18
6 Feb 2009	Wild	Fry	47	6	0.128	37	37	169	0.208	1.08
16 Feb 2009	Wild	Fry	36	1	0.028	36	36	170	0.188	7.67
21 Feb 2009	Wild	Fry	31	5	0.161	37	37	168	0.181	2.05
6 Mar 2009	Wild	Fry	74	20	0.270	44	44	169	0.204	48.70
9 Mar 2009	Wild	Fry	263	53	0.202	40	45	168	0.176	6.07
13 Mar 2009	Wild	Fry	51	4	0.078	49	49	170	0.167	2.47
20 Mar 2009	Wild	Fry	35	1	0.029	50	34	170	0.199	2.82
21 Jan 2010	Wild	Fry	110	22	0.200	35	35	225	0.202	33.30
22 Jan 2010	Wild	Fry	82	9	0.110	35	35	226	0.209	21.20
9 Feb 2010	Wild	Fry	34	1	0.029	37	40	226	0.201	7.99
10 Feb 2010	Wild	Fry	116	8	0.069	37	37	224	0.233	1.16
19 Feb 2010	Wild	Fry	42	3	0.071	35	32	225	0.240	1.66
20 Feb 2010	Wild	Fry	33	1	0.030	36	35	224	0.166	1.14
23 Feb 2010	Wild	Fry	29	2	0.069	36	37	232	0.224	0.20
1 Mar 2010	Wild	Fry	36	5	0.139	35	36	224	0.154	15.50
2 Mar 2010	Wild	Fry	44	8	0.182	36	36	223	.	5.50
11 Mar 2010	Wild	Fry	32	4	0.125	36	35	225	0.210	1.68
14 Mar 2010	Wild	Fry	35	3	0.086	36	36	222	0.244	1.99

...continued

Appendix Table 1 continued.

Release Date	Origin	Size Class	Adjusted Number Released	Number Recaptured	% Recaptured	Length at Release (mm)	Length at Recapture (mm)	Flow (cfs)	% Flow Sampled	Turbidity (NTU)
12 Jan 2011	Wild	Fry	22	0	0.000	35	.	2940	0.025	2.23
15 Jan 2011	Wild	Fry	142	1	0.007	35	35	2150	0.042	2.57
20 Jan 2011	Wild	Fry	116	0	0.000	35	.	4970	0.015	2.45
21 Jan 2011	Wild	Fry	120	0	0.000	35	.	5130	0.016	2.24
1 Feb 2011	Wild	Fry	96	1	0.010	35	35	1610	0.055	1.71
2 Feb 2011	Wild	Fry	100	3	0.030	38	38	1580	0.059	1.84
9 Feb 2011	Wild	Fry	116	2	0.017	36	36	2450	0.037	1.66
7 Jan 2012	Wild	Fry	38	8	0.211	33.8	33.0	367	0.144	1.16
11 Jan 2012	Wild	Fry	44	6	0.136	36	36.3	368	0.143	0.91
14 Jan 2012	Wild	Fry	66	4	0.061	34.7	35.3	327	0.154	1.09
25 Jan 2012	Wild	Fry	55	1	0.018	34.5	37.0	332	0.129	1.99
27 Jan 2012	Wild	Fry	30	8	0.267	34.5	34.8	328	0.130	2.00
31 Jan 2012	Wild	Fry	42	3	0.071	33.5	34.7	327	0.161	0.25
2 Feb 2012	Wild	Fry	66	6	0.091	36.2	35.2	353	0.085	0.95
7 Feb 2012	Wild	Fry	46	4	0.087	42.3	36.8	342	0.125	1.08
10 Feb 2012	Wild	Fry	39	2	0.051	41.5	29.5	339	0.133	1.03
18 Feb 2012	Wild	Fry	80	10	0.125	42.1	36.2	340	0.155	1.72
21 Feb 2012	Wild	Fry	39	2	0.051	35.4	33.0	340	0.155	0.82
22 Feb 2012	Wild	Fry	43	1	0.023	40.3	31.0	340	0.126	1.28
28 Feb 2012	Wild	Fry	53	1	0.019	44.4	35.0	342	0.118	1.11
29 Feb 2012	Wild	Fry	47	2	0.043	40.3	34.5	333	0.113	1.07
5 Mar 2012	Wild	Fry	32	4	0.125	34.1	34.8	328	0.123	0.25
3 Apr 2012	Wild	Smolts	96	4	0.042	71.3	69.3	317	0.151	0.75
4 Apr 2012	Wild	Smolts	50	2	0.040	67.4	62.0	316	0.151	0.45
15 Apr 2012	Wild	Smolts	43	1	0.023	82.6	75.0	235	0.203	3.77
16 Apr 2012	Wild	Smolts	32	1	0.031	78.4	71.0	198	0.190	0.77
29 Apr 2012	Wild	Smolts	43	0	0.000	82.6	.	367	0.144	1.86

Appendix Table 2. Release and recapture data recorded for each of the 78 catch efficiency experiments conducted at Grayson between 1999 and 2012, along with flow and turbidity data. Experiments with missing %flow data were excluded from analyses.

Release Date	Origin	Size Class	Adjusted Number Released	Number Recaptured	% Recaptured	Length at Release (mm)	Length at Recapture (mm)	Flow (cfs)	% Flow Sampled	Turbidity (NTU)
11 Mar 1999	Hatchery	Medium	1946.465	28	0.014	54	53	4620	0.040	9.10
24 Mar 1999	Hatchery	Medium	1938.48	67	0.035	61	61	3130	0.051	5.20
31 Mar 1999	Hatchery	Medium	1884.623	73	0.039	65	64	2250	0.059	5.90
7 Apr 1999	Hatchery	Large	1948.849	50	0.026	68	68	2280	0.052	5.00
14 Apr 1999	Hatchery	Large	1953.066	34	0.017	73	72	2000	0.072	3.90
20 Apr 1999	Hatchery	Large	2007	45	0.022	73	75	1800	0.076	4.40
29 Apr 1999	Hatchery	Large	1959.335	14	0.007	79	80	3220	0.050	8.80
4 May 1999	Hatchery	Large	2007.52	18	0.009	83	82	3030	0.052	6.50
18 May 1999	Hatchery	Large	2001	29	0.014	86	84	677	0.141	6.70
26 May 1999	Hatchery	Large	1984	75	0.038	96	92	518	0.142	9.60
1 Mar 2000	Hatchery	Medium	1964	30	0.015	56	53	4690	0.032	16.11
16 Mar 2000	Hatchery	Medium	1548	22	0.014	56	56	5980	0.027	7.48
23 Mar 2000	Hatchery	Medium	1913	55	0.029	59	60	3190	.	7.13
30 Mar 2000	Hatchery	Medium	1942	60	0.031	62	63	2820	0.051	6.30
29 Apr 2000	Hatchery	Large	1931	22	0.011	81	82	1470	0.085	9.16
6 May 2000	Hatchery	Large	1987	41	0.021	85	85	2430	0.060	14.23
24 May 2000	Hatchery	Large	2010	24	0.012	85	85	1010	0.106	9.09
18 Jan 2001	Hatchery	Small	1810	120	0.066	37	.	487	0.217	4.30
8 Feb 2001	Hatchery	Small	1980	276	0.139	47	.	434	0.177	3.20
1 Mar 2001	Hatchery	Small	2017	57	0.028	41	.	2130	0.083	4.20
14 Mar 2001	Hatchery	Small	1487	75	0.050	46	.	703	0.135	7.90
21 Mar 2001	Hatchery	Medium	3025	207	0.068	61	.	519	0.162	7.50
28 Mar 2001	Hatchery	Medium	1954	219	0.112	51	.	515	0.182	6.80
11 Apr 2001	Hatchery	Large	2021	141	0.070	66	.	535	.	5.20
18 Apr 2001	Hatchery	Large	2060	95	0.046	68	.	483	.	7.90
25 Apr 2001	Hatchery	Large	1515	34	0.022	71	.	753	0.118	7.20
2 May 2001	Hatchery	Large	3053	163	0.053	72	.	1460	0.086	7.00
9 May 2001	Hatchery	Large	3002	147	0.049	75	.	1160	0.112	6.20
16 May 2001	Hatchery	Large	2942	93	0.032	76	.	1020	0.113	9.20
20 Feb 2002	Hatchery	Medium	2094	444	0.212	57	.	265	.	5.90
6 Mar 2002	Hatchery	Large	2331	316	0.136	68	.	278	0.291	5.30
13 Mar 2002	Hatchery	Large	2042	324	0.159	65	.	300	0.247	10.10
20 Mar 2002	Hatchery	Large	2105	242	0.115	68	.	328	.	8.40
27 Mar 2002	Hatchery	Large	2121	147	0.069	68	.	314	0.244	10.00
3 Apr 2002	Hatchery	Large	1962	130	0.066	76	.	312	.	8.90
9 Apr 2002	Hatchery	Large	1995	56	0.028	79	.	319	0.295	13.30
17 Apr 2002	Hatchery	Large	2048	40	0.020	84	.	889	0.127	12.90
25 Apr 2002	Hatchery	Large	2001	22	0.011	86	.	1210	0.074	12.60
1 May 2002	Hatchery	Large	2033	14	0.007	89	.	1250	0.096	9.20
8 May 2002	Hatchery	Large	2021	31	0.015	95	.	798	0.12084	9.80
15 May 2002	Hatchery	Large	2047	26	0.013	97	.	653	0.139	8.00
22 May 2002	Hatchery	Large	2043	10	0.005	94	.	403	0.188	11.30

...continued

Appendix Table 2 continued.

Release Date	Origin	Size Class	Adjusted Number Released	Number Recaptured	% Recaptured	Length at Release (mm)	Length at Recapture (mm)	Flow (cfs)	% Flow Sampled	Turbidity (NTU)
10 Apr 2003	Hatchery	Large	1956	138	0.071	77	.	297	.	.
17 Apr 2003	Hatchery	Large	2047	65	0.032	77	.	1350	.	.
24 Apr 2003	Hatchery	Large	1979	31	0.016	88	.	1210	.	.
1 May 2003	Hatchery	Large	2044	113	0.055	96	.	685	.	.
8 May 2003	Hatchery	Large	2078	206	0.099	83	.	726	.	.
15 May 2003	Hatchery	Large	1996	125	0.063	83	.	559	.	.
20 May 2003	Hatchery	Large	1989	60	0.030	89	.	317	.	.
28 May 2003	Hatchery	Large	1950	125	0.064	94	.	685	.	.
13 Apr 2004	Hatchery	Large	1991.88	84	0.042	79	74	1140	0.121	4.80
20 Apr 2004	Hatchery	Large	1979.802	48	0.024	81	79	1660	0.094	2.97
27 Apr 2004	Hatchery	Large	1941.006	118	0.061	86	85	826	0.143	4.67
4 May 2004	Hatchery	Large	2007.91	50	0.025	90	87	789	0.150	4.75
11 May 2004	Hatchery	Large	1971.52	104	0.053	86	79	815	0.148	4.05
18 May 2004	Hatchery	Large	1996	178	0.089	88	77	446	0.208	4.29
25 May 2004	Hatchery	Large	2013	59	0.029	92	90	337	0.268	3.94
9 Feb 2006	Wild	Small	37	5	0.135	35	35	3290	0.056	4.30
11 Feb 2006	Wild	Small	26	4	0.154	35	37	3340	0.050	3.15
12 Feb 2006	Wild	Small	23	1	0.043	36.09	37.0	3310	0.041	2.65
13 Feb 2006	Wild	Small	28	1	0.036	35.5	33.0	3310	0.058	3.37
3 Mar 2006	Wild	Small	89	4	0.045	34.78	35.3	4300	0.050	4.97
5 May 2006	Hatchery	Large	949	4	0.004	73.18	74.3	8770	0.022	3.05
12 May 2006	Hatchery	Large	1286	5	0.004	81.76	76.6	8280	0.023	2.07
25 May 2006	Hatchery	Large	1532	2	0.001	83.7	69.5	7070	0.023	1.82
1 Jun 2006	Hatchery	Large	1694	0	0.000	91.87	.	4960	.	2.79
14 Jun 2006	Hatchery	Large	1507	2	0.001	85.42	83.0	5050	0.037	1.78
1 Mar 2008	Wild	Small	73	5	0.068	37.78	37.6	342	0.209	25.90
15 Apr 2008	Hatchery	Large	1131	109	0.096	77.12	75.7	300	0.237	4.24
25 Apr 2008	Hatchery	Large	1005	17	0.017	86.3	84.5	1290	0.113	2.66
7 May 2008	Hatchery	Large	526	8	0.015	95.62	95.5	1310	0.111	2.85
14 May 2008	Hatchery	Large	519	13	0.025	92.66	90.8	973	0.112	3.98
21 May 2008	Hatchery	Large	515	19	0.037	91.64	90.9	703	0.141	2.75
14 Jan 2011	Wild	Small	87	3	0.034	36	35.0	3300	0.040	2.50
20 Jan 2011	Wild	Small	51	1	0.015	36	32.0	5130	0.025	2.24
21 Jan 2011	Wild	Small	63	1	0.016	36	30.0	5230	0.032	4.28
25 Jan 2011	Wild	Small	62	1	0.015	36	36.0	4330	0.037	2.13
26 Jan 2011	Wild	Small	45	1	0.018	36	29.0	3970	0.040	2.15

STUDY REPORT W&AR-06
CHINOOK SALMON POPULATION MODEL STUDY

ATTACHMENT E

**CHINOOK SALMON STOCK PRODUCTION MODEL DATA
STRUCTURE**

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Table E-1. Output data frame fields produced by the stock-production models.

Attribute	Description	Date Type
Spawner Lifestage		
rm	location (as river-mile) at which fish enters the inventory	numeric
date	date at which fish enters the inventory	POSIXct
sex	female or male	factor, levels=c("F", "M")
age	age in years (by usual convention)	integer
Redd Lifestage		
feature	location of redd (as a gravel feature)	text
rm	location of redd (as river-mile)	numeric
construct.date	date redd is complete	POSIXct
abandon.date	date spawner stops defending redd	POSIXct
area.defend	area of gravels from which spawner excludes other females	numeric
area.disturb	area of gravels reworked during redd construction	numeric
eggs	number of eggs initially deposited in redd	numeric
gravel.qual	expected survival-to-emergence of eggs deposited in this redd	numeric, between 0 and 1
superimposal	fraction of existing undefended redd area in the feature destroyed by the construction of this one	numeric, between 0 and 1
Carcass Lifestage		
feature	location of death (as a gravel feature)	text
rm	location of death (as river-mile)	numeric
date	date of death	POSIXct
sex	female or male	factor, levels=c("F", "M")
age	age in years (by usual convention)	integer
eggs	number of unspawned eggs	numeric
Swim-up Lifestage		
count	number of swimup-fry represented by this record	numeric
feature	location of emergence (as a gravel feature)	text
rm	location of redd (as river-mile)	numeric
date	date of emergence	POSIXct
Parr Lifestage		
count	number of parr represented by this record	numeric
date	date of promotion to parr	POSIXct
rm	location of promotion (rm)	numeric
length	fork length at promotion (mm)	numeric
Dead Fry Lifestage		
count	number of fry represented by this record	numeric
date	date of death or exit from river	POSIXct
rm	location of death or exit (rm)	numeric
length	fork length at death or exit (mm)	numeric
Passage Fry Lifestage		
count	number of fry represented by this record	numeric
date	date of passage of landmark	POSIXct
m	location of landmark (rm)	numeric
length	fork length at passage (mm)	numeric
Smolt Ready Lifestage		
count	number of parr represented by this record	numeric
date	date of promotion to parr	POSIXct
rm	location of promotion (rm)	numeric
length	fork length at promotion (mm)	numeric

Attribute	Description	Date Type
Dead Juvenile Lifestage		
count	number of juveniles represented by this record	numeric
date	date of death or exit from river	POSIXct
rm	location of death or exit (rm)	numeric
length	fork length at death or exit (mm)	numeric
Passage Juvenile Lifestage		
count	number of juveniles represented by this record	numeric
date	date of passage of landmark	POSIXct
rm	location of landmark (rm)	numeric
length	fork length at passage (mm)	numeric

Table E-2. Output data frame fields produced by each habitat generator.

Attribute	Description	Date Type
Spawning Habitat		
feature	name of feature (e.g., a patch name or reach label)	text
rm	location (as river-mile) of feature	numeric
gravel.qual	expected survival-to-emergence of eggs deposited in this feature	numeric, between 0 and 1
preference	feature preference at requested time	numeric
area	usable spawning area at requested time (square feet)	numeric
Fry Habitat		
reach	name of reach	text
us	upstream extent of reach (rm)	numeric
ds	downstream extent of reach (rm)	numeric
rm	reference location for feature (rm)	numeric
LD50	exposure time over which 50% of migrating fry would be lost (days)	numeric
R	ration level (dimensionless)	numeric
density	maximum fish per unit wua (fish/ft ²)	numeric
wua	weighted usable area of fry habitat (square feet)	numeric
Juvenile Habitat		
reach	name of reach	text
us	upstream extent of reach (rm)	numeric
ds	downstream extent of reach (rm)	numeric
rm	reference location for feature (rm)	numeric
LD50	exposure time over which 50% of migrating fry would be lost (days)	numeric
R	ration level (dimensionless)	numeric
density	maximum fish per unit wua (fish/ft ²)	numeric
wua	weighted usable area of fry habitat (square feet)	numeric