ONCORHYNCHUS MYKISS POPULATION
AMENDED STUDY REPORT
DON PEDRO PROJECT
FERC NO. 2299



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Modesto Irrigation District

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

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Stillwater Sciences

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Oncorhynchus mykiss Population Study
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
CMAP ....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 Usable 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
MWAT.......................maximum weekly average temperature
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.........................microSiemens 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.
Iteroparous	A reproductive strategy exhibited by steelhead trout, characterized by multiple reproductive episodes before death.
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 *O. mykiss* 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 *O. mykiss*.
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 patform 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.
Semelperous	A reproductive strategy characterized by a single reproductive episode before death.

Smolt	Salmonid life stage between the parr and adult stages. Age 1+ and older 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 *O. mykiss* 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 (mi^2). 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 Don Pedro 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 agreements between the Districts and City and County of San Francisco (CCSF), the Don Pedro Reservoir also includes a “water bank” of up to 570,000 AF of storage which CCSF uses 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 Don Pedro 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 Don Pedro 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 a water surface elevation of 845 ft (31 FPC ¶ 510 [1964]). The Project Boundary encompasses approximately 18,370 ac with 74 percent of the lands owned jointly by the Districts and the remaining 26 percent (approximately 4,802 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 Don Pedro 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 Don Pedro Project and its primary facilities is shown in Figure 1.1-1.

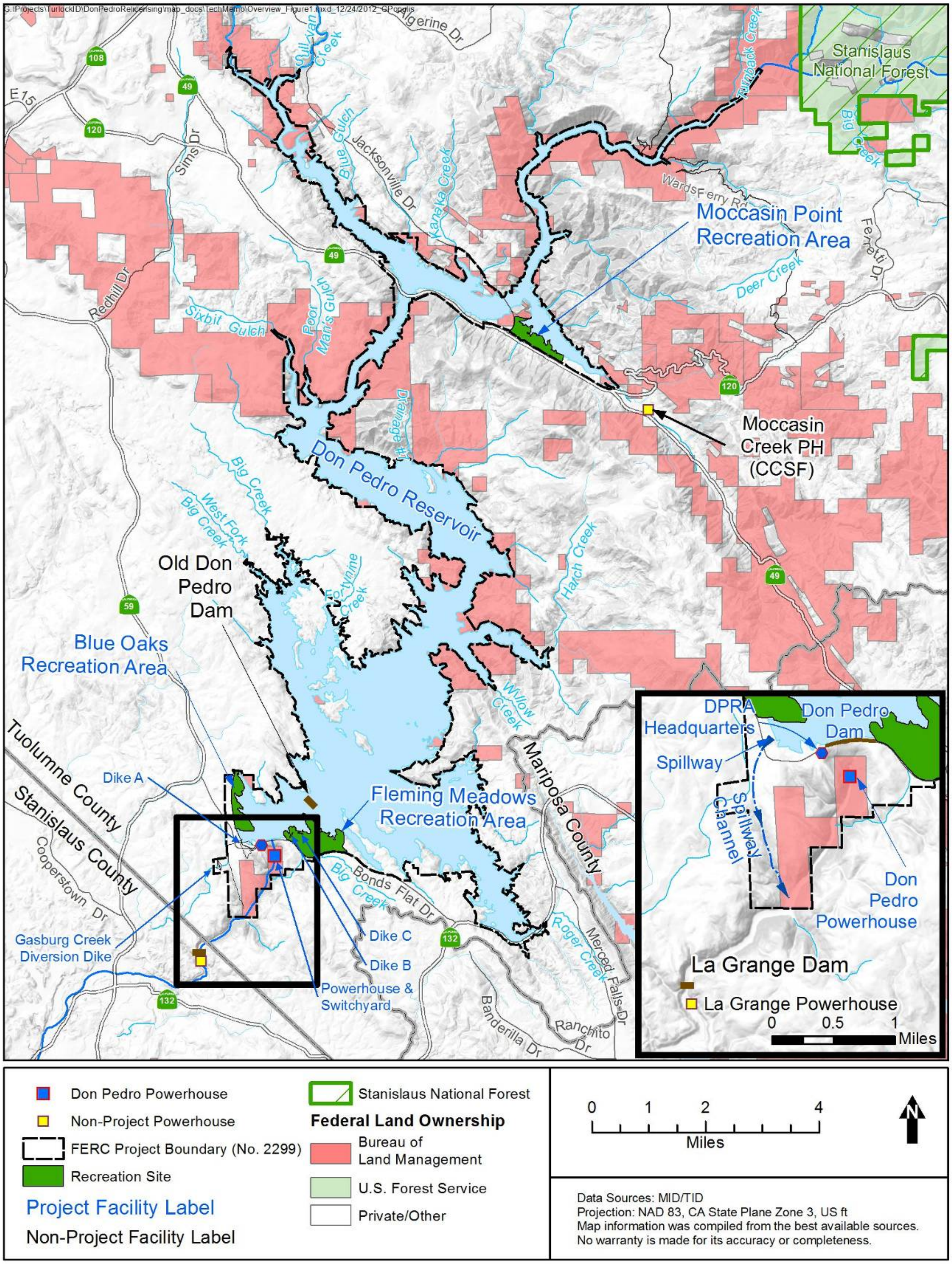

Figure 1.1-1. Don Pedro Project site location map.

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. The dispute did not involve W&AR-10: *O. mykiss* Population Study.

On January 17, 2013, the Districts issued the Initial Study Report (ISR) and held an ISR meeting on January 30 and 31, 2013. The Districts filed a summary of the ISR meeting with FERC on February 8, 2013. Comments on the meeting summary and requests for new studies and study modifications were filed by relicensing participants on or before March 11, 2013 and the Districts filed reply comments on April 9, 2013. FERC issued the Determination on Requests for Study Modifications and New Studies on May 21, 2013. No modifications were recommended to W&AR-10: *O. mykiss* Population Study.

The Districts filed the Updated Study Report (USR) on January 6, 2014; held a USR meeting on January 16, 2014; and filed a summary of the meeting on January 27, 2014. Comments on the meeting summary and requests for new studies and study modifications were filed by relicensing participants on or before February 26, 2014 and the Districts filed reply comments on March 28, 2014. The Commission's Study Plan Determination is due April 28, 2014.

This study report describes the objectives, methods, and results of the *Oncorhynchus mykiss* (*O. mykiss*) Population Study (W&AR-10) as implemented by the Districts in accordance with FERC's SPDs 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 the potential for the Project to contribute to cumulative effects to 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 *O. mykiss*. The *O. mykiss Population Study Plan* (W&AR-10) was accepted by FERC in its 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 *O. mykiss Population Study Plan* (W&AR-10), population modeling 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 held the first of two relicensing Workshop 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 *O. mykiss Population Study Plan* (W&AR-10). 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 including a preliminary list of processes and parameters for modeling. Comments were received from CDFW on January 14, 2013 and 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 November 5, 2013, the Districts held a second workshop with relicensing participants on the *Tuolumne River Oncorhynchus Mykiss Population Study* (W&AR-10). Consultation Workshop No. 2 was held to: (1) review and discuss the selected modeling approach; (2) present the

Tuolumne River O. Mykiss Population Model (TROm) 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 TROm modeling results for the base case hydrology from the Tuolumne River Operations Model. A meeting agenda was provided to relicensing participants on October 1, 2013 along with directions to the Don Pedro website where the Draft *O. Mykiss Population 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 TROm 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 November 23, 2013 and a joint comment letter by the Tuolumne River Trust, California Sportfishing Protection Alliance, and Trout Unlimited ("Conservation Groups") was received on January 7, 2014.

This final model report being submitted with the Final License Application contains revisions consistent with comments received on the draft report provided by Conservation Groups, as well as report clarifications consistent with March 28, 2014 responses to relicensing participant comments on the January 6, 2014 Updated Study Report Meeting Notes. In addition to the description of the Workshop No. 2 comments and consultation process for this study discussed above, other changes to the draft report include: (1) updated historical estimates of upstream *O. mykiss* passage past the counting weir at river mile (RM) 24.5; (2) QC corrections of model report entries of fry movement parameters to match previous model parameter files; (3) QC corrections of model parameter file entries of maximum juvenile rearing densities to match previously reported estimates included in the draft report; and (4) updated model validation, sensitivity testing, and base case scenario model results depicting juvenile productivity necessitated by the revised juvenile rearing density estimates in the model parameter file.

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 *O. mykiss* 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 *O. mykiss Population Study* is to provide a quantitative population model to investigate the relative influences of various factors on the life-stage specific production of *O. mykiss*[1] in the Tuolumne River, identify critical life-stages that may represent a life-history "bottleneck," and to compare relative changes in population sizes 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 relative abundance of *O. mykiss* in the Tuolumne River may be affected by in-river factors.

[1] Throughout this report, the term '*O. mykiss*' is used to represent both resident and anadromous life history forms of *Oncorhynchus mykiss*. In circumstances when the discussion is specifically limited to one or the other life history form, the terms 'rainbow trout' or 'resident' will be used to identify resident *O. mykiss*, whereas the terms 'steelhead' or 'anadromous' will be used to denote the anadromous form of *O. mykiss*.

3.0 STUDY AREA

Figure 3.0-1 provides an overview of the broad geographic range of resident and anadromous *O. mykiss* life stages occurring in the Tuolumne River, Delta, and ocean. The study area includes habitat used by in-river life stages (i.e., upmigration, resident and any anadromous spawning, egg incubation, fry/juvenile rearing, as well as smolt emigration of anadromous progeny) along the Tuolumne River from the La Grange Dam (RM 52) downstream to the San Joaquin River confluence (RM 0).

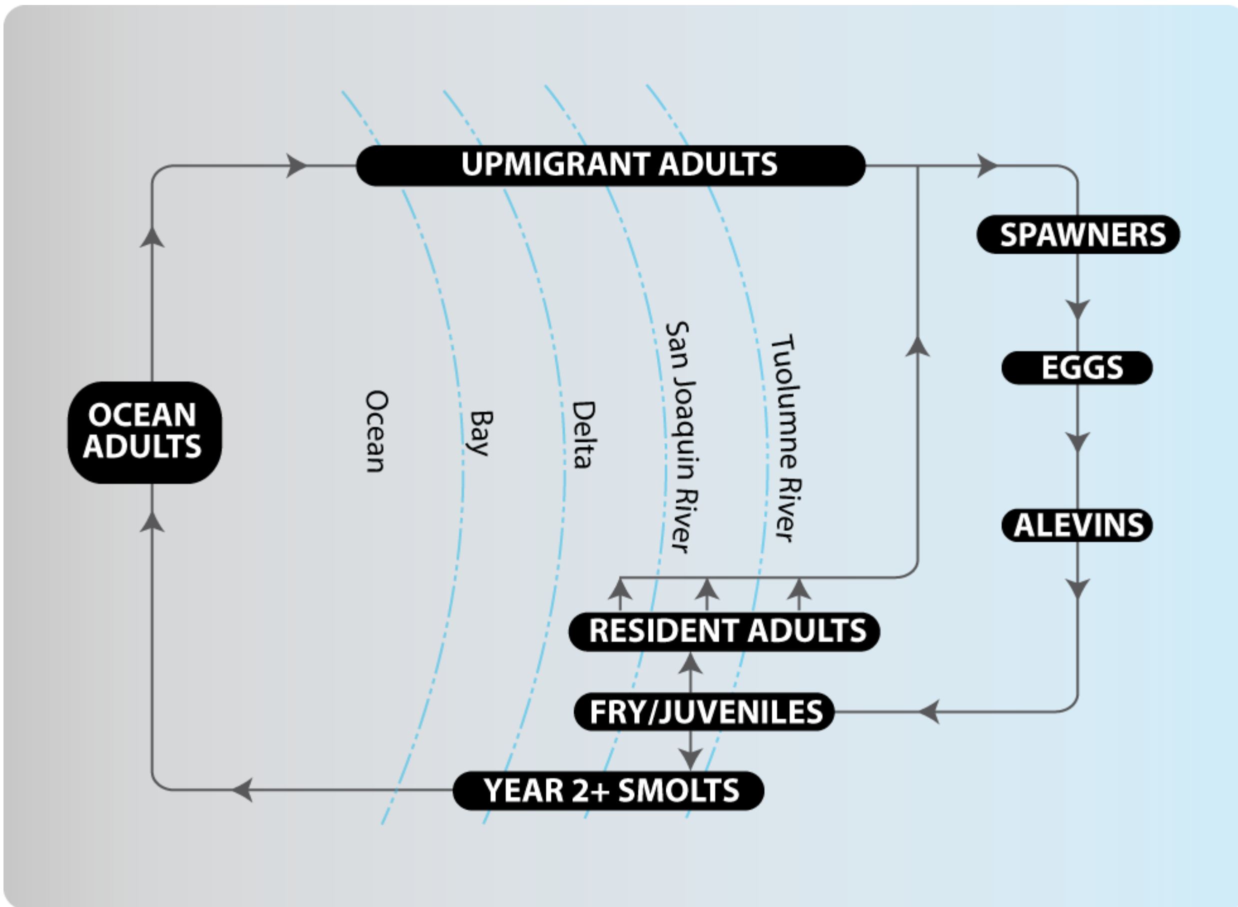

Figure 3.0-1. Generalized distribution of resident and anadromous *O. mykiss* life stages using the Tuolumne River, San Joaquin River, Bay-Delta, and Pacific Ocean.

As discussed in the Synthesis Study (W&AR-05), *O. mykiss* exhibit a variety of life history patterns (Shapovalov and Taft 1954, Quinn and Myers 2005). Information regarding anadromous *O. mykiss* entering the Tuolumne River is very limited, however weir and screw trap monitoring indicate that very few steelhead enter the Tuolumne and few to no smolts leave. The majority of fisheries and habitat data collected on the Tuolumne River indicate that the resident rainbow trout life history is predominant. Following the generalized life history timing for the Stanislaus River (NMFS 2009), Table 3.0-1 provides a generalized life-history timing assumed for the Tuolumne River. Spawning of adults may occur from December through April (light grey cells), with peak activity assumed to occur in February and March (dark grey cells). Following egg incubation for 2–3 months (peak activity assumed to occur in March and April), Age 0+ fry and juveniles over-summer, with in-river rearing of multiple adult age-classes (Age 1+, 2+, 3+, 4+ and older) during the following year(s).

Table 3.0-1. Generalized life history timing for Central Valley steelhead and rainbow trout in the lower Tuolumne River

Life Stage	Fall (Sep-Nov)			Winter (Dec-Feb)			Spring (Mar-May)			Summer (Jun-Aug)		
Adult Upstream Migration	grey	grey	grey	dark grey	dark grey	dark grey	grey				grey	grey
Adult Spawning				grey	grey	dark grey	dark grey	grey				
Egg Incubation and Fry Emergence					grey	grey	dark grey	dark grey	grey			
Rearing (Age 0+, 1+, and older)	grey	grey	grey	grey	grey	grey	grey	grey	grey	grey	grey	grey
Smolt Outmigration					grey	grey	dark grey	dark grey	dark grey	grey		

Note: Timing adapted from Stanislaus River data in NMFS (2009) with periods of life-stage absence (no shading), potential presence (grey), and peak activity (dark grey) shown.

Information on life-history timing specific to the Tuolumne River is limited. Nevertheless, *O. mykiss* spawning documented between January and April 2013 as part of the *Redd Mapping Study* (W&AR-08) as well as historical observations of fry sized fish (<50 mm fork length [FL]) in summer snorkel surveys documented as part of the Synthesis Study (W&AR-05) are consistent with the assumed spawning timing in Table 3.0-1. The low rates of anadromy suggested by Zimmerman et al. (2009) provide little evidence of a self-sustaining steelhead run occurring on the Tuolumne River. Emigration of any anadromous *O. mykiss* smolts would potentially occur as early as Age 1+ or older, with Age 2+ as the most common age at smolting reported in Central Valley rivers supporting steelhead populations (McEwan 2001).

4.0 METHODOLOGY

The *O. mykiss Population 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 in the Central Valley. As detailed further below, the population model development is separated into four steps: (1) conceptual model review and refinement, (2) quantitative model development, (3) sensitivity analyses, and (4) evaluation of relative *O. mykiss* 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 *O. mykiss* in the Tuolumne River were identified as part of the initial conceptual model development in the Synthesis Study (W&AR-05). A workshop was held with relicensing participants on November 15, 2012 to consider preliminary conceptual models and to identify and discuss the relevant factors and preliminary parameters to be included in the model (Section 1.3). Attachment B provides graphical depictions of primary factors for modeling of in-river *O. mykiss* life stages. The following sections draw upon these sources and additional 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 of any steelhead; adult *O. mykiss* spawning; egg incubation and fry emergence, in-river juvenile rearing, adult residency, as well as potential emigration of any steelhead smolts.

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 very low rates of *O. mykiss* immigration into the Tuolumne River, either as resident or anadromous *O. mykiss*. Since counting weir operations at RM 24.5 were initiated in 2009, upstream passage of a single *O. mykiss* was documented in the first year of operation, no observations occurred in Fall 2010, sixteen individuals were detected between September 2011 and June 2012, four were detected between September 2012 and May 2013 (TID/MID 2014, *unpublished data*). Because the counting weir operations are limited to flows below approximately 1,400 cfs, immigration of anadromous *O. mykiss* as well as residents from nearby river locations may potentially occur during flood control releases such as those that occurred during winter/spring 2011. Including weir detections and *O. mykiss* spawning activity documented between January and April 2013 as part of the *Redd Mapping Study* (W&AR-08), timing of spawning activity potentially spans September through May. However, because so little information on spawning migrations of *O. mykiss* into the Tuolumne River exists, potential upmigration and spawning timing is represented on the basis of the timing assumed from the Stanislaus River (Table 3.0-1). Although McCullough et al. (2001) suggested high temperatures on the order of 21°C (69.8°F) were associated with upstream migratory blockages for steelhead on the Snake River (WA), as discussed in the Synthesis Study (W&AR-05) the majority of adult upmigrants would be expected to enter the Tuolumne under lower temperatures during fall and winter (Table 3.0-1). On the basis of acoustic telemetry studies of summer-run steelhead in the Columbia River basin, English et al. (2006) documented migration rates on the order of 17–23 km/day (11–23 mi/day). However, because weir passage rates are very low in the Tuolumne River, any potential steelhead spawners assumed to arrive at the weir in future modeling scenarios will be assumed to arrive at preferred habitat locations within 1–2 days of passing through the weir.

4.1.1.2 Spawning Habitat Use

Selection of suitable habitat by spawning female *O. mykiss* is affected by (1) the availability of suitably-sized spawning gravels, (2) site-specific hydraulic conditions (i.e., depth, velocity, hyporheic flows), and (3) avoidance of locations with unsuitable water temperatures. Use of weighted usable area (WUA) estimates for predicting spawning habitat use is based upon comparison of 2-dimensional (2D) modeling results with spawning redd locations on the Yuba River (Gard 2010) as well as on the Klamath River (Hardy and Addley 2001). On this basis, spawning habitat availability for the model is estimated from directly mapped areas of suitable gravels in riffle habitats from the *Spawning Gravel Study* (W&AR-04). Using 1-dimensional (1D) PHABSIM modeling from the *Lower Tuolumne River Instream Flow Study* (Stillwater Sciences 2013), 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 4.1-1 shows the variation of total usable area with discharge as estimated within riffle habitats of various sub-reaches of the lower Tuolumne River.

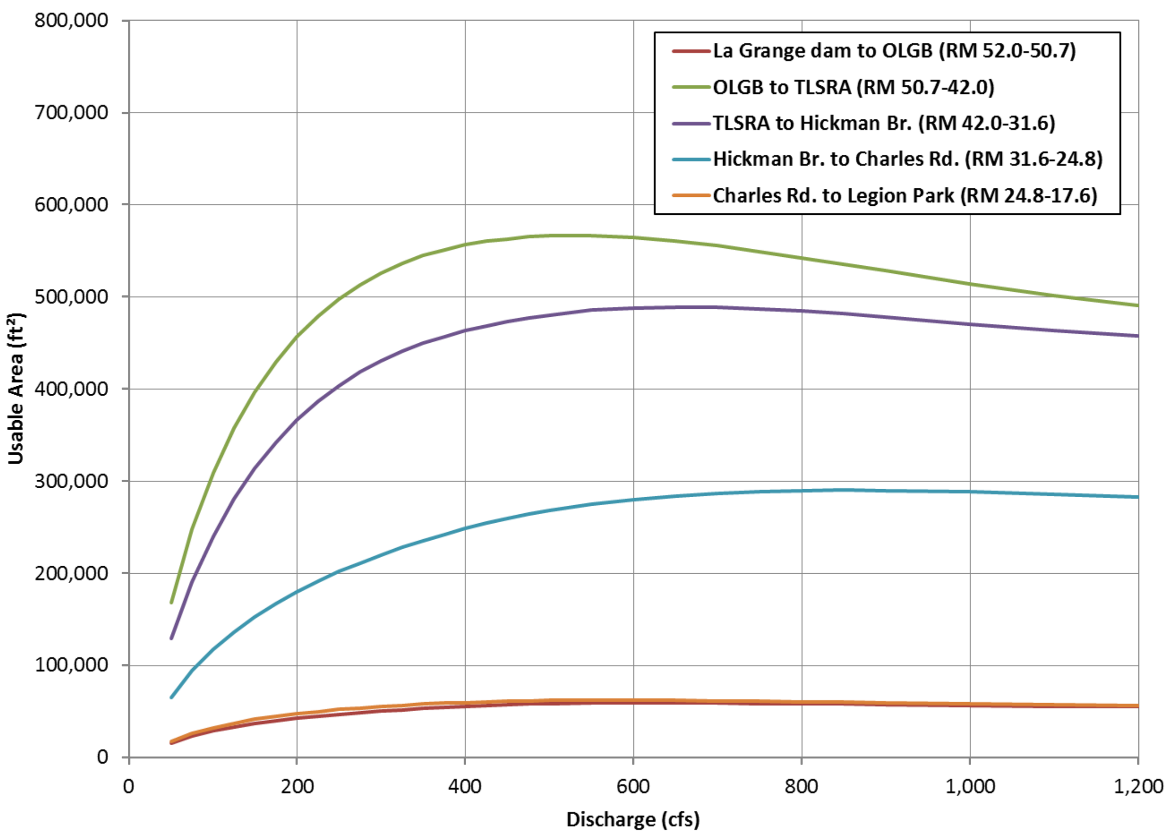

Figure 4.1-1. Variation of usable spawning area estimates with discharge for *O. mykiss* in sub-reaches of the lower Tuolumne River.

In order to address any potential temperature limits for spawning habitat selection, area estimates provided in Figure 4.1-1 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 no literature information could be identified regarding upper temperature limits for spawning initiation, maximum temperature limits for spawning are assumed to be on the order of 15°C (59°F) inferred from egg mortality thresholds for resident *O. mykiss* (Velsen 1987) as well as steelhead (Rombough 1988). Although McCullough et al. (2001) suggested that body cavity temperatures in salmon spawners may be several degrees cooler than ambient conditions, *O. mykiss* spawners are assumed to avoid locations with water temperature above this threshold.

In addition to the effects of hydraulic and water temperature conditions upon spawning habitat selection, results of the *Salmonid Redd Mapping Study* (W&AR-08) were examined to identify any apparent spawning preferences for *O. mykiss*. Figure 4.1-2 shows cumulative gravel availability occurring downstream of mapped redd locations, with approximate redd locations shown as a secondary (upper) axis.

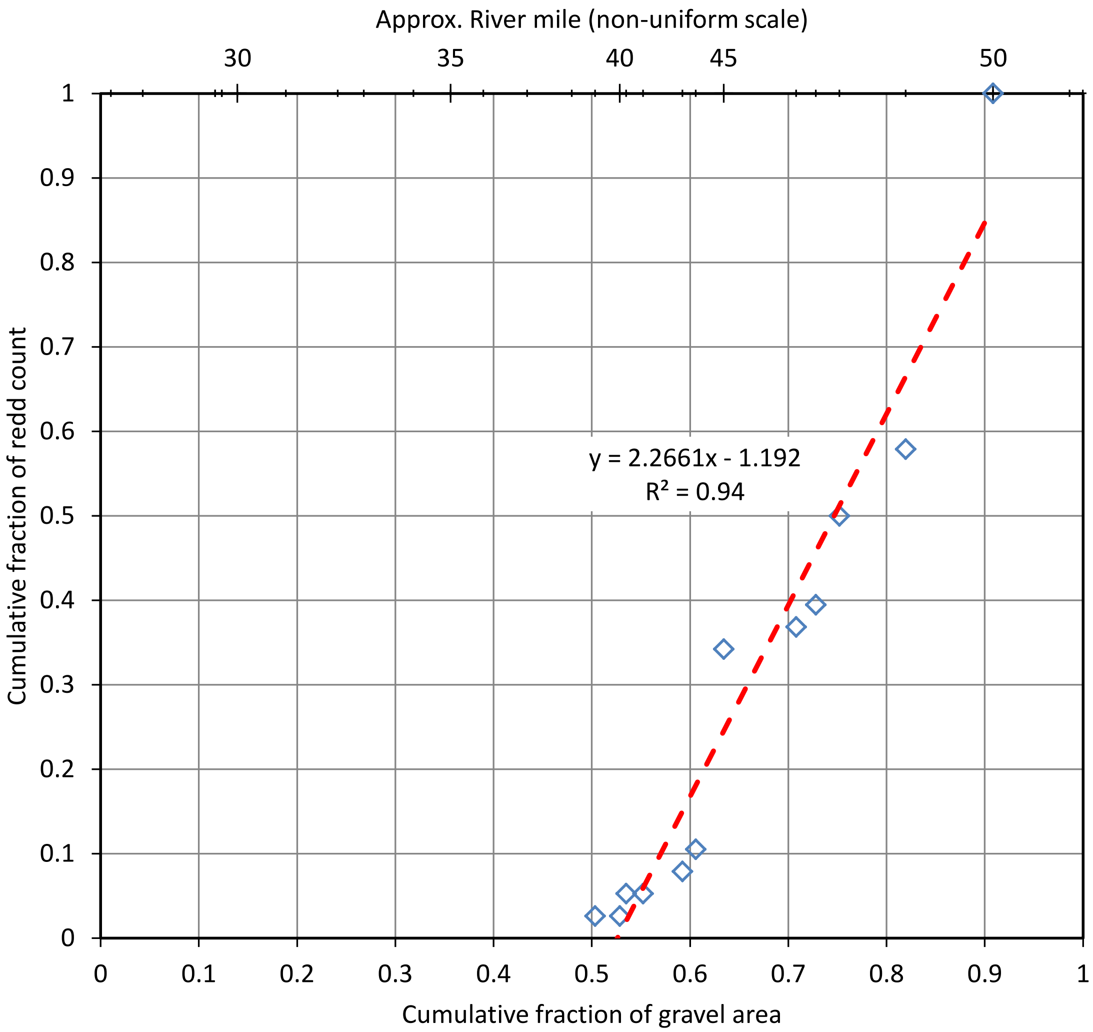

Figure 4.1-2. Cumulative proportion of total *O. mykiss* spawning activity (2013) as a function of total spawning gravel areas occurring downstream of mapped redds.

Unlike spawning habitat use patterns for Chinook salmon mapped as part of the *Salmonid Redd Mapping Study* (W&AR-08), no *O. mykiss* spawning occurred downstream of RM 39 in 2013 and habitat use upstream of this location occurred in direct proportion to available gravel area (Figure 4.1-2). Although the sample size is small (n=38 spawners at 12 riffles), approximately 50 percent of *O. mykiss* redds in 2013 were located within the 75 percent of the spawning gravels mapped downstream of approximately RM 48, with the other 50 percent of spawning occurring within the remaining 25 percent of the spawning gravels mapped as part of the *Spawning Gravel Study* (W&AR-04) located between RM 48 and the La Grange powerhouse tailrace (RM 51.5). The fitted line in Figure 4.1-2 represents this apparent preference based on the model in Equation 1 below.

$$G(i) = -1.192 + 2.2661\ F(i) \qquad \text{Equation 1}$$

Equation 1 represents the fitted preference line in Figure 4.1-2, where *F(i)* is the cumulative fraction of gravel availability and *G(i)* is the cumulative fraction of the female spawners expected to spawn within and downstream of riffle number (*i*).

Depending upon the spawner preferences discussed above, adult female *O. mykiss* arriving at a particular location will construct redds over a period of several days. Although information reviewed as part of the Synthesis Study (W&AR-05) indicated that typical *O. mykiss* redd sizes were on the order of 47 ft^2 (4.4 m^2) based on studies conducted in Washington and Idaho (Hunter 1973, Reiser and White 1981), redd sizes estimated as part of the *Salmonid Redd Mapping Study* (W&AR-08) were smaller, averaging 0.9 m^2 (9.2 ft^2) in 2013 (n=31). This is also smaller than the 1.7 m^2 (18 ft^2) reported in steelhead redd surveys (n=399) on the American River between 2002–2005 (Hannon and Deason 2005), which suggests that spawning in the Tuolumne River is by smaller (i.e., predominantly resident) *O. mykiss*. Using the Tuolumne River estimate, defended areas for individual females are assumed to be approximately four times the redd size (Burner 1951), or 3.4 m^2 (37 ft^2).

No evidence of redd superimposition by *O. mykiss* was found on the Tuolumne River in 2013 as part of the *Salmonid Redd Mapping Study* (W&AR-08), but redd superimposition is assumed to potentially occur and is modeled within suitable gravel areas (Figure 4.1-1) on the basis of redd size and spawner preferences (Equation 1). Bjornn (1991) indicated that typical redd defense times for steelhead were on the order of 1–2 days, with Briggs (1953) indicating that male and female steelhead moved downstream shortly after spawning in coastal streams. Redd defense times for rainbow trout were assumed to be of similar magnitude as these estimates for coastal steelhead.

4.1.1.3 Spawning and Egg Deposition

All *O. mykiss* have the ability to spawn more than once (iteroparous) and both resident and anadromous life history variants can be produced from either resident or anadromous parents (Hallock 1989, Zimmerman et al. 2009) or a combination thereof (Thrower et al. 2004; Olsen et al. 2006; Courter et al. 2013). Because no *O. mykiss* spawning or fecundity data are available for the Tuolumne River or San Joaquin River tributaries, spawner fecundity and egg deposition is estimated based upon fish size and egg count data from Scott Creek (Shapovalov and Taft 1954). Parameterization of these data by Satterthwaite et al. (2009) is shown in Equation 2 as a function of length (*L*) in millimeters. Fish size at spawning is based upon *O. mykiss* age structure documented in 2012 as part of the *O. mykiss Scale Collection and Age Determination Study*. Probabilities of sexual maturity and repeat spawning at a given age are assumed from Courter et al. (2009) based on mixed populations of steelhead and resident rainbow trout populations from the Yakima River, WA.

$$Eggs = 0.007236 \times L^{2.1169} \qquad \text{Equation 2}$$

To estimate the probability of smoltification on the basis of anadromous parentage (Section 4.1.6), the model allows for cross-ecotype spawning between resident and anadromous *O. mykiss*. For any steelhead assumed to migrate into the lower Tuolumne River, the frequencies of crossings, that is, the probability that eggs from an anadromous female will be fertilized by a resident male or eggs from a resident female by an anadromous male are determined by the relative abundances of resident males (f_r) and anadromous males (f_a). To account for the probability that eggs of resident or anadromous origin females may be fertilized by these males, Table 4.1-1 shows the result of a sequence of the probability of encounters between a particular female and various males.

Table 4.1-1. Probability of spawning between resident and anadromous male/female pairings.

Origin of Female	Probability that Eggs will be Fertilized by Either:	
	Resident Male	Anadromous Male
Resident	$\frac{f_r F_r}{f_r F_r + f_a}$	$\frac{f_a}{f_r F_r + f_a}$
Anadromous	$\frac{f_r}{f_r + f_a F_a}$	$\frac{f_a F_a}{f_r + f_a F_a}$

The parameters F_r and F_a represent "spawning fidelity" of resident and anadromous female spawners, each estimated as the ratio of two probabilities: (1) the probability that a female of a particular origin will allow her eggs to be fertilized by a male of the same origin, divided by (2) the probability that the same female will allow her eggs to be fertilized by a male of the other origin. For example, if F_r is high it is more likely that resident females will spawn with resident males. Estimation of these parameters is based upon data and reviews by McMillan et al. (2007), who showed higher spawning fidelity between resident and anadromous males with anadromous females than either ecotype spawning with resident females.

4.1.1.4 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 (McCullough et al. 2001). However, because no occurrences of pre-spawn mortality due to elevated water temperatures were identified for the Tuolumne River or other rivers of the Central Valley, mortality during upmigration and spawning is considered to be negligible and is not represented in the model. Rainbow trout and steelhead are iteroparous, spawning more than once in a lifetime. Repeat spawning rates of 50 percent have been estimated for rainbow trout in the Deschutes River (OR) (Schroeder and Smith 1989). Multiple spawning events per lifetime were documented in Scott Creek (CA) steelhead by Shapovalov and Taft (1954). Post-spawn survival is assumed to be 41 percent for resident *O. mykiss* (Satterthwaite et al. 2009) as well as steelhead. This is of similar magnitude as found for in recent steelhead kelt reconditioning programs conducted at the Coleman National Fish Hatchery on Battle Creek, CA (Provencher 2012) and the Yakama Nation's Prosser Hatchery on the Yakima River, WA (Courter et al. 2013).

4.1.2 Egg Incubation

4.1.2.1 Embryo Development

Normal *O. mykiss* 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

20–100 days have been observed, depending upon water temperature (Shapovalov and Taft 1954, Beacham and Murray 1990). Water temperature degree-day models have been used to successfully predict emergence timing of Chinook salmon fry (TID/MID 2007, Report 2006-7). Recognizing that accumulated degree days or accumulated thermal units (ATUs) to hatching and emergence vary slightly with temperature (Leitriz and Lewis 1976) as well as with egg weight (Beacham and Murray 1990), *O. mykiss* fry emergence is assumed to occur after accumulation of 647 ATU (°C) in the spawning gravels (Burton and Little 1997).

4.1.2.2 Embryo Mortality during Incubation

O. mykiss 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 *O. mykiss* on the Tuolumne River. Nevertheless, to allow evaluation of a broad range of flow and water temperature conditions using the completed model, an initial acute mortality threshold of 15°C (59°F) was included based upon a literature review by Myrick and Cech (2001). This is consistent with multiple studies summarized by McCullough et al. (2001) showing large losses of steelhead and rainbow trout eggs within the range of 15–16°C (59–61°F).

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). As discussed in the Synthesis Study (W&AR-05), very low levels of redd superimposition (1 of 51 redds, or 2%) by steelhead in the Mokelumne River were documented by Del Real and Rible (2009). Nevertheless, as discussed in Section 4.1.1.2, redd superimposition is included in the model with potential egg mortality occurring on the fraction of redd area superimposed.

The Districts have conducted a range of gravel quality studies related to Chinook salmon egg survival-to-emergence (TID/MID 1992, Appendix 8; TID/MID 2001, Report 2000-6; TID/MID 2007, Report 2006-7). Estimates of *O. mykiss* egg survival-to-emergence for the lower Tuolumne River are on the order of 45 percent based upon bulk gravel quality samples collected in 1988 (TID/MID 1992, Appendix 8) using the Tappel and Bjornn (1983) model at a function of percent fine sediments smaller than 9.5mm and 0.85mm.

4.1.3 Fry Rearing

4.1.3.1 Fry Habitat Use

After hatching, *O. mykiss* alevins remain in the gravel for two to three weeks and absorb their yolk sac before emerging from the gravels into the water column (Shapovalov and Taft 1954). Following emergence, fry rearing generally occurs in low velocity, shallow water habitat along channel margins (Everest and Chapman 1972). Because Chinook salmon fry rearing habitat use has been related to PHABSIM modeling of WUA at the site scale in studies by USFWS (1991) and direct observation was used in the validation of *O. mykiss* habitat suitability criteria (HSC) for the Tuolumne River (Stillwater Sciences 2013), in-channel fry rearing habitat availability was estimated as a function of flow and WUA within individual sub-reaches (Figure 4.1-3). Reach-specific estimates of carrying capacity are calculated on the basis of usable habitat (Figure 4.1-3) and the maximum attainable densities under optimum habitat conditions (e.g., Burns 1971). The maximum attainable fry density is estimated at 1.1 fry/ft^2 based upon territory size estimates at a 50 mm FL using relationships by Grant and Kramer (1990). Although no information on maximum attainable fry rearing density for fish smaller than 50 mm FL was identified in recent monitoring summaries of the Tuolumne River or other San Joaquin River tributaries as part of the Synthesis Study (W&AR-05), this maximum density estimate is comparable to those from territory size estimates for fry (39–50 mm TL) by Keeley (1998) from the Salmon and Chilliwack Rivers in British Columbia.

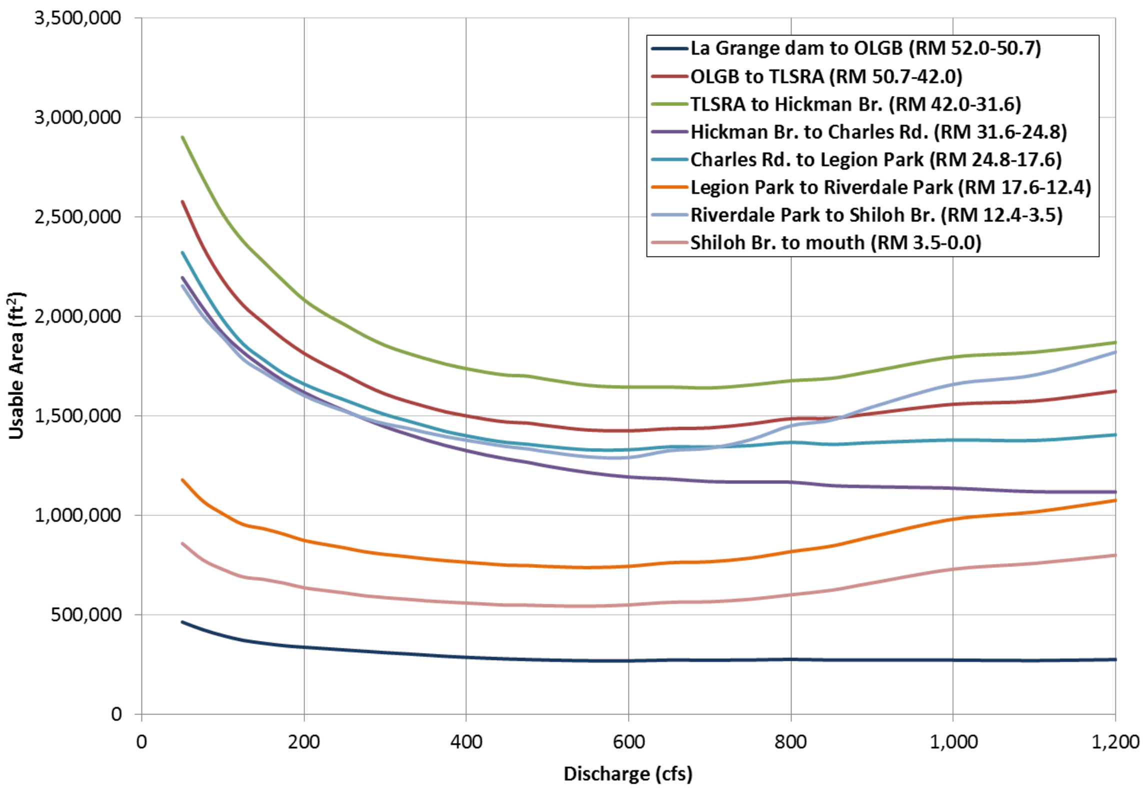

Figure 4.1-3. Variation of usable fry rearing area estimates with discharge for *O. mykiss* in sub-reaches of the lower Tuolumne River.

Newly emerged *O. mykiss* fry seek cover from high flows in larger substrates (Everest and Chapman 1972) and generally have not been found using floodplain habitats in the Tuolumne River or in floodplain studies in the Cosumnes River (Moyle et al. 2007). However, for any fry potentially using floodplain habitats, rearing habitat availability was estimated by expansion of WUA estimates at study sites evaluated by 2D modeling as part of the *Pulse Flow Study Report* (Stillwater Sciences 2012a). WUA at these study sites was determined by summation of the combined (depth and velocity) suitability for each polygon across the model grid. The resulting site-scale usable habitat estimates at each flow were then expanded in proportion to overbank inundation areas occurring within individual Tuolumne River sub-reaches (Figures 4.1-4 and 4.1-5) using digitized historical aerial photography collected as part of the Tuolumne River GIS development (TID/MID 1997, Report 96-14). Figure 4.1-4 represents the estimate of usable overbank habitat availability from these existing information sources without consideration of fry movement (Section 4.1.3.2) or temperature suitability (4.1.3.4).

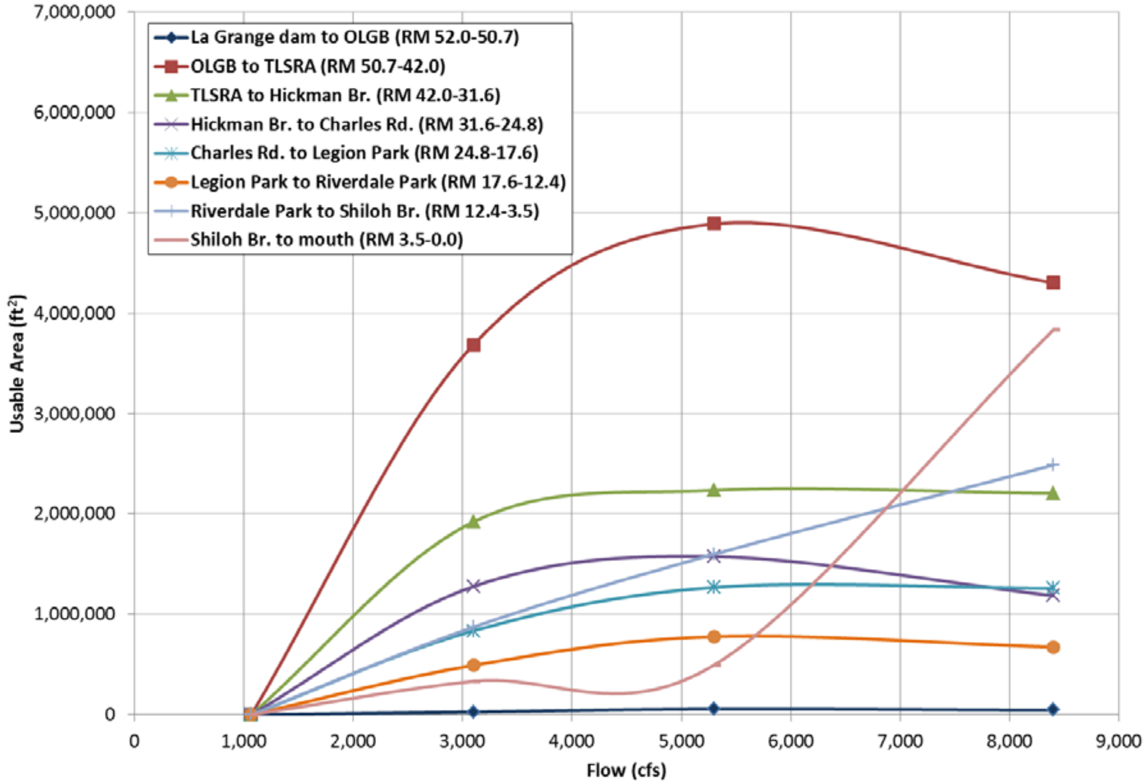

Figure 4.1-4. Estimated total usable overbank habitat for Tuolumne River *O. mykiss* fry.

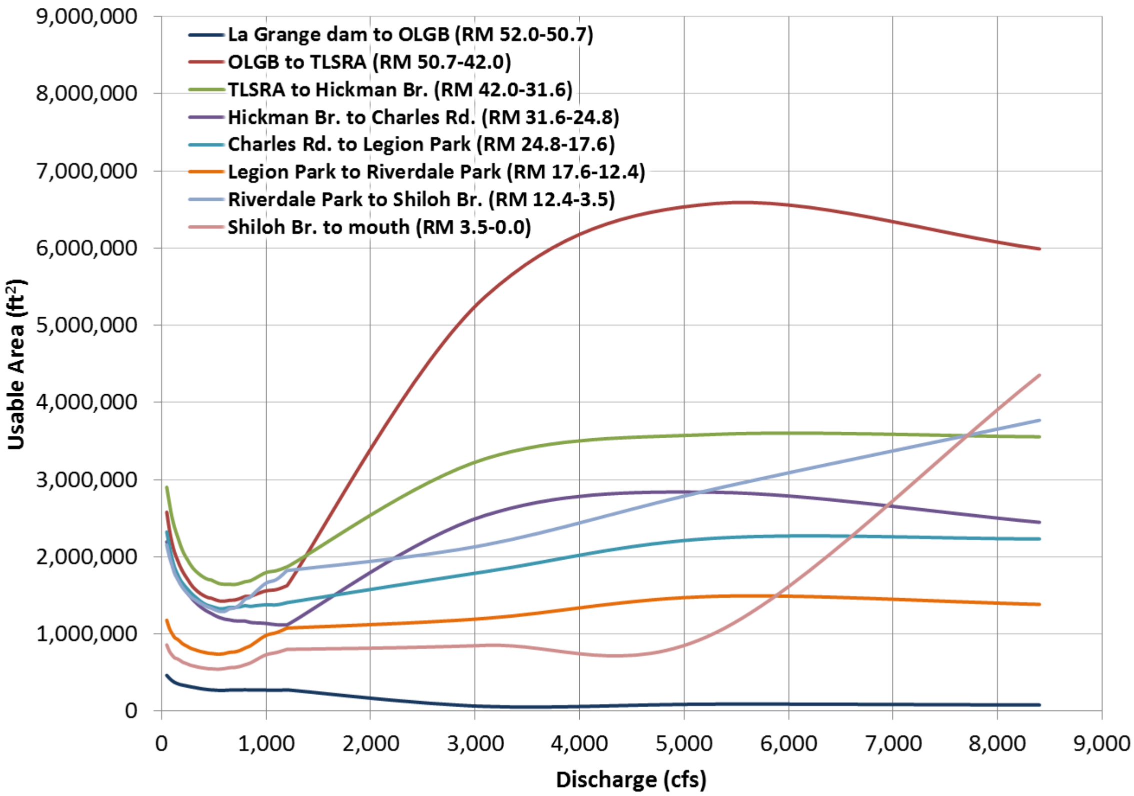

Figure 4.1-5 Estimated total combined usable in-river and overbank habitat for Tuolumne River *O. mykiss* fry.

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 and 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 4.1-4 and 4.1-5 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, low numbers of *O. mykiss* fry have been documented in routine seining surveys during April and May in the Tuolumne River (Ford and Kirihara 2010) or as part of annual rotary screw trap (RST) monitoring conducted between January and early June (Stillwater Sciences 2012b). Seine recoveries of fry-sized fish (24–49 mm FL) are generally restricted to sites upstream of RM 42, with snorkel observations of larger juveniles (Section 4.1.4.2) extending downstream of this location in some years. Although insufficient *O. mykiss* seining and RST data are available to estimate downstream movement of emergent fry, the following movement assumptions are applied.

Based upon the high proportions of Chinook salmon fry to total Chinook and *O. mykiss* seasonal passage in RST sampling near Grayson (RM 5.2) in years following high escapements as well as during years with extended flood control releases such as occurred in 2011 (TID/MID 2012, Report 2011-4), 30 percent of all *O. mykiss* fry are assumed to emigrate from the Tuolumne River following emergence, with the remainder assumed to be displaced for a period of 30 minutes. This early emigration is generally consistent with mechanisms of flow displacement as well as volitional emigration found in other systems (Healey 1991). 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 PHABSIM Study (Stillwater Sciences 2013) fitted to a simple hydraulic geometry relationship between velocity (v) and stream discharge (Q) by Leopold and Maddock (1953). The relationship is shown in Equation 3, with identical parameters k, and m to those fitted as part of the *Chinook Salmon Population Model Study* (W&AR-06).

$$v = kQ^m \qquad \text{Equation 3}$$

In addition to volitional emigration following emergence, fry movement may be attributed to potential competitive exclusion from near-shore rearing locations due to limited habitat availability. To account for the limited observations of *O. mykiss* in downstream habitats in historical seine surveys summarized as part of the Synthesis Study (W&AR-05) as well as the greater swimming ability of Age 0+ fry and juveniles relative to Chinook salmon (Cavallo et al. 2003; Everest and Chapman 1972), a lower daily movement probability of 0.1 d^{-1} was chosen than used to represent downstream fry movements in the *Chinook Salmon Population Model Study* (W&AR-06). Conceptually, this movement rate corresponds to 10% of the modeled fish moving each day, with an assumed travel distance calculated over a 30-minute time period using the velocity estimates above (Equation 3). For areas with fry densities in excess of habitat carrying capacity, fry movement is re-initiated using the duration and velocity estimates described above.

It should be noted that the potential occurrence of higher flow events corresponding to floodplain inundation (Figure 4.1–4) during fry rearing periods (April–May) would have the effect of displacing *O. mykiss* fry into downstream habitats that are subject to unsuitable water temperatures during summer. Although some studies have shown avoidance of habitats with water temperatures as high as 24°C (75°F) (Myrick and Cech 2001), no avoidance behavior by fry is included in the model for temperatures in excess of this level because of the poor swimming ability of the fry life stage. That is, since fry are assumed to be unable to move upstream, displacement into downstream habitats by early season high-flows may potentially subject these fish to subsequent temperature related mortality (Section 4.1.3.4) during summer.

4.1.3.3 Fry Growth

For newly emerged fry at a size of approximately 24 mm FL (Shapovalov and Taft 1954), 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 Satterthwaite et al. (2009) shown in Equation 4. Specific growth rate ($\boldsymbol{g}$) (% weight change/day) for a fish of weight W (g) at temperature T (°C) is given as a function of the maximum consumption rate GM and catabolic costs GC reflecting breakdown of cellular tissues.

$$g = \frac{a}{a+\kappa}\mathrm{GC} - (1+a)\mathrm{GM}, \quad \text{where}$$

$$a = \max\left(\sqrt{\kappa GC/GM} - \kappa, 0\right), \quad \text{and} \qquad \text{Equation 4}$$

$$\mathrm{GC} = \Psi(T) f c W^{0.86-1}, \ \mathrm{GM} = \alpha e^{0.071T}$$

To allow the use of a broad range of optimum growth rates as a function of temperature, Equation 5 includes a Thornton-Lessem (1978) function ***Ψ***, with all parameters except foraging activity (***a***) and energy consumption (***κ***) assumed to be constants, applicable to coastal and Central Valley steelhead populations (Satterthwaite et al. 2009, 2010). Equation 4 is similar to more general bioenergetic models, where food availability provides the energy for foraging, temperature controls the metabolic processes, and body weight is used to scale the metabolic processes according to the body size of the growing fish. The foraging activity (***a***) is chosen so as to maximize growth for a given weight, water temperature, and energy consumption kappa (***κ***). Kappa, which may be considered as the inverse of food ration (Rf) availability for foraging fish within particular rearing habitats, is the feeding activity level needed for a fish to reach half its maximum daily energy consumption.

Initial parameter estimates for Equation 4 follow those used by Satterthwaite et al. (2010) for Mokelumne River *O. mykiss* populations, with adjustments made in the calibration step to match the observed length to weight relationship (Figure 4.1-6) as well as interannual growth rate estimates obtained from the *O. mykiss Scale Collection and Age Determination Study* (W&AR-20). As documented in the Synthesis Study (W&AR-05), with the exception of stomach content samples collected in Chinook salmon juveniles 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) (TID/MID 1997, Report 96-9). Although no equivalent stomach content sampling has been conducted on *O. mykiss* in the Tuolumne River due to permitting restrictions on handling ESA-listed species, food availability levels in the lower Tuolumne River are relatively high, consistent with relatively high length at age of adults sampled as part of the *O. mykiss Scale Collection and Age Determination Study* (W&AR-20). 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), correspondingly lower energy consumption requirements (***κ***) are assumed within Equation 4 for any *O. mykiss* fry rearing in overbank habitat areas.

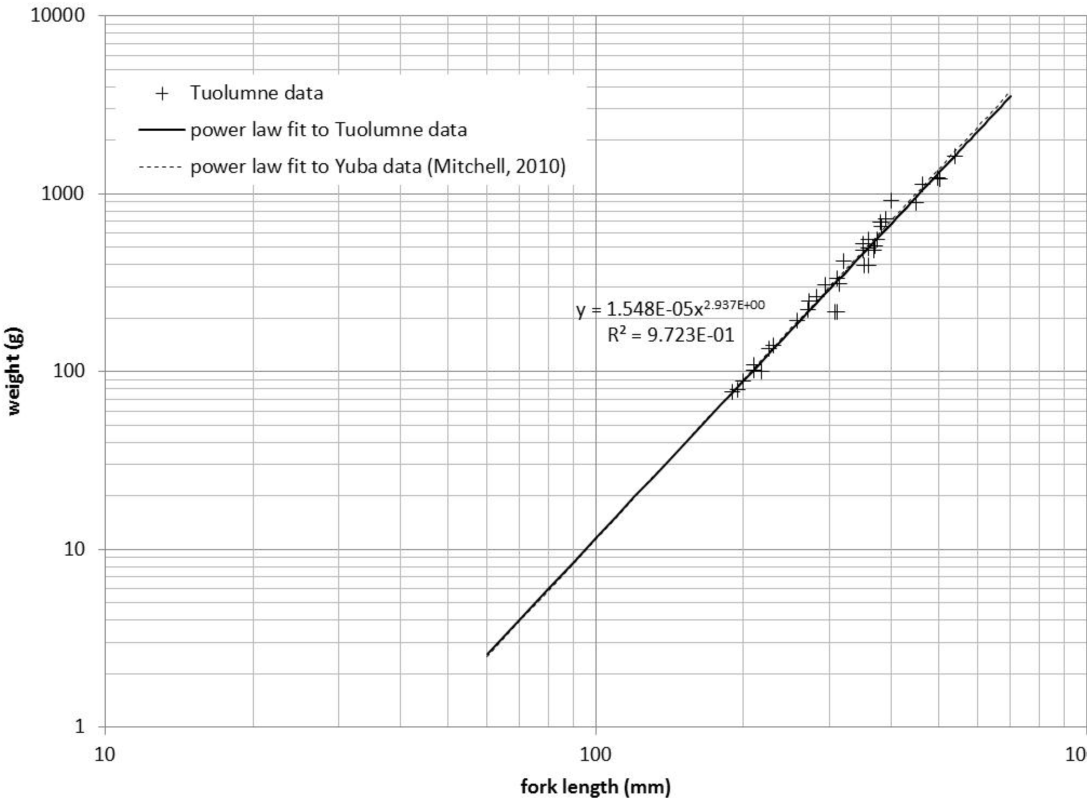

Figure 4.1-6. Length vs. Weight relationship for *O. mykiss* in the Tuolumne River (2012) compared with power law from Mitchell 2010).

Figure 4.1-6 shows weight-length conversions obtained by linear regression of log-weight and log-length of fish collected for scale samples using hook and line sampling in the Tuolumne River between February and April 2012. To broaden the represented size range to smaller fish (Age 0+ and Age 1+), these data are plotted in comparison to additional length-weight data collected in 2000 and 2001 from the Yuba River by Mitchell (2010). Because Figure 4.1-6 shows the two relationships differ only slightly across the size ranges represented in the Yuba River study (68–720 mm FL), use of the Tuolumne River-specific relationship was considered justified.

4.1.3.4 Fry Mortality

Potential mortality sources to fry include predation effects due to the relative habitat availability for predators and juvenile *O. mykiss* as well as due to high water temperatures. As summarized in the Synthesis Study (W&AR-05), many of the same mechanisms affecting Chinook salmon fry survival in habitats preferred by predatory fish species also apply to *O. mykiss* fry. However, because no survival data are available for *O. mykiss* fry on a reach- or river-wide scale, survival is estimated using parameterization applicable to Chinook salmon fry as part of the *Chinook Salmon Population Model Study* (W&AR-06). Specifically, predation mortality of fry due to displacement from near-shore rearing areas is estimated on the basis of exposure time as an exponential function of the instantaneous mortality $m(t)dt$ between times t_1 and t_2 shown in Equation 5 below.

$$Survival = e^{-\int_{t_1}^{t_2} m(t)dt}$$ Equation 5

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. *O. mykiss* mortality rates vary substantially between strains and with acclimation temperature, with the critical thermal maxima (CTM) as assessed by locomotory impairment and death ranging from 27.5–32°C (80–90°F) (Myrick and Cech 2001). In laboratory studies, UUILT for *O. mykiss* juveniles has been estimated at 22.8–25.9ºC (73–79°F) by Threader and Houston (1983). Based upon this information, an initial mortality threshold of 25°C (77°F) as a daily average temperature was selected for *O. mykiss* fry. Although potential water temperature related mortality may occur at higher water temperatures during late spring or summer, this is unlikely to affect the majority of fry emerging in March and April of each year (Table 3.0-1).

Lastly, although no data are available to provide an estimate for the Tuolumne River, a background mortality rate 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). Initial parameter estimates from the *Chinook salmon Population Model Study* (W&AR-06) were adjusted as a fitting parameter to produce a stable *O. mykiss* population size in the calibrated model (Section 4.4).

4.1.4 Juvenile Rearing

4.1.4.1 Juvenile Habitat Use

As rearing *O. mykiss* 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). In addition to periodic captures in routine RST sampling (Stillwater Sciences 2012b), parr-sized individuals (50–149 mm FL) may be found as far downstream as RM 37 in September of some years (TID/MID 2006, Report 2005-3 (TID/MID 2007, Report 2006-3) with the designated lower size limits for Age 1+ adults (150 mm FL) based upon historical conventions for the Tuolumne River and validated by the *O. mykiss Scale Collection and Age Determination Study* (W&AR-20).

Following the same rationale for predicting fry habitat use from PHABSIM modeling (Section 4.1.3.1), *O. mykiss* rearing habitat for parr up to approximate sizes at Age 1+ (50–149 mm FL) is represented as a function of flow using habitat suitability criteria presented in the *Lower Tuolumne River Instream Flow Study* (Stillwater Sciences 2013). Reach-specific estimates of carrying capacity are calculated on the basis of usable habitat (Figure 4.1-7) and the maximum attainable densities under optimum habitat conditions. The maximum attainable juvenile density is estimated at 0.06 juveniles/ft^2 based upon territory size estimates at the upper size limit for parr (149 mm FL) using relationships by Grant and Kramer (1990). Although no information on maximum attainable juvenile rearing density for fish smaller than 149 mm FL was identified in recent monitoring summaries of the Tuolumne River or other San Joaquin River tributaries as part of the Synthesis Study (W&AR-05), this maximum density estimate is comparable to those from territory size estimates for parr (50–149 mm FL) from the Salmon and Chilliwack Rivers in British Columbia (Keeley 1998).

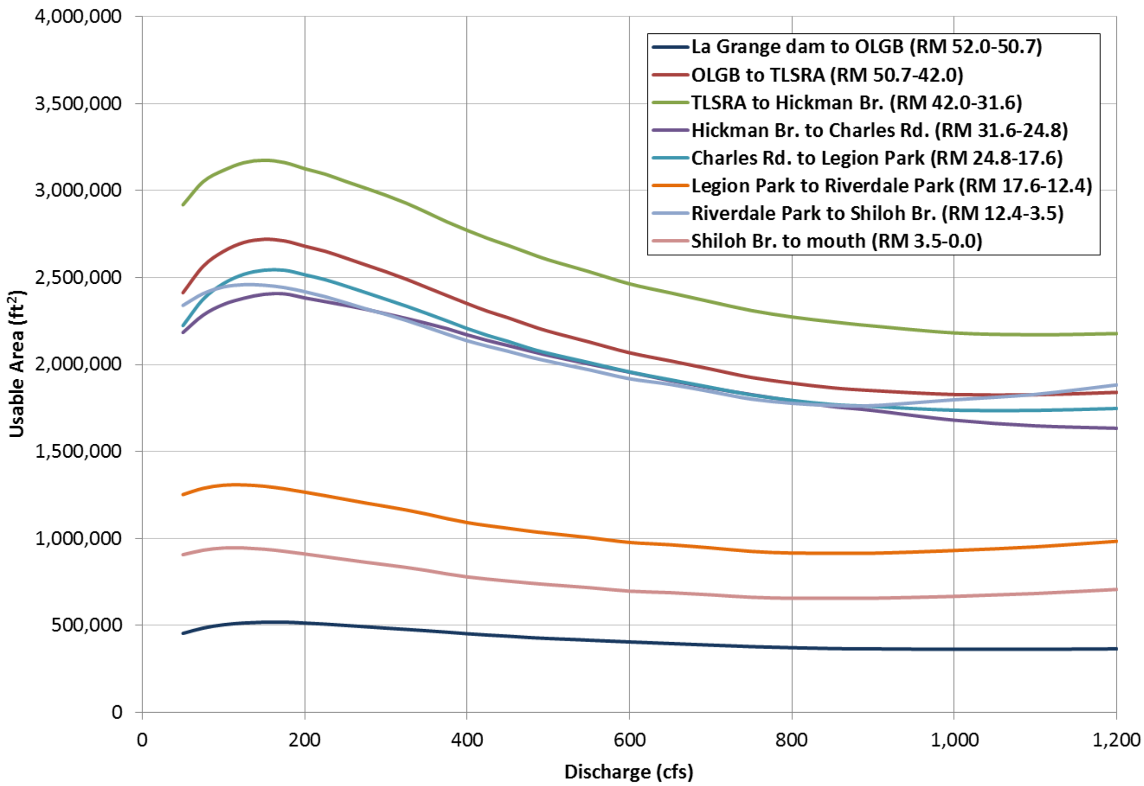

Figure 4.1-7. Variation of usable juvenile rearing area estimates with discharge for *O. mykiss* in sub-reaches of the lower Tuolumne River.

In order to represent juvenile rearing habitat use of overbank habitat occurring at higher flows, the usable habitat estimates for study sites evaluated using 2D modeling for the *Pulse Flow Study Report* (Stillwater Sciences 2012a) were expanded in proportion to overbank inundation occurring on a river-wide basis (Figures 4.1.-8 and 4.1-9) 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 and 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 4.1-8 and 4.1-9 as well as whether those results alter model predictions, the results of this study may be updated at that time.

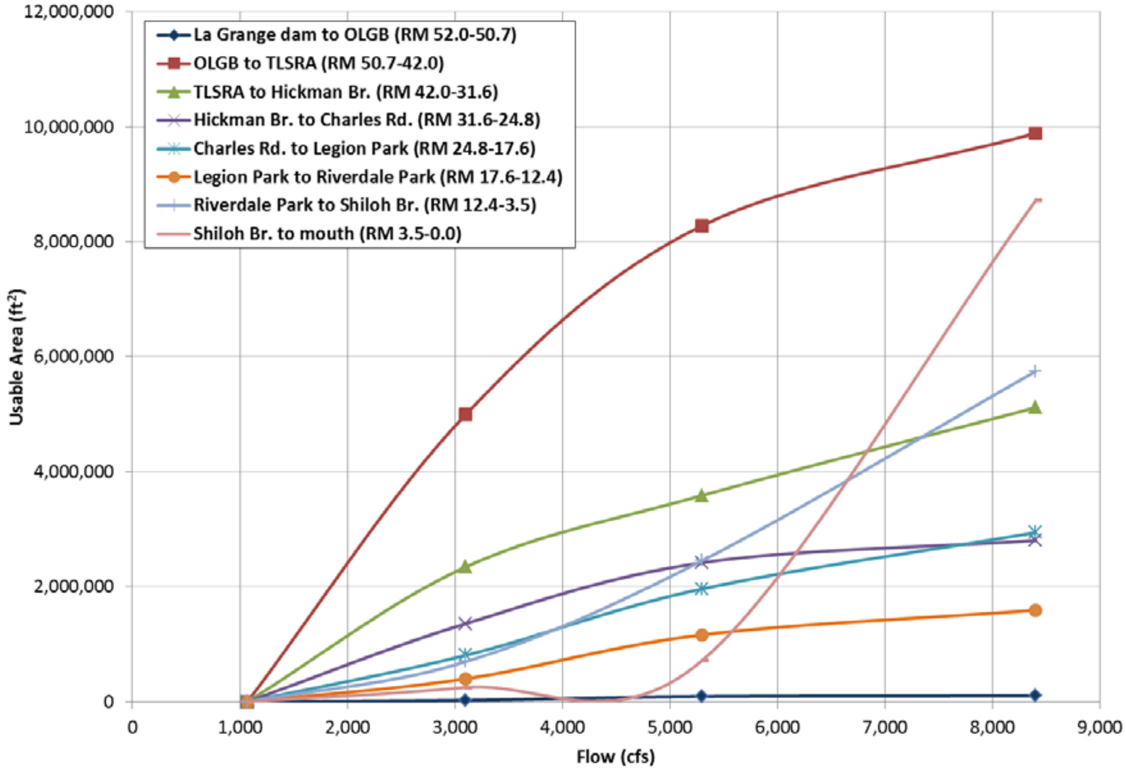

Figure 4.1-8. **Estimated total usable overbank habitat for Tuolumne River *O. mykiss* juveniles.**

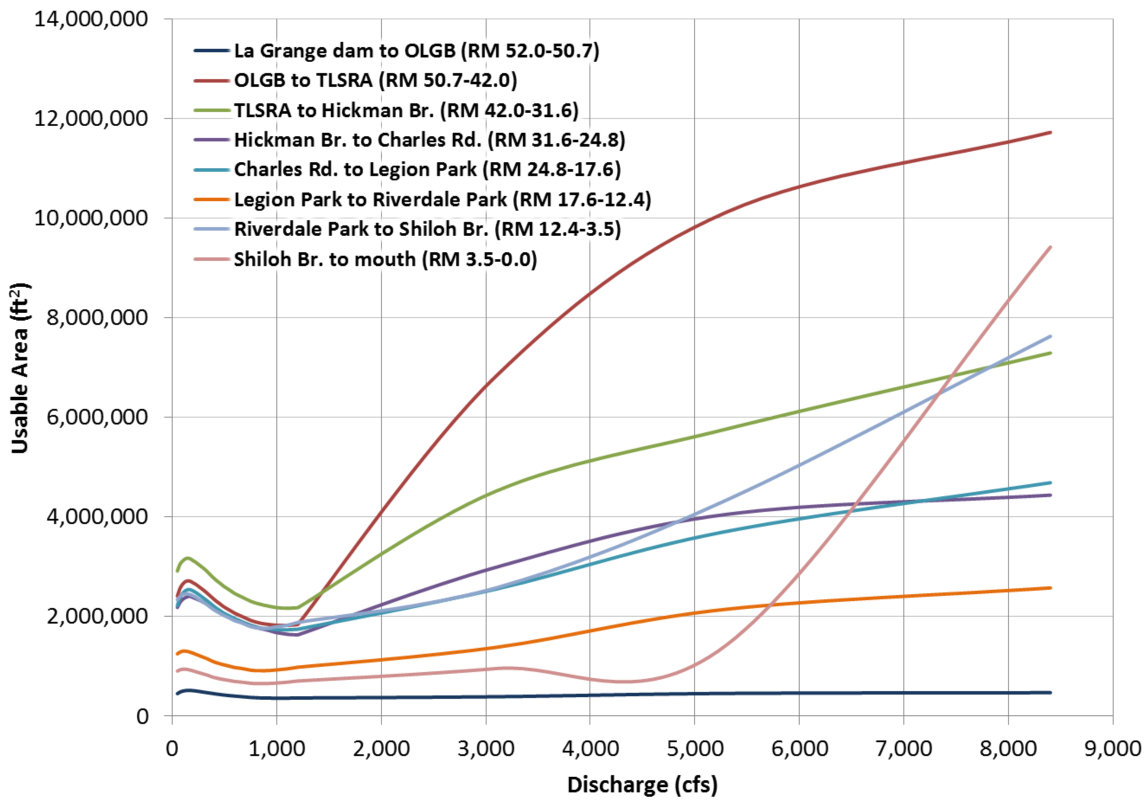

Figure 4.1-9 **Estimated total combined usable in-river and overbank habitat for Tuolumne River *O. mykiss* juveniles.**

4.1.4.2 Juvenile Movement

Estimates of movement during the juvenile *O. mykiss* rearing period uses the same methods as applied to fry (Section 4.1.3.2), which were drawn from biweekly Chinook salmon seining data used for juvenile movement estimates as part of the *Chinook Salmon Population Model Study* (W&AR-06). Juvenile movements are represented as low daily movement probability of 0.01 d^{-1} followed by a movement period of 2 hrs, with distance travelled calculated from Equation 3. 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.

As assumed for fry, displacement of *O. mykiss* juveniles in excess of carrying capacity into downstream habitats may subject these fish to unsuitable water temperatures during summer. Some studies have shown avoidance of habitats with water temperatures as high as 24°C (75°F) (Myrick and Cech 2001) and studies investigating the effects of geothermal influences on stream temperatures on *O. mykiss* (Kaeding 1996; Kubicheck and Price 1976) indicate that juvenile *O .mykiss* may seek out cooler tributary habitats to avoid high summer water temperatures. Hay (2004) concluded that seeking out local thermal *refugia* as well as larger scale upstream movements in response to high water temperatures are broadly observed in stream fishes including *O. mykiss*. However, the current model does not include any avoidance of high water temperature by parr. Age 0+ juveniles are assumed to have limited ability to move upstream, thus, displacement into downstream habitats during spring may subject these fish to subsequent temperature related mortality (Section 4.1.4.4) during summer. However, to account for greater swimming ability of larger juvenile size classes relative to fry, all Age 0+ juveniles are assumed to move according to adult movement rules after October 1st (Section 4.1.5.2).

4.1.4.3 Juvenile Growth

Juvenile *O. mykiss* growth for parr-sized fish (50–149 mm FL) in the lower Tuolumne River is represented in the same manner as for fry (Equation 4) on the basis of the growth model by Satterthwaite et al. (2009). Initial estimates of reach-specific food availability, as represented by the energy consumption term kappa (κ) in Equation 4, are used in combination with daily water temperature to model growth, with final parameter fitting used to match observed inter-annual growth rates documented in the *O. mykiss Scale Collection and Age Determination Study* (W&AR-20).

4.1.4.4 Juvenile Mortality

Potential mortality sources to juveniles include predation effects due to the relative habitat availability for predators and juvenile *O. mykiss*, as well as due to high water temperatures. Predation mortality for juveniles is represented in the same manner as for fry (Equation 5) for any fish excluded from habitat areas in excess of carrying capacity (Section 4.1.4.2). Based upon literature reviews by Myrick and Cech (2001), UUILT for *O. mykiss* juveniles has been estimated at 22.8–25.9ºC (73–79°F) (Threader and Houston 1983). In the model, an initial mortality threshold of 25°C (77°F) daily average temperature was selected for *O. mykiss* juveniles.

Lastly, although no data are available to provide an estimate for the Tuolumne River, a background mortality rate 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). Initial parameter estimates from the *Chinook Salmon Population Model Study* (W&AR-06) were adjusted as a fitting parameter to produce a stable *O. mykiss* population size in the calibrated model (Section 4.4).

4.1.5 Resident Rearing

4.1.5.1 Adult Habitat Use

As rearing *O. mykiss* juveniles pass from Age 0+ to Age 1+ fish at approximately 150 mm FL as validated by the *O. mykiss Scale Collection and Age Determination Study* (W&AR-20), they are considered adults for the purposes of modeling. As summarized in the Synthesis Study (W&AR-05), habitat use by *O. mykiss* is generally restricted to upstream locations with the exception of isolated detections of *O. mykiss* passage at the RM 24.5 counting weir (TID/MID 2013, Report 2012-6) as well as in routine RST sampling (TID/MID 2013, Report 2012-6). Adult-sized fish (280 mm TL) were documented as far downstream as RM 31.5 in November 2011 (TID/MID 2012, Report 2011-5) and individual *O. mykiss* were observed as far downstream of RM 29.5 during intensive snorkel surveys conducted in 2009 (Stillwater Sciences 2009) and 2010 (Stillwater Sciences 2011). Based upon these observations, routine habitat use by adults downstream of Hickman Bridge (RM 31.6) is considered unlikely.

Following the same rationale for predicting fry and juvenile habitat use (Sections 4.1.3.1 and 4.1.4.1), usable habitat area estimates for in-channel rearing of *O. mykiss* adults (Age 1+ to Age 4+) are represented as a function of flow (Figure 4.1-10) using habitat suitability criteria presented in the *Lower Tuolumne River Instream Flow Study* (Stillwater Sciences 2013). Reach-specific estimates of carrying capacity are calculated on the basis of usable habitat (Figure 4.1-10) and the maximum attainable densities under optimum habitat conditions. The maximum attainable adult rearing density is estimated at 0.01 adults/ft^2 based upon territory size estimates at adult sizes (300 mm FL[2]) using relationships by Grant and Kramer (1990). Lastly, because *O. mykiss* adults generally seek deeper habitats with higher velocities (Stillwater Sciences 2013) and that little evidence of floodplain habitat use by adults exists, habitat use in overbank habitats is not included in the model.

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[2] 300 mm FL corresponds to approximately Age 3+ adults in 2012 hook and line sampling conducted for the *O. mykiss Scale Collection and Age Determination Study* (W&AR-20).

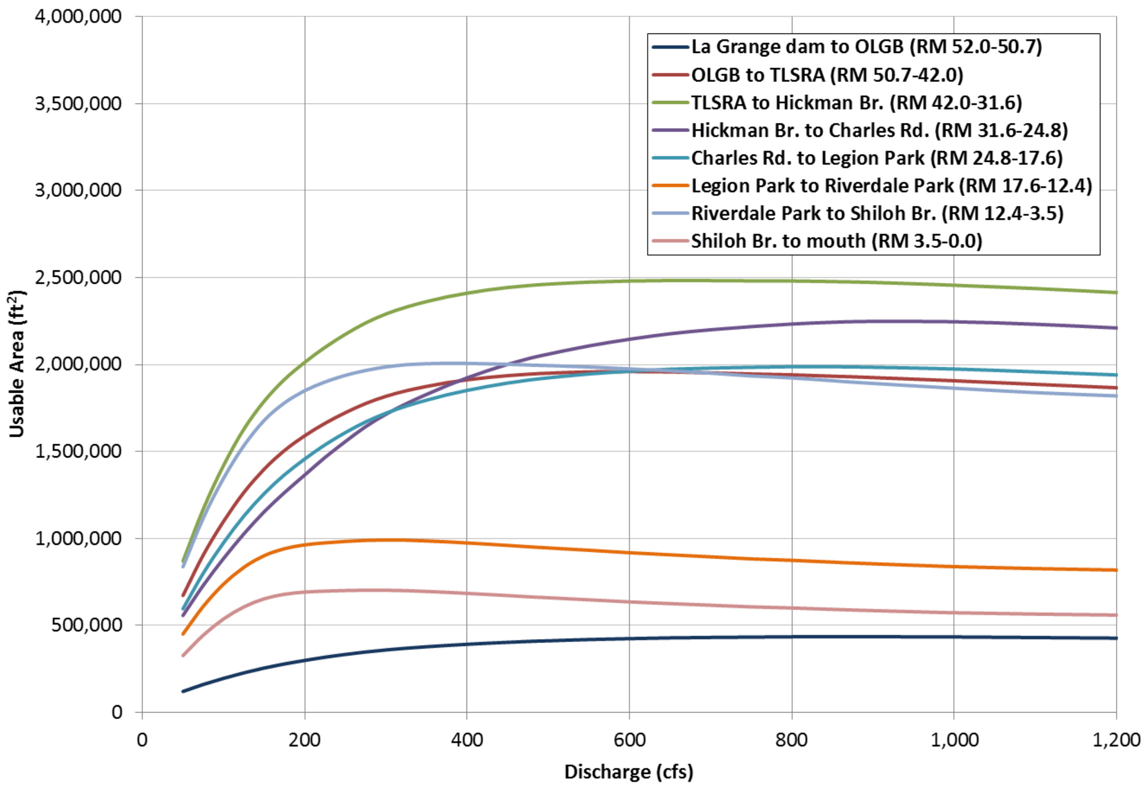

Figure 4.1-10. Variation of usable adult rearing area estimates with discharge for *O. mykiss* in sub-reaches of the lower Tuolumne River.

4.1.5.2 Adult Movement

Because *O. mykiss* are territorial (Grant and Kramer 1990) and little adult movement was documented as part of the *Tuolumne River O. mykiss Acoustic Tracking Study* (FISHBIO 2012), movement of adults is limited to circumstances when rearing densities are in excess of reach-specific carrying capacities. The maximum attainable density in the Tuolumne River is estimated at 0.5 adults/m^2 based upon territory size relationships for larger juveniles summarized by Grant and Kramer (1990). For areas with adult densities in excess of habitat carrying capacity on the basis of usable area estimates (Figure 4.1-10) and the density estimates above, adults are modeled to seek out new territories that may potentially contain additional carrying capacity. Although we have assumed fry and juvenile *O. mykiss* may not actively swim upstream to avoid unsuitable water temperatures during summer (Sections 4.1.3.2 and 4.1.4.2), because some studies have shown avoidance of habitats with unsuitable temperatures (Myrick and Cech 2001), habitat avoidance by adults is modeled as a Thornton and Lessem (1978) preference function (Equation 6).

$$\Psi(T) = \frac{K_1 e^{\gamma_1 (T-\theta_1)}}{1+K_1(e^{\gamma_1(T-\theta_1)}-1)} \frac{K_4 e^{\gamma_2(\theta_4 - T)}}{1+K_4(e^{\gamma_2(\theta_4-T)}-1)}, \text{ where}$$

Equation 6

$$\gamma_1 = \frac{1}{\theta_2-\theta_1} \ln \frac{K_2(1-K_1)}{K_1(1-K_2)}, \text{ and } \gamma_2 = \frac{1}{\theta_4-\theta_3} \ln \frac{K_3(1-K_4)}{K_4(1-K_3)}.$$

The function $\Psi(T)$ describes preference as the product of two sigmoid curves: one curve is fit to the increasing portion of the temperature dependence function (γ_1 by parameters θ_1, θ_2, K_1, and K_2), and the other to the decreasing portion (γ_2 by parameters θ_3, θ_4, K_3, and K_4). Parameter values were selected to bound temperature preferences representing upper temperature limits (K_4=0.01 at θ_4=24°C [75°F]) as well as lower temperature limits (K_1=0.1 at θ_1=8°C [46°F]) summarized by Myrick and Cech (2001) from Cherry et al. (1975) with preferred temperature ranges (K_2,K_3 ≈ 1.0) between temperatures of θ_2=12°C (53.6°F) and θ_3=20°C (68°F), respectively (Figure 4.1-11). Although avoidance of habitats on the basis of low temperatures is not expected at ambient winter-time temperatures in the lower Tuolumne River, the upper temperature limit is consistent with the highest temperatures observed corresponding to observations of *O. mykiss* individuals >149 mm FL during intensive snorkel surveys in July of 2008 (Stillwater Sciences 2008).

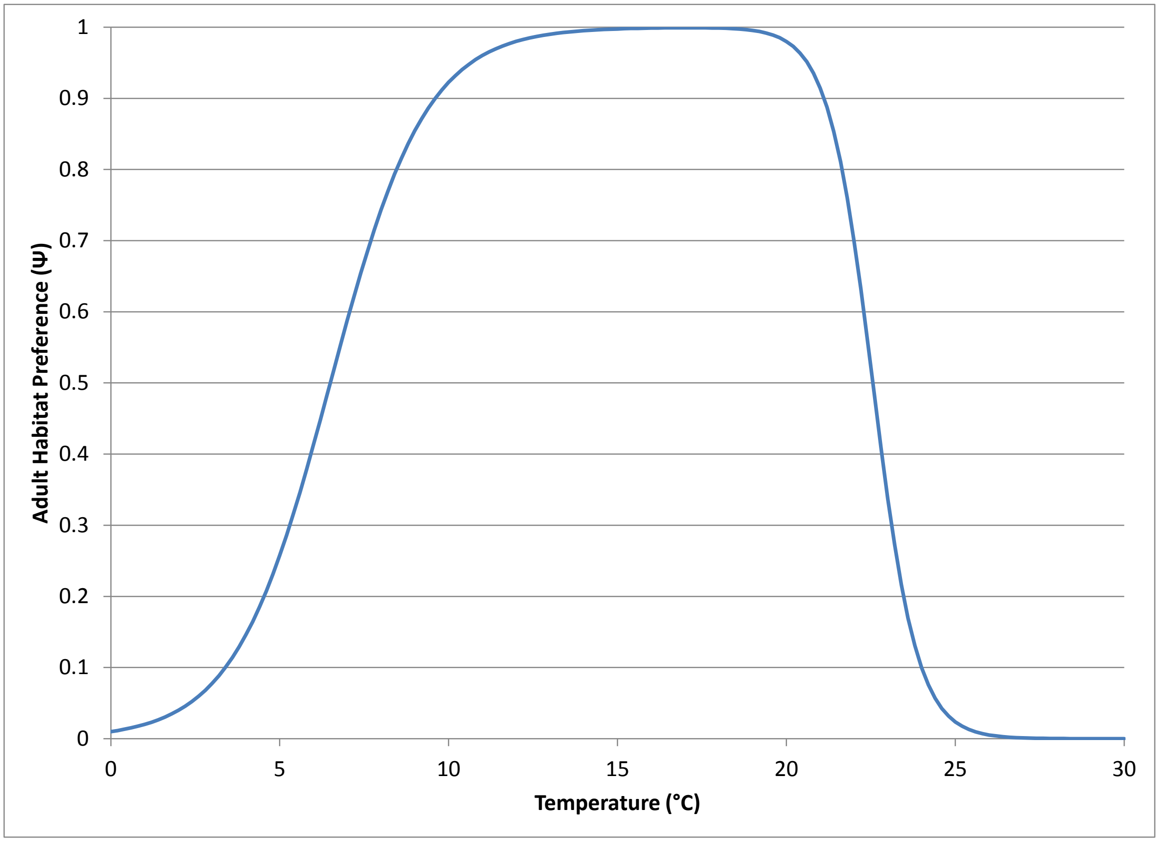

Figure 4.1-11. Adult *O. mykiss* rearing habitat preference with temperature using a Thornton-Lessem (1978) function

4.1.5.3 Adult Growth

O. mykiss growth for adult-sized fish (>149 mm FL) in the lower Tuolumne River is represented in the same manner as for fry (Equation 4) on the basis of the growth model by Satterthwaite et al. (2009). Growth rate can vary depending on the ultimate age of maturation and after the maturation process is initiated as energy is increasingly diverted away from somatic growth and into gonadal growth. Initial estimates of reach-specific food availability, as represented by the energy consumption term kappa (**κ**) in Equation 4, are used in combination with daily water temperature to model growth, with final parameter fitting used to match observed inter-annual growth rates documented in the *O. mykiss Scale Collection and Age Determination Study* (W&AR-20). Due to increased energy demands by the developing gonadal tissues, lower growth rates by a factor of 0.83 are applied within any growth year that females reach sexual maturity and a life-history "decision" to spawn (Satterthwaite et al. 2009). Lastly, to match observations of increased growth rates leading to smoltification by steelhead (Beakes et al. 2010), higher growth rates by a factor of 1.10 are applied in Equation 4 in growth years which adults reach a smolting decision (Section 4.1.6).

4.1.5.4 Adult Mortality

As summarized in the Synthesis Study (W&AR-05), potential mortality of *O. mykiss* adults is primarily related to high water temperatures in downstream locations. Because the size of the prey that can be eaten is determined in large part by predator mouth size (gape) (Hoyle and Keast 1987 as cited in Mittelbach and Persson 1998), prey are vulnerable to an increasingly narrow size range of predators (i.e., only larger predators) as they grow. Swimming ability also increases with size so that Age 1+ and older *O. mykiss* can be assumed to avoid predators more successfully than can salmonids of smaller size classes. An initial mortality threshold of 25°C (77°F) daily average temperature was selected for *O. mykiss* adults on the basis of literature reviews by Myrick and Cech (2001).

Lastly, although no data are available to provide an estimate for the Tuolumne River, a background mortality rate is applied to account for potential mortality due to other causes that may not be well represented in the model (e.g., disease, stranding, and hooking mortality). Initial parameter estimates from the *Chinook Salmon Population Model Study* (W&AR-06) were adjusted as a fitting parameter to produce a stable *O. mykiss* population size in the calibrated model (Section 4.4).

4.1.6 Anadromous Life History Strategy

As discussed in the Synthesis Study (W&AR-05), *O. mykiss* exhibit the most complex life history variation of all *Oncorhynchus* species (Quinn 2005). The expression of a given life history in a population or for a specific individual has been shown to be determined by both genetic (Martyniuk et al. 2003; Beakes et al. 2010; Thrower et al. 2004) and environmental (Zimmerman and Reeves 2000; Sloat 2013; McMillan et al. 2012; Beakes et al. 2010) factors. Population modeling of *O. mykiss* therefore requires considering the influence of factors such as parentage, age, size, growth, and temperature in determining the expression of anadromous versus resident life histories (Satterthwaite et al. 2009). In addition, the low survival of any emigrating smolts, among other factors, can contribute to predominantly resident variants in a population either separate from or combination with genetic predisposition towards residency (Beakes et al. 2010; Satterthwaite et al. 2010). As summarized in the Synthesis Study, recent otolith analysis in the Tuolumne River (Zimmerman et al. 2009) indicates very low numbers and proportions of fish with anadromous life histories; nonetheless, modeling the factors potentially affecting expression of residency versus anadromy, including smoltification, is important for assessing the potential effects of current or future Project operations.

4.1.6.1 Growth Variations for Anadromous and Resident *O. mykiss*

As summarized in the Synthesis Study (W&AR-05), growth of juvenile salmonids varies depending on location and the associated spatial and temporal specific levels of food, competition, and the water temperatures. Fry and juvenile growth (Sections 4.1.3.3 and 4.1.4.3) can influence life-history expression but genetically controlled life-history variants also have specific growth trajectories, which can interact with environmental conditions (Beakes et al. 2010; Satterthwaite et al. 2010; Yoshiyama and Moyle 2012) and with changes in growth rates occurring as fish move from one life-stage into the next.

Modeling growth for juvenile life stages requires accounting for standard bioenergetic variables (e.g., water temperature, size, food rations), and also for the effects of these parameters upon smoltification and sexual maturation. For example, individual fish destined to smolt and follow an anadromous life-history have been shown to exhibit faster growth rates and development rates from the earliest life-stages (Beakes et al. 2010) and yet not all fast growing members of a cohort will smolt and enter into anadromy (Yoshiyama and Moyle 2012; Sloat 2013). Although Beakes et al. (2010) were able to show growth rate increases for future smolts of near 50 percent when compared to resident *O. mykiss* maintained at the same water temperatures and under high food ration, we have assumed that fish undergoing smoltification grow faster than resident *O. mykiss* by a factor of 1.10 approximately 6-months in advance of smoltification and emigration (Section 4.2.5). Lastly, studies have shown that for resident *O. mykiss* adults reaching minimum sizes for engaging in piscivory, the increased food resource availability represented by Chinook salmon juveniles could potentially favor a resident life-history (Naman and Sharpe 2012).

4.1.6.2 Smolt Transformation

Salmon and anadromous *O. mykiss* undergo a physiological transformation prior to and during emigration to the ocean, which prepares them for migration and ocean rearing in salt water (Quinn 2005). Although the timing and fish size at smolting has strong ramifications for survival during emigration and early ocean life (Wedemeyer et al. 1980), because of the low occurrence of steelhead on the Tuolumne River (Zimmerman et al. 2009) and complexities in determining which factors may select for preferential selection of anadromy (Yoshiyama and Moyle 2012), we do not attempt to represent the influence of all factors potentially influencing smoltification. For example, the process, timing, and triggers for smoltification in salmonids has been shown to be influenced by variety of genetic and environmental factors including parentage and population of origin (Høgåsen 1998), water temperature (Myrick and Cech 2001, Zaugg and Wagner 1973), growth rate and size (Beakes et al. 2010), photoperiod (Thorarensen and Clarke 1989), lunar phase (Grau et al. 1981), as well as interactions between a number of these factors (Ewing et al. 1979; Clarke and Shelbourn 1985; Zaugg et al. 1986; Beakes et al. 2010). Based upon review of this information, the assumed smoltification timing from the Stanislaus River (Table 3.0-1) reflects both genetically controlled adaptations to longer term-average conditions throughout the species range as well as local adaptations to inter-annual environmental variability.

For the purposes of this study, the probability of smolting is modeled on the basis of age as well as parentage determined by spawning parentage between resident and anadromous pairings (Section 4.1.1.3). Although pure anadromous pairings generally results in high smolting rates (Courter et al. 2009), there are few studies available that have determined the probability of smoltification as a function of anadromous versus resident parentage. Such studies have started to reduce but have not eliminated uncertainty regarding the probability of anadromy in primarily resident *O. mykiss* populations, which appear to vary based upon both genetic and environmental determinants. For example, Courter et al. (2013) used otolith analysis to determine that 7–20 percent of returning adult steelhead had resident female parentage in the Yakima River. However, this was a basin wide average and sub-basin proportions ranged from 2–26 percent with some sub-basins showing very little annual variation with others showed a high amount of annual variability. Because of lack of Tuolumne River specific information regarding smoltification resulting from pure resident pairings we have assumed very low rates of anadromy from resident parents, on the order of 2 percent (Section 4.2.5).

For individuals predicted to undergo smoltification, water temperatures must be below identified thresholds to avoid impairment of smoltification. These thresholds have been shown to be species-specific (McCullough et al. 2001), and in the case of *O. mykiss* has been shown to range from 12–15°C (53.6-59°F) (Zaugg and Wagner 1973; Adams et al. 1973; Zaugg 1981; Hoar 1988). Although desmoltification has been shown to occur in some steelhead populations (Folmar et al. 1982) at temperatures of 13–15°C (55.4-59°F)(McCullough et al. 2001), desmoltification is not represented in the model. The rationale for this decision is that for any emigrant smolt there is always a high potential for exposure to elevated temperatures as the fish travels downstream, and thus the effect of imposing a desmoltification temperature is the same as setting a lower smoltification threshold. On this basis, an upper water temperature limit for smoltification of 12°C (53.6°F) daily average temperature was selected, consistent with recommendations by Richter and Kolmes (2005).

4.1.6.3 Smolt Emigration and Mortality Sources

Smolt emigration speeds are relatively fast, as smolting reduces feeding activity and increases migratory behaviors such as preferentially selecting main currents as opposed to edge water. Emigration speeds are typically estimated as a function of discharge (Giorgi et al. 1997; Michel et al. 2012). Although no migration rates are available for the Tuolumne River, emigration rates of tagged fish on the Mokelumne River have been estimated to vary by as much as 0.2–60 miles per day (Del Real et al. 2012).

Potential mortality sources to emigrant steelhead smolts include predation effects due to the relative habitat availability for predators, as well as due to high water temperatures in downstream locations. A positive relationship with smolt survival and emigration rate has been found in multiple settings, partly reflecting the influence of exposure to piscivorous predators (Petrosky and Schaller 2010). As discussed for adults (Section 4.1.4.3), because of gape limitations of predators and increased swimming ability of smolts with size, the relatively large Age 1+ and Age 2+ smolts resulting from steelhead can be assumed to avoid predators more successfully than Chinook salmon smolts that are typically much smaller. Fish emigrating at larger sizes (Age 3+ and older) are even less likely to be susceptible to predators. An initial mortality threshold of 25°C (77°F) daily average temperature was selected for *O. mykiss* smolts on the basis of literature reviews by Myrick and Cech (2001). Lastly, although no data are available to provide an estimate for the Tuolumne River, a background mortality rate of 0.002 d^{-1} is applied to account for potential mortality due to other causes that may not be well represented in the model (e.g., disease, stranding, avian predation, hooking mortality, and entrainment).

4.2 Model Implementation

The Tuolumne River *O. mykiss* population model (TROm) 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.

Figure 4.2-1 shows the TROm model representation of the in-river portions of the overall *O. mykiss* life history (Figure 3.0-1). Ellipses represent particular life stages (e.g., swim-up fry, parr, etc.), with connecting arrows representing stock-production relations ("life stanzas") regulating progression from one life stage to the next. The model begins with a starting population of in-river residents on October 1st of each water year, with the Adult Upmigration and Spawning sub-model simulating spawning by residents as well as any anadromous spawners assumed to arrive at the counting weir (RM 24.5). The Egg Incubation sub-model starts with the numbers of eggs in completed redds predicted by the preceding spawning sub-model and determines the number of swim-up fry. The Fry Rearing sub-model determines the number of parr as well as tracking any dead fry, whereas the Juvenile Rearing model determines the number of Age 0+ residents to be promoted to adults in the following year in a separate "assembly" step between these fish and remaining adult residents. In addition to determining the number of adult residents remaining at the end of the model year on September 30th, the Resident Rearing sub-model determines the potential numbers of resident spawners and emigrant smolts in the next model year.

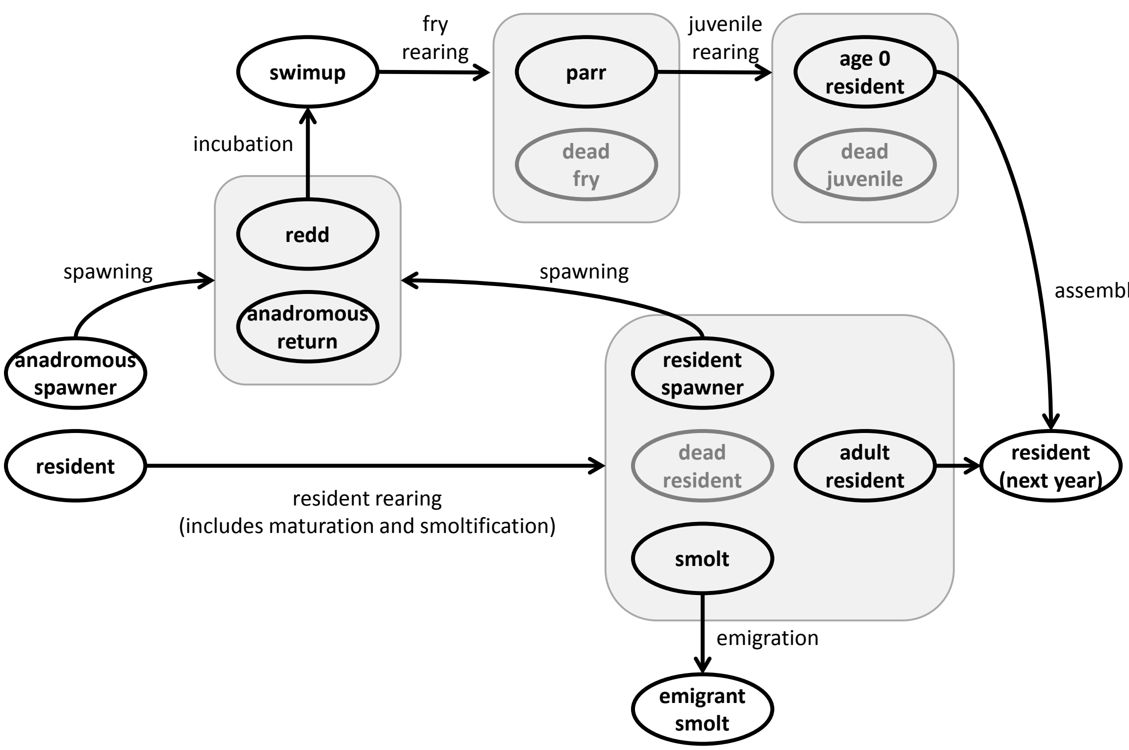

Figure 4.2-1. TROm model representation of the in-river portions of the overall *O. mykiss* life history in the Tuolumne River

Except for the final "assembly" step, all the relations shown in Figure 4.2-1 are implemented as individual-based sub-models 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. 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 C-1 (Attachment C). However, because the numbers of individuals within the fry and juvenile 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 and 10,000 parr.

The model includes random elements for many mechanisms affecting life history progression, relying on probability distributions for events such as age-based probability of spawning within a particular model year, spawning timing, spawning locations, juvenile and adult movements, and smoltification, as well as predation related mortality. 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 interpolated discharge and water temperature estimates at more specific locations and times. 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 C, Table C-2), which comprises 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.

The stock-production models developed for each life stage are discussed in the following sections, organized by life history progression in Section 4.1.

4.2.1 Adult Upmigration and Spawning

The Adult Upmigration and Spawning stock-production model draws a spawner population from both the resident adult population (Section 4.2.5) and any steelhead potentially arriving at the weir (RM 24.5). This model then simulates redd construction and returns a redd life stage and an anadromous return life stage (Figure 4.2-1), drawing upon information from the following sources:

(1) spawner population data from the Resident Rearing stock-production model as well as actual or assumed RM 24.5 weir count information on steelhead spawners,
(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
spawning.day	152	peak activity as days from October 1st	Table 3-1 activity based on NMFS 2009
	15	standard deviation of peak activity	
	93	date of 1st spawning from October 1st	
	213	date of last spawning from October 1st	
spawning.duration	1–30 days (7 days)	time required for spawners to travel to spawning habitat, build redds, and for kelts to return to rearing or emigrate	Shapovalov and Taft 1954
resident.fidelity	10	ratio of probabilities describing whether a female of a particular origin will allow her eggs to be fertilized by either a resident or anadromous males.	Table 4-1, McMillan et al. 2007
anadromous.fidelity	10		
fecundity.bylength	0.007236	base of power law relationship between number of eggs produced and fork length of female spawner	Equation 2 from Shapovalov and Taft 1954, and Satterthwaite et al. 2009
	2.1169	exponent of power law relationship	
spawn.wtemp.max	15°C (59°F)	maximum temperature at which spawning habitat is considered usable by spawners	Velsen (1987), and Rombough (1988)
redd.disturb.area	8–47 ft² (9.2 ft²)	area of region excavated by a spawning female	*Redd Mapping Study* (W&AR-08), Hunter 1973, Reiser and White 1981, Hannon and Deason 2005
redd.defense.area	32–188 ft² (37 ft²)	defended area excluding later arriving spawners (~ 4x redd disturbance area)	Burner, 1951
redd.defense.time	1–2 days (2 days)	time female will prevent other spawners from disturbing her redd	Bjornn 1991, Briggs 1953
residentF.postspawn.survival	0.55	resident female survival through spawning event	Courter et al. 2009
residentM.postspawn.survival	0.55	resident male survival through spawning event	
anadromousF.postspawn.survival	0.42	anadromous female survival through spawning event	Satterthwaite et al. 2009
anadromousM.postspawn.survival	0.42	anadromous male survival through spawning event	

The spawning habitat generator defines the suitability of spawning habitat at a specific location and time. Using functional relationships described in Section 4.1.1.2, the spawning habitat sub-model calculates temporally and spatially varying availability of suitable spawning gravels and assigns spawner usage probability based upon variations in discharge, water temperature, areas of suitable gravel, gravel quality, and spawner preferences by river mile.

The model receives a "spawning run" drawn from individuals of the resident rearing population on the basis of age and parentage (Section 4.2.5) as well as any steelhead assumed to arrive at the counting weir (RM 24.5). Migration rates are not represented in this model and any spawners are assumed to arrive at preferred habitat locations within 1-2 days of arriving at the counting weir. 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. Once a spawner reaches its assigned feature, it is assumed to stay there. Male spawners are assumed to mate with females based upon the probability of cross-ecotype spawning (Table 4.1-1) and associated spawning fidelity parameters (Table 4.2-1).

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.

Mortality during migration to the assigned feature is assumed to be negligible (Section 4.1.1.4). After the spawning duration of 7 days, post-spawn survival was initially assumed to be 55 percent for all resident *O. mykiss* spawners (Courter et al. 2009), and 42 percent for all steelhead spawners (Satterthwaite et al. 2009). The final post-spawn mortality rates were used as a model calibration parameter (Section 4.3) to allow fitting to observed size class structure in recent population surveys. Post-spawn anadromous survivors are accounted for in the anadromous return life stage. The eggs of a spawning female are assigned to her redd according to Equation 2 and associated fecundity parameters (Table 4.2-1).

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 (Figure 4.2-1). 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
embryo.uuilt	15–16°C (15 °C)	temperature at which mortality increases from 0% to 100%	McCullough et al. 2001; Myrick and Cech 2001

Parameter	Range (selected value)	Description	Reference
embryo.atu	600–722 ATU°C (647 ATU °C)	accumulated thermal units (degree days) for incubation to emergence	Campbell et al. 2008; Burton and Little 1997
embryo.survival	0–100% (45%)	egg survival to fry emergence due to gravel quality effects upon intra-gravel conditions	TID/MID 1992, App. 8; Tappel and Bjornn 1983

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 fry life stage into a juvenile (i.e., parr) life stage or a dead fry life stage (Figure 4.2-1). 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	20–30 mm (24 mm)	fork-length at swim-up	Shapovalov and Taft 1954; Satterthwaite et al. 2009
fry.emigrate.p	0.3	fraction of swim-up fry assumed to leave the river entirely	Based upon early Chinook fry estimate for W&AR-06 study (TID/MID unpublished)
fry.displace.rate	0.1 days^{-1}	instantaneous rate at which fish will become displaced	Based upon Chinook fry movement estimates fitted to seine/RST data for W&AR-06 study (TID/MID unpublished)
fry.displace.time.mean	0.02 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	
fry.density	1.1 fry/ft^2	maximum fry rearing density up to parr transition at 50 mm FL	Grant and Kramer 1990, Keeley 1998

Parameter	Range (selected value)	Description	Reference
fry.kappa.mult	0–4 (1.7)	foraging activity level needed for a fish to reach half its maximum daily energy consumption.	Satterthwaite et al. 2009 estimates calibrated to *O. mykiss* growth study (W&AR-20) data
fry.migr.mrate	2.704 days^{-1}	mortality rate applied to fry moving downstream	Based upon Chinook fry mortality estimate for W&AR-06 study
fry.mrate	0.02 days^{-1}	mortality rate applied to all fry	Bartholow and Henriksen 2006
fry.uuilt	23–26°C (25°C)	temperature at which mortality increases from 0% to 100%	Threader and Houston 1983; Myrick and Cech 2001
length.parr	50 mm	fork-length at parr	Operational size class definition

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 energy consumption rates 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, energy consumption rates, fry densities, and flow-dependent velocities and usable habitat areas. It receives discharge and water temperature values from the discharge and water temperature module. Using relationships discussed in Section 4.1.3, the model simulates fry growth at a daily time 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 are assumed to emigrate from the river entirely. This fraction is given by the parameter "fry.emigrate.p." 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 which is implemented as a log-normal deviate whose mean and coefficient of variation are provided by the user (as parameters "fry.displace.time.mean" and "fry.displace.time.CV", respectively).

Mortality of *O. mykiss* fry during any movements or redistribution is simulated based upon potential exposure to predation and excessive temperatures. 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 immediate death if temperatures exceed a critical value. In addition to water temperature (Table 4.2-4), reach-specific estimates of mortality probability per unit time are based upon estimates from Chinook fry passage at the upstream and downstream RSTs developed for the *Chinook Salmon*

Population Model Study (W&AR-06). 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 resident juvenile life stage or a dead juvenile life stage (Figure 4.2-1). This stock-production model tracks groups of juveniles from their promotion to parr status until they emigrate out of the system, attain resident juvenile status, or die through predation or water temperature related mortality. 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	Range (selected value)	Description	Reference
juv.displace.rate	0.01 days^{-1}	instantaneous rate at which fish will become displaced	Based upon Chinook juvenile movement estimates fitted to seine/RST data for W&AR-06 study (TID/MID unpublished)
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	0.06 juveniles/ft^2	maximum juvenile rearing density at Age 1+ (approx. 150 mm FL)	Grant and Kramer 1990, Keeley 1998
juvenile.kappa.mult	0–4 (1.5)	foraging activity level needed for a fish to reach half its maximum daily energy consumption.	Satterthwaite et al. 2009 estimates calibrated to *O. mykiss* growth study (W&AR-20) data
juvenile.uuilt	23–26°C (25°C)	temperature at which mortality increases from 0% to 100%	Threader and Houston 1983; Myrick and Cech 2001
juvenile.migr.mrate	0.14 days^{-1}	aquatic predation rate due to downstream movement	Calibration parameters based upon mortality estimate for Chinook study (W&AR-06)
juvenile.mrate	0.017 days^{-1}	background mortality rate due to disease, stranding, avian predation, and entrainment	
age0.fraction.female	0.5	fraction of juvenile rearing population that is female	Shapovalov and Taft 1954

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, energy consumption rates, maximum fry and juvenile densities, as well as flow-dependent usable habitat areas by reach. It receives discharge and water temperature values from the discharge and water temperature module. The model predicts locations of rearing juveniles and tracks their daily growth rates using growth relationships, water temperature and estimates of energy consumption rates (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 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 mechanism that is only represented when habitat rearing capacity is exceeded (Section 4.1.4). The model tracks the redistribution of juveniles on the basis of discharge and habitat usage. 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 which is implemented as a log-normal deviate whose mean and coefficient of variation are provided by the user (as parameters "juv.displace.time.mean" and "juv.displace.time.CV", respectively).

Mortality of juveniles during any movements or redistribution is simulated based upon potential exposure to predation and excessive temperatures, with dead individuals passed into the dead juvenile life stage. In addition to water temperature (Table 4.2-4), reach-specific estimates of mortality probability per unit time are used as model calibration parameters (Section 4.3) using initial estimates the interrelated *Chinook Salmon Population Model Study* (W&AR-06).

4.2.5 Resident Rearing

The Resident Rearing stock-production model follows the progression of either resident or anadromous *O. mykiss* into a smolt life stage, a resident spawner life stage, a resident life stage to be promoted into the next year class, or a dead resident life stage used to track any mortality (Figure 4.2-1). Age-classes represented on October 1st include the population of Age 0+ residents to be promoted to Age 1+ fish on January 1st as well as Age 2+ and older fish to be promoted to the next year classes as well as to potential smolt emigrants (Section 4.2.6). 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,
(3) the resident habitat generator, and
(4) a list of parameters (Table 4.2-5).

Table 4.2-5. Parameters and associated references for resident rearing.

Parameter	Range (selected value)	Description	Reference
adult.density	0.01 adults/ft^2	maximum adult rearing density at Age 3+ (approx. 300 mm FL)	Grant and Kramer 1990, Keeley 1998
adult.kappa	1.31, Age 0+	age-specific foraging activity level needed for a fish to reach half its maximum daily energy consumption.	Satterthwaite et al. 2009 estimates calibrated to age-specific growth data from *O. mykiss* growth study (W&AR-20)
	1.16, Age 1+		
	0.90, Age 2+		
	0.73. Age 3+		
	0.62, Age 4+		
maturation.growth.factor	0.83	scaling for reduced within-year growth rates by maturing fish	Satterthwaite et al. 2009

Parameter	Range (selected value)	Description	Reference
smolting.growth.factor	1.10	scaling for increased within-year growth rates by smolting fish	Beakes et al. 2010
adult.wtemp.TL	0.0°C, 0.01	probability of habitat use by adults at four temperatures for use in Thornton and Lessem (1978) preference function	McCullough et al. 2001; Myrick and Cech 2001
	12°C, 0.98		
	20°C, 0.98		
	24°C. 0.10		
adult.uuilt	23–26°C (25°C)	temperature at which mortality increases from 0% to 100%	Threader and Houston 1983; Myrick and Cech 2001
adult.mrate	0.01, Age 0+	background mortality rate (days^{-1}) due to disease, stranding, hooking mortality, and entrainment	Calibration parameter
	0.002, Age 1+		
	0.0002, Age 2-4+		
mature.prob2F, mature.prob2M	0.05, Age 1+	probability of females (F) or males (M) reaching sexual maturity in the next growth year as a function of the number of anadromous parents (e.g., 0F, 0M, 1F, 1M, 2F, 2M) and age (0–5 years).	Courter et al. 2009
	0.40, Age 2–4+		
mature.prob1F mature.prob1M	0.08, Age 1+		
	0.22, Age 2+		
	0.47. Age 3+		
	0.73, Age 4+		
	0.90, Age 5+		
mature.prob0F mature.prob0M	0.08, Age 1+		
	0.22, Age 2+		
	0.47. Age 3+		
	0.73, Age 4+		
	0.90, Age 5+		
smolt.wtemp.max	11.3–13.6°C (12°C)	maximum temperature at which smoltification occurs	McCullough et al. 2001, Richter and Kolmes 2005
smolt.prob2F	0.01, Age 0+	probability of smoltification by females (F) in the next growth year as a function of the number of anadromous parents (e.g., 0F, 1F, 2F) and age (0–4 years).	Courter et al. 2009, 2013
	0.9, Age 1–4+		
smolt.prob1F	0.01, Age 0+		
	0.55, Age 1–4+		
smolt.prob0F	0.01, Age 0+		
	0.02, Age 1-2+		
	0.0, Age 3–4+		
smolt.prob2M	0.01, Age 0+	probability of smoltification by males (M) in the next growth year as a function of the number of anadromous parents (e.g., 0M, 1M, 2M) and age (0–4 years).	Courter et al. 2009, 2013
	0.5, Age 1–4+		
smolt.prob1M	0.01, Age 0+		
	0.2, Age 1–4+		
smolt.prob0M	0.01, Age 0+		
	0.02, Age 1–2+		
	0.0, Age 3–4+		

The resident habitat generator defines daily in-channel habitat suitability based upon discharge and water temperature. It draws upon a user-provided table of mortality rates, energy consumption rates, maximum adult density, as well as flow-dependent usable habitat areas by reach. It receives discharge and water temperature values from the discharge and water temperature module.

The Resident Rearing model predicts locations of rearing resident and tracks their daily growth rates using water temperature at its current location, estimated food availability in its current reach, as well as age-specific estimates of energy consumption rate (Table 4.2-5). During each time step (one day), growth of each resident *O. mykiss* is simulated from these inputs by the relationships shown in Equation 4. Adults that are expected to reach sexual maturity in the following growth year are assigned reduced growth rates (maturation.growth.factor) with maturation probabilities assigned on the basis of anadromous parentage and age (e.g., mature.prob2F, mature.prob1F, etc.)(Table 4.2-5). The commitment date for maturity is assigned on May 15th of the model year and all adult fish are afforded reduced growth rates for the remainder of the model year. As discussed in Section 4.1.6.1, adults that are expected to smolt and emigrate in the following growth year (e.g., smolt.prob2F, smolt.prob1F, etc.) are, in contrast, assigned increased growth rates (smolting.growth.factor). The commitment date for smoltification is November 1st of the model year, approximately 6 months in advance of the expected smoltification period in Table 3.0-1. Fish not undergoing sexual maturation are drawn from the remaining resident rearing population, with probabilities of smolting based upon age-class and anadromous parentage (Table 4.2-5).

The Resident Rearing model is otherwise similar to the Juvenile Rearing model except that adults may potentially relocate to other usable habitat areas in various sub-reaches depending upon local habitat carrying capacity. The model tracks the redistribution of adults on the basis of discharge and habitat usage. Adults are initially assigned to model sub-reaches in proportion to the product of three factors: (1) usable habitat area (Figure 4.1-10), (2) an overall reach based habitat preference based on frequency of historical *O. mykiss* observations (Section 4.1.5.1), and (3) a temperature based preference function (Equation 6) to reflect avoidance of unsuitable temperatures (Section 4.1.5.2). The exact rearing location (i.e., territories) within a sub-reach is assigned at random in 0.1 RM increments. As the model simulation progresses through time, the population of each sub-reach is compared with the rearing habitat carrying capacity (i.e., usable habitat area multiplied by adult.density), with any excess adults assumed to be displaced. In the event that the carrying capacity of all sub-reaches has been exceeded and no rearing habitat within temperature preference limits is available, the excess adults are assumed to be killed.

Mortality during redistribution is estimated by exposure to excessive temperatures as well as a background mortality rate (Section 4.1.5.3). The background mortality rate was used as a model calibration parameter (Section 4.3) to allow fitting to observed size class structure in recent population surveys.

4.2.6 Smolt Emigration

The Smolt Emigration stock-production model follows the outmigration of a smolt life stage from the Tuolumne River, by tracking movements of smolts past landmarks (e.g., RM 29.5 or RM 5.2 RSTs, RM 24.5 weir, or San Joaquin River confluence at RM 0) with the emigrant smolt life stage module. This stock-production model draws upon information from the following sources:

(1) results of the Resident Rearing stock-production model,
(2) the discharge and water temperature module, and
(3) a list of parameters (Table 4.2-6).

Table 4.2-6. Parameters and associated references for smolt emigration.

Parameter	Range (selected value)	Description	Reference
smolting.day	197	peak activity as days from October 1st	Table 3-1 activity based on NMFS 2009
	23	standard deviation of peak activity	
	152	date of 1st smolt from October 1st	
	244	date of last smolt from October 1st	
smolt.wtemp.max	11.3–13.6°C (12°C)	maximum temperature at which smoltification occurs	McCullough et al. 2001
smolt.uuilt	23–26°C (25°C)	temperature at which mortality increases from 0% to 100%	Threader and Houston 1983; Myrick and Cech 2001
smolt.migr.velocity	0.2–60 mi/day (11 mi/day)	emigration rate of smolts in excess of reach specific velocity	Del Real et al. 2012
smolt.migr.mrate	0.14 $days^{-1}$, Age 1+	aquatic predation rate due to downstream movement	Age 1+ rate based upon Chinook juvenile mortality estimate for W&AR-06 study. Lower rates for Age 2+ and older fish based upon predator gape size limits.
	0.01 $days^{-1}$, Age 2+		
	0.0 $days^{-1}$, Age 3+ and older		

Smoltification of rearing adults not undergoing sexual maturation is based upon probabilities based upon the relative degree of anadromous parentage (Section 4.2.5) within Table 4.2-6 showing the overall smoltification period (smolting.day) according to the generalized timing in Table 3.0-1. For rearing adults Age 1+ through Age 3+ within particular reaches of the lower Tuolumne River, smoltification is prevented at higher water temperatures (smolt.wtemp.max). Mortality during smolt emigration is estimated due to excess water temperatures (smolt.uuilt) as well as due to exposure to predation using an emigration speed (smolt.migr.velocity) and migration mortality rate (smolt.migr.maret).

4.3 Model Calibration and Validation

Due to the limited occurrences of *O. mykiss* in routine monitoring activities (e.g., RST, river-wide seining, RM 24.5 counting weir) (Stillwater Sciences 2012b), opportunities for model calibration or validation are limited. Some model mechanisms (e.g., temperature based mortality) and functional relationships discussed in Section 4.2 have been studied in detail under controlled conditions. Hence, the appropriate values for the relevant model parameters (Section 4.2) are constrained by experimental data. Other relationships are 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 population monitoring data, and (2) to examine the degree to which the modeled mechanisms account for the year-to-year variability in these data.

Model calibration was conducted in two steps. First, fitting of growth parameters used in Equation 4 for fry (Table 4.2-3), juveniles (Table 4.2-4), and adults (Table 4.2-5) was conducted to match inter-annual growth rates from the *O. mykiss Scale Collection and Age Determination Study* (W&AR-20). Next, baseline mortality parameters for these life-stages were adjusted to achieve a stable long-term average population size over a multi-year simulation (1996–2009) using end-of-year results as start-of-year populations for the next model year.

Model validation was carried out using the fitted growth and mortality parameters from the calibrated model by comparisons of age structure and summer-rearing population sizes from the TROm model with those found in recent population estimates (2008–2011) developed through intensive snorkel surveys (e.g., Stillwater Sciences 2008, 2009, 2011, 2012c). Using the *O. mykiss* population estimates and observed proportions of individuals in various size classes for a particular survey year (e.g., July 2008), an initial population size and age structure was developed as an input to the model with size classes converted to age-classes from the *O. mykiss Scale Collection and Age Determination Study* (W&AR-20). Parameter estimates for the calibrated model (Table 4.2-1 through 4.2-6) were used to estimate mid-summer population sizes for comparison to historical population size estimates.

4.4 Sensitivity Analyses

The sensitivity analysis consisted of making a large number of model runs by varying one parameter at a time in the calibrated TROm model at two population sizes: 500 Age 1+ and older fish (Low) and 10,000 Age 1+ and older fish (High). For each change in a particular parameter value, the model was used to recalculate the estimated end-of-year metrics of juvenile and adult *O. mykiss* population size, holding all other values constant. To establish a starting population, the stable population size simulation used for model calibration (Section 4.3) was repeated using the calibrated model parameters. Starting populations for the sensitivity analyses were a random sample of either 500 (Low) or 10,000 (High) Age 1+ and older fish drawn from the accumulated year-end totals over the simulation period (1996–2009). Age 0+ population size were assumed to be in proportion to the accumulated totals of year-end Age 0+ versus Age 1+ and older fish. Using age-class composition corresponding to stable populations of 500 (Low) and 10,000 (High) Age 1+ and older fish, model sensitivity testing was conducted using flow and water temperature data for two water years representing “dry” (WY 2009) and “wet” (WY 2011) conditions. Table 4.4-1 shows the forty-six parameters that were selected for examination along with the calibrated value and the parameter range tested (i.e., Min, Max).

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

Model Parameter	Description	Calibrated Value	Min Tested	Max Tested
Upmigration and Spawning				
fecundity.bylength	eggs deposited (Equation 2)	0.007236	0.003618	0.010854
postspawn.survival.mult	multiplier of spawning survival (Table 4-2)	1	0.5	2
redd.defense.area	area defended by spawning female (ft2)	37	32	188
redd.defense.time	redd defense time (d)	2	1	5
redd.disturb.area	area reworked by redd construction (ft2)	9.2	8	47
spawn.wtemp.max	maximum temperature for spawning (C)	15	13	17
spawning.day	spawning timing from October 1st (days)	152	138	166
spawning.duration	duration outside of rearing population (days)	7	2	30
Egg Incubation and Fry Emergence				
embryo.atu	accum. thermal units to emergence (C-days)	647	600	722
embryo.survival	egg survival-to-emergence	0.45	0.05	0.95
embryo.uuilt	lethal temperature for egg/alevins (C)	15	13	17

Model Parameter	Description	Calibrated Value	Min Tested	Max Tested
Fry Rearing				
fry.density	maximum fry rearing density (#/ft2)	1.11	0.555	1.665
fry.displace.rate	probability of fry displacement (1/day)	0.1	0.05	0.15
fry.displace.time.mean	duration of fry displacement (day)	0.02	0.01	0.03
fry.emigrate.p	fraction of fry emigrating at swim-up	0.3	0.15	0.45
fry.kappa	energy required for fry foraging	1.7	0.85	2.55
fry.migr.mrate	fry migration mortality rate (1/day)	2.704	1.352	4.056
fry.mrate	fry background mortality rate (1/day)	0.017	0.0085	0.0255
fry.uuilt	lethal temperature for fry (C)	25	23	27
length.swimup	fry size at emergence (mm)	24	20	30
Juvenile Rearing				
juvenile.density	maximum juvenile rearing density (#/ft2)	0.06	0.03	0.09
juvenile.displace.rate	probability of juvenile displacement (1/day)	0.01	0.005	0.015
juvenile.displace.time.mean	duration of juvenile displacement (day)	0.0833	0.04165	0.12495
juvenile.kappa	energy required for juvenile foraging	1.5	0.75	2.25
juvenile.migr.mrate	juvenile migration mortality rate (1/day)	0.1386	0.0693	0.2079
juvenile.mrate	juvenile background mortality rate (1/day)	0.017	0.0085	0.0255
juvenile.uuilt	lethal temperature for juveniles (C)	25	23	27
Resident Rearing				
adult.density	max adult rearing density (#/ft2)	0.0103	0.00515	0.01545
adult.kappa	energy required for adult foraging	1	0.5	1.5
adult.mrate, age0	age 0+ background mortality rate (1/day)	0.01	0.005	0.015
adult.mrate, age1	age 1+ background mortality rate (1/day)	0.002	0.001	0.003
adult.mrate, age2 up	ages 2–5 background mortality rate (1/day)	0.0002	0.0001	0.0003
adult.uuilt	lethal temperature for adults (C)	25	23	27
adult.wtemp upper pref.	upper preferred temperature for adults (C)	20	18	22
maturation.growth.factor	fraction of predicted growth for maturing fish	0.83	0.4	1
mature.prob0F, age1	probability of maturity for Age 1+ fish	0.1	0	0.4
mature.prob0F, age2	probability of maturity for Age 2+ fish	0.1	0	0.4
mature.prob0F, age3 up	probability of maturity for Age 3-5 fish	0.85	0.2	1
smolt.mult	multiplier of smolting probability (Table 4-6)	1	0.5	2
smolting.growth.factor	fraction of predicted growth for smolts	1.1	1	1.6
Smolt Emigration				
smolt.migr.mrate age 1	age 1+ smolt migration mortality rate (1/day)	0.14	0.07	0.21
smolt.migr.mrate age 2	age 2+ smolt migration mortality rate (1/day)	0.01	0.005	0.015
smolt.migr.mrate age 3 up	age 3-5 smolt migr. mortality rate (1/day)	0	0.005	0.02
smolt.migr.velocity	smolt emigration speed (mi/day)	11	0.2	60
smolt.uuilt	lethal temperature for smolts (C)	25	23	27
smolt.wtemp.max	maximum temperatures for smolting (C)	12	10	14
smolting.day	smolt timing from October 1st (days)	197	183	211

Parameter ranges shown in Table 4.4-1 may be varied as a proportion as shown in the Study Plan (e.g., ± 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). Several parameters were expected to function together in such a way that it would be redundant to consider them all separately. For example, the model has a parameter representing male post-spawning survival (anadromousM.postspawn.survival), but this number has little effect on the rest of the life history (the model assumes that there are always enough males present to fertilize any redds constructed), and so this parameter was evaluated using a scaling multiplier (post.survival.mult) that allowed variations in individual parameters together.

To examine the model sensitivity to factors potentially affecting production of resident *O. mykiss*, two sensitivity metrics were evaluated: (1) "juvenile productivity", calculated as the ratio of end-of-year (Age 0+) juvenile population size to the number of spawners (Age 2+ and older), and (2) "adult replacement", calculated as the ratio of end-of-year adult population size (Age 2+ and older) to the starting population size (Age 2+ and older) on October 1st.

A separate sensitivity analysis was conducted to examine factors affecting potential steelhead using a "smolt productivity" metric calculated as the ratio of annual smolt production (Age 1+ and older) to the starting adult population size (Age 1+ and older) on October 1st. Variations in smolt production were examined for the low population size (500 Age 1+ and older fish) and high population size (10,000 Age 1+ and older fish) with a hypothetical steelhead run of 100 steelhead (50 females) at these population levels. Steelhead were assumed to spawn according to the same spawning timing used for resident *O. mykiss* (Table 3.0-1). To establish a starting population of mixed anadromous-resident parentage within each age-class, the stable population size simulation described above was modified by adding 100 steelhead spawners to the starting population size (i.e., 500 or 10,000 Age 1+ and older fish) at the beginning of each model year. Because a fixed number of anadromous fish were introduced in each model year, end-of-year results were recorded and then re-scaled to the starting population sizes for the remaining model simulations in each successive model year. Final mixed anadromous-resident populations used for the sensitivity analyses were then formed using 100 steelhead spawners added to a random sample of either 500 (Low) or 10,000 (High) Age 1+ and older fish drawn from the accumulated year-end totals over the simulation period (1996–2009). As for the evaluation of factors affecting resident *O. mykiss* production, factors affecting smolt production were examined by varying the parameters in Table 4.4-1, with the model used to recalculate the estimated year end Smolt Productivity ratio, holding all other values constant.

4.5 Evaluation of *O. mykiss* Production under Current and Potential Future Project Operations

Using the parameterized and validated TROm model, juvenile and adult *O. mykiss* productivity metrics (Section 4.4) were estimated at three population sizes (i.e., 500, 2,000, and 10,000 resdient Age 1+ and older fish), with the starting age-class composition developed as described in Section 4.4 for sensitivity testing purposes. The *O. mykiss* productivity metrics were also those used in sensitivity testing: (1) a "juvenile productivity" ratio calculated as the end-of-year estimate of Age 0+ fish divided by the number of female spawners (Age 2+ and older); and (2) an "adult replacement" ratio calculated as the end-of- year estimate of total adults (Age 2+ and older) divided by the starting population size (Age 2+ and older) on October 1st of the model year.

Resident *O. mykiss* production metrics were evaluated 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' current irrigation and M&I water management practices. For the purposes of this study, the Base Case hydrology represents flow conditions downstream of La Grange Dam from the fall of 1970 through September 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 37-year time series of varying hydrology and meteorology to examine variations in juvenile and adult *O. mykiss* production under a variety of water year types as well as to provide a basis of comparison for any alternative operating scenarios. Because little information was identified as part of the Synthesis Study (W&AR-05) to suggest a self-sustaining steelhead population on the Tuolumne River, factors affecting potential smolt production from a hypothetical steelhead run were evaluated as part of sensitivity testing only (Section 4.4).

5.0 RESULTS

5.1 Model Validation

Validation of the calibrated model was conducted using *O. mykiss* population data collected between July 2008 and September 2011 (Stillwater Sciences 2008, 2009, 2011, 2012c). Using parameter estimates for upmigration, spawning, egg incubation, fry rearing, juvenile and resident rearing (Table 4.2-1 through 4.2-6), population sizes were estimated by the model by age-class for comparison to historical population size estimates. Figure 5.1-1 shows one-year model projections of *O. mykiss* population age structure for Age 1+ and older fish from 2008 to 2011. The connecting arrows reflect one-year model simulations starting with the snorkel survey estimates from July 2008 that were used as TROm model inputs along with average daily discharge and corresponding water temperatures from July 2008 to July 2009.

Figure 5.1-1. Model-based and snorkel survey based age composition of *O. mykiss* in the Tuolumne River (2008–2011).

Comparison of the Figure 5.1-1 model predictions of the age-class composition in 2009–2011 with the corresponding snorkel survey results for each year show that the model tends to over-represent the oldest age-classes (Age 5+ and above) and under-represent the proportion of Age 2+ and Age 3+ fish when compared to the snorkel survey-based estimates. Extending the calibration results to *O. mykiss* cohort abundance, Figure 5.1-2 shows model-based and survey-based population estimate by age-class from 2008 to 2011.

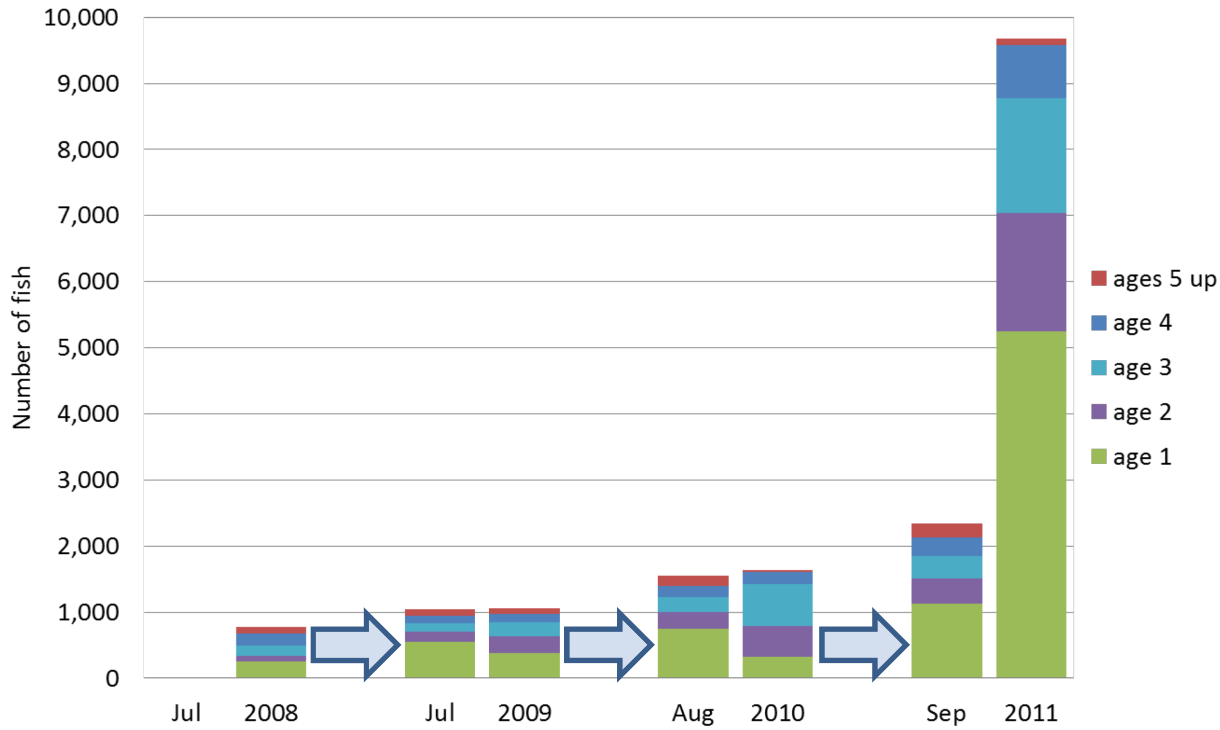

Figure 5.1-2. Model-based and snorkel survey based population estimate by age-class for *O. mykiss* in the Tuolumne River (2008–2011).

The numbers of individuals in each age-class shown in Figure 5.1-2 are generally lower than the snorkel survey-based estimates for the same year. However, year-to-year changes in cohort size appear to be more consistently represented by the model-based results than the survey-based results. For example, large increases in the survey-based results for Age 3+ fish occurring from 2009–2011 that should have originated as Age 2+ fish in the prior year (i.e., from 2008–2010) suggests some errors in the underlying data. Most dramatically, population size of Age 2+ and Age 3+ fish estimated from the 2011 snorkel survey data are much higher than the corresponding survey-based cohort estimates for Age 1+ and Age 2+ fish occurring in 2010 (Figure 5.1-2).

A more direct comparison of model-based results with snorkel survey-based results is provided in Figure 5.1-3 for fish larger than 149 mm FL, and in Figure 5.1-4 for fish smaller than 149 mm FL. Overall, the *O. mykiss* direct abundance estimates after one-year model simulation compares reasonably well with the survey-based estimates except for 2011. The model-based results were below the survey-based results for larger (> 149 mm FL) fish, but within the confidence bounds of these estimates for all years except in 2011 (Figure 5.1-3). Model-based results were above survey-based results in 2009–2010, but below survey-based results in 2011 (Figure 5.1-4). Potential upmigration of resident adult *O. mykiss* during periods that the RM 24.5 counting weir was non-operational in 2011 as well as potential introduction of juvenile and adult *O. mykiss* from habitats upstream of La Grange Dam (RM 52) may confound evaluation of the year-to-year variations in snorkel survey-based estimates of cohort sizes (e.g., Age 3+ vs. preceding Age 2+, etc.) and suggests that replication of the 2011 abundance estimates may not be attainable.

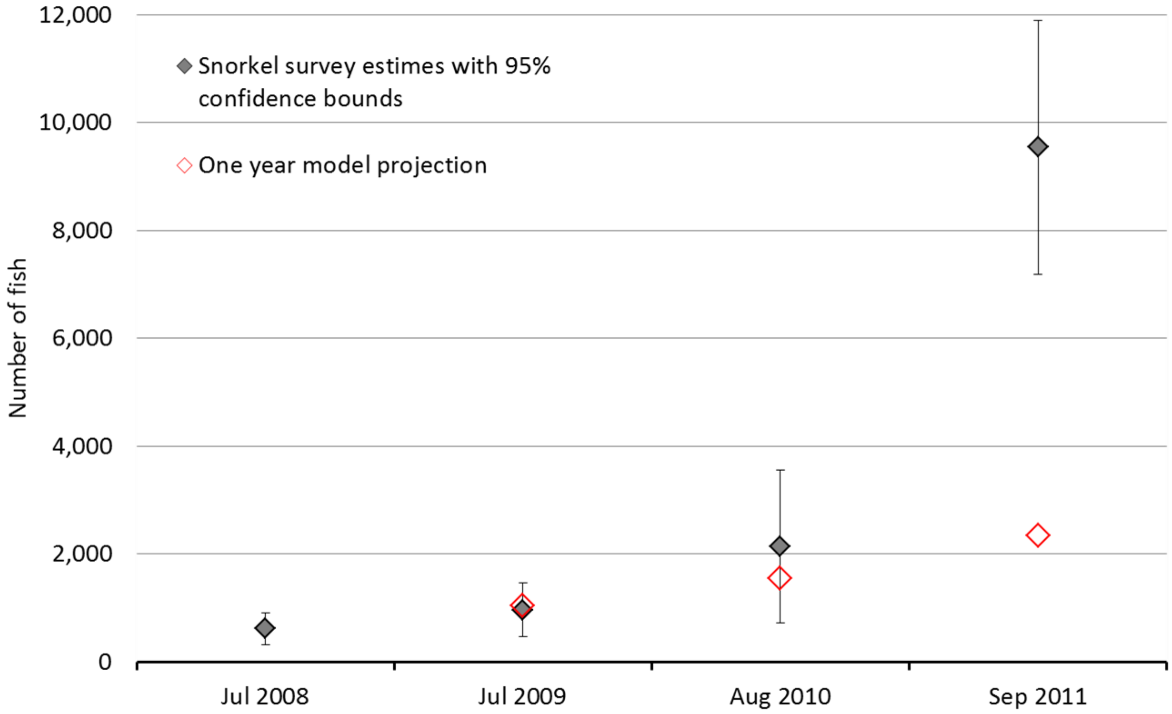

Figure 5.1-3. Model-based and snorkel survey based population estimate for *O. mykiss* > 149 mm FL in the Tuolumne River (2008–2011).

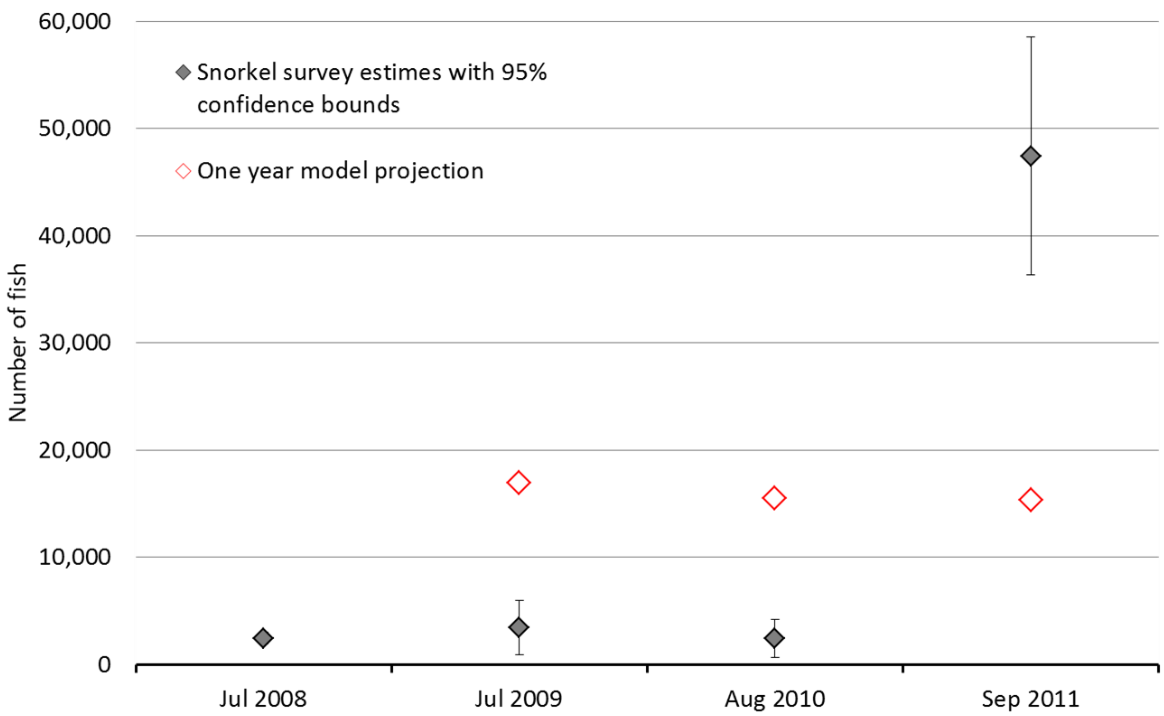

Figure 5.1-4. Model-based and snorkel survey based population estimate for *O. mykiss* ≤ 149 mm FL in the Tuolumne River (2008–2011).

Based upon long-term variations in the downstream extent of *O. mykiss* habitat use and relative abundance summarized in the Synthesis Study (W&AR-05), juvenile (≤149 mm FL) population size estimates were expected to vary substantially year-to-year. However, several issues affecting the survey-based population size estimates were identified in the individual survey reports (Stillwater Sciences 2008, 2009, 2011, 2012c), including:

(1) the infeasibility of using electrofishing of ESA listed salmonids to calibrate observed fish counts within individual sampling units;
(2) poor observability of individual fish due to higher turbidity progressing downstream;
(3) inability to see fish along the channel bottom of deeper pool sampling units; and
(4) potential introductions of unknown numbers of resident *O. mykiss* into the lower Tuolumne River over La Grange Dam during high flow conditions (e.g., 2010 and 2011).

In addition to the issues identified above, the September 2011 surveys by Stillwater Sciences (2012c) were preceded by season-long high flow conditions in excess of 8,000 cfs during April and only reduced from summer flows of 2,000–3,000 cfs to 300 cfs for the survey period (September 20–24, 2011). The late-season flow changes occurring in September may have resulted in the displacement of many juvenile and adult *O. mykiss* from previously established rearing territories and thus potentially increased the observability of these fish as compared to prior years. For example, follow-up snorkel surveys in November 2011 found lower relative densities at the common sampling locations sampled in September 2011, suggesting fish may have been redistributed during the intervening weeks between the two surveys.

5.2 Sensitivity Analyses

To examine the model sensitivity to factors potentially affecting production of resident *O. mykiss*, sensitivity testing was conducted for a “Low” population size (500 Age 1+ and older fish) and a “High” population size (10,000 Age 1+ and older fish). Figure 5.2-1 shows variations in juvenile productivity (i.e., ratio of end-of-year Age 0+ juveniles to spawners) to parameters related to adult rearing through spawning and fry emergence. Figure 5.2-2 shows sensitivity of juvenile productivity to parameters related to fry and juvenile rearing, whereas Figure 5.2-3 shows sensitivity of the adult replacement ratio (i.e., Age 2+ and older fish/Age 2+ and older fish 1 year prior) to parameters related to adult rearing and spawning. Lastly, Figure 5.2-4 shows sensitivity of smolt productivity (i.e., ratio of Age 1+ and older smolts/Age 1+ and older fish one year prior) to parameters related to adult rearing and smoltification at two population sizes including 100 steelhead spawners. In each of the figures below, the calibration value for the tested parameter is shown as a vertical black line and the results for each sensitivity test (i.e., alternate parameter value, WY and population size scenario) connected by a horizontal or sloping line with colors representing hydrology type (i.e., orange for “dry” and blue for “wet”) and line style representing population size (i.e., dashed for “Low” and solid for “High”). 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 4.2-1.

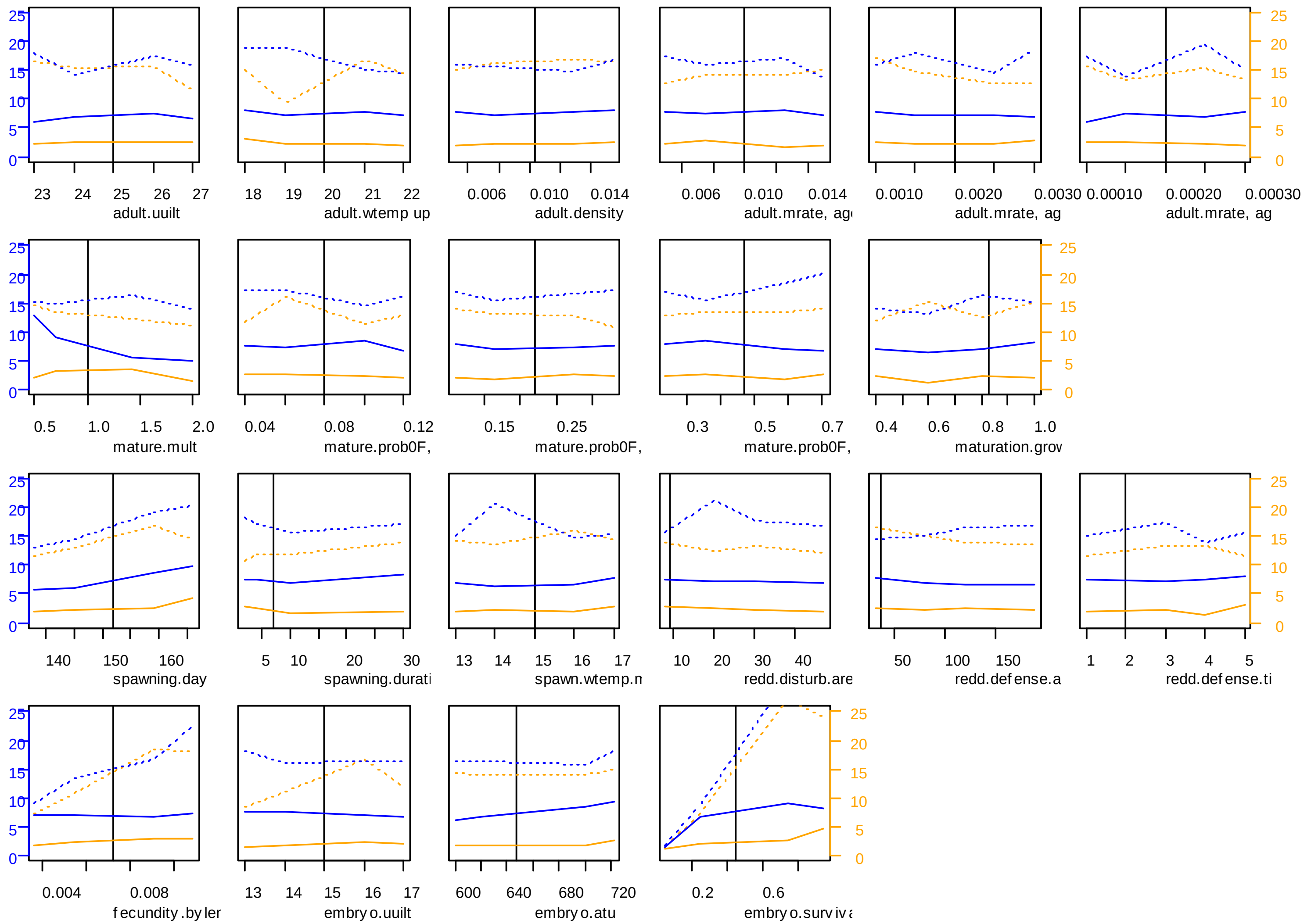

Figure 5.2-1. Model sensitivity of juvenile *O. mykiss* productivity to parameters related to adult rearing through spawning and fry emergence at two population sizes and under "dry" and "wet" water year types.

Note: Results shown for Low population size (500 fish, dashed lines) and high population size (10,000 fish, solid lines) under "dry" (WY 2009, orange lines) and "wet" (WY 2011, blue lines) water year hydrology.

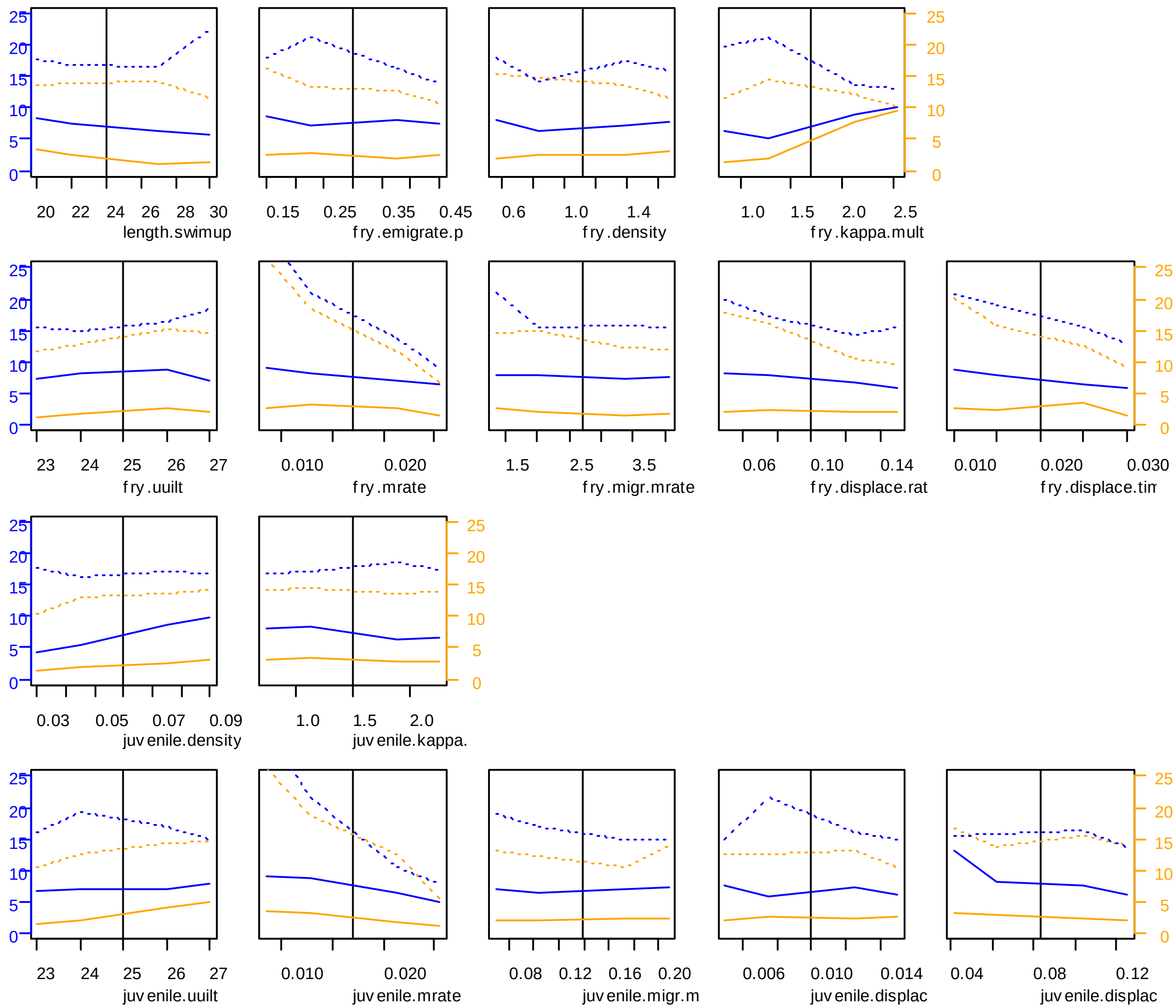

Figure 5.2-2. Model sensitivity of juvenile *O. mykiss* productivity to parameters related to fry and juvenile rearing at two population sizes and under "dry" and "wet" water year types.

Note: Results shown for Low population size (500 fish, dashed lines) and high population size (10,000 fish, solid lines) under "dry" (WY 2009, orange lines) and "wet" (WY 2011, blue lines) water year hydrology.

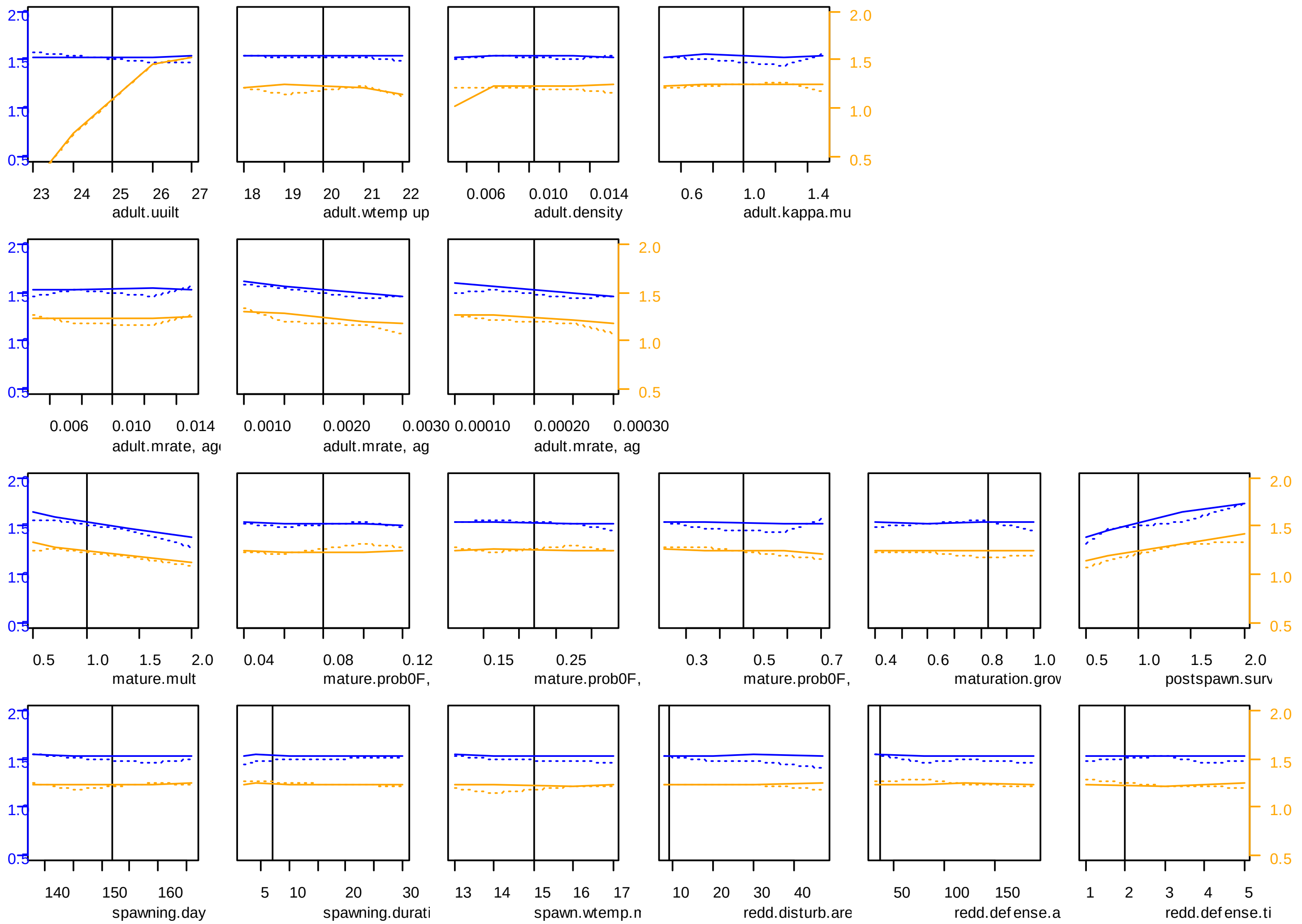

Figure 5.2-3. Model sensitivity of adult *O. mykiss* replacement ratio to parameters related to adult rearing and spawning at two population sizes and under "dry" and "wet" water year types.

Note: Results shown for Low population size (500 fish, dashed lines) and high population size (10,000 fish, solid lines) under "dry" (WY 2009, orange lines) and "wet" (WY 2011, blue lines) water year hydrology.

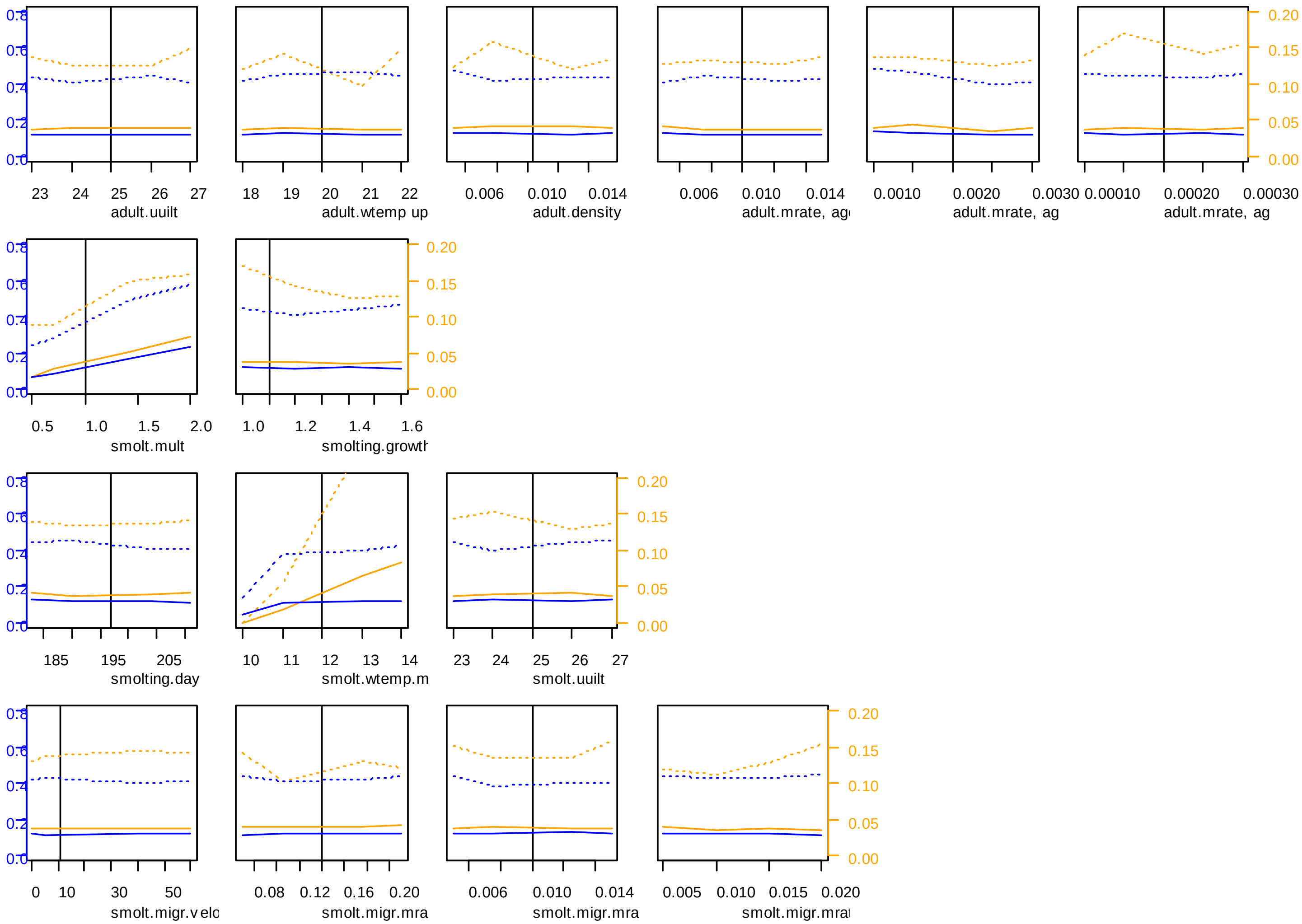

Figure 5.2-4. Model sensitivity of *O. mykiss* smolt productivity to parameters related to adult rearing and smoltification at two population sizes including 100 steelhead spawners and under "dry" and "wet" water year types.

Note: Results shown for Low population size (500 fish, dashed lines) and high population size (10,000 fish, solid lines) under "dry" (WY 2009, orange lines) and "wet" (WY 2011, blue lines) water year hydrology.

In addition to identifying individual model parameter sensitivity, parameters that are shown to result in greater changes in juvenile productivity (Figure 5.2-1 and Figure 5.2-2) and adult replacement (Figure 5.2-3) may also be used to indicate potential factors controlling overall population levels. Within the overall life-history framework (Figure 4.2-1), juvenile and adult *O. mykiss* production is simulated using 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 5.2-1 through Figure 5.2-4 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).

5.2.1 Adult Upmigration and Spawning

Of the parameters used to represent the influences of spawning success upon juvenile productivity (Figure 5.2-1), sensitivity testing indicates that spawning timing (spawning.day) and spawner fecundity (fecundity.bylength) have the greatest influence. Sensitivity is less pronounced at high population sizes due to density dependent effects upon juvenile productivity related to juvenile rearing habitat availability (Section 5.2.4). Increases in end-of-year juvenile productivity with later spawning reflect a combination of faster fry growth due to warmer temperatures as well as a shorter overall period when these fish are subject to migration related mortality sources (i.e., predation). Changes in the maximum water temperature preference for spawning (spawn.wtemp.max) resulted in no changes in juvenile productivity. Lastly, the lack of sensitivity to redd disturbance area (redd.disturb.area) and the related defended area (redd.defense.area) suggest no sensitivity to spawning habitat availability.

5.2.2 Egg Incubation and Fry Emergence

Of the parameters used to represent conditions affecting egg incubation, egg survival-to-emergence (embryo.survival) is shown to exert the greatest influence on juvenile productivity (Figure 5.2-1). This effect is less pronounced at high population sizes due to density dependent effects upon juvenile productivity related to juvenile rearing habitat availability (Section 5.2.4). The temperature related development parameter (embryo.atu) also affects juvenile productivity estimates to some degree with longer development times corresponding to shorter exposure to migration related mortality sources (i.e., predation). Juvenile productivity was shown to be insensitive to variation in egg mortality thresholds (embryo.uuilt) within reasonable ranges. Based upon the assumed spawning timing for *O. mykiss* (Table 3.0-1), water temperature related egg mortality is unlikely to affect juvenile production. Lastly, 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 pronounced for all flow scenarios at low starting population levels (Figure 5.2-1). This suggests that potential measures to improve gravel quality (e.g., gravel augmentation, gravel cleaning) would result in proportionate increases in juvenile *O. mykiss* production.

5.2.3 Fry Rearing

Of the parameters used to represent fry rearing, several parameters related to fry mortality (fry.mrate) and movement (fry.emigrate.p, fry.displace.rate, fry.displace.time.mean), were shown to affect the resulting smolt productivity (Figure 5.2-2). Model sensitivity is less pronounced at high population sizes due to density dependent effects upon juvenile productivity related to juvenile rearing habitat availability (Section 5.2.4). The proportion of fry emigrating upon emergence (fry.emigrate.p) directly affects subsequent juvenile production, although as suggested by available information summarized in the Synthesis Study (W&AR-05) little evidence for Delta or estuarine rearing exists and it is likely these fish are lost to predation and other out-of-basin mortality sources. Because these parameters were estimated through model fitting, more direct estimates of fry movement and survival with flow may be required to assess model uncertainty. Since parr-sized fish (50–149 mm FL) were assigned lower mortality rates (Table 4.2-4) compared to fry (Table 4.2-3), food availability (fry.kappa.mult) affected the number and timing of fish making the fry/parr transition and was shown to affect juvenile productivity (Figure 5.2-2). 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). Lastly, juvenile productivity was also shown to be insensitive to the water temperature mortality threshold for fry (fry.uuilt) (Figure 5.2-2). This is consistent with predation as a primary mortality source for fry, since fry rearing occurs at upstream locations where high temperatures approaching mortality thresholds do not normally occur. It should also be noted that for fry displaced into downstream habitats by high flows during spring, high air temperatures likely result in water temperatures exceeding mortality thresholds by mid- to late-summer, regardless of water year type. For this reason, relatively few fish are affected by reasonable variations in the selected parameter value.

5.2.4 Juvenile Rearing

Of the parameters used to represent juvenile rearing of parr-sized fish (50–149 mm FL), year-end juvenile productivity was sensitive to variations in the background mortality rate (juvenile.mrate) at all population sizes and the maximum rearing density parameter (juvenile.density) at high population sizes (Figure 5.2-2). Because daily juvenile movement rates are relatively low as compared to fry, displacement of juveniles in excess of rearing capacity is the primary mechanism initiating movement (Section 4.1.4.2) and model sensitivity is greater during “wet” water year types than for “dry”. These results suggest that limited availability of juvenile rearing habitat at higher population sizes may have the potential for increased migration related mortality (i.e., predation) as well as water temperature related mortality for any juveniles displaced into downstream rearing locations during late spring and summer. Although the date of 1st transgression of lower or higher thresholds than those tested (Table 4.4-1) may occur earlier (or later) in the summer within these downstream habitats, model sensitivity testing suggests some sensitivity to the water temperature mortality threshold (juvenile.uuilt) during “dry” water year types (Figure 5.2-2).

5.2.5 Resident Rearing

Of the parameters used to represent resident rearing, parameters related to background mortality (adult.mrate for Age 1+, and Age 2+ and older fish), spawning probability (mature.mult; mature.prob0F for Age 1+, Age 2+, and Age 3+ and older fish), and spawning related mortality (postspawn.survival.mult) were shown to affect the resulting adult replacement ratio (Figure 5.2-3). Because values for these parameters were assigned from out-of-basin information sources (Table 4.2-5) and little information on resident *O. mykiss* spawning is available for the Tuolumne River beyond the 2013 spawning locations identified in the *Redd Mapping Study* (W&AR-08), more direct estimates of spawning related mortality may be required to reduce model uncertainty. Lastly, sensitivity of adult replacement ratio to water temperature mortality thresholds (adult.uuilt) in "dry" water year types suggests that over-summering habitat for adults may be limiting under some conditions. It should be noted that although the TROm model implementation allows adults (Age 1+ and older) rearing in habitats exceeding water temperature preference limits (i.e., increased avoidance for temperatures between 20–24°C [68–75°F]) to redistribute to areas meeting those limits (Section 4.1.5.2), this habitat selection is made on a weekly time-step. As a result, any model fish occupying habitats exceeding assumed daily mean water temperature mortality thresholds (25°C [77°F]) on a daily time step would be subject to temperature-related mortality.

5.2.6 Potential Smolt Productivity

Using an assumption of 100 steelhead spawners in addition to the Low (500 fish) and High (10,000) population sizes, Figure 5.2-4 shows model sensitivity to parameters used to represent smoltification and emigration. Smolt productivity was most sensitive to the scaling parameter (smolt.mult) used to explore the effects of varying the various smoltification probabilities for each age-class and proportion of number of anadromous parents (0, 1, 2). In addition, water temperature for smoltification (smolt.wtemp.max) had a nearly linear relationship with smolt productivity in "dry" water year types at both population sizes, with lower sensitivity in "wet" water year types across the expected 12–15°C (53.6–59°F) temperature range for smoltification discussed in Section 4.1.6.2. Of other parameters tested, small effects of increased adult mortality rate (adult.mrate for Age 0+, Age 1+, and Age 2+ and older fish) could be expected to reduce the numbers of potential smolt outmigrants. In addition, because the commitment to maturity would occur in the prior model year prior to the commitment to smoltification (Section 4.2.5), increasing the proportion of adults reaching sexual maturity (mature.prob0F, 1F, 2F) above the values shown in Table 4.2-5 would also be expected to reduce the number of fish available for smoltification.

5.3 Evaluation of *O. mykiss* Production under Current and Potential Future Project Operations

Using the parameterized and validated TROm model, *O. mykiss* production was estimated for three resident population sizes (i.e., 500, 2,000, and 10,000 resident Age 1+ and older fish) under "Base Case" conditions contained in the *Project Operations/Water Balance Model Study* (W&AR-02). Variations in juvenile productivity and adult replacement metrics were evaluated for the Base Case simulation period (1971–2012). For the Base Case hydrology and water temperature data, the "juvenile productivity" (i.e., end-of-year estimate of Age 0+ fish divided by the total number of spawners within the model year) in relation to river discharge measured at the USGS La Grange gage is presented in Figure 5.3-1 for the three population sizes. Although model simulations were conducted on a full water year basis, results are sorted by water year type as well as by decreasing discharge for the expected juvenile rearing period (March–September). Density-dependent effects are apparent, with consistently lower juvenile productivity predicted at higher population sizes.

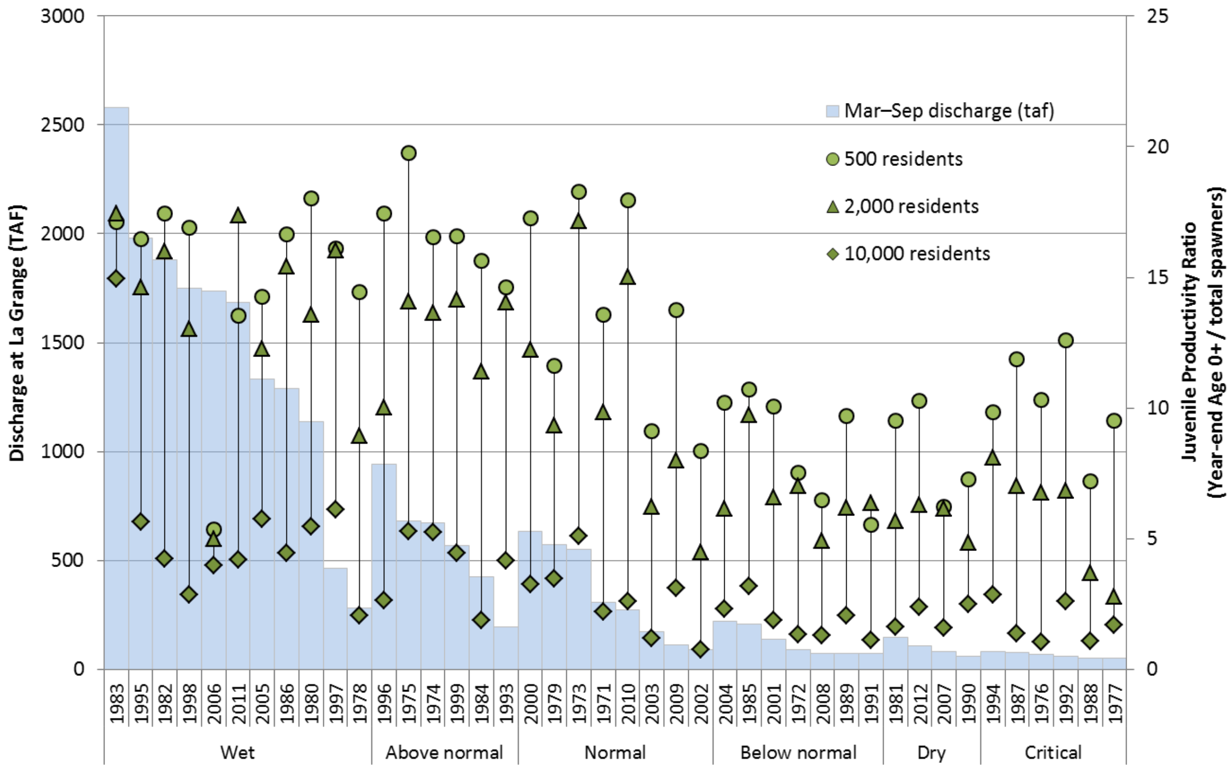

Figure 5.3-1. Modeled juvenile *O. mykiss* productivity for the Base Case (1971–2012) sorted by water year type and La Grange discharge (March–September) for three resident population sizes.

The general pattern in juvenile productivity shown in Figure 5.3-1 is consistent with variations in the historical snorkel survey data summarized as part of the Synthesis Study (W&AR-05), with decreased extent of downstream habitat use by juveniles during periods of extended droughts that generally matches decreasing La Grange discharge. In order to examine the potential influences of year-to-year variations in regional meteorology upon water temperatures, Figure 5.3-2 presents juvenile productivity sorted by water year type and maximum weekly average temperature (MWAT) during summer (June-August) at Roberts Ferry Bridge (RM 39.5) for three resident population sizes. This location was selected as an indicator of over-summering conditions and generally corresponds to the downstream extent of *O. mykiss* habitat use in most years (Stillwater Sciences 2012b). In the same manner as the results presentation with La Grange discharge (Figure 5.3-1), it should be noted that model simulations were conducted on a full water year basis using daily average water temperatures, but the results shown in Figure 5.3-2 are presented by water year type as well as by increasing MWAT for the expected hottest over-summering period (July–September).

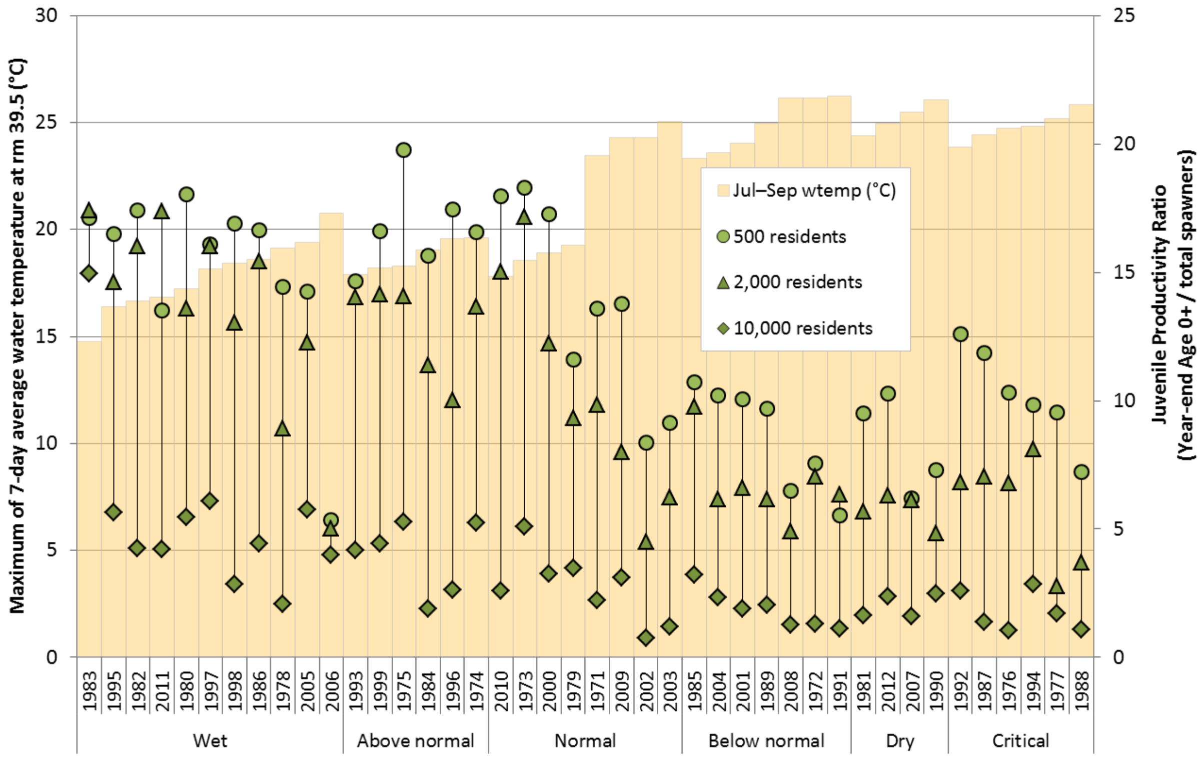

Figure 5.3-2. Modeled juvenile *O. mykiss* productivity for the Base Case (1971–2012) sorted by water year type and summertime (July–September) MWAT at Roberts Ferry Bridge (RM 39.5) for three resident population sizes.

In addition to variations in juvenile productivity under differing hydrologic conditions, adult replacement ratio (i.e., end-of-year estimate of Age 2+ and older fish divided by the starting population size of Age 2+ and older fish) is presented in Figure 5.3-3 for the three population sizes, sorted by La Grange discharge and water year type. Model predictions suggest an overall increase in year-over-year adult population size (i.e., adult replacement > 1.0) for most Above Normal and Wet water years simulated with lower replacement in Normal and drier water years. To a far lesser degree than for juvenile productivity (Figure 5.3-1), minor density dependent effects are apparent with marginally lower adult replacement predicted at higher population sizes. It should be noted that a number of random elements related to adult mortality are included in the model (Section 4.2.5) and these influence year-to-year estimates of adult replacement in Figure 5.3-3. This variation is large enough that the simulated adult replacement for a High population size is above that of the Low population size in some years (Figure 5.3-3). Due to the random elements discussed above, these exceptions would likely not be repeated in successive simulations and the overall pattern showing low levels of density dependence upon adult replacement would be maintained. As with juvenile productivity, adult replacement is presented in Figure 5.3-4 for the three population sizes, sorted by water year type and summertime MWAT at Roberts Ferry Bridge (RM 39.5) for three resident population sizes.

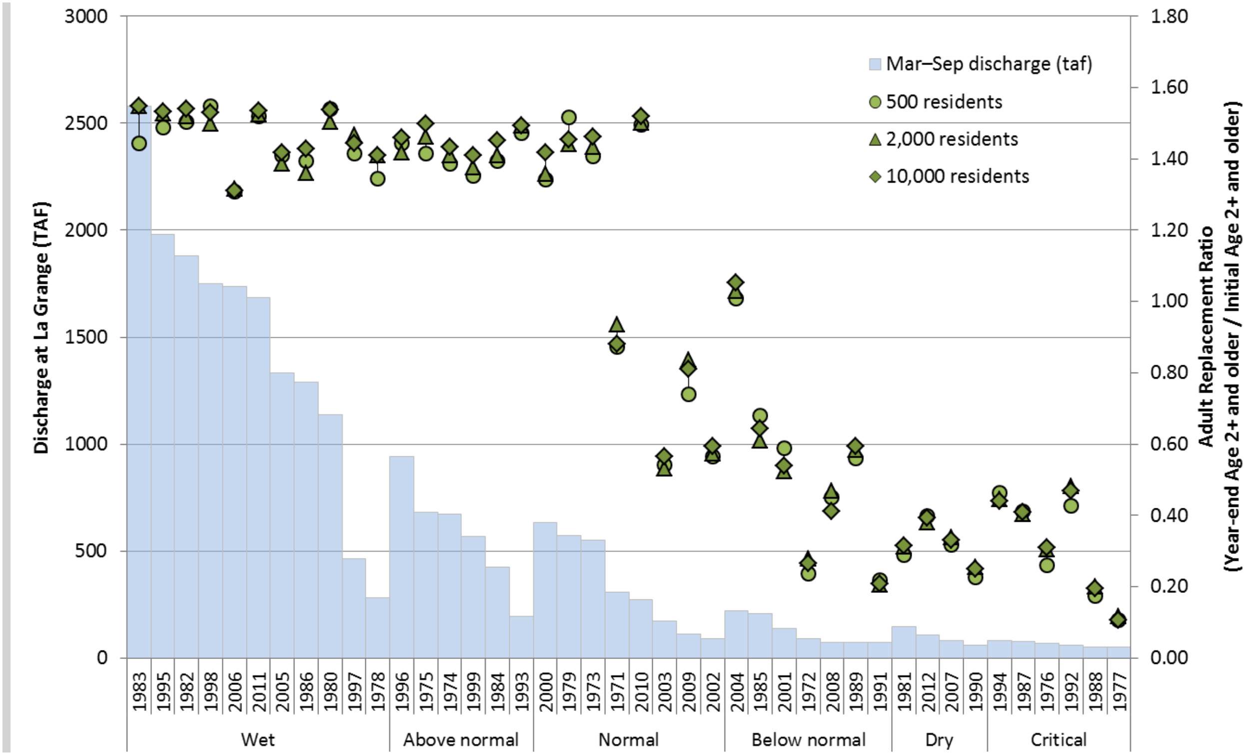

Figure 5.3-3. Modeled adult *O. mykiss* replacement for the Base Case (1971–2012) sorted water year type and La Grange discharge (March–September) for three resident population sizes.

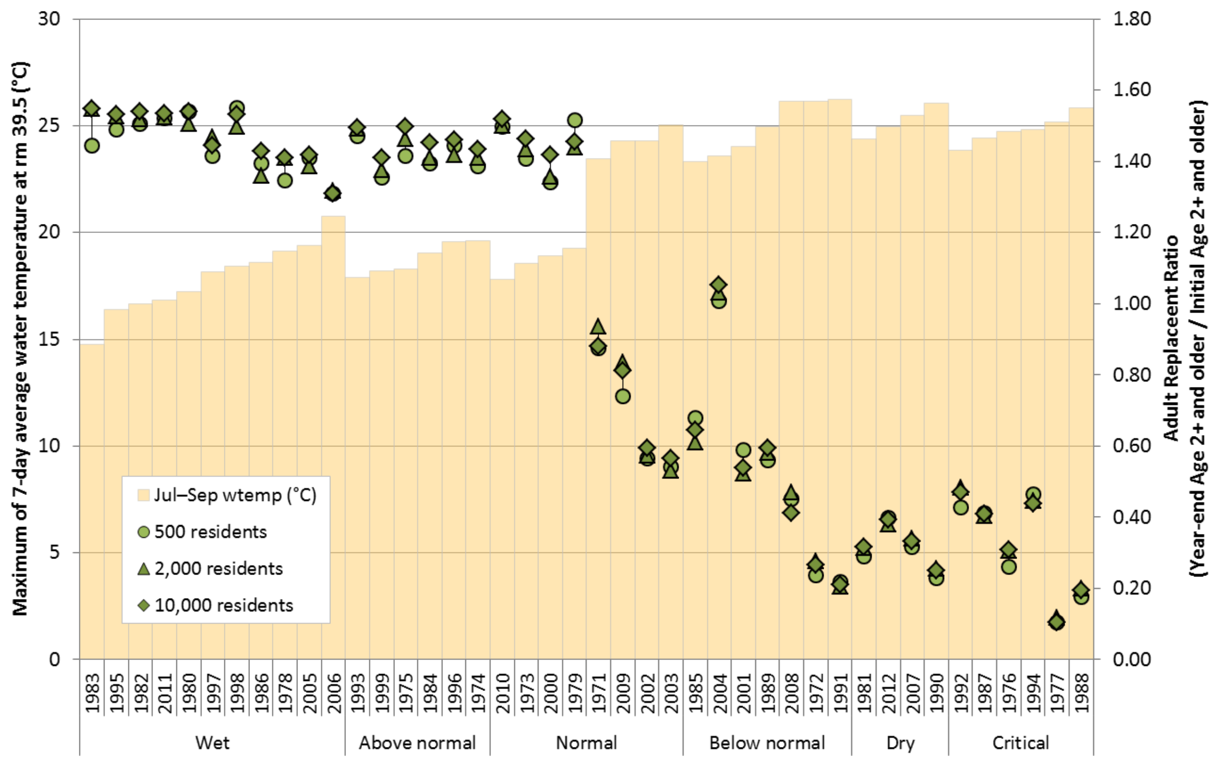

Figure 5.3-4. Modeled adult *O. mykiss* replacement for the Base Case (1971–2012) sorted by water year type and summertime (July–September) MWAT at Roberts Ferry Bridge (RM 39.5) for three resident population sizes.

6.0 DISCUSSION AND FINDINGS

In accordance with the approved *O. mykiss Population Study Plan* (W&AR-10), the TROm model has been developed to examine the relative influences of various factors on the production of in-river life stages of *O. mykiss* in the Tuolumne River, identify critical life-stages that may represent a life-history "bottleneck", and compare ***relative*** changes in the population between alternative resource management scenarios. As recommended in the June 2011 Integrated Life Cycle Models Workshop Report (Rose et al. 2011), this *O. Mykiss Population Study* was developed to compare relative *O. mykiss* 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, resident rearing, to smolt emigration. In the absence of reliable information on the numbers and timing of any anadromous *O. mykiss* spawning and the factors contributing to anadromy in the Tuolumne River, the relative changes in the production of *O. mykiss* smolts resulting from different flow and temperature conditions within the Tuolumne River cannot be reliably assessed using the TROm model. The following sections discuss model results, modeling inferences regarding factors affecting *O. mykiss* production, expression of anadromy in the Tuolumne River, as well as potential future information needs to address assumptions made in the TROm model development.

6.1 Model Validation

Using recent *O. mykiss* population survey estimates from intensive snorkel surveys in the lower Tuolumne River along with recorded river discharge and water temperature data from 2008–2011, validation of the calibrated TROm model was carried out by comparing survey data to modeling results of age-class composition and abundance for young-of-year (Age 0+) juveniles as well as older age-classes of *O. mykiss*. Using snorkel-based survey results as model inputs, model-based results matched snorkel-based estimates of the proportions of individuals in each age-class from snorkel surveys conducted in the following year. Model-based abundance estimates were generally higher than snorkel survey-based estimates for young-of-year juveniles, but within 95 percent confidence bounds of survey-based estimates of older age-classes for all years except 2011. Because several issues affected population size estimates in the historical survey results, particularly related to extended high flows during 2011, year-to-year changes in age-class abundance compared to the same cohort one year prior are better represented in the model than in the survey-based results. For example, suitable sampling conditions for snorkel surveys were limited to a narrow flow range (<300 cfs) which likely had a large effect upon the 2011 survey results (Stillwater Sciences 2012c). Because use of the TROm model to confidently predict absolute population size estimates is constrained by the reliability of the existing population monitoring data, the approved *O. mykiss Population Study Plan* (W&AR-10) describes the intended use of the model as limited to comparing *relative* changes in population levels, as well as *relative* influences of in-river factors affecting *O. mykiss* production.

6.2 Model Scenario Results

Using the calibrated TROm model, *O. mykiss* production was evaluated for the Base Case simulation period (1971–2009). The Base Case provides a 37-year time series of varying hydrology and meteorology to examine variations in *O. mykiss* 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 and adult *O. mykiss* productivity was estimated at three population sizes of resident *O. mykiss*: 500, 2,000 and 10,000 fish. Modeling results showed that the juvenile productivity (i.e., ratio of end-of-year Age 0+ juveniles to spawners) was consistently lower at higher population sizes and generally higher during "wet" water year than for "dry" water year scenarios with these patterns reflective of cooler summertime water temperatures upstream of RM 39.5 in "wet" water year types. For older age-classes, adult *O. mykiss* replacement (i.e., Age 2+ and older fish/Age 2+ and older fish 1 year prior), was also higher during "wet" water year than for "dry" water year scenarios with the understanding that older *O. mykiss* are more able to avoid unsuitable water temperatures or areas in excess of habitat carrying capacity than juveniles. As discussed in the Synthesis Study (W&AR-05), these results are generally consistent with water temperature effects upon over-summering of young-of-year juveniles as well as historical information showing increased habitat use further downstream and higher relative abundance of *O. mykiss* in years with larger flood control releases.

Results for the Base Case scenario suggests some density-dependent effects with higher juvenile and adult replacement predicted at lower population levels. As discussed in the sections below, in addition to evaluating alternative flow scenarios on the extent of suitable over-summering habitat, the identified model sensitivity to particular parameters suggests that some non-flow measures could potentially affect *O. mykiss* productivity (e.g., predator removal, predator suppression, etc.).

6.3 Evaluation of Factors Affecting *O. mykiss* Production

Model sensitivity testing identified those model parameters affecting juvenile and adult *O. mykiss* population levels as well as potential smolt production from any steelhead arriving in the Tuolumne River. Using *O. mykiss* productivity metrics for juveniles (end-of-year Age 0+ fish/spawners), adults (Age 2+ and older fish/Age 2+ and older fish 1 year prior), and smolts (Age 1+ and older smolts/Age 1+ and older fish one year prior), parameters related to the following life stage processes were shown to exert the greatest influence on subsequent *O. mykiss* production through sensitivity testing of the calibrated model.

- Upmigration and Spawning
  - Moderate sensitivity to parameters related to spawning timing and fecundity.
  - Low sensitivity of juvenile productivity to parameters related to redd construction or other spawning related parameters.
- Egg incubation and fry emergence
  - High sensitivity of juvenile productivity to parameters related to survival-to-emergence.
  - Low sensitivity of juvenile productivity to development and mortality thresholds, both temperature related parameters.
- Fry rearing
  - High sensitivity of juvenile productivity to parameters related to growth, fry movement, and background related mortality.
  - Moderate sensitivity of juvenile productivity to maximum fry rearing density parameter.
  - Low sensitivity of juvenile productivity to initial fish size and temperature related mortality parameters.
- Juvenile rearing
  - High sensitivity of juvenile productivity to parameters related to background mortality rates.
  - Moderate sensitivity of juvenile productivity to parameters related to maximum rearing density at high population sizes as well as parameters related to water temperature related mortality and movement rates.
  - Low sensitivity of juvenile productivity to food availability parameters.
- Resident rearing
  - High sensitivity of adult replacement to parameters related to water temperature related mortality in “dry” water year types.
  - Moderate sensitivity of adult replacement to spawning probability, spawning-related mortality, and background mortality rate parameters.
  - Low sensitivity of adult replacement to food availability, temperature preference, and maximum adult rearing density parameters.
- Smolt emigration
  - High sensitivity of smolt productivity to parameters related to the probability of smoltification based upon anadromous parentage as well as water temperatures for smoltification.
  - Low sensitivity of smolt productivity to parameters related to adult or smolt emigration mortality.

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

The lack of sensitivity to redd disturbance area (redd.disturb.area) and the related defended area (redd.defense.area) suggest no model sensitivity to spawning habitat availability. No evidence of *O. mykiss* redd superimposition was found during 2013 surveys for the *Redd Mapping Study* (W&AR-08). Because usable spawning habitat for *O. mykiss* spawning (Figure 4.1-1) is near optimal at base flows in the current FERC (1996) flow schedule 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 for *O. mykiss*. Because the *Spawning Gravel Study* (W&AR-04) indicates relatively little change in available spawning areas as compared to historical estimates, the model results suggest that other than gravel quality improvements related to egg survival-to-emergence, potential spawning habitat enhancements such as gravel augmentation would have little effect on juvenile productivity. Given the large availability of potential spawning habitat documented as part of the *Spawning Gravel Study* (W&AR-04), however, it is unlikely that existing gravel availability is limiting juvenile productivity of *O. mykiss* under current conditions.

6.3.2 Juvenile Rearing Habitat Availability

Separate from temperature related issues (Section 6.3.5), modeling results to date show that in-channel juvenile habitat may be limiting at higher population sizes. Sensitivity testing conducted for this study shows that reductions in the maximum juvenile rearing density parameter used in the calibrated TROm model were accompanied by reductions in subsequent juvenile productivity and juvenile productivity is consistently lower at higher population sizes under the Base Case. Rearing density information summarized from recent snorkel surveys summarized as part of the Synthesis Study (W&AR-05) suggested an apparent exclusion of juveniles from riffle/pool transitions, and it is apparent density-dependence in the modeled juvenile productivity for the Base Case (Figure 5.3-1) is primarily due to migration related mortality (i.e., predation) as well as water temperature related mortality for any juveniles displaced into downstream rearing locations during late spring and summer. Model sensitivity testing shows some response in juvenile productivity to variation in the water temperature mortality threshold for the “dry” water year conditions represented (WY 2009) (Figure 5.2-2). Fry and juvenile movement rules in the current model implementation do not include avoidance of unsuitable temperatures so that any model fish displaced into downstream habitats may potentially be subject to subsequent water temperature related mortality during summer (Section 6.3.5). However, the available literature on juvenile *O. mykiss* movements indicates active responses to water temperature variations (Section 4.1.4.2), so re-evaluation of juvenile movement rules may be necessary in future refinements of the model (Section 6.4.1). Lastly, although increased food availability was shown to affect the timing of the fry/parr transition and increased subsequent juvenile productivity, materials reviewed as part of the Synthesis Study (W&AR-05) found that adequate food resources supporting juvenile rearing of *O. mykiss* were present in the lower Tuolumne River.

6.3.3 Adult Rearing Habitat Availability

Although adult replacement was shown to be sensitive to assumed background mortality rates as well as spawning related mortality, modeling results to date show that separate from temperature related issues (Section 6.3.5) rearing habitat is not limiting adult *O. mykiss* under current conditions. Information developed as part of the *O. mykiss Habitat Survey Study* (W&AR-12) suggests the absence of structural elements on the Tuolumne River (e.g., boulders, LWD) that are typical of high gradient habitats for coastal steelhead populations may increase effective territory size of rearing adults. Nevertheless, model simulations show very little differences in adult replacement with increased population size for the Base Case (Figure 5.3-3) and sensitivity testing conducted for this study show that reductions in adult rearing density parameters used in the calibrated TROm model are not accompanied by reductions in subsequent adult replacement (Figure 5.2-3). This implies that even for the highest population size evaluated (10,000), the number of adult *O. mykiss* is insufficient to fully saturate available rearing habitat under current conditions. Lastly, sensitivity testing indicates that increased food availability was not shown to affect modeled adult replacement (Figure 5.2-3).

6.3.4 Flow Effects

Sensitivity to parameters related to fry movement (Figure 5.2-2) as well as Base Case results for juvenile productivity (Figure 5.3-1) and adult replacement (Figure 5.3-3) suggests modeled *O. mykiss* production is affected by the relative influences of flow magnitude and timing upon life stage progression. Modeling results for the Base Case show that juvenile productivity and adult replacement is generally higher with increased La Grange discharge. Although Figure 5.3-1 and Figure 5.3-3 show model results plotted with La Grange discharge from March through September, model simulations were conducted on a full water year basis (i.e., October 1st through September 30th). In comparing the sensitivity and Base Case results by water year type, it is apparent that juvenile productivity is generally higher in "wet" years than in "dry" water year types (Figures 5.2-1, 5.2-2, 5.3-1 and 5.3-2). Adult replacement (Figure 5.2-3 and 5.3-3) is also higher in "wet" year types than in "dry" year types. For juveniles, early fry displacement with higher flows in "wet" water years has the effect of reducing subsequent movement related mortality due to exceedance of local rearing density thresholds (i.e., carrying capacity). For both juveniles and adults, greater downstream extent of cool water habitat during summer in "wet" water year types corresponds to lower levels of water temperature related mortality (Section 6.3.5).

6.3.5 Water Temperature

Water temperature is an important factor controlling egg incubation rates as well as juvenile and adult *O. mykiss* growth rates. Water temperatures for over-summering *O. mykiss* are generally below the identified mortality thresholds upstream of Roberts Ferry Bridge (RM 39.5) in Above Normal and Wet water years evaluated for the Base Case and the corresponding estimates of juvenile productivity are relatively high in comparison to juvenile productivity and adult replacement metrics evaluated in the drier water year types shown (Figures 5.3-2 and 5.3-4). In contrast to movement rules for adults (Section 4.1.5.2), TROm model implementation does not allow redistribution of fry or parr life stages from areas approaching mortality thresholds

(Sections 4.1.3.2 and 4.1.4.2) and low levels of juvenile mortality during summer are apparent for model fish displaced into downstream habitats. Because available literature suggests that juvenile *O. mykiss* may seek out cold water *refugia* at both the site scale and reach scale (Section 4.1.4.2), model assumptions regarding downstream fry and juvenile movement may be re-evaluated in the future (Section 6.4.1). Nevertheless, Base Case results and model sensitivity testing indicates that summertime water temperature conditions may be limiting juvenile productivity and adult replacement in "dry" water years. For adults, model implementation includes avoidance and redistribution from habitats exceeding water temperature preference limits (i.e., increased avoidance for temperatures between 20–24°C [68–75°F]) (Section 4.1.5.2). However, because adult habitat selection is made on a weekly time-step, any model fish occupying habitats exceeding assumed daily mean water temperature mortality thresholds (25°C [77°F]) at a daily time step are subject to temperature-related mortality. Overall, the territoriality of *O. mykiss* juveniles and adults (Grant and Kramer 1990) suggests some probability that individuals excluded from previously established territories due to exceedance of maximum rearing densities or exceedances of water temperature preference limits may be unable to locate undefended territories in other portions of the river with cooler temperatures. These results are consistent with summaries of historical monitoring data provided in the Synthesis Study (W&AR-05), which showed reduced relative *O. mykiss* abundance as well as reduced extent of habitat use downstream of La Grange Dam (RM 52.2) in "dry" water year types. Lastly, for the progeny of any steelhead arriving in the lower Tuolumne River, model sensitivity to parameters related to water temperatures for smoltification (Figure 5.2-4) suggests smolt emigration may be affected by water temperature conditions relative to assumed smoltification timing (Table 3.0-1).

6.3.6 Factors Affecting Expression of Anadromy of *O. mykiss* in the Tuolumne River

As discussed in the Synthesis Study (W&AR-05) and Section 4.1.6, the tendency for anadromy or residency in sympatric populations of resident *O. mykiss* and any steelhead that may arrive in the Tuolumne River is poorly understood. Satterthwaite et al. (2009) previously modeled the probability of smolting versus freshwater maturation of coastal populations of *O. mykiss*. Their modeling approach focused on modeling the body length and growth rates of females during a "maturation decision window" in which the tradeoff between future growth and survival is the primary determinant of smoltification at a given age. Satterthwaite et al. (2009) were able to successfully predict the dominance of anadromy in steelhead from the central California coast but acknowledge a key uncertainty as high growth rates could potentially contribute to either high or low rates of anadromy. Subsequently, Satterthwaite et al. (2010) repeated the same growth modeling described above for sympatric populations of Central Valley steelhead and resident *O. mykiss* on the American and Mokelumne rivers. Neither population in those rivers was observed or predicted to exhibit a predominantly resident life history like the Tuolumne River *O. mykiss* population; thus the applicability of the Satterthwaite et al. (2010) approach to determining the probability of smolting among Tuolumne River *O. mykiss* is uncertain.

In addition to the studies by Satterthwaite et al. (2009, 2010), the smoltification probabilities used in the TROm model (Table 4.2-5) are consistent with findings by Hendry et al. (2004), who showed that females tend to smolt at much higher rates than males due to the need for greater energy intake associated with producing energy-rich eggs by females versus the lower energy demands of sperm production in males. The uncertainty and conflicting observations regarding juvenile growth rates and probability of smolting versus freshwater maturation discussed above may be explained by recent advances in understanding the underlying mechanistic linkages. In a series of laboratory stream experiments using family groups and variations in fish density, feeding conditions, and water temperatures, Sloat (2013) determined that individual variation in standard metabolic rate was a key determinant in growth trajectories and probability of smolting. Specifically, Sloat (2013) found that fish with higher standard metabolic rate established and defended larger rearing territories in order to increase food consumption to compensate for higher metabolic rate and less efficient food assimilation. The lower food assimilation efficiency, in turn, led to lower growth rates and lower body lipid stores but was counterbalanced by greater total fish size and higher probability of smolting. As found by other researchers (Beakes et al. 2010), the observed differences in standard metabolic rate occurred in the study fish prior to full yolk sac absorption and thus appeared to be under control of genetic predisposition and variation within family (Sloat 2013). The probability of smolting also varied with water temperature, however, with fish held in cold thermal regimes more likely to mature in freshwater than fish held in warm thermal regimes. Fish held in warm thermal regimes had higher rates of smolting because they were able to grow to larger total sizes but had lower body lipid stores than fish held in cold thermal regimes. McMillan et al. (2012) found that higher body lipid stores were significantly correlated with an increased probability of maturation in freshwater, with the probability being sensitive to minor changes in total lipid stores. McMillan et al. (2012) concluded that this finding was due to the higher energetic requirements for growing gonadal tissue compared to somatic tissue. In other words, if a juvenile has sufficient lipid reserves to allow maturation in freshwater then there is no need to undergo smoltification and migrate to the ocean in order to gain sufficient lipid stores to mature.

The implications of the above discussion for *O. mykiss* in the lower Tuolumne River are that fish with higher early life history growth and larger body size due to warmer temperatures are more likely to smolt due to their larger body size (i.e., greater survival during outmigration and early ocean rearing) and lower lipid stores (i.e., greater need for the food rich environment of the ocean). Applying the lipid store findings discussed above to the Tuolumne River and tailwater fisheries within the San Joaquin River tributaries (i.e., Merced, Stanislaus rivers) as well as other Delta east side streams (e.g., Mokelumne, Calaveras), cold-water releases downstream of dams on these rivers may favor residency by increasing the efficiency of conversion of food rations into body lipid stores, thus encouraging maturation as resident *O. mykiss*. The low numbers of returning anadromous adults to the Tuolumne River and in other San Joaquin basin tributaries found by Zimmerman et al. (2009) support this interpretation, suggesting that increased cold water releases during summer would reduce, but not necessarily eliminate, the possibility of smoltification within the overall sympatric *O. mykiss* population of these rivers. However, Delta and ocean factors are likely more important than in-river factors in influencing smolt-to-adult survival affecting expression of anadromy in the Tuolumne River *O. mykiss* population. Satterthwaite et al. (2010) conclude that the single most important factor in preserving an anadromous life history is survival during the period between emigration to the ocean and returning to spawn. As found by Delaney et al. (2014) and also discussed by Yoshiyama and Moyle (2012), the poor migration survival conditions along the migratory pathway (e.g., lower San Joaquin River and south Delta) of any juveniles that do smolt would result in low probability of returning to spawn. The balance of the increased costs of emigration and early ocean survival with the benefits of ocean growth has been found elsewhere; Narum et al. (2008) and Satterthwaite et al. (2010) suggested suggested that low smolt survival through the Delta was the greatest management concern if the goal was to preserve or enhance expression of anadromy among Central Valley *O. mykiss* populations.

6.4 Potential Information Needs to Address Modeling Assumptions

As recommended by FERC Staff in Element No.1 of the December 22, 2011 SPD for the *O. mykiss Population Study Plan* (W&AR-10), the TROm model includes mechanisms and parameters to "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." However, in contrast to the large body of information summarized for Chinook salmon as part of the Synthesis Study (W&AR-05) and the *Chinook Salmon Population Model Study* (W&AR-06), *O. mykiss* information used for this study is limited to short-term assessments from interrelated relicensing studies referenced in this report. Longer-term information summarized as part of the Synthesis Study (W&AR-05) includes summertime habitat use by resident *O. mykiss* (1983–present), population size estimates (2008–2011), a small number of individuals detected at the Tuolumne River weir at RM 24.5 (2009–present), as well as short-term adult tracking studies (2010–2011) summarized by the Districts (Ford and Kirihara 2010, Stillwater Sciences 2012b, c). Because little information specific to the Tuolumne River is available directly informing representation and parameterization of processes and mechanisms affecting *O. mykiss* life history progression, a number of simplifying assumptions have been made in the TROm model development. To improve our understanding of the mechanisms represented in the model as well as to confirm or adjust the assumptions made in the model implementation, potential future information needs, as well as active areas of investigation are discussed below.

6.4.1 *O. mykiss* Movement Data

Because little information on *O. mykiss* fry and juvenile movement exists for the Tuolumne River, movement parameter estimates were assumed to be of the same as for the *Chinook Salmon Population Model Study* (W&AR-06). Juvenile productivity is shown to be highly sensitive to the assumed movement rates and temperature related mortality threshold because of the rapid increase in summertime water temperature with increasing distance downstream of the La Grange powerhouse (RM 51.5). The available literature suggests that juvenile *O. mykiss* may seek out local thermal *refugia* as well as larger scale upstream movements in response to high water temperatures (Kubicek and Price 1976, Kaeding 1996, Hay 2004). However, the current implementation of the TROm model only allows re-distribution of adults on the basis of temperature preferences (Section 4.1.5.2). Other than the limited acoustic tracking data for adult *O. mykiss* collected as part of FISHBIO (2012), little information exists regarding the degree to which juveniles and adults may avoid unsuitable temperatures. Thus any conclusions drawn from the TROm Model regarding population level effects on juvenile productivity and adult replacement should be cognizant of the uncertainty associated with the movement rates and temperature thresholds used in the current version of the model. At this time, ESA-limitations on tagging studies designed to assess *O. mykiss* movement prevent direct assessment of this issue. Collection of *O. mykiss* movement data may be considered in the future to improve our ability to assess the impact of alternative water management options on *O. mykiss* juvenile productivity or adult replacement.

6.4.2 Local Water Temperature Adaptations

TROm model parameterization for particular life stages relied primarily upon EPA-funded temperature reviews (McCullough et al. 2001) and other empirical sources of information related to habitat selection, incubation, growth, and mortality (e.g., Velsen 1987, Rombough 1988, Myrick and Cech 2001, Richter and Kolmes 2005). The TROm Model includes a background mortality parameter to account for disease and other unaccounted mortality sources, but the model does not include sub-lethal effects on life-history progression as a direct function of temperature. To address information needs related to sub-lethal effects of water temperatures found in the lower Tuolumne River, the Districts are continuing the development of the *Temperature Criteria Study* (W&AR-14). The Districts have proposed to conduct a study of the temperature tolerance of juvenile and sub-adult *O. mykiss* captured from the lower Tuolumne River to assess any local adaptation to warmer temperatures occurring in the southern extent of the species range for *O. mykiss*. Information from these active areas of investigation may be used to guide further refinement of the selected parameter values and movement rules in the TROm model implementation, as well as to help determine the extent of thermally suitable habitat under various flow conditions.

6.4.3 Other Potential Sources of Adult *O. mykiss* Recruitment

Occurrence of a reproducing resident *O. mykiss* population upstream of La Grange Dam (RM 52.2) has been documented in the Synthesis Study (W&AR-04) as well as the *Fish Assemblage and Population Between Don Pedro and La Grange Dam Study* (W&AR-13). As discussed as part of the TROm model validation results (Section 5.1), year-over-year increases in adult age-class size found in the recent population estimate surveys in 2010 and 2011 are consistent with introduction of resident juvenile and adult *O. mykiss* into the rearing population downstream of La Grange Dam (RM 52.2). For example, the September 2011 population estimates for both juvenile and larger fish were substantially higher than in previous years, with observations of larger fish (≥150 mm) dominated by fish in the 150–200-mm size class (54% of all observations) (Stillwater Sciences 2012c). As discussed in Section 5.1, since these fish are generally too large to be Age 0+ and the adult population size was substantially larger than in 2010, these fish may have either originated as resident adult upmigrants during periods that the RM 24.5 counting weir was non-operational in 2011, or may have originated from rearing locations upstream of La Grange Dam (RM 52.2). The potential interaction of these resident *O. mykiss* with the population downstream of La Grange Dam is poorly understood and complicates the use of population data in validating the model as well as any future monitoring of population response to potential management measures intended to benefit any Central Valley steelhead in the lower Tuolumne River.

6.4.4 Predation Mortality Sources

For fry and parr life stages, the TROm model currently attributes migration related mortality to predation using movement and exposure based mechanisms as well as parameterization from the

Chinook salmon Population Model Study (W&AR-06). In addition, predation risk was assumed to be uniform with distance from La Grange Dam (RM 52.2). At this time, ESA-limitations on tagging studies designed to assess juvenile movement or predation effects on *O. mykiss* juveniles prevent direct assessment of this issue. Additional Predation Study (W&AR-07) experiments on predation rates and predator abundance in 2015, while focused on juvenile on juvenile Chinook, may provide additional information on the magnitude of predation on juvenile *O. mykiss*.

6.4.5 Expression of Anadromy in the Tuolumne River

As highlighted by the anadromous life history discussion in Section 6.3.6, significant uncertainty exists regarding the probability of smoltification versus freshwater maturation in Tuolumne River *O. mykiss*. Other than the occurrence of one steelhead and several resident fish exhibiting maternal anadromy demonstrated in otolith analyses by Zimmerman et al. (2009), no information exists regarding steelhead life history or *O. mykiss* smoltification specific to the Tuolumne River. Because of the uncertainty in establishing mechanistic linkages of the relevant factors affecting the expression of *O. mykiss* anadromy in the Tuolumne River, the TROm model has simplified smoltification processes by representing them as assumed probabilities of smolting based on parentage, as well as prohibiting smoltification at water temperatures in excess of identified thresholds. For these reasons, use of the TROm model in evaluating the relative benefits of potential management measures for any Central Valley steelhead in the Tuolumne River (as opposed to the more numerous resident *O. mykiss* documented in historical snorkel surveys) is limited to evaluation of temperature suitability of specific river reaches for any smolt-ready individuals that may arise within the overall mixed anadromous-resident *O. mykiss* population. This aspect of temperature suitability for smoltification portrayed in the TROm model is in agreement with the results of previous studies that demonstrate the key role of environmental temperatures in determining the life-history pathways of various anadromous salmonids, including *O. mykiss* (Yoshiyama and Moyle 2012; Beakes et al. 2010; Sloat 2013; Clarke and Hirano 1995). However, the lack of Tuolumne-specific data on steelhead highlights the need for continuing research regarding the expression of anadromous versus resident life history forms of *O. mykiss* in the Central Valley. Future evaluations should consider comparisons of early life history growth rates and mortality outcomes in rivers supporting greater or lesser degrees of anadromy than occurs in the Tuolumne River.

7.0 STUDY VARIANCES AND MODIFICATIONS

There are no study variances for Study W&AR-10.

8.0 REFERENCES

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STUDY REPORT W&AR-10
***ONCORHYNCHUS MYKISS* POPULATION**

ATTACHMENT A

ADDENDUM TO THE TUOLUMNE RIVER
***ONCORHYNCHUS MYKISS* POPULATION MODEL**

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ADDENDUM TO THE TUOLUMNE RIVER *ONCORHYNCHUS MYKISS* 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 *Oncorhynchus Mykiss* Population Model Study Report

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List of Acronyms

AAS............................absolute aerobic scope
°C ....degrees celsius
cfs...............................cubic feet per second
Districts......................Turlock Irrigation District and Modesto Irrigation District
FERC..........................Federal Energy Regulatory Commission
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
SS ....sum of squares
TID.............................Turlock Irrigation District
TLSRA.......................Turlock Lake State Recreation Area
USEPA.......................U.S. Environmental Protection Agency
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 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 *O. mykiss* 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 *O. mykiss*.
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.
Semelperous	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 *O. mykiss* 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 2013c). Information from the Synthesis Study and building upon modeling approaches used in the development of the Tuolumne River Chinook salmon population model (TID/MID 2017a), the Tuolumne River *O. mykiss* population model (TROm model) was developed to simulate riverine life stages of Central Valley resident and anadromous *O. mykiss*, including any Central Valley steelhead that may spawn in the Tuolumne River (TID/MID 2017d).

The TROm model) is a spatially-explicit (1-dimensional) model that uses an individual-based framework to represent the major life history processes affecting *O. mykiss* maturation, spawning, egg incubation, juvenile growth, movement, mortality and anadromy rates to provide estimates of juvenile and smolt production as a function of varying flows and water temperatures in the lower Tuolumne River (TID/MID 2017d). Based upon updates since the publication of the TROm model study report, a number of enhancements have been made to the model to improve its use in comparing the effectiveness of alternative flow operational changes of the Don Pedro Project (FERC No. 2299).

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 TROm 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 updated 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 *O. MYKISS* POPULATION MODEL

As an update to the final study reports and code of the TROm model (TID/MID 2017d), 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 *O. mykiss* was included to account for floodplain inundation at high flows.
- Section 2.3 described updates to bioenergetic growth modeling of juvenile *O. mykiss* based upon evaluation of recent Swim Tunnel thermal tolerance testing results.
- Section 2.4 presents updated calibration and validation results of the TROm model using updated growth, movement and mortality parameters, as well as updated estimates of overbank habitat.

Unlike the 2013 study reports, the updated TROm model has been calibrated by tuning juvenile growth rates to available size at age information an adjustment of mortality parameters for all life stages to achieve a stable population size and age class composition. Model validation was carried out by comparisons of age structure and summer-rearing population sizes as estimated by the calibrated TROm model with those found in recent population estimates (Water Year [WY] 2008–2011) developed through intensive snorkel surveys (e.g., Stillwater Sciences 2008, 2009, 2011).

For simulation purposes, model inputs for discharge are provided by the Tuolumne River Operations Model (Operations Model) (TID/MID 2017e); water temperature inputs are provided by the Don Pedro Reservoir Temperature Model (Reservoir Temperature Model) (TID/MID 2017f) 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. 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 provide the background of the TROm population model development, a description of the modeling approach, assumptions, model implementation, as well as the results of model calibration and validation simulations.

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 (TID/MID 2017a). Using flow simulations from the Operations Model (TID/MID 2017e), 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 *O. mykiss* 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 2012a) or floodplain geographical 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 TROm 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 *O. mykiss* as a function of flow from 1,000 cfs to 9,000 cfs. Estimates of usable floodplain habitat area for rearing fry and any juvenile life stages of *O. mykiss* were conducted using joint habitat suitability indices (i.e., 0–100%) from the Stillwater Sciences (2013a) 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 *O. mykiss* 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 2013a) (0–1,000 cfs) were used to represent in-channel habitat area availability for fry rearing.

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 2013a). 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 2013a) 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 *O. mykiss* juveniles.

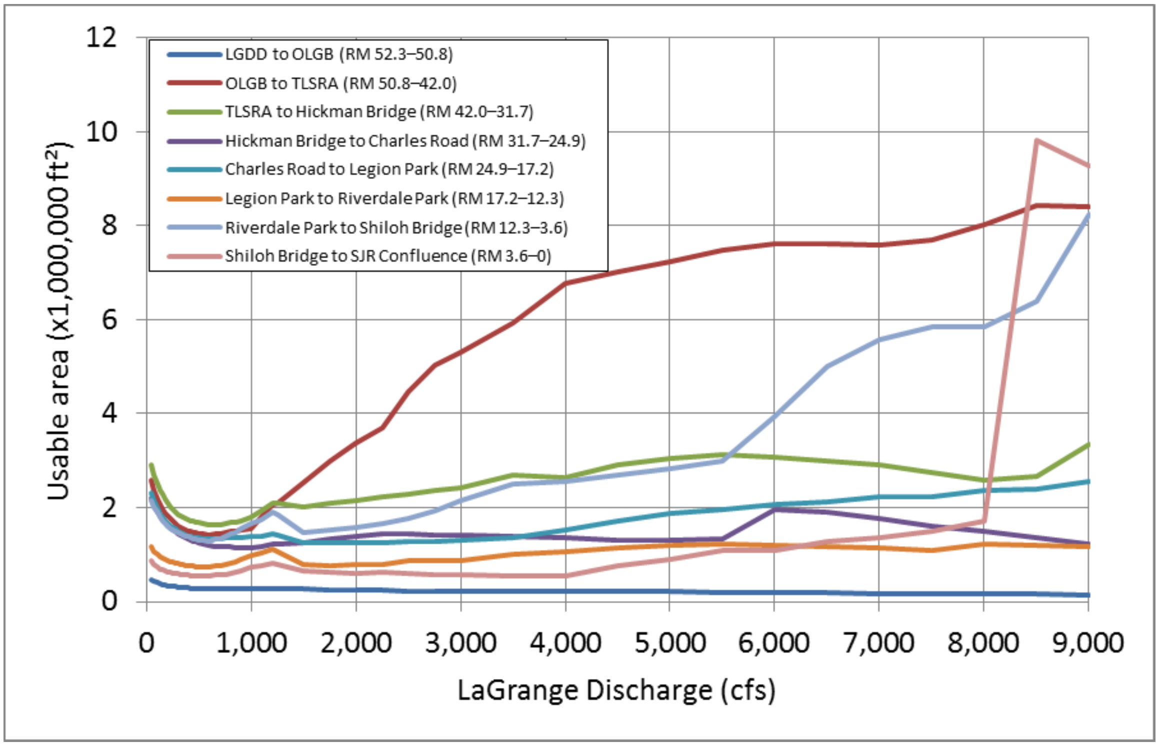

Figure 2.1-1. Estimated total combined usable in-river and overbank habitat for Tuolumne River *O. mykiss* fry.

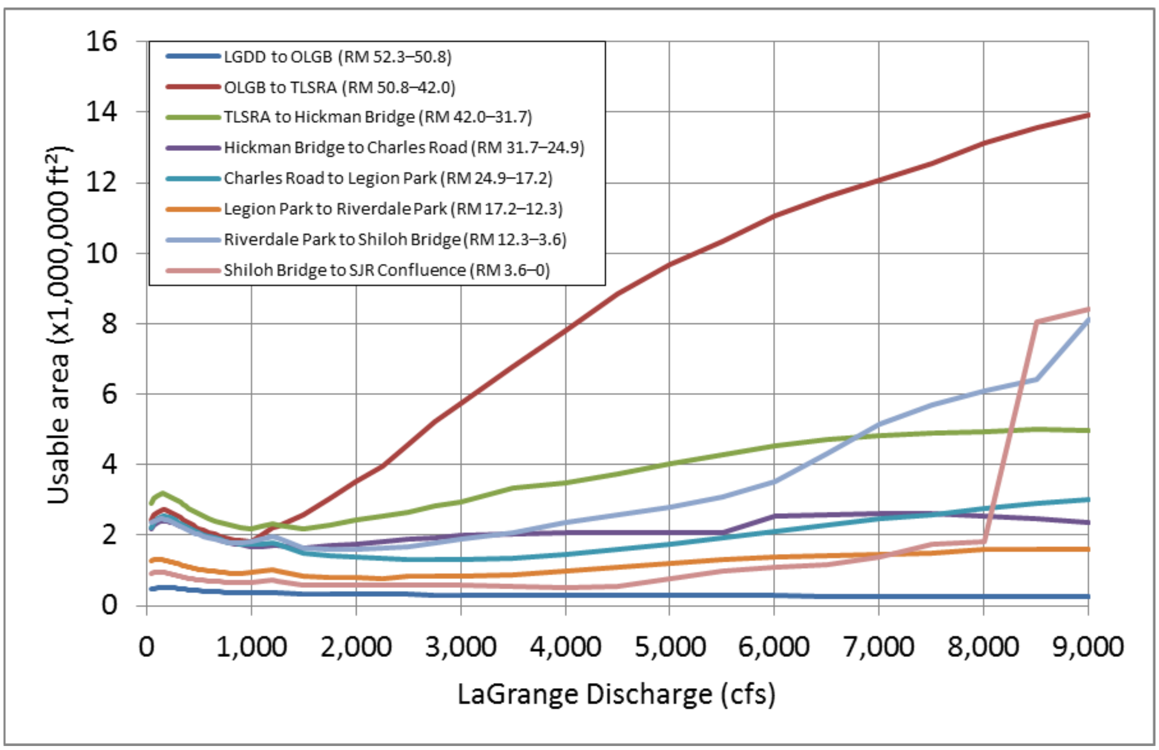

Figure 2.1-2. Estimated total combined usable in-river and overbank habitat for Tuolumne River *O. mykiss* juveniles.

2.2 Updated Estimates of Reach Specific Predation Related Mortality

Information reviewed in the Synthesis Study (TID/MID 2013c) suggests that aquatic predation is the primary mechanism of *O. mykiss* 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 *O. mykiss* (fry, juvenile, smolt), although it does represent water temperature-related mortality and background mortality from other sources as well.

Although predation of *O. mykiss* by predatory fish species has not been documented in the Tuolumne River, 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. To estimate predation risk for juvenile *O. mykiss*, 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 2013b), predation-related mortality risk factors can be used to apportion river wide juvenile salmonid mortality estimates to specific river reaches.

From the information above, predation risk in the TROm 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). Although stomach content sampling conducted by the Predation Study (TID/MID 2013b) did not identify *O. mykiss* in predator diets, predation efficiency of fry and juvenile size *O. mykiss* was weighted by 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.

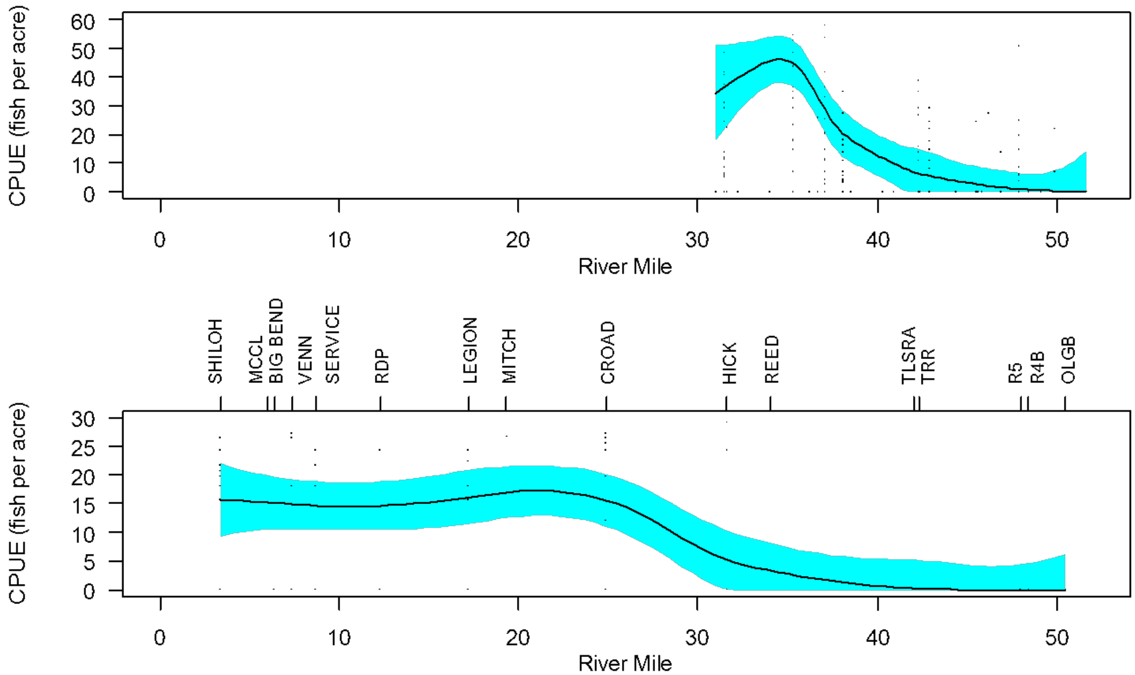

Figure 2.2-1. **Relative abundance of black bass (*Micropterus spp*.) in the lower Tuolumne River (1997–2014) as indicated by snorkel observations (top) and seine recoveries (bottom).**

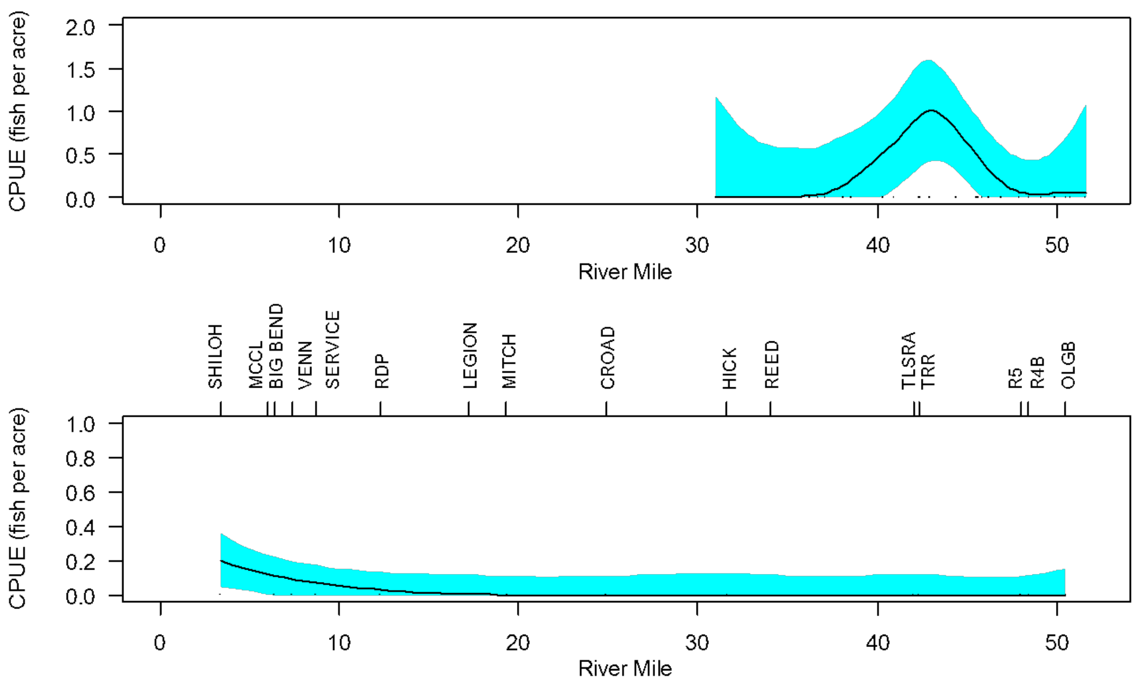

Figure 2.2-2. **Relative abundance of Striped Bass (*Morone saxatilis*) in the lower Tuolumne River (1997–2014) as indicated by snorkel observations (top) and seine recoveries (bottom).**

Equation 1 represents the probability of survival of fry and juvenile *O. mykiss* 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.

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

2.3 Bioenergetic Growth Modeling Updates

Growth of juvenile and adult *O. mykiss* 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 Satterthwaite et al. (2010) shown in Equation 1. Specific growth rate (g) (% weight change/day) for a fish of weight W (g) at temperature T (°C) is given as a function of the maximum consumption rate GC and catabolic costs GM reflecting breakdown of cellular tissues.

$$g = \frac{a}{a+\kappa}\mathrm{GC} - (1+a)\mathrm{GM}, \text{ where}$$ Equation 2

$$a = \max\left(\sqrt{\kappa GC/GM} - \kappa, 0\right), \text{ and}$$

$$\mathrm{GC} = \Psi(T) f c W^{0.86-1}, \; \mathrm{GM} = \alpha e^{0.071T}$$

Equation 2 is similar to more general bioenergetic models where food availability provides the energy for foraging, temperature controls the metabolic processes, and body weight is used to scale the metabolic processes. The foraging activity (a) is assumed to maximize growth for a given weight, water temperature, and energy consumption kappa (κ). Kappa is the feeding activity level needed for a fish to reach half its maximum daily energy consumption, and is conceptually equivalent to the inverse of food ration. Although no stomach content sampling has been conducted on *O. mykiss* in the Tuolumne River due to permitting restrictions on handling ESA-listed species, food availability levels in the lower Tuolumne River are relatively high, consistent with high length at age of adults sampled as part of the *O. mykiss* Scale Collection and Age Determination Study (TID/MID 2013a). Additionally, although no direct studies of overbank habitat use or growth of *O. mykiss* have been conducted on the Tuolumne River and no information from other locations was identified, because of higher growth rates observed for juvenile Chinook in published floodplain rearing studies (Sommer et al. 2001; Jeffres et al. 2008), lower energy consumption requirements (κ) are assumed for any *O. mykiss* fry rearing in overbank habitat areas. Kappa was adjusted as a calibration parameter to fit the size-at-age distribution observed in the Tuolumne River from the *O. mykiss* Scale Collection and Age Determination Study (TID/MID 2013a).

Equation 2 includes a Thornton-Lessem (1978) function Ψ which relates maximum potential consumption to temperature and allows the model to reflect near optimal consumption at a range of temperatures. We parameterize this function in the same manner as Railsback and Rose (1999) which used data from laboratory studies by Myrick (1998) to update previous bioenergetics models. Based on this parameterization, Railsback and Rose (1999) found optimal consumption rates at temperatures 20–22^{o}C. This is consistent with recent site-specific experimental data which showed that *O. mykiss* from the Lower Tuolumne River reach maximum absolute aerobic scope (AAS; the capacity of *O. mykis*s to supply oxygen to tissues above and beyond a basic routine need) at 21.2^{o}C (Farrell et al. 2017). Additionally, the Swim Tunnel Study found that 95% of the optimum AAS peak was maintained between 17.8°C and 24.6°C, suggesting that Tuolumne River *O. mykiss* are locally adapted to temperatures well above the 7-Day Average of the Daily Maximum (7DADM) criterion of 18°C set out by the U.S. Environmental Protection Agency (USEPA) (2003) for Pacific Northwest *O. mykis*s. Accordingly, all other initial parameter estimates for Equation 1 follow those used by Satterthwaite et al. (2010) for *O. mykiss* populations in tributaries to the San Joaquin River.

2.4 Updated TROm Model Calibration and Validation

As an update to the calibration approach in the 2013 study report, the TROm model has been simplified by tuning juvenile growth rates to available size at age information an adjustment of mortality parameters for all life stages in order to achieve a stable population size and age class composition. Due to the limited occurrences of *O. mykiss* in routine monitoring activities (e.g., RSTs, river-wide seining, RM 24.5 counting weir) (TID/MID 2013c), opportunities for model calibration or validation are limited. Some model mechanisms (e.g., temperature-based mortality) and functional relationships have been studied in detail under controlled conditions. Hence, the appropriate values for the relevant model parameters are constrained by experimental data. Other relationships are based on simple models and use parameter values constrained only loosely by theoretical arguments. The purpose of TROm model calibration was to fine-tune the less well constrained parameter values to maximize the agreement between model estimates and available monitoring data.

TROm model calibration was conducted in three steps. First, fitting of growth parameters used in Equation 2 for fry, juveniles, and adults was conducted to match inter-annual growth rates from the *O. mykiss* Scale Collection and Age Determination Study (TID/MID 2013a), as well as the ratio of fry to juveniles derived from snorkel survey data (2008–2011). While snorkel survey data are useful for inferring relative metrics, such as the ratio of fry to juveniles, a high level of uncertainty exists in snorkel based estimates of total population size. Accordingly, baseline mortality parameters for fry, juvenile, and adult life stages were adjusted to achieve a stable long-term average population size over a multiple water year (WY) simulation (1996–2009) in which the end-of-year TROm model results are used as start-of-year populations for the next modeled year. Finally, a stable age composition for initial population inputs was constructed by running the model multiple times over the four-year calibration period, adjusting the initial population each time until the final age composition was similar to the initial composition.

2.4.1 Initial Conditions

Initial conditions relevant to *O. mykiss* life stages in the Tuolumne River are summarized for the period 2007–2012 in Table 2.4-1 to describe antecedent and initial conditions for calibration and validation of the TROm model. Water temperature briefly exceeded the assumed embryo temperature mortality threshold (15^{o}C) during mid-April in 2008 and late March in 2009 at RM 39.5. Downstream of RM 36.5, water temperature during the summer rearing period (Jun–Sept) exceeded the fry, juvenile, and adult temperature mortality threshold (25^{o}C) on multiple occasions in all calibration years except 2011.

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

Initial Conditions (WY)		2007	2008	2009	2010	2011	2012
Spawning/incubation flow (cfs)[1] (15-Jan–1-May)	min	308	166	165	217	1,580	168
	max	869	1,310	681	2,130	8,380	389
Spawning/incubation temp (°C)[1] (15-Jan–1-May)	min	8.9	8.3	9.4	8.8	9.2	9.6
	max	14.5	16.4	15.4	14.1	10.8	18.5
Adult/juvenile Rearing flow (cfs)[1] (Oct–May)	min	208	97	154	208	357	168
	max	869	1,310	955	3,300	8,380	2,120
Adult/juvenile rearing temp (°C)[1] (Oct–May)	min	8.5	7.6	8.1	8.2	9.2	9.4
	max	17.1	17.2	18.8	15.5	15.2	18.5
Adult/juvenile rearing flow (cfs)[1] (Jun–Sep)	min	76	80	95	301	280	96
	max	189	125	281	5,520	7,030	197
Adult/juvenile rearing temp (°C)[1] (Jun–Sep)	min	11.0	11.0	10.3	10.7	10.1	11.3
	max	23.4	25.2	23.7	18.0	16.3	24.6
Adult/juvenile rearing flow (cfs)[2] (Oct–May)	min	208	97	154	190	357	168
	max	1,015	1,679	1,004	3,329	8,998	2,120
Adult/juvenile rearing temp (°C)[2] (Oct–May)	min	6.2	5.4	5.3	5.5	8.0	6.3
	max	24.7	22.5	25.0	20.8	22.5	25.3
Adult/juvenile rearing flow (cfs)[2] (Jun–Sep)	min	76	80	95	301	280	95
	max	329	271	421	5,520	7,030	318
Adult/juvenile rearing temp (°C)[2] (Jun–Sep)	min	17.4	18.4	15.7	12.8	10.6	16.5
	max	31.7	32.9	32.3	26.2	22.6	32.2

[1] Based on daily flow and temperature estimates upstream of Robert's Ferry Bridge (RM 39.5).
[2] Based on daily flow and temperature estimates downstream of Robert's Ferry Bridge (RM 39.5).

2.4.2 Bioenergetic Growth Model Calibration

The growth model used in the model is taken from Satterthwaite et al. (2010), which is in turn based largely on the model of Railsback and Rose (1999). In the TROm model, only kappa, a measure of feeding efficiency, is suitable as a Tuolumne-specific fitting parameter. Other parameters are physiological, and are derived from the experimental literature. The model uses different values of kappa for fry and juveniles, and for different ages of fish after the first year, so there are many parameters to be set with a very small amount of data. Because no site-specific data are available to estimate feeding efficiency *per se*, it is an ideal candidate for calibration of the growth model to site-specific data on *O. mykiss* growth.

Estimates of adult growth parameters are based on length-at-age and growth data from the 2012 Scale Study (TID/MID 2013a). For modeling purposes, any individuals beyond the fry and juvenile life stages are considered adults. This includes age 0+ individuals, which may not be reproductively mature (thus the working definition of "adult" deviates from biological convention). The average fork lengths calculated from the 1st, 2nd, 3rd, and 4th annuli for the scales examined were 110, 182, 257, and 331mm, respectively, with the average growth increments of 73, 72, 74, and 78mm in the corresponding years of life. To reduce the degrees of freedom, we assumed that the kappa values vary with age according to Equation 3 so that only two parameters (b0 and b1) are fitted. Calibration of the kappa (κ) parameter assumes that the ability to obtain food changes with size. Age promotion in the model takes place on 1 January.

$$\kappa_{\text{age}} = \frac{1}{b0 + b1 \cdot \text{age}} \qquad \text{Equation 3}$$

The values of (b0, b1) were set by minimizing the function SS(b0, b1), where SS represents the sum of squares of modeled versus observed growth increments. For each of the four ages from the Scale Study (TID/MID 2013a), the model was initialized with a standard population. Ages and fork lengths for the standard population were determined by running the model with water year 2012 flow and temperature time series (the year in which scales were collected for the study), and average fork lengths at the end of the model year were calculated. After all four age classes were run, SS(b0, b1) was set to equal the sum of squares of the differences between the modeled growth increments and the increments from the Scale Study (TID/MID 2013a). This process was repeated for many random pairs of b0 and b1, with the best pair used as the model parameters. Figure 2.4-1 shows the smoothed surface generated from this process.

The kappa parameter for the growth of young-of-the-year fish (YOY), defined here as fry (emerged fry <50mm) and juveniles (fish >50mm that have not yet been promoted to age 0+), was calibrated to the relative abundance of fry and juveniles derived from abundance and size estimates from snorkel surveys conducted in 2008–2011 (the "BCE reports"). The fry kappa parameter determines how long fish spend in the fry stage, and thus the relative abundance of fry versus juveniles at a given date. We therefore used the ratio of fry to juvenile at the time of the snorkel survey (which differs from survey to survey) as the main calibration target for determining the value of kappa for the fry growth model. For each trial value of the fry kappa, the model was initialized with a standard starting population, and run with the historical flows and temperatures of the appropriate year. A "snapshot" was taken of the YOY populations on a model day corresponding to actual survey dates.

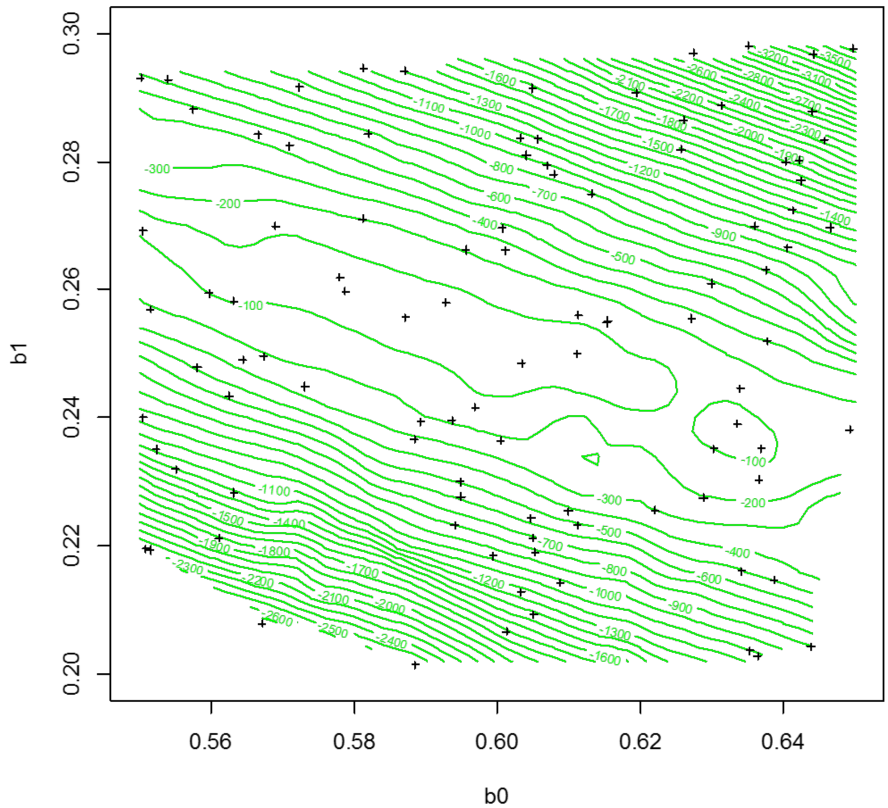

Figure 2.4-1. Contour lines showing sum of squares (SS) between observed (Scale Study) and predicted (TROm model) FL used to fit the age-specific growth parameter (κ age).

The 2010 data were not used for calibration because there were no fry observed in the snorkel survey that year. For the 2008 and 2009 model data, a value of kappa near 1.4 yielded the best match to the snorkel data. For 2011, the estimated kappa was 2.52. Although Satterthwaite et al. (2010) do not report numerical values for the kappa parameters they obtained for Central Valley populations, both 1.4 and 2.52 were consistent with the ranges of values shown in Figure 4 of their report. Because the kappa value for 2008 is consistent with that of 2009, 1.4 was used for the final model. Figure 2.4-2 shows the ratio of fry to juveniles as a function of the fry kappa value for the three calibration years.

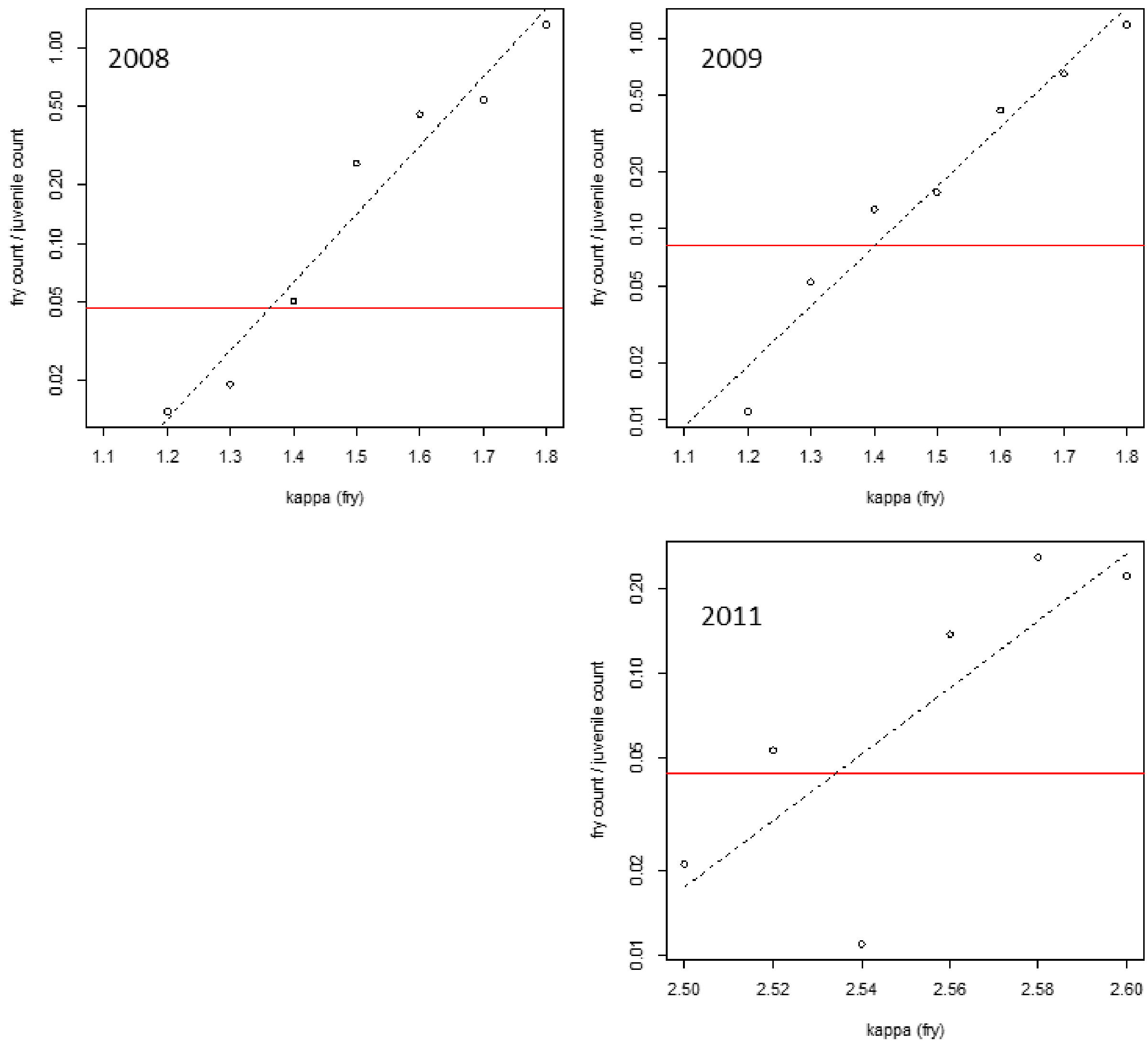

Figure 2.4-2. Modeled predictions of the ratio of fry to juveniles at the time of snorkel surveys (markers) as a function of the fry kappa parameter values, as well as the ratio of the fry to juveniles estimated from the snorkel survey analyses (horizontal red lines).

The juvenile kappa value was calibrated to mean fork length at a given date using snorkel survey data from 2008, 2009, and 2011 (Figure 2.4-3). As with fry kappa calibration, the calculated 2011 juvenile kappa varies considerably from 2008 and 2009. Because the calculated juvenile kappa for 2008 and 2009 were consistent, the calibration from these years was accepted for parameterizing growth in the final model.

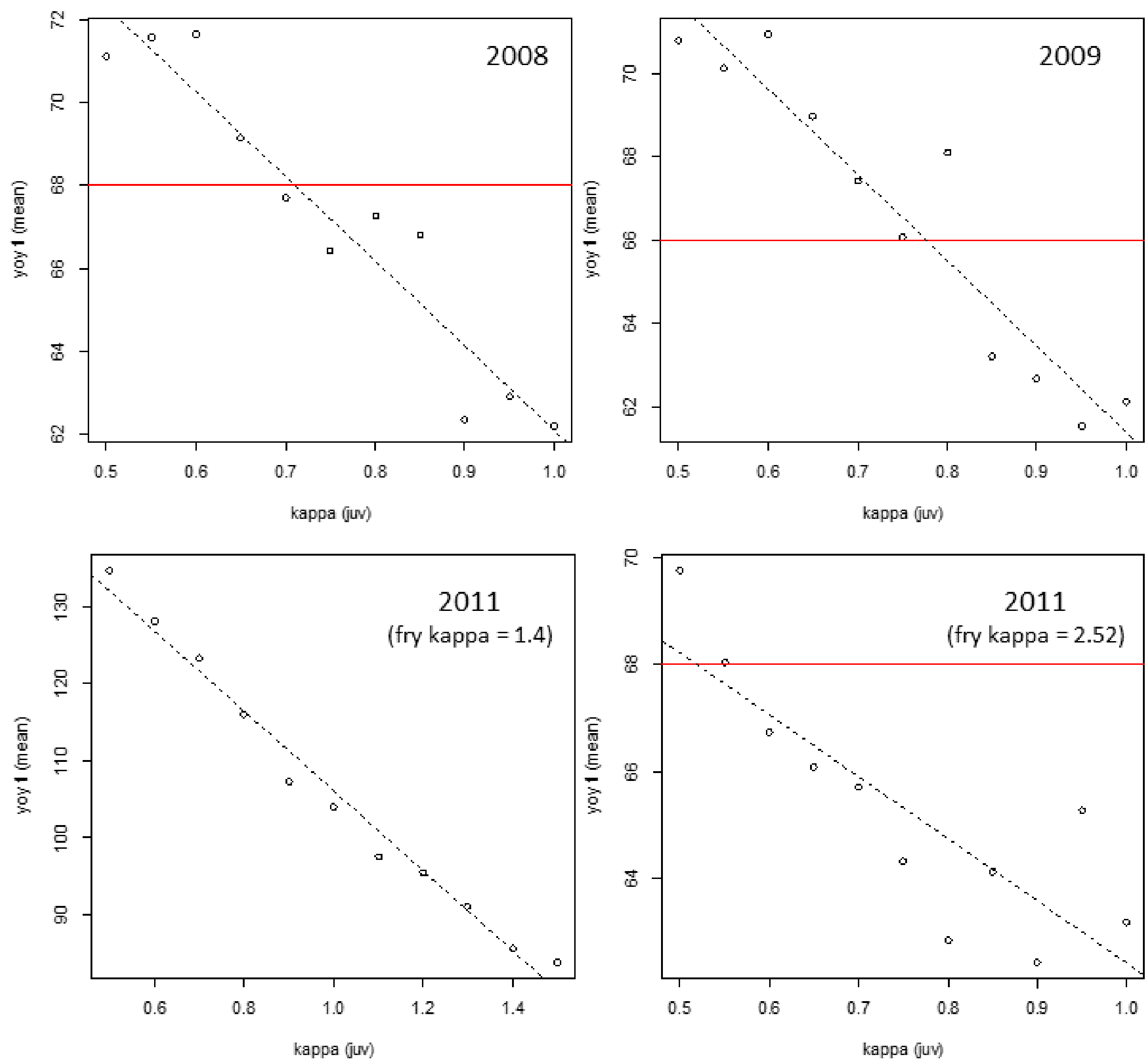

Figure 2.4-3. Modeled predictions of fork length (mean) as a function of the juvenile kappa parameter values, with the observed mean fork length estimated from snorkel survey analyses (horizontal red lines).

2.4.3 Stable Population Size and Age Class Calibration

Following calibration of the juvenile and fry growth models, mortality rates for all fish were adjusted such that over multiple years, the population would neither experience exponential growth nor exponential decay. This was achieved by setting initial mortality parameters for all age classes that were consistent with ecological theory regarding differences in mortality across age and size classes. These initial estimates were then adjusted using a single multiplier to reach a stable population over a multi-year simulation in which a given model year was initialized with output from the previous model year. This was performed for model years 2007–2012, beginning with a standard population of 500 resident fish aged one and above. The mortality rate multiplier was adjusted so that the final number of adults would remain close to the initial number of adults. Figure 2.4-4 shows the dependence of the adult replacement rate on the mortality rate multiplier.

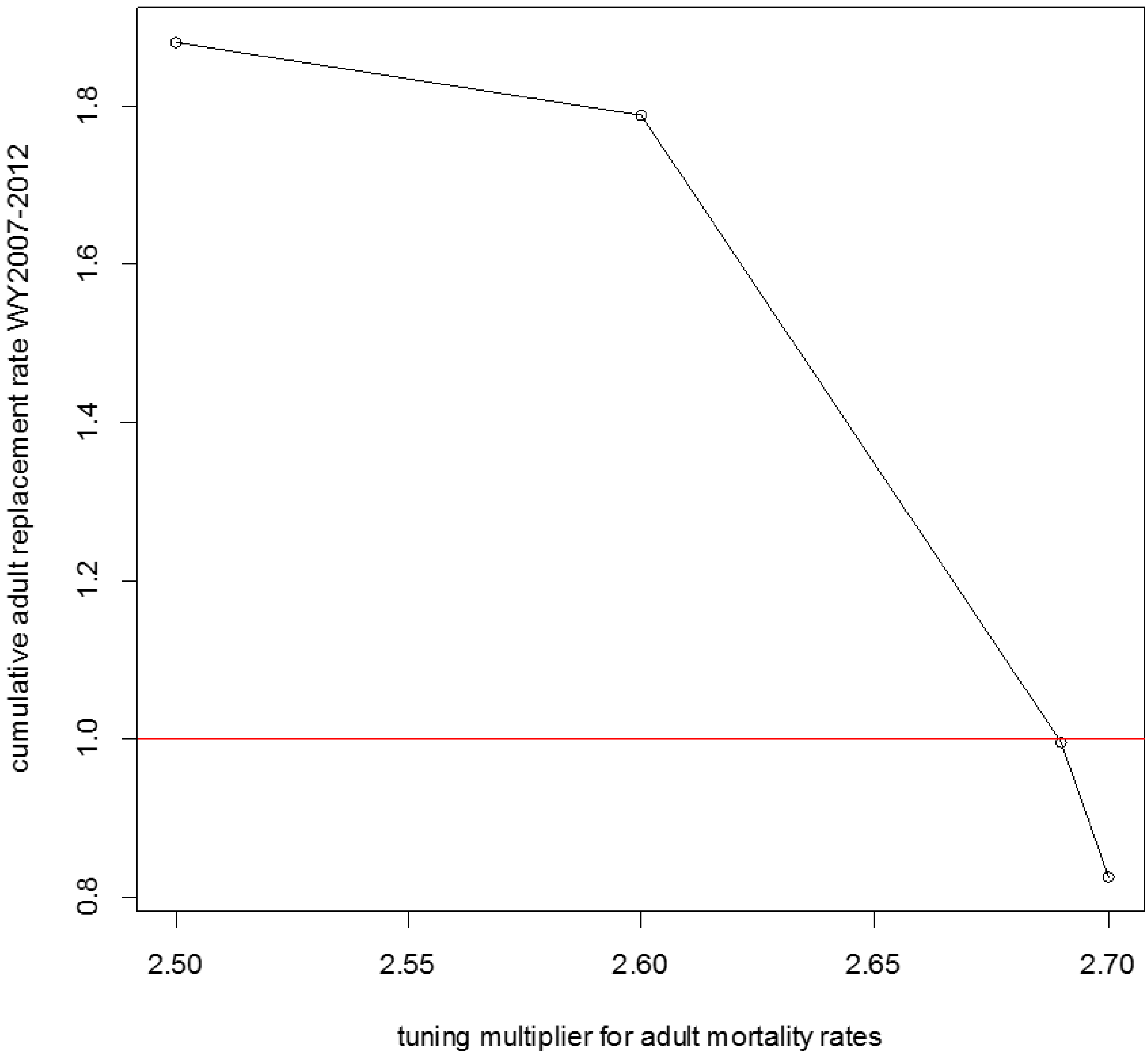

Figure 2.4-4. Adult replacement rate as a function of the mortality rate multiplier, with the target replacement rate (1.0) shown as a red horizontal line.

Unlike the TRCh model, for which initial populations can be constructed from redd count or weir count data (TID/MID 2017a), limited data are available for constructing initial populations of *O. mykiss* for TROm model operation. Additionally, the complex life history of *O. mykiss* relative to Chinook salmon complicates the construction of initial populations for analysis. The TROm model requires input for the number and size of YOY from the previous model year, the number of resident adults from the previous model year, any anadromous upmigrants, as well as information regarding which fish will spawn or smolt in the following model year. Because limited data are available to estimate these factors, we used the model to construct an initial population age structure that would remain consistent over the model calibration period. Beginning with 500 resident trout age 1+, the model was run over 2007–2012 multiple times, each time readjusting the initial age composition to agree with the final age composition. This process was repeated until the age composition stabilized over the multi-year model run. This age composition was then applied to an initial population of 10,000 resident trout to construct a "high abundance" initial population for use in scenario evaluation.

2.4.4 Updated TROm Model Validation

Updates to the TROm 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.

Validation was carried out by comparisons of age structure and summer-rearing population sizes as estimated by the calibrated TROm model with those found in recent population estimates (WY 2008–2011) developed through intensive snorkel surveys (e.g., Stillwater Sciences 2008, 2009, 2011). Using parameter estimates for the calibrated model, the TROm model was run using observed flow and temperature ranges from for the validation period (2008–2011) as summarized in Table 2.4-1 to estimate mid-summer population sizes and age structures, which were then validated against snorkel data for the corresponding year. Figure 2.4-5 shows one-year model projections of *O. mykiss* population age structure for Age 1+ and older fish from 2008 to 2011, as well as the stable age composition developed for default population inputs. The vertical bars reflect single-year model simulations starting with the snorkel survey estimates. For example, starting from July 2008, snorkel estimates were used as TROm model inputs along with average daily discharge and corresponding water temperatures from July 2008 to July 2009 to arrive at a modeled age class composition.

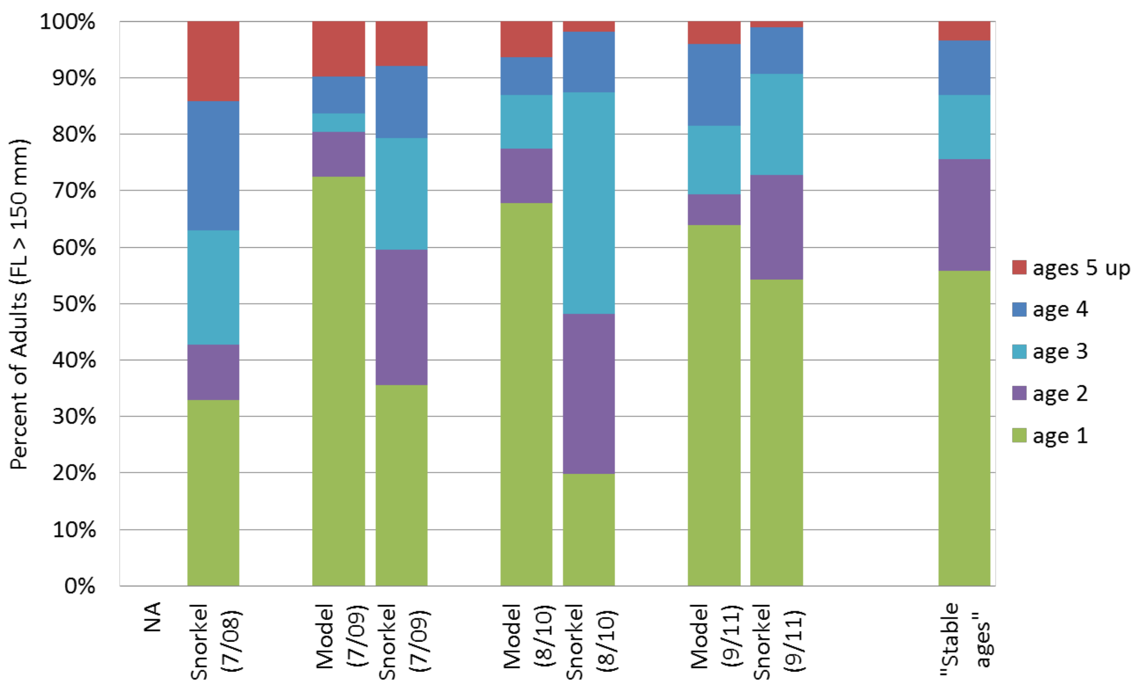

Figure 2.4-5. Comparison of model-based (left bars) and snorkel survey-based (right bars) estimates of age composition of *O. mykiss* in the Tuolumne River (2008–2011), with snorkel survey data from the previous year serving as input for a given model year

Comparison of the Figure 2.4-5 model predictions of the age-class composition in 2009–2011 with the corresponding snorkel survey results for each year show that the model tends to over-represent the youngest and oldest age-classes (age 1 and age 5+, respectively) and under-represent the proportion of Age 2+ and Age 3+ fish. Figure 2.4-6 shows model-based and survey-based estimates of total adult abundance and cohort size for WY 2008–2011.

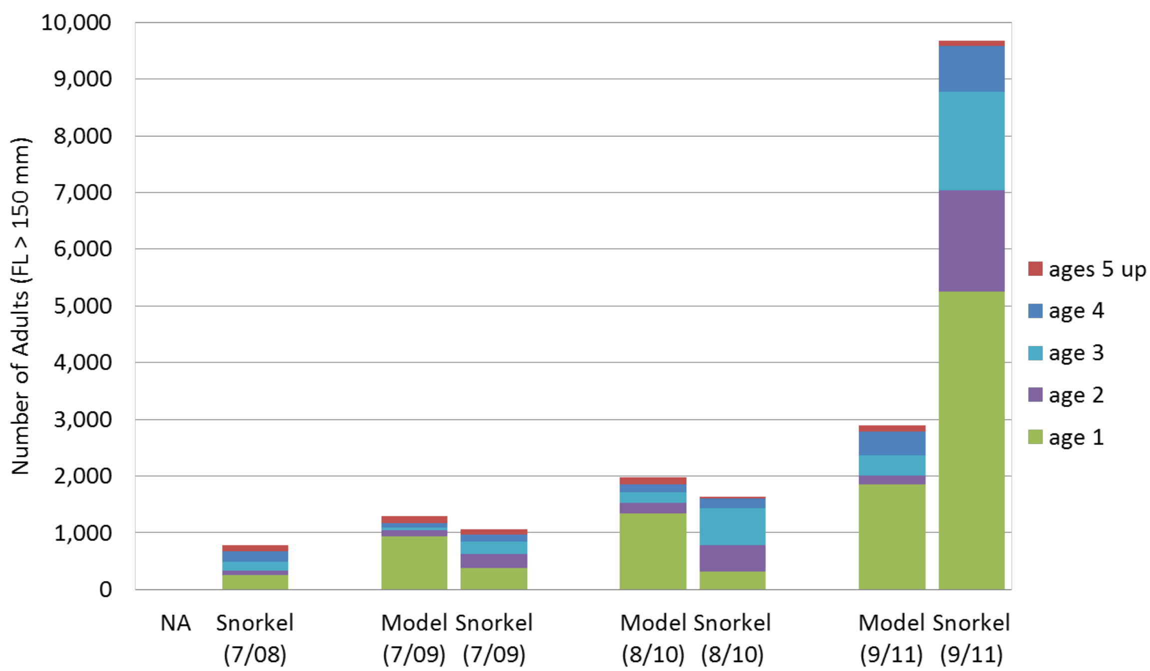

Figure 2.4-6. Model-based (left bars) and snorkel survey-based (right bars) population estimates by age-class for *O. mykiss* in the Tuolumne River (2008–2011), with snorkel survey data from the previous year serving as input for a given model year.

Validation results presented in Figure 2.4-6 show that the model tends to underestimate the abundance of age 2-4 fish and overestimate age 1 and age 5+ fish in low abundance years. In 2011, a high abundance year as estimated by snorkel survey data, the model under-predicts total population size. However, year-to-year changes in cohort size appear to be more consistently represented by the model-based results than the survey-based results. For example, large increases in the survey-based results for Age 3+ fish occurring from 2009–2011 that should have originated as Age 2+ fish in the prior year (i.e., from 2008–2010) suggests some uncertainty in the underlying validation data. Most dramatically, population size of Age 2+ and Age 3+ fish estimated from the 2011 snorkel survey data are much higher than the corresponding survey-based cohort estimates for Age 1+ and Age 2+ fish occurring in 2010 (Figure 2.4-6). Figure 2.4-7 shows total adult *O. mykiss* abundance as estimated by the model (initialized with the previous year's snorkel survey data) compared with estimates from snorkel survey data, with error bars representing the 95% confidence interval.

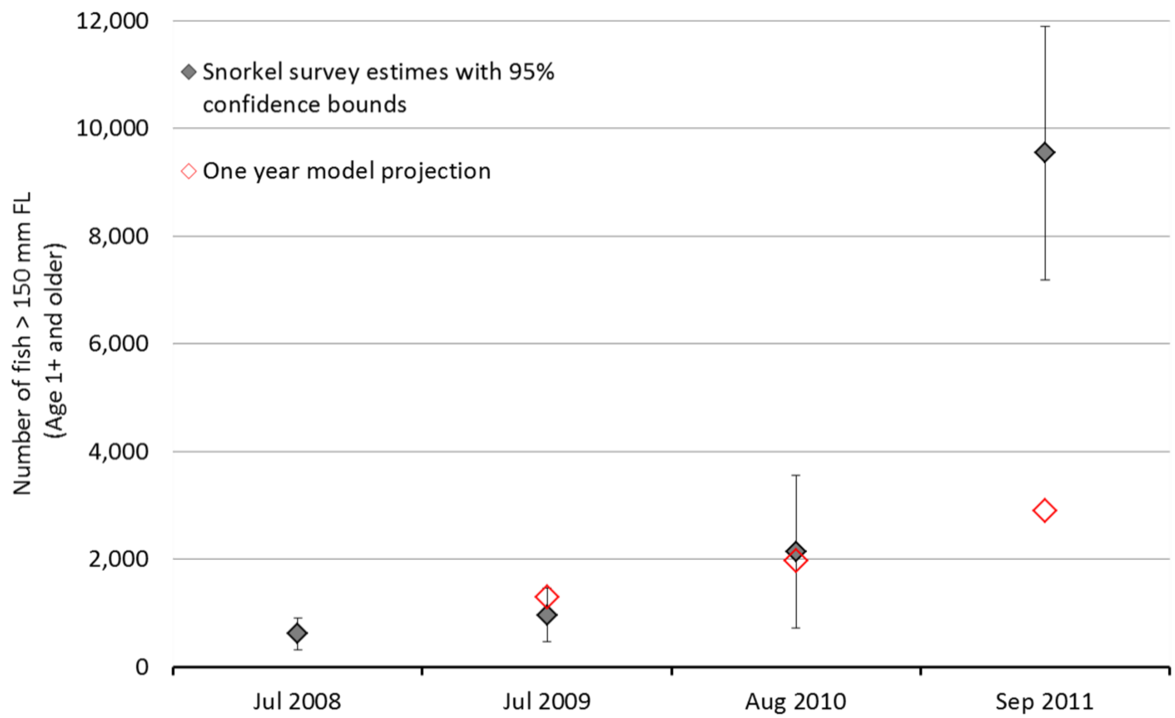

Figure 2.4-7. Model-based and snorkel survey-based population estimates for *O. mykiss* > 150 mm FL in the lower Tuolumne River (2008–2011).

As found in the 2013 study report, the *O. mykiss* direct abundance estimates from one-year model simulations fall within the 95% confidence interval of survey-based estimates for 2009 and 2010, but under-predict adult abundance in 2011. The difference between model estimates of abundance and snorkel survey-based estimates may be attributable to error in the underlying data. Based upon long-term variations in the downstream extent of *O. mykiss* habitat use and relative abundance summarized in the Synthesis Study (TID/MID 2013c), population size estimates were expected to vary substantially year-to-year. However, several issues affecting the survey-based population size estimates were identified in the individual survey reports (Stillwater Sciences 2008, 2009, 2011, 2012b). Focusing upon the large differences between modeled and observed abundances in September 2011, TID/MID (2013a) notes that the population surveys were preceded by season-long high flow conditions in excess of 8,000 cfs during April and only reduced from summer flows of 2,000–3,000 cfs to 300 cfs for the survey period (September 20–24, 2011). The late-season flow changes occurring in September may have resulted in the displacement of many juvenile and adult *O. mykiss* from previously established rearing territories and thus potentially increased the observability of these fish as compared to prior years. For example, follow-up snorkel surveys in November 2011 found lower relative densities at the common sampling locations sampled in September 2011, suggesting fish may have been redistributed during the intervening weeks between the two surveys. Given the flow reductions necessary to conduct the population surveys during September 2011 and the variability in apparent abundance in the follow-up snorkel surveys conducted in November 2011, the lack of agreement between model and survey based population estimates for 2011 was not considered sufficient to invalidate the TROm model calibration and the model was considered suitable to evaluate relative production benefits of alternative flow scenarios.

3.0 UPDATED STUDY RESULTS

Using the calibrated and validated TROm model, juvenile and adult *O. mykiss* productivity metrics salmonid have been estimated under Base Case conditions. Using daily flow estimates from the Operations Model (TID/MID 2017e) along with accompanying water temperature estimates provided by the Reservoir Temperature Model (TID/MID 2017f) 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 TROm 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 TROm Model Base Case Scenario Results

O. mykiss production was estimated for two resident population sizes (i.e., 500 and 10,000 resident Age 1+ and older fish) under "Base Case" conditions contained in the Project Operations/Water Balance Model Study (TID/MID 2017e). Variations in juvenile productivity and adult replacement metrics were evaluated for the Base Case simulation period (1971–2012). For the Base Case hydrology and water temperature data, the "juvenile productivity" (i.e., end-of-year estimate of Age 0+ fish divided by the total number of spawners within the model year) in relation to river discharge measured at the U.S. Geological Survey (USGS) La Grange gage is presented in Figure 3.1-1 for the two population sizes. Although model simulations were conducted on a full water year basis, results are sorted by water year type as well as by decreasing discharge for the expected juvenile rearing period (March–September).

Although juvenile productivity is shown to be reduced in the wettest years simulated, the general pattern in juvenile productivity shown in Figure 3.1-1 is consistent with variations in the historical snorkel survey data summarized as part of the Synthesis Study (TID/MID 2013c). During consistently high discharge due to extended flood control releases, fry and juvenile life stages are displaced to locations farther downstream than under normal WY types that typically do not have flood control releases. This has the effect of displacing juveniles into locations that may experience elevated temperatures during summer, resulting in higher mortality rates. For below normal and dry WY types, reduces juvenile productivity is consistent with decreased extent of downstream habitat use by juveniles that generally matches decreasing La Grange discharge. Lastly, density-dependent effects are also apparent, with consistently lower juvenile productivity predicted at the higher overall population sizes.

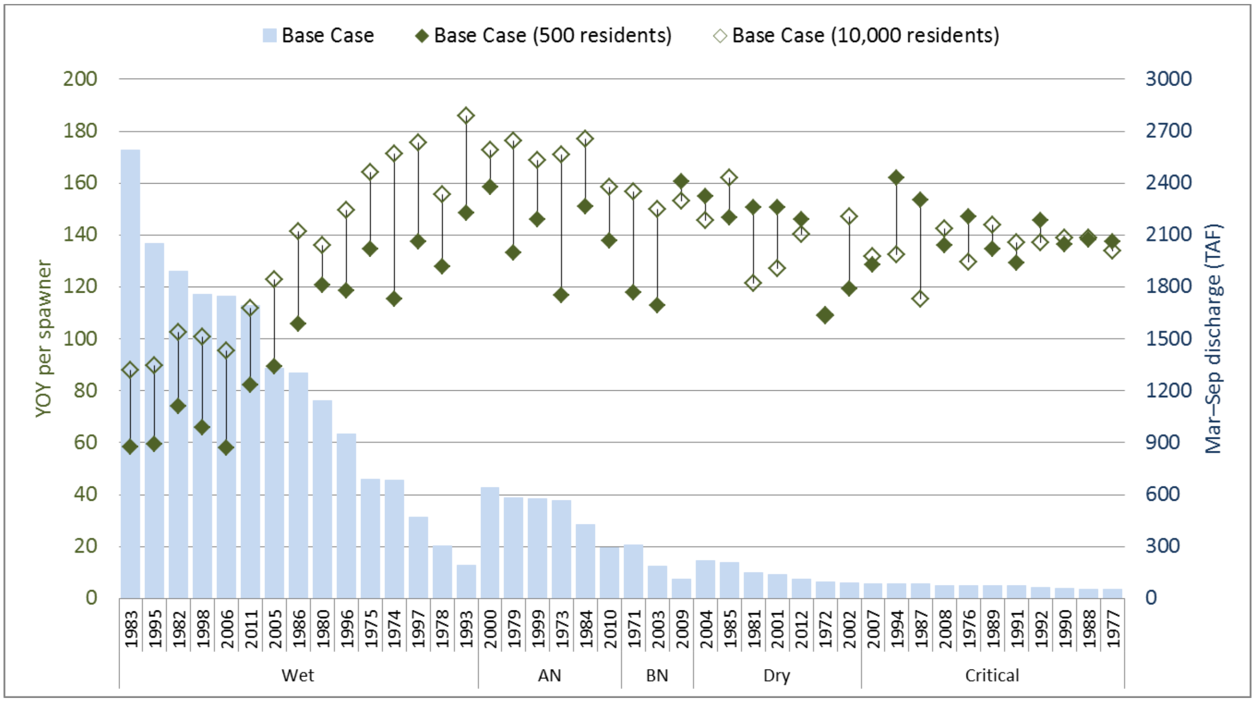

Figure 3.1-1. Modeled yearly (1971–2012) juvenile *O. mykiss* productivity for the base case sorted by La Grange discharge (Feb–May) and water year type for two reference runs.

In addition to variations in juvenile productivity under differing hydrologic conditions, adult replacement ratio (i.e., end-of-year estimate of Age 2+ and older fish divided by the starting population size of Age 2+ and older fish) is presented in Figure 3.1-2 for the two population sizes, sorted by La Grange discharge and water year type. Model predictions suggest an overall increase in year-over-year adult population size (i.e., adult replacement > 1.0) for most Above Normal and Wet water years simulated with lower replacement in Normal and drier water years. To a far lesser degree than for juvenile productivity (Figure 3.1-1), minor density-dependent effects are apparent with marginally lower adult replacement predicted at higher population sizes in the driest water years. It should be noted that a number of random elements related to adult mortality are included in the TROm model (TID/MID 2017a) and these influence year-to-year estimates of adult replacement in Figure 3.1-2. This variation is large enough that the simulated adult replacement for a high population size is above that of the low population size in some years (Figure 3.1-2). Due to the random elements discussed above, these exceptions would likely not be repeated in successive simulations and the overall pattern showing low levels of density dependence upon adult replacement would be maintained.

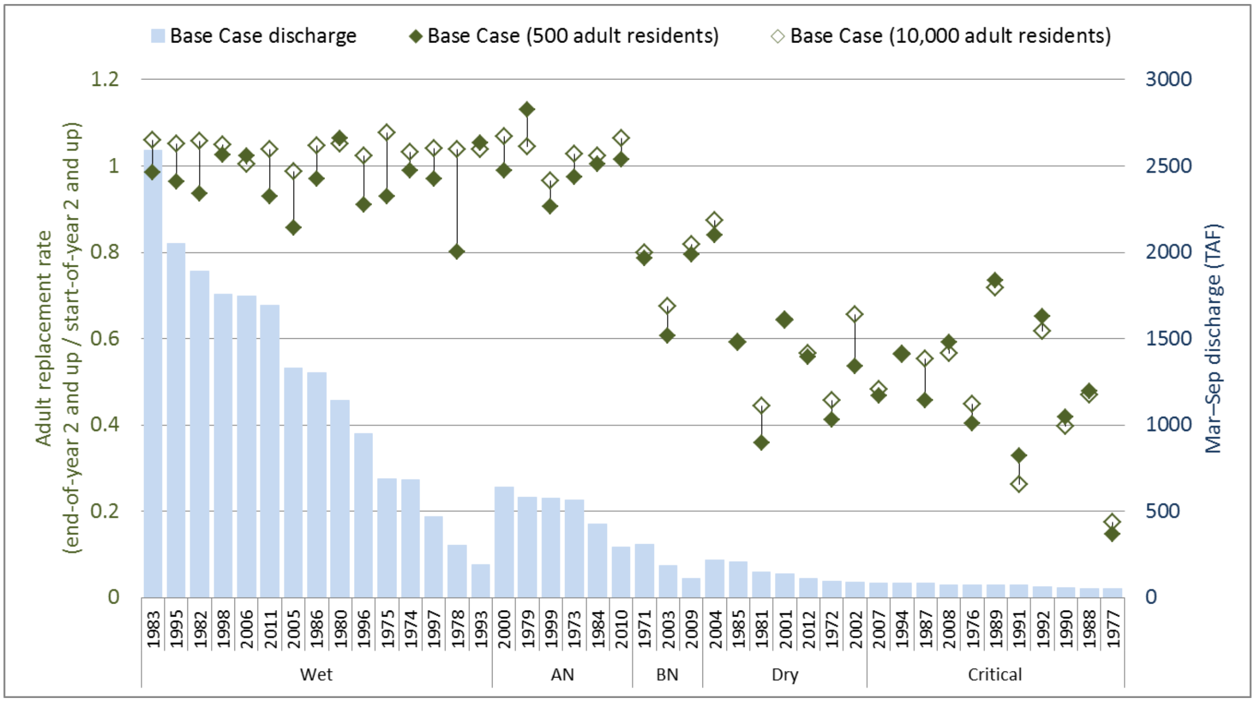

Figure 3.1-2. **Modeled yearly (1971–2012) adult *O. mykiss* replacement for the Base Case sorted water year type and La Grange discharge (Mar–Sep) for two resident population sizes.**

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STUDY REPORT W&AR-10
ONCORHYNCHUS MYKISS POPULATION

ATTACHMENT B

CONCEPTUAL MODELS FOR IN-RIVER LIFE STAGES OF *O. MYKISS* IN THE TUOLUMNE RIVER

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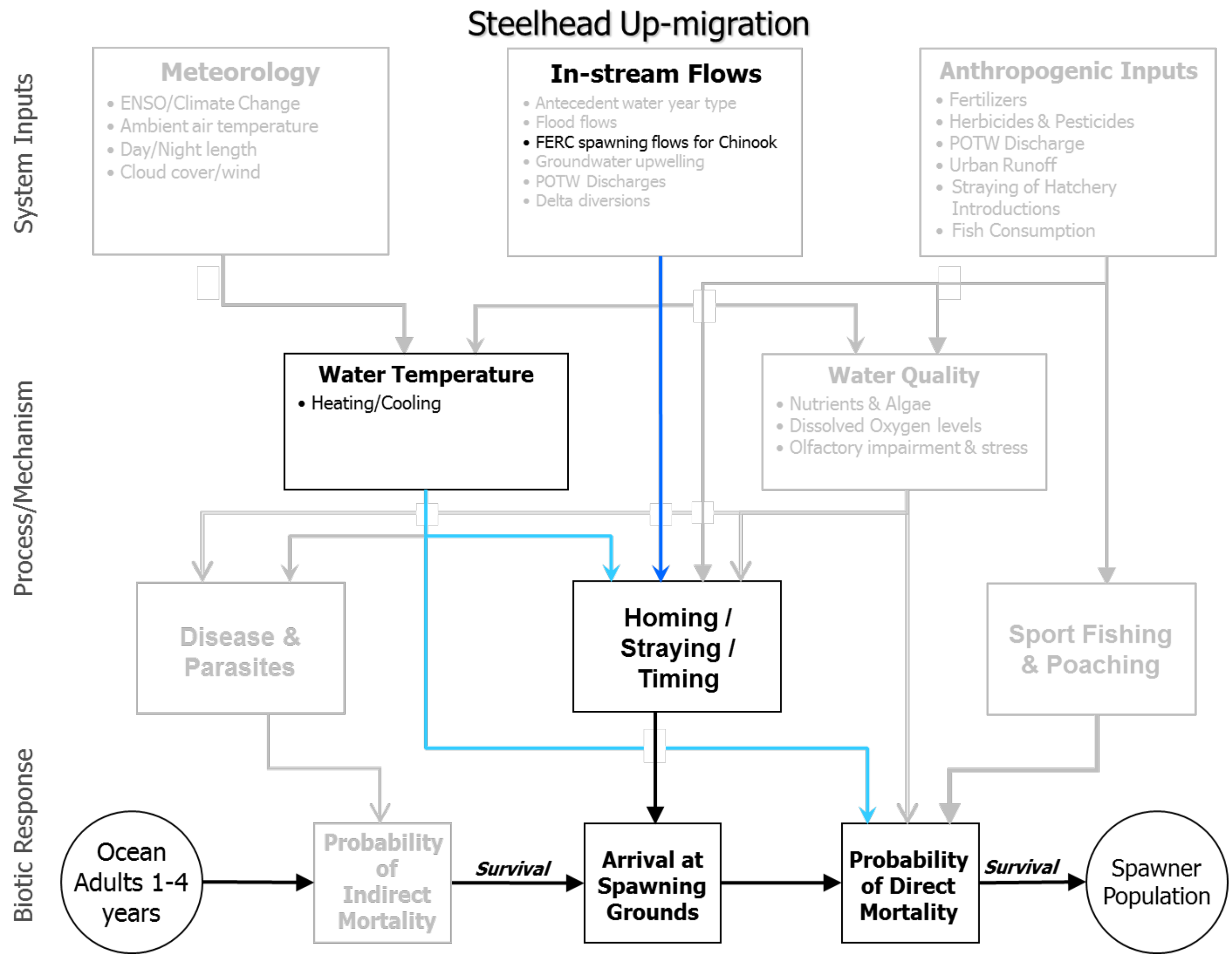

Steelhead Up-migration
System Inputs
Process/Mechanism
Biotic Response
Meteorology
• ENSO/Climate Change
• Ambient air temperature
• Day/Night length
• Cloud cover/wind
In-stream Flows
• Antecedent water year type
• Flood flows
• FERC spawning flows for Chinook
• Groundwater upwelling
• POTW Discharges
• Delta diversions
Anthropogenic Inputs
• Fertilizers
• Herbicides & Pesticides
• POTW Discharge
• Urban Runoff
• Straying of Hatchery Introductions
• Fish Consumption
Water Temperature
• Heating/Cooling
Water Quality
• Nutrients & Algae
• Dissolved Oxygen levels
• Olfactory impairment & stress
Disease & Parasites
Homing / Straying / Timing
Sport Fishing & Poaching
Ocean Adults 1-4 years
Probability of Indirect Mortality
Survival
Arrival at Spawning Grounds
Probability of Direct Mortality
Survival
Spawner Population

Figure B-1.

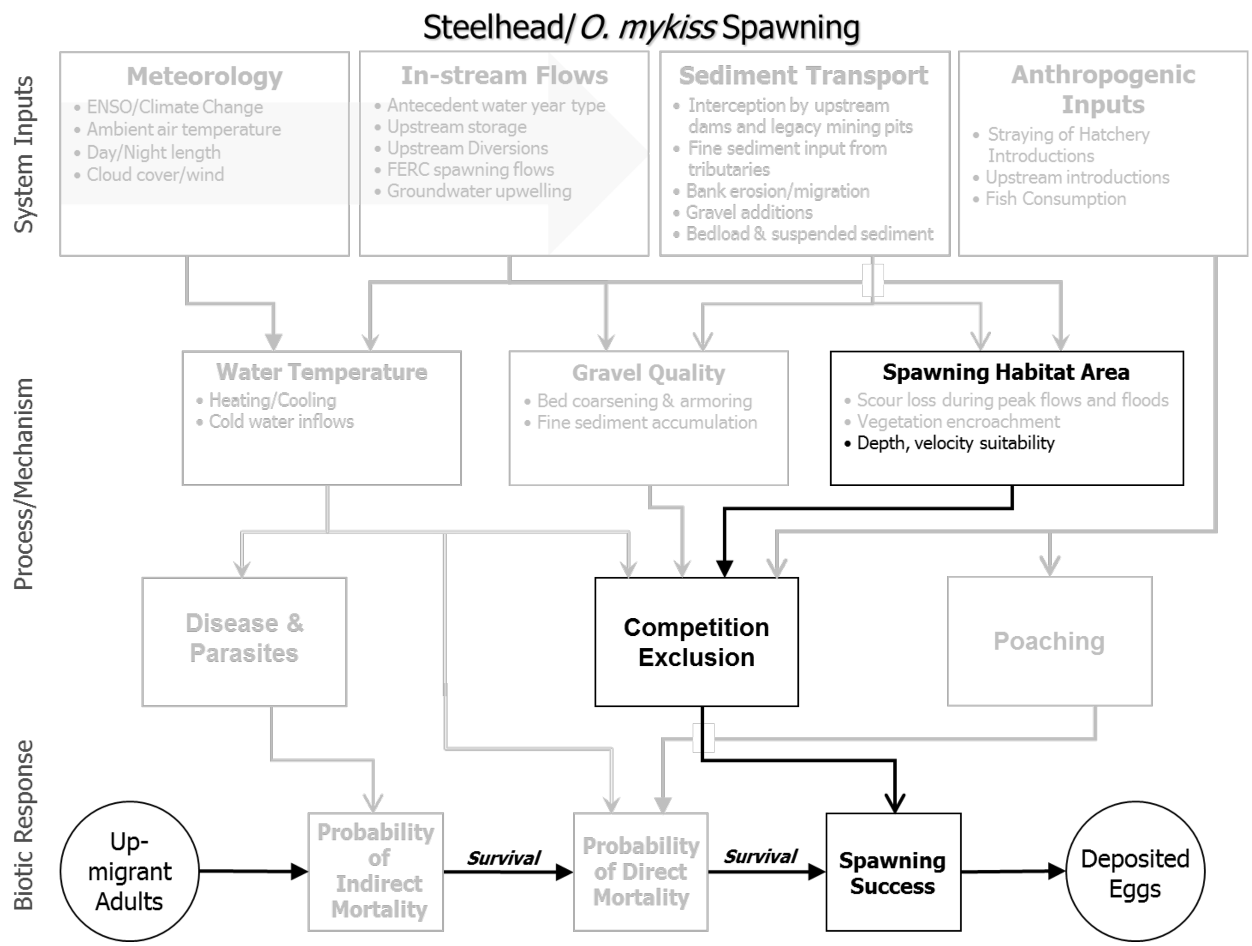
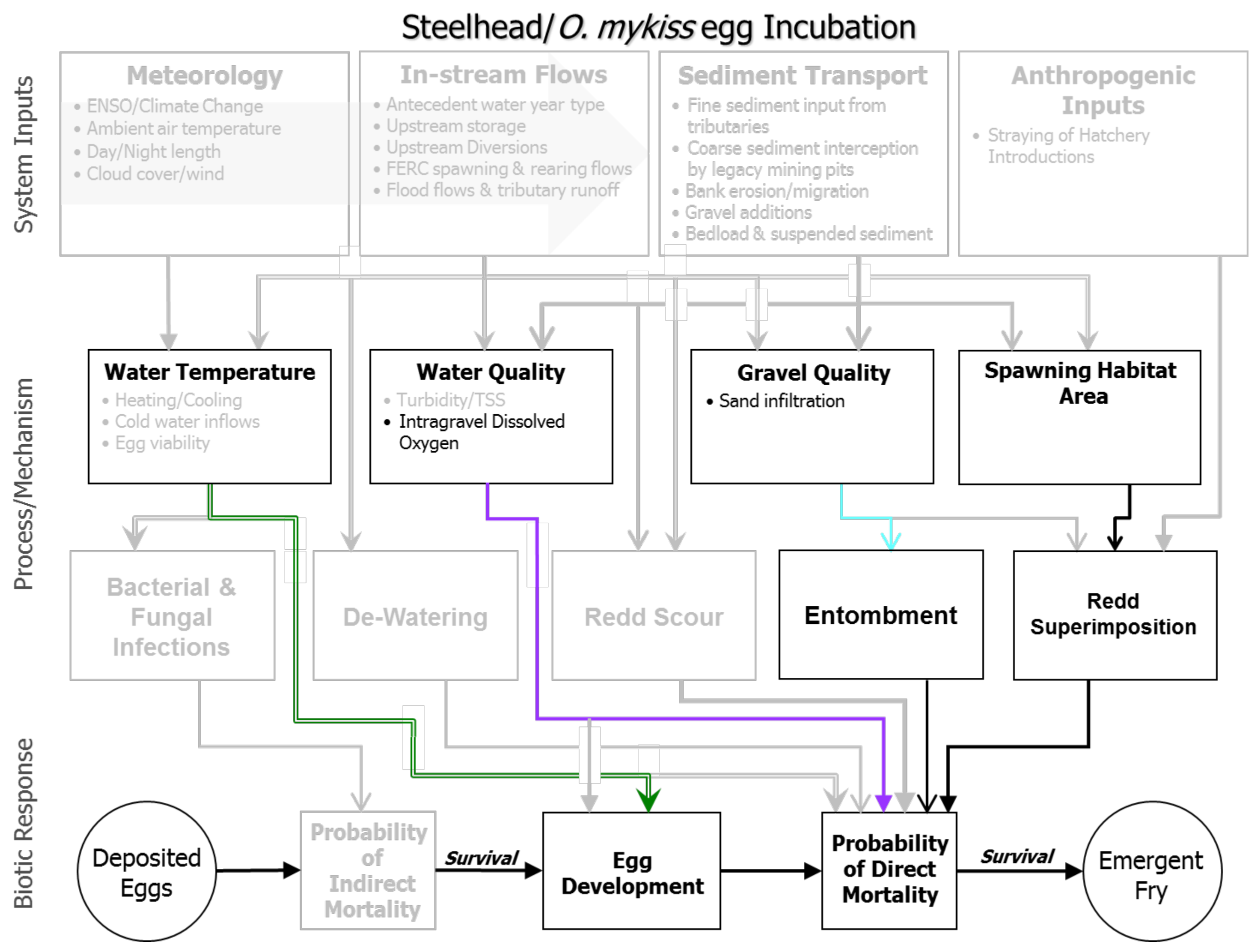
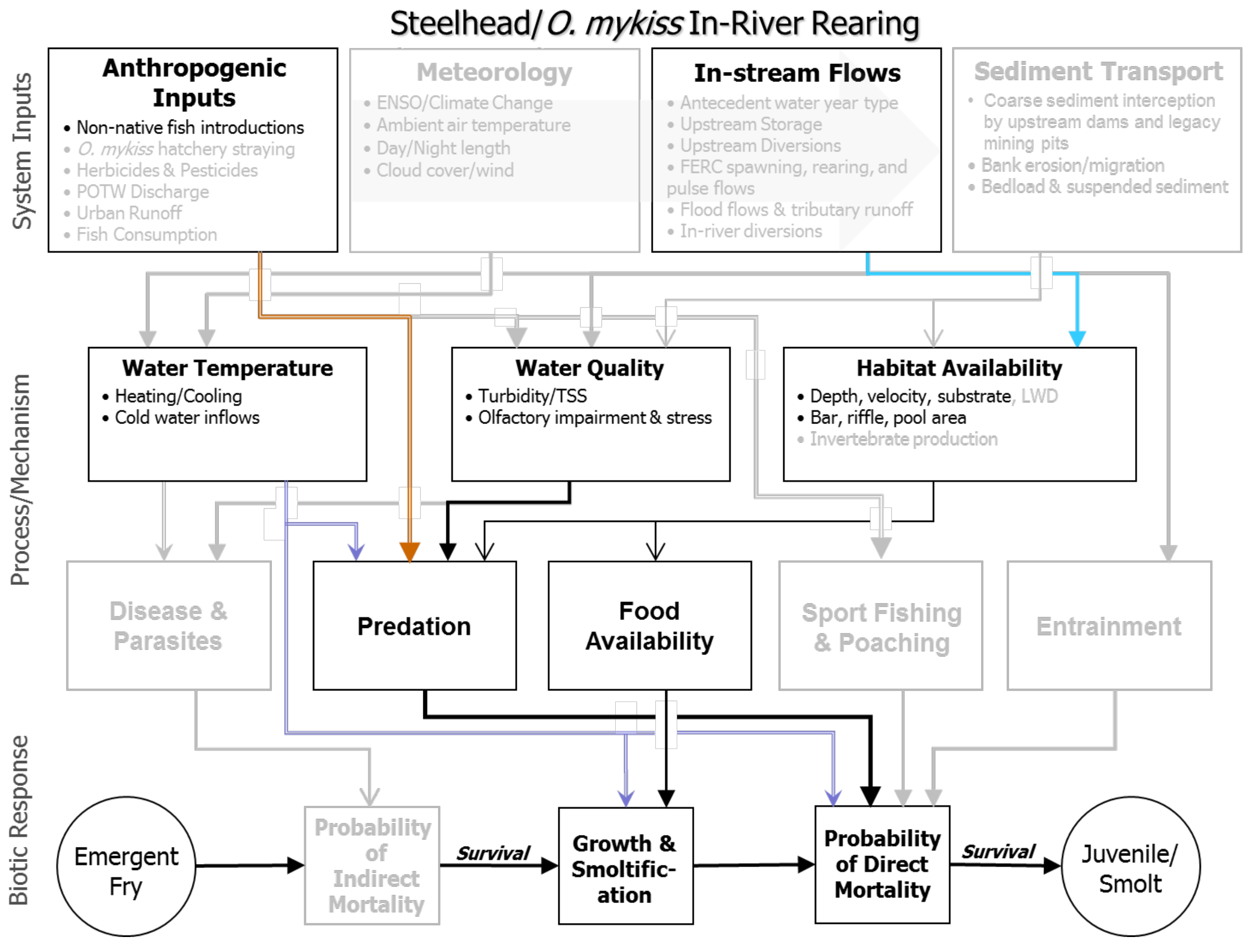

Steelhead/O. mykiss Spawning
System Inputs
Meteorology
• ENSO/Climate Change
• Ambient air temperature
• Day/Night length
• Cloud cover/wind
In-stream Flows
• Antecedent water year type
• Upstream storage
• Upstream Diversions
• FERC spawning flows
• Groundwater upwelling
Sediment Transport
• Interception by upstream dams and legacy mining pits
• Fine sediment input from tributaries
• Bank erosion/migration
• Gravel additions
• Bedload & suspended sediment
Anthropogenic Inputs
• Straying of Hatchery Introductions
• Upstream introductions
• Fish Consumption
Process/Mechanism
Water Temperature
• Heating/Cooling
• Cold water inflows
Gravel Quality
• Bed coarsening & armoring
• Fine sediment accumulation
Spawning Habitat Area
• Scour loss during peak flows and floods
• Vegetation encroachment
• Depth, velocity suitability
Disease & Parasites
Competition Exclusion
Poaching
Biotic Response
Up-migrant Adults
Probability of Indirect Mortality
Survival
Probability of Direct Mortality
Survival
Spawning Success
Deposited Eggs

Figure B-2.



Steelhead/O. mykiss egg Incubation
System Inputs
Meteorology
• ENSO/Climate Change
• Ambient air temperature
• Day/Night length
• Cloud cover/wind
In-stream Flows
• Antecedent water year type
• Upstream storage
• Upstream Diversions
• FERC spawning & rearing flows
• Flood flows & tributary runoff
Sediment Transport
• Fine sediment input from tributaries
• Coarse sediment interception by legacy mining pits
• Bank erosion/migration
• Gravel additions
• Bedload & suspended sediment
Anthropogenic Inputs
• Straying of Hatchery Introductions
Process/Mechanism
Water Temperature
• Heating/Cooling
• Cold water inflows
• Egg viability
Water Quality
• Turbidity/TSS
• Intragravel Dissolved Oxygen
Gravel Quality
• Sand infiltration
Spawning Habitat Area
Bacterial & Fungal Infections
De-Watering
Redd Scour
Entombment
Redd Superimposition
Biotic Response
Deposited Eggs
Probability of Indirect Mortality
Survival
Egg Development
Probability of Direct Mortality
Survival
Emergent Fry

Figure B-3.



Steelhead/O. mykiss In-River Rearing
System Inputs
Anthropogenic Inputs
• Non-native fish introductions
• O. mykiss hatchery straying
• Herbicides & Pesticides
• POTW Discharge
• Urban Runoff
• Fish Consumption
Meteorology
• ENSO/Climate Change
• Ambient air temperature
• Day/Night length
• Cloud cover/wind
In-stream Flows
• Antecedent water year type
• Upstream Storage
• Upstream Diversions
• FERC spawning, rearing, and pulse flows
• Flood flows & tributary runoff
• In-river diversions
Sediment Transport
• Coarse sediment interception by upstream dams and legacy mining pits
• Bank erosion/migration
• Bedload & suspended sediment
Process/Mechanism
Water Temperature
• Heating/Cooling
• Cold water inflows
Water Quality
• Turbidity/TSS
• Olfactory impairment & stress
Habitat Availability
• Depth, velocity, substrate, LWD
• Bar, riffle, pool area
• Invertebrate production
Disease & Parasites
Predation
Food Availability
Sport Fishing & Poaching
Entrainment
Biotic Response
Emergent Fry
Probability of Indirect Mortality
Survival
Growth & Smoltific-ation
Probability of Direct Mortality
Survival
Juvenile/ Smolt

Figure B-4.

STUDY REPORT W&AR-10
ONCORHYNCHUS MYKISS POPULATION

ATTACHMENT C

TUOLUMNE RIVER *O. MYKISS* (TROm) STOCK PRODUCTION MODEL DATA STRUCTURE

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

Attribute	Description	Data Type
Resident Lifestage		
date	date of inventory	POSIXct
rm	location (river mile) at time of inventory	numeric
sex	female or male	factor, levels=c("F", "M")
length	fork length	numeric
age	age of individual	numeric
is.mature	whether individual will mature and spawn this season	logical
parentage	number of anadromous parents	numeric (0, 1, or 2)
Resident Spawner Lifestage		
date	date of arrival at location	POSIXct
rm	location (river mile) at which fish was added to population	numeric
sex	female or male	factor, levels=c("F", "M")
length	fork length	numeric
age	age of individual	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)
Smolt Lifestage		
date	date of promotion to smolt	POSIXct
rm	location (river mile) at time of promotion	numeric
sex	female or male	factor, levels=c("F", "M")
length	fork length	numeric
age	age of individual	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)
Dead Adult Lifestage		
date	date of death	POSIXct
rm	location (river mile) at time of death	numeric
sex	female or male	factor, levels=c("F", "M")
length	fork length	numeric
age	age of individual	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)
Resident Adult Lifestage		
date	date of inventory	POSIXct
rm	location (river mile) at time of inventory	numeric
sex	female or male	factor, levels=c("F", "M")
length	fork length	numeric
age	age of individual	numeric
is.mature	whether individual will mature and spawn this season	logical
parentage	number of anadromous parents	numeric (0, 1, or 2)
Redd Lifestage		
feature	location of redd (as a gravel feature)	text
rm	location (river mile) of redd (as a gravel feature)	numeric
date	redd constructed, eggs fertilized	POSIXct
abandon.date	redd abandoned by spawner	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 deposited in redd	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)
gravel.qual	expected survival-to-emergence of eggs based on gravel characteristics	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

Attribute	Description	Data Type
Anadromous Spawner Lifestage		
date	date of arrival at location	POSIXct
rm	location (river mile) at which fish was added to population	numeric
sex	female or male	factor, levels=c("F", "M")
length	fork length	numeric
age	age of individual	numeric
Anadromous Return Lifestage		
date	date of arrival at location	POSIXct
rm	location (river mile) at which fish was added to population	numeric
sex	female or male	factor, levels=c("F", "M")
length	fork length	numeric
age	age of individual	numeric
Swim-up Lifestage		
count	number of swim-up fry represented by this record	numeric
feature	location of emergence (as a gravel feature)	text
rm	location (river mile) of redd	numeric
date	date of emergence	POSIXct
parentage	number of anadromous parents	numeric (0, 1, or 2)
Parr Lifestage		
count	number of parr represented by this record	numeric
date	date of promotion to parr	POSIXct
rm	location (river mile) of promotion to parr	numeric
length	fork length	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)
atu	accumulated thermal units	numeric
Dead Fry Lifestage		
count	number of fry represented by this record	numeric
date	date of death or exit from the river	POSIXct
rm	location (river mile) of death	numeric
length	fork length at death	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)
Emigrant Fry Lifestage		
count	number of fry represented by this record	numeric
date	date of exit from the river	POSIXct
length	fork length at exit	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)
Passage Fry Lifestage		
count	number of fry represented by this record	numeric
date	date of passage of landmark	POSIXct
rm	location (river mile) of passage	numeric
length	fork length at passage	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)
Resident Juvenile Lifestage		
count	number of juveniles added to summer-rearing population	numeric
date	date of entry to population	POSIXct
rm	location (river mile) of entry to population	numeric
length	fork length at entry to population	numeric
Dead Juvenile Lifestage		
count	number of juveniles represented by this record	numeric
date	date of death or exit from the river	POSIXct
rm	location (river mile) of death	numeric
length	fork length at death	numeric

Attribute	Description	Data Type
Emigrant Juvenile Lifestage		
count	number of juveniles represented by this record	numeric
date	date of exit from the river	POSIXct
length	fork length at exit	numeric
Passage Juvenile Lifestage		
count	number of juveniles represented by this record	numeric
date	date of passage of landmark	POSIXct
rm	location (river mile) of landmark	numeric
length	fork length at passage	numeric
Dead Smolt Lifestage		
count	number of smolts represented by this record	numeric
date	date of death or exit from river	POSIXct
rm	location (river mile) of death	numeric
length	fork length at death	numeric
age	age at death	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)
Emigrant Smolt Lifestage		
count	number of smolts represented by this record	numeric
date	date of exit from the river	POSIXct
length	fork length at exit	numeric
age	age at exit	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)
Passage Smolt Lifestage		
count	number of smolts represented by this record	numeric
date	date of passage of landmark	POSIXct
rm	location (river mile) of landmark	numeric
length	fork length at passage	numeric
age	age at passage	numeric
parentage	number of anadromous parents	numeric (0, 1, or 2)