Final

Modeling Appendix

Shasta Lake Water Resources Investigation, California

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Contents

Tables

Figures

Attachments

Abbreviations and Acronyms

°C	degrees Celsius
°F	degrees Fahrenheit
µS/cm	microsiemens per centimeter
2008 Long-Term Operation BA	Reclamation 2008 Biological Assessment on the Continued Long-Term Operations of the CVP and SWP
ACID	Anderson-Cottonwood Irrigation District
AF	acre-feet
AFSP	Anadromous Fish Screen Program
Ag	agricultural
AIC	Agricultural Issues Center
BA	Biological Assessment
Bay Area	San Francisco Bay Area
Bay-Delta	San Francisco Bay/Sacramento-San Joaquin Delta
BDCP	Bay Delta Conservation Plan
BMP	Best Management Practices
BO	Biological Opinion
BST	Benchmark Study Team
CACMP	Common Assumptions Common Model Package
CALFED	CALFED Bay-Delta Program
CCWD	Contra Costa Water District
CDEC	California Data Exchange Center
CDFW	California Department of Fish and Wildlife
CES	Constant Elasticity of Substitution

cfs	cubic feet per second
CGE	Computable General Equilibrium
CIMIS	California Irrigation Management Information System
CL2	Friant Class 2 Surface Water
cm	centimeter
CNP	Current Normalized Price
COA	Coordinated Operations Agreement
CONV	conveyance
CP	control point
CSDP	Cross Section Development Program
CVC	Cross Valley Canal
CVGSM	Central Valley Groundwater-Surface Water Model
CVP	Central Valley Project
CVP1	Friant Class 1 Surface Water
CVPIA	Central Valley Project Improvement Act
CVPM	Central Valley Production Model
CVPS	Water Rights Settlement and Exchange Delivery
D-xxxx	State Water Resources Control Board Water Right Decision No. xxxx
DAU	Detailed Analysis Unit
DEIS	Draft Environmental Impact Statement
Delta	Sacramento-San Joaquin Delta
District Court	District Court for the Eastern District of California
DICU	Delta Island Consumptive Use
DMC	Delta-Mendota Canal
DSM2	Delta Simulation Model Version 2
DWR	California Department of Water Resources
DFG	California Department of Fish and Game
EBMUD	East Bay Municipal Utility District
EC	electrical conductivity
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
FC&WSD	Flood Control and Water Service District

FDM	Fischer Delta Model
FERC	Federal Energy Regulatory Commission
FRSA	Feather River Service Area
FRWP	Freeport Regional Water Project
fry/m^2	fry per square meter
g	grams
g/m^3	grams per square meter
GCC	Glenn-Colusa Canal
GCID	Glenn-Colusa Irrigation District
GIS	geographical information system
HCP	Habitat Conservation Plan
HSI	habitat suitability index
I-O	input-output
IOS	Interactive Object oriented Salmon
IAIR	Initial Alternatives Information Report
IEP	Interagency Ecological Program
IFIM	Instream Flow Incremental Methodology
IL4	Incremental Level 4
IMPLAN	IMpact Analysis for PLANning
JPOD	Joint Point of Diversion
KCWA	Kern County Water Agency
kg	kilogram
km	kilometer
kWh	kilowatt-hour
kWh/acre-foot	kilowatt-hour per acre-foot
LOC	local surface water
LOD	level of development
LT	lethal temperature
LTGen	LongTermGen
LYRA	Lower Yuba River Accord
m	meter
M&I	municipal and industrial
MAF/yr	million acre-feet per year
mgd	million gallons per day
mm	millimeter
MWD	Metropolitan Water District
NAICS	North American Industry Classification System (formerly Standard Industry Codes (SIC))

NASS	National Agricultural Statistics Service
NBA	North Bay Aqueduct
NED	National Economic Development
NMFS	National Marine Fisheries Service
NPS	National Park Service
O&M	operations and maintenance
OCAP	Operating Criteria and Plan
OCO	Operations Control Office
OMR	Old and Middle River
P&G	Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation
PCWA	Placer County Water Agency
PFR	Plan Formulation Report
PG&E	Pacific Gas & Electric Company
PHABSIM	Physical Habitat Simulation System
PMP	Positive Mathematical Programming
PN xxxx-x	Public Notice xxxx-x
PP	Pumping Plant
PROSIM	Process Simulation
PVA	population viability analysis
R&D	research and development
RBDD	Red Bluff Diversion Dam
RBPP	Red Bluff Pumping Plant
Reclamation	U.S. Department of the Interior, Bureau of Reclamation (see also USBR)
RMA	Resource Management Associates
ROD	Record of Decision
RPA	Reasonable and Prudent Alternative
S44	simulated Shasta Storage
SA	sensitivity analysis
SALMOD	Salmon Mortality Model
SBA	South Bay Aqueduct
SEWD	Stockton East Water District
SIC	Standard Industry Codes
SLWRI	Shasta Lake Water Resources Investigation
SRWQM	Sacramento River Water Quality Model
SWAP	Statewide Agricultural Production Model

SWP	State Water Project
SWPPower	State Water Project Power
State Water Board	State Water Resources Control Board
TAF	thousand acre feet
TCC	Tehama-Colusa Canal
TCCA	Tehama-Colusa Canal Authority
TCD	temperature control device
TDL	total dynamic lift
TMDL	total maximum daily load
TMS	Temperature Modeling System
TS	time series
TXFR	transfer
UC Davis	University of California – Davis
UCCE	University of California Co-operative Extension
USACE	U.S. Army Corps of Engineers
USBR	U.S. Department of the Interior, Bureau of Reclamation (see also Reclamation)
USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
USWS	U.S. Weather Service
UVM	ultrasonic velocity meter
VAMP	Vernalis Adaptive Management Plan
WASP	Water Quality Analysis Simulation Program
WES	U.S. Army Corps of Engineers Waterways Experiment Station
Western	Western Area Power Administration
WR xx-xx	Water Right Order xx-xx
WRESL	Water Resources Simulation Language
WRIMS	Water Resources Integrated Modeling System
WUA	weighted usable area
YOY	young-of-year

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Chapter 1
Introduction

To support the Shasta Lake Water Resources Investigation (SLWRI), a suite of modeling tools was used to analyze the effects of all alternatives on different resource areas. Many of these tools were developed or refined by the CALFED Bay-Delta Program (CALFED) Surface Storage Investigation Common Assumptions effort to provide a consistent approach and methodology in evaluations between the storage projects.

Evaluations in the November 2011 SLWRI Preliminary Draft Environmental Impact Statement (DEIS) were based on the Common Assumptions Common Model Package (CACMP), Version 8D. Since the release of the Preliminary DEIS, the U.S. Department of Interior, Bureau of Reclamation (Reclamation) and the California Department of Water Resources (DWR) have updated modeling to reflect current operational conditions. This modeling update incorporated the requirements in the 2008 U.S. Fish and Wildlife Service (USFWS) and 2009 National Marine Fisheries Service (NMFS) biological opinions (BO) and other recent changes in Central Valley Project (CVP) and State Water Project (SWP) facilities and operations, such as implementation of the San Joaquin River Restoration Program. Throughout this process, Reclamation has continued to coordinate modeling efforts among the CALFED surface storage projects to maintain consistency in evaluations.

Modeling tools used for evaluations in this Environmental Impact Statement (EIS) are as follows:

- CalSim-II is a statewide water resource planning tool and is a specific application of the Water Resources Integrated Modeling System (WRIMS) to simulate Central Valley water operations. The CalSim-II model developed in 2012 for the SLWRI provides information about CVP and SWP operations, including reservoir storages, river and canal flows, and project deliveries. Output from CalSim-II is used as an input to all other models listed below, except Impact Analysis for Planning (IMPLAN).

- Sacramento River Water Quality Model (SRWQM), Version 9B, is a water temperature model that uses Sacramento River flows and inflows, and Shasta, Trinity, and Whiskeytown reservoir storages from CalSim-II to determine water temperatures in the Sacramento River between Shasta Lake and Red Bluff. SRWQM is implemented in the HEC-5Q modeling software.

- Salmon Mortality Model (SALMOD), Version 3.8, uses CalSim-II Sacramento River flows and inflows, and SRWQM water temperatures to simulate Chinook salmon mortality and escapement.

- Statewide Agricultural Production Model (SWAP), Version 6, is an agricultural production and economics model that uses CalSim-II water supply deliveries to agricultural contractors to simulate the decisions of agricultural producers (farmers) in California. The model selects crops, water supplies, and irrigation technology to maximize profit.

- Delta Simulation Model Version 2 (DSM2), Version 8.0.6, is a Sacramento-San Joaquin Delta (Delta) hydrodynamic and water quality model that uses CalSim-II Delta inflows, outflows, and exports to determine Delta water quality and water levels.

- LongTermGen (LTGen), Version 1.18, and State Water Project Power (SWPPower), Benchmark Study Team (BST) April 6, 2010, version, are power generation models for the CVP and the SWP, respectively, that use CalSim-II reservoir storages, releases, and project pumping to determine the energy generation and usage of the CVP and SWP.

- IMPLAN, Version 3.0.17.2, is a regional economic model that uses construction cost estimates to simulate the effect of construction-related expenditures on the regional economy in terms of changes in industry output, employment, and income.

This modeling appendix documents the assumptions used for each modeling tool, and describes the usage of the tools in the context of the SLWRI studies.

Chapter 2
CalSim-II

CalSim-II, a water resources planning model, was used in the SLWRI to evaluate the potential environmental and water supply benefits and impacts of each alternative. This chapter describes CalSim-II and its application in reservoir operations studies for the SLWRI.

Background

WRIMS

CalSim-II is an application of the WRIMS. WRIMS is a generalized water resources software developed by the DWR Bay-Delta Office. WRIMS is entirely data driven and can be applied to most reservoir-river basin systems. WRIMS represents the physical system (reservoirs, streams, canals, pumping stations, etc.) by a network of nodes and arcs. The model user describes system connectivity and various operational constraints using a modeling language known as Water Resources Simulation Language (WRESL). WRIMS subsequently simulates system operation using optimization techniques to route water through the network based on mass balance accounting. A mixed integer programming solver determines an optimal set of decisions in each monthly time step for a set of user-defined priorities (weights) and system constraints. The model is described by DWR (2000) and Draper et al. (2004).

CalSim-II

CalSim-II was jointly developed by Reclamation and DWR for performing planning studies related to CVP and SWP operations. The primary purpose of CalSim-II is to evaluate the water supply reliability of the CVP and SWP at current or future levels of development (e.g., 2005, 2030), with and without various assumed future facilities, and with different modes of facility operations. Geographically, the model covers the drainage basin of the Delta, CVP and SWP deliveries to the Tulare basin, and SWP deliveries to the San Francisco Bay Area (Bay Area), Central Coast, and Southern California.

CalSim-II typically simulates system operations for an 82-year period using a monthly time step. The model assumes that facilities, land-use, water supply contracts, and regulatory requirements are constant over this period, representing a fixed level of development (LOD). The historical flow record of October 1921 to September 2003, adjusted for the influence of land-use change and upstream flow regulation, is used to represent the possible range of water supply conditions. Results from a single simulation may not necessarily correspond to actual system operations for a specific month or year, but are representative of general water supply conditions. Model results are best interpreted using various statistical measures such as long-term or year-type averages.

A general external review of the methodology, software, and applications of CalSim-II was conducted in 2003 (Close et al. 2003) and an external review of the San Joaquin River Valley CalSim-II model was conducted in 2006 (Ford et al. 2006). Several limitations of the CalSim-II models were identified in these external reviews. The main limitations of the CalSim-II model are as follows:

- Model uses a monthly time step
- Accuracy of the inflow hydrology is uncertain
- Model lacks a fully explicit groundwater representation

In addition, Reclamation, DWR, and external reviewers identified the need for a comprehensive error and uncertainty analysis for various aspects of the CalSim II model. DWR issued the CalSim-II Model Sensitivity Analysis Study (DWR 2005) and Reclamation completed a similar sensitivity and uncertainty analysis for the San Joaquin River basin (Reclamation and DWR 2006). This information is intended to improve understanding of model results.

Despite these limitations, monthly CalSim-II model results remain useful for comparative purposes. It is important to differentiate between “absolute” or “predictive” modeling applications and “comparative” applications. A comparative study consists of comparing two model runs: one that contains modifications representing an alternative and one that does not. Differences in certain factors, such as deliveries or reservoir storage levels, are analyzed to determine the impact of the alternative. For an absolute study, results of a single model run, such as the amount of delivery or reservoir levels, are considered directly. Model assumptions are generally believed to be more reliable in a comparative study than an absolute study. All of the assumptions are the same for baseline and alternative model runs, except the action itself, and the focus of the analysis is the differences in the results. For the purposes of the SLWRI, the CalSim-II modeling output is used as a comparative application rather than an absolute application.

Model Assumptions

Table 2-1 summarizes the SLWRI 2012 Version CalSim-II assumptions for existing and future condition studies, including assumed levels of development, demands, facilities, regulatory standards, operations, and water management actions. As shown, existing conditions are based on a 2005 LOD and future conditions are based on 2020 and 2030 LODs for the Sacramento and San Joaquin valleys, respectively.

Table 2-1. SLWRI 2012 Version CalSim-II Assumptions

	Existing Condition[1]	Future Condition[1]
Planning Horizon	2005	2020
Period of Simulation	82 years (1922–2003)	Same
HYDROLOGY		
Level of Development (land-use)	2005 Level[2]	2030 Level[3]
DEMANDS		
North of Delta (excluding the American River)		
CVP	Land-use based, limited by contract amounts[4]	Land-use based, full build-out of contract amounts
SWP (FRSA)	Land-use based, limited by contract amounts[5]	Same
Nonproject	Land-use based, limited by water rights and State Water Board Decisions for Existing Facilities	Same
Antioch Water Works	Pre-1914 water right	Same
Federal refuges	Recent historical Level 2 water needs[6]	Firm Level 2 water needs[6]
American River Basin		
Water rights	Year 2005[7]	Year 2025, full water rights[7]
CVP	Year 2005[7]	Year 2025, full contracts, including FRWP[7]
San Joaquin River Basin[8]		
Friant Unit	Limited by contract amounts, based on current allocation policy	Same
Lower basin	Land-use based, based on district level operations and constraints	Same
Stanislaus River basin[9, 10]	Land-use based, based on New Melones Interim Operations Plan, up to full SEWD deliveries (155 TAF/yr) depending on New Melones Index	Same
In-Delta		
CCWD	195 TAF/yr CVP contract supply and water rights[11]	Same[11]
South of Delta		
CVP	Demand based on contract amounts[4]	Same
Federal refuges	Recent historical Level 2 water needs[6]	Firm Level 2 water needs[6]
SWP [5, 12]	Variable demand, of 3.0-4.1 MAF/yr, up to Table A amounts including all Table A transfers through 2008	Demand based on full Table A amounts
Article 56	Based on 2001–2008 contractor requests	Same
Article 21	MWD demand up to 200 TAF/month from December to March subject to conveyance capacity, KCWA demand up to 180 TAF/month and other contractor demands up to 34 TAF/month in all months, subject to conveyance capacity.	Same

Table 2-1. SLWRI 2012 Version CalSim-II Assumptions (contd.)

	Existing Condition	Future Condition
North Bay Aqueduct	71 TAF/yr demand under SWP contracts, up to 43.7 cfs of excess flow under Fairfield, Vacaville, and Benecia Settlement Agreement	Same
FACILITIES		
Systemwide	Existing facilities	Same
Sacramento Valley		
Shasta Lake	Existing, 4,552 TAF capacity	Same
Red Bluff Diversion Dam	Diversion dam operated with gates out all year, NMFS BO (June 2009) Action I.3.1[10]; assume permanent facilities in place	Same
Colusa basin	Existing conveyance and storage facilities	Same
Upper American River	PCWA American River pump station	Same
Lower Sacramento River	None	FRWP, SRWRS Project[21]
In-Delta		
Los Vaqueros Reservoir	Enlarged storage capacity, 160 TAF, existing pump location. Alternate Intake Project included[15]	Same
Delta Export Conveyance		
SWP Banks Pumping Plant (South Delta)	Physical capacity is 10,300 cfs but 6,680 cfs permitted capacity in all months up to 8,500 cfs during December 15–March 15, depending on Vernalis flow conditions[13]; additional capacity of 500 cfs (up to 7,180 cfs) allowed for reducing impact of NMFS BO (June 2009) Action IV.2.1[10] on SWP[14]	Same
CVP C.W. “Bill” Jones Pumping Plant (formerly Tracy PP)	Permit capacity is 4,600 cfs in all months (allowed for by the DMC–California Aqueduct Intertie)	Same
Upper DMC	Existing (exports limited to 4,200 cfs plus diversion upstream from DMC–constriction) plus 400 cfs Delta-Mendota Canal-California Aqueduct Intertie	Same
San Joaquin River		
Millerton Lake (Friant Dam)	Existing, 520 TAF capacity	Same
Lower San Joaquin River	None	City of Stockton Delta Water Supply Project, 30 mgd capacity
South of Delta (CVP/SWP project facilities)		
South Bay Aqueduct	Existing capacity	SBA rehabilitation, 430 cfs capacity from junction with California Aqueduct to Alameda County FC&WSD Zone 7 point
California Aqueduct East Branch	Existing capacity	Same
REGULATORY STANDARDS		
Trinity River		
Minimum Flow below Lewiston Dam	Trinity EIS Preferred Alternative (369-815 TAF/yr)	Same
Trinity Reservoir end-of-September minimum storage	Trinity EIS Preferred Alternative (600 TAF as able)	Same

Table 2-1. SLWRI 2012 Version CalSim-II Assumptions (contd.)

	Existing Condition	Future Condition
Clear Creek		
Minimum flow below Whiskeytown Dam	Downstream water rights, 1963 Reclamation proposal to USFWS and NPS, and USFWS predetermined CVPIA 3406(b)(2) flows[16], and NMFS BO (June 2009) Action I.1.1[10]	Same
Upper Sacramento River		
Shasta Lake end-of-September minimum storage	NMFS 2004 Winter-run BO (1900 TAF in non-critical dry years), and NMFS BO (June 2009) Action I.2.1[10]	Same
Minimum flow below Keswick Dam	State Water Board WR 90-5, predetermined CVPIA 3406(b)(2) flows, and NMFS BO (June 2009) Action I.2.2[10]	Same
Feather River		
Minimum flow below Thermalito Diversion Dam	2006 Settlement Agreement (700/800 cfs).	Same
Minimum flow below Thermalito Afterbay outlet	1983 DWR and CDFW agreement (750 –1,700 cfs)	Same
Yuba River		
Minimum flow below Daguerre Point Dam	State Water Board D-1644 Operations (Lower Yuba River Accord)[17]	Same
American River		
Minimum flow below Nimbus Dam	American River Flow Management as required by NMFS BO (Jun 2009) Action II.1[10]	Same
Minimum flow at H Street Bridge	State Water Board D-893	Same
Lower Sacramento River		
Minimum flow near Rio Vista	State Water Board D-1641	Same
Mokelumne River		
Minimum flow below Camanche Dam	FERC 2916-029[18], 1996 (Joint Settlement Agreement) (100–325 cfs)	Same
Minimum flow below Woodbridge Diversion Dam	FERC 2916-029, 1996 (Joint Settlement Agreement) (25–300 cfs)	Same
Stanislaus River		
Minimum flow below Goodwin Dam	1987 Reclamation, CDFW agreement, and flows required for NMFS BO (June 2009) Action III.1.2 and III.1.3[10]	Same
Minimum dissolved oxygen	State Water Board D-1422	Same
Merced River		
Minimum flow below Crocker-Huffman Diversion Dam	Davis-Grunsky (180–220 cfs, November–March), and Cowell Agreement	Same
Minimum flow at Shaffer Bridge	FERC 2179 (25–100 cfs)	Same
Tuolumne River		
Minimum flow at Lagrange Bridge	FERC 2299-024, 1995 (Settlement Agreement) (94–301 TAF/yr)	Same

Table 2-1. SLWRI 2012 Version CalSim-II Assumptions (contd.)

	Existing Condition	Future Condition
San Joaquin River		
San Joaquin River below Friant Dam/Mendota Pool	Interim San Joaquin River Restoration flows	Full San Joaquin River Restoration flows
Maximum salinity near Vernalis	State Water Board D-1641	Same
Minimum flow near Vernalis	State Water Board D-1641 and single-step VAMP with water from Merced Irrigation District.[19] NMFS BO (June 2009) Action IV.2.1 Phase II flows not provided due to lack of agreement for purchasing water.	State Water Board D-1641 and VAMP San Joaquin River Agreement.[19] NMFS BO (June 2009) Action IV.2.1 Phase II flows not provided due to lack of agreement for purchasing water.
Sacramento-San Joaquin Delta		
Delta Outflow Index (flow and salinity)	State Water Board D-1641 and USFWS BO (December 2008) Action 4[10]	Same
Delta Cross Channel gate operation	State Water Board D-1641 with additional days closed from October 1–January 31 based on NMFS BO (June 2009) Action IV.1.2[10] (closed during flushing flows from October 1–December 14 unless adverse water quality conditions)	Same
South Delta exports (Jones PP and Banks PP)	State Water Board D-1641 export limits, not including VAMP period export cap under the San Joaquin River Agreement; Vernalis flow-based export limits in April–May as required by NMFS BO (June 2009) Action IV.2.1 Phase II[10] (additional 500 cfs allowed for July–September for reducing impact on SWP)[14]	Same
Combined Flow in Old and Middle River (OMR)	USFWS BO (December 2008) Actions 1, 2, and 3 and NMFS BO (June 2009) Action IV.2.3[10]	Same
OPERATIONS CRITERIA: River-Specific		
Upper Sacramento River		
Flow objective for navigation (Wilkins Slough)	NMFS BO (June 2009) Action I.4[10]; 3,500 – 5,000 cfs based on CVP water supply condition	Same
American River		
Folsom Dam flood control	Variable 400/670 flood control diagram (without outlet modifications)	Same
Feather River		
Flow at mouth of Feather River (above Verona)	Maintain CDFW/DWR flow target of 2,800 cfs for April–September dependent on Oroville inflow and FRSA allocation	Same
Stanislaus River		
Flow below Goodwin Dam	Revised Operations Plan and NMFS BO (June 2009) Action III.1.3[10]	Same
San Joaquin River		
Salinity at Vernalis	Grassland Bypass Project (partial implementation)	Grassland Bypass Project (full implementation)

Table 2-1. SLWRI 2012 Version CalSim-II Assumptions (contd.)

	Existing Condition	Future Condition
OPERATIONS CRITERIA: Systemwide		
CVP Water Allocation		
CVP settlement and exchange	100% (75% in Shasta critical years)	Same
CVP refuges	100% (75% in Shasta critical years)	Same
CVP agriculture	100%–0% based on supply. South-of-Delta allocations are additionally limited due to State Water Board D-1641, USFWS BO (December 2008), and NMFS BO (June 2009)[10]	Same
CVP municipal & industrial	100%–50% based on supply. South-of-Delta allocations are additionally limited due to State Water Board D-1641, USFWS BO (December 2008), and NMFS BO (June 2009)[10]	Same
SWP Water Allocation		
North of Delta (FRSA)	Contract specific	Same
South of Delta (including North Bay Aqueduct)	Based on supply; equal prioritization between Ag and M&I based on Monterey Agreement; allocations are limited due to State Water Board D-1641, USFWS BO (December 2008), and NMFS BO (June 2009)[10]	Same
CVP/SWP Coordinated Operations		
Sharing of responsibility for in-basin use	1986 Coordinated Operations Agreement (FRWP, EBMUD, and 2/3 of the North Bay Aqueduct diversions are considered as Delta export, 1/3 of the North Bay Aqueduct diversion is considered as in-basin use)	Same
Sharing of surplus flows	1986 Coordinated Operations Agreement	Same
Sharing of restricted export capacity for project-specific priority pumping	Equal sharing of export capacity under State Water Board D-1641, USFWS BO (December 2008), and NMFS BO (June 2009) export restrictions[10]	Same
Water transfers	Acquisitions by SWP contractors are wheeled at priority in Banks PP over non-SWP users; LYRA included for SWP contractors[14]	
Sharing of export capacity for lesser priority and wheeling-related pumping	Cross Valley Canal wheeling (max of 128 TAF/yr), CALFED Programmatic ROD defined Joint Point of Diversion (JPOD)	Same
San Luis Reservoir	San Luis Reservoir is allowed to operate to a minimum storage of 100 TAF	Same

Table 2-1. SLWRI 2012 Version CalSim-II Assumptions (contd.)

	Existing Condition	Future Condition
CVPIA 3406(b)(2)		
Policy decision	May 2003 Department of Interior decision	Same
Allocation	800 TAF/yr, 700 TAF/yr in 40-30-30 dry years, and 600 TAF/yr in 40-30-30 critical years	Same
Actions	Pre-determined non-discretionary USFWS BO (December 2008) upstream fish flow objectives (October-January) for Clear Creek and Keswick Dam, non-discretionary NMFS BO (June 2009) actions for the American and Stanislaus Rivers, and USFWS BO (December 2008) and NMFS BO (June 2009) actions leading to export restrictions[10]	Same
Accounting adjustments	No discretion assumed under USFWS BO (December 2008) and NMFS BO (June 2009)[10], no accounting	Same
WATER MANAGEMENT ACTIONS		
Water Transfer Supplies (long term programs)		
LYRA[14]	Yuba River acquisitions for reducing impact of NMFS BO export restrictions[10] on SWP	Same
Phase 8	None	None
Water Transfers (short term or temporary programs)		
Sacramento Valley acquisitions conveyed through Banks PP	Post-analysis of available capacity[20]	Same

Notes:

[1] These assumptions were initially developed under the direction of the DWR and Reclamation management team for the BDCP HCP and EIR/EIS. Additional modifications were made by Reclamation for SLWRI baselines and other 2012 Reclamation study baselines.

[2] The Sacramento Valley hydrology used in the Existing Condition CalSim-II model reflects nominal 2005 land-use assumptions. The nominal 2005 land-use was determined by interpolation between the 1995 and projected 2020 land-use assumptions associated with DWR Bulletin 160-98 (1998). The San Joaquin Valley hydrology reflects 2005 land-use assumptions developed by Reclamation to support Reclamation studies.

[3] The Sacramento Valley hydrology used in the Future Condition CalSim-II model reflects 2020 land-use assumptions associated with Bulletin 160-98. The San Joaquin Valley hydrology reflects draft 2030 land-use assumptions developed by Reclamation to support Reclamation studies.

[4] CVP contract amounts have been reviewed and updated according to existing and amended contracts, as appropriate.

[5] SWP contract amounts have been updated as appropriate based on recent Table A transfers/agreements.

[6] Water needs for Federal refuges have been reviewed and updated, as appropriate. Refuge Level 4 (and incremental Level 4) water is not included. Firm Level 2 water deliveries only. Annual acquisitions of Incremental Level 4 (IL4) water vary from year to year, depending on annual hydrology, water availability, water market pricing, and funding. Therefore, it would be speculative to predict or assume quantities and locations of annual acquisitions from willing sellers. Without that information, it could not be incorporated into the CalSim-II modeling assumptions or other analyses. It would not be possible to quantitatively assess effects of the action alternatives on deliveries of IL4 water. See Chapter 3 of the EIS for a qualitative discussion of potential impacts of IL4 refuge water deliveries.

[7] The Sacramento Area Water Forum agreement, its dry year diversion reductions, Middle Fork Project operations and “mitigation” water is not included.

Table 2-1. SLWRI 2012 Version CalSim-II Assumptions (contd.)

Notes: (contd.)

[8] The new CalSim-II representation of the San Joaquin River has been included in this model package (CalSim-II San Joaquin River Model, Reclamation 2005). The model reflects the difficulties of ongoing groundwater overdraft problems. The 2030 level of development representation of the San Joaquin River basin does not make any attempt to offer solutions to groundwater overdraft problems. In addition, a dynamic groundwater simulation is not yet developed for the San Joaquin River Valley. Groundwater extraction/recharge and stream-groundwater interaction are static assumptions and may not accurately reflect a response to simulated actions. These limitations should be considered in the analysis of results.

[9] The CalSim-II model representation for the Stanislaus River does not necessarily represent Reclamation's current or future operational policies. A suitable plan for supporting flows has not been developed for NMFS BO (June 2009) Action III.1.3.

[10] In cooperation with NMFS, USFWS, and CDFW, Reclamation and DWR have developed assumptions for implementation of the USFWS BO (December 15, 2008) and NMFS BO (June 4, 2009) in CalSim-II.

[11] The actual amount diverted is reduced because of supplies from the Los Vaqueros project. Los Vaqueros storage capacity is 160 TAF for both the existing and future conditions. Associated water rights for Delta excess flows are included.

[12] Under existing conditions it is assumed that SWP Contractors demand for Table A allocations vary from 3.0 to 4.1 MAF/year. Under the Future No-Action baseline, it is assumed that SWP Contractors can take delivery of all Table A allocations and Article 21 supplies. Article 56 provisions are assumed and allow for SWP Contractors to manage storage and delivery conditions such that full Table A allocations can be delivered. Article 21 deliveries are limited in wet years under the assumption that demand is decreased in these conditions. Article 21 deliveries for the NBA are dependent on excess conditions only, all other Article 21 deliveries also require that San Luis Reservoir be at capacity and that Banks PP and the California Aqueduct have available capacity to divert from the Delta for direct delivery.

[13] The SWP's Banks PP has capacity to pump up to 10,350 cfs. However, the U.S. Army Corps of Engineers Public Notice 5820-A (PN 5820-A) limits daily diversions into Clifton Court Forebay to 13,870 acre-feet and limits 3-day average diversions to 13,250 AF/day, except in the winter when San Joaquin River flow is high. From December 15 to March 15, DWR may divert an additional amount equal to one-third of the total flow at Vernalis when flows at Vernalis exceed 1,000 cfs. The conditions of PN 5820-A effectively limit the operating capacity of Banks Pumping Plant to 6,680 cfs much of the time.

[14] Acquisitions of Component 1 water under the LYRA, and use of 500 cfs dedicated capacity at Banks PP during July–September, are assumed to be used to reduce as much of the impact of the April-May Delta export actions on SWP Contractors as possible.

[15] The CCWD Alternate Intake Project (also known as Middle River Intake Project), an intake at Victoria Canal, which operates as an alternate Delta diversion for Los Vaqueros Reservoir. Construction was completed in Fall of 2010.

[16] Delta actions, under USFWS discretionary use of CVPIA 3406(b)(2) allocations, are no longer dynamically operated and accounted for in the CalSim-II model. The Combined OMR flow and Delta export restrictions under the USFWS BO (December 15, 2008) and the NMFS BO (June 4, 2009) severely limit any discretion that would have been otherwise assumed in selecting Delta actions under the CVPIA 3406(b)(2) accounting criteria. Therefore, it is anticipated that CVPIA 3406(b)(2) account availability for upstream river flows below Whiskeytown, Keswick, and Nimbus dams would be very limited. It appears the integration of BO RPA actions will likely exceed the 3406(b)(2) allocation in all water year types. For these baseline simulations, upstream flows on the Clear Creek and Sacramento River are predetermined, based on CVPIA 3406(b)(2) based operations from the August 2008 BA Study 7.0 and Study 8.0 for Existing and Future No-Action baselines, respectively. The procedures for dynamic operation and accounting of CVPIA 3406(b)(2) are not included in the CalSim-II model.

[17] State Water Board D-1644 and the LYRA are assumed to be implemented for Existing and Future No-Action baselines. The Yuba River is not dynamically modeled in CalSim-II. Yuba River hydrology and availability of water acquisitions under the LYRA are based on modeling performed and provided by the LYRA EIS/EIR study team.

[18] Mokelumne River flows reflect EBMUD supplies associated with the FRWP.

[19] It is assumed that either VAMP, a functional equivalent, or State Water Board D-1641 requirements would be in place in 2020. CVP and SWP VAMP export restrictions during the April 15 to May 15 pulse period were not included in CalSim-II modeling.

[20] Only acquisitions of LYRA Component 1 water are included.

[21] Assumptions reflecting implementation of the SRWRS Project were incorporated into future conditions CalSim-II modeling, including the proposed diversion on the Sacramento River for a portion of both PCWA and the City of Sacramento demands. At the time the SLWRI 2012 CalSim-II modeling was developed, this was considered a reasonably foreseeable project. Since that time, PCWA has delayed implementation of the project. However, these assumptions minimally affect a small portion of CalSim-II outputs, and would not change overall results of SLWRI evaluations, which use CalSim-II outputs on a comparative basis.

Table 2-1. SLWRI 2012 Version CalSim-II Assumptions (contd.)

Key:
AF = acre-feet
Ag = agricultural
BA = Biological Assessment
BDCP = Bay Delta Conservation Plan
BO = Biological Opinion
CALFED = CALFED Bay-Delta Program
CCWD = Contra Costa Water District
CDFW = California Department of Fish and Wildlife
cfs = cubic feet per second
COA = Coordinated Operations Agreement
CVP = Central Valley Project
CVPIA = Central Valley Project Improvement Act
D-xxxx = State Water Resources Control Board Water Right Decision No. xxxx
Delta = Sacramento-San Joaquin Delta
DMC = Delta-Mendota Canal
DWR = California Department of Water Resources
EBMUD = East Bay Municipal Utility District
EIR = Environmental Impact Report
EIS = Environmental Impact Statement
FC&WSD = Flood Control and Water Service District
FERC = Federal Energy Regulatory Commission
FRSA = Feather River Service Area
FRWP = Freeport Regional Water Project
HCP = Habitat Conservation Plan
IL4 = Incremental Level 4
JPOD = Joint Point of Diversion
KCWA = Kern County Water Agency
LYRA = Lower Yuba River Accord
M&I = municipal and industrial
MAF/yr = million acre-feet per year
mgd = million gallons per day
MWD = Metropolitan Water District
NBA = North Bay Aqueduct
NMFS = National Marine Fisheries Service
NPS = National Park Service
OMR = Old and Middle River
PCWA = Placer County Water Agency
PN xxxx-x = Public Notice xxxx-x
PP = Pumping Plant
Reclamation = U.S. Department of the Interior, Bureau of Reclamation
ROD = Record of Decision
RPA = Reasonable and Prudent Alternative
SBA = South Bay Aqueduct
SEWD = Stockton East Water District
SLWRI = Shasta Lake Water Resources Investigation
SRWRS = Sacramento River Water Reliability Study
SWP = State Water Project
State Water Board = State Water Resources Control Board
TAF = thousand acre-feet
TAF/yr = thousand acre-feet per year
USFWS = U.S. Fish and Wildlife Service
VAMP = Vernalis Adaptive Management Plan
WR xx-xx = Water Right Order xx-xx

Regulatory conditions include Reclamation's *2008 Biological Assessment* (BA) *on the Continued Long-Term Operations of the CVP and SWP* (2008 Long-Term Operation BA), the 2008 USFWS BO and the 2009 NMFS BO and associated Reasonable and Prudent Alternatives (RPA), and the Coordinated Operations Agreement (COA) between Reclamation and DWR for the CVP and SWP. Table 2-2 summarizes the SLWRI 2012 Version CalSim-II assumptions for the NMFS and USFWS RPAs.

Table 2-2. SLWRI 2012 Version CalSim-II Assumptions for NMFS and USFWS RPAs

NFMS[1] AND USFWS[2] RPAs STANDARD	REPRESENTATION IN THE SLWRI 2012 VERSION CALSIM-II MODEL
NFMS RPA Standard	
I. SACRAMENTO RIVER DIVISION	
Action Suite I.1. Clear Creek	
Action I.1.1. Spring Attraction Flows	Represented in CalSim-II as written in the RPA.
Action I.1.2. Channel Maintenance Flows	Not represented in CalSim-II modeling.
Action I.1.3. Spawning Gravel Augmentation	Not represented in CalSim-II modeling.
Action I.1.4. Spring Creek Temperature Control Curtain	Not represented in CalSim-II modeling.
Action I.1.5. Thermal Stress Reduction	Not represented in CalSim-II modeling. Temperature targets cannot be represented directly in CalSim-II.
Action I.1.6. Adaptively Manage to Habitat Suitability/IFIM Study Results	Not represented in CalSim-II modeling.
Action Suite I.2. Shasta Operations	
Action 1.2.1. Performance Measures	Not represented in CalSim-II modeling. Temperature targets cannot be represented directly in CalSim-II.
Action I.2.2. November Through February Keswick Release Schedule (Fall Actions)	Not represented in CalSim-II modeling.
Action I.2.3. February Forecast; March – May 14 Keswick Release Schedule (Spring Actions)	Not represented exactly as written. CalSim-II does not determine a water supply forecast for the project until March. In March, the 90% exceedance forecast is used to determine water supply, but a less conservative forecast is modeled in April and May. Keswick operations based on Shasta storage and temperature are not represented in CalSim-II.
Action 1.2.4 May 15 Through October Keswick Release Schedule (Summer Action)	Not represented in CalSim-II modeling. Temperature targets cannot be represented directly in CalSim-II.
Action I.2.5. Winter-Run Passage and Re-Introduction Program at Shasta Dam	Not represented in CalSim-II modeling.
Action I.2.6. Restore Battle Creek for Winter-Run, Spring-Run, and CV Steelhead	Not represented in CalSim-II modeling.
Action Suite I.3. Red Bluff Diversion Dam Operations	
Action I.3.1. Operations After May 14, 2012: Operate RBDD with Gates Out Action I.3.2. Interim Operations Action I.3.3. Interim Operation for Green Sturgeon	CalSim-II represents RBDD with no limitations on downstream flow or diversions. This is equivalent to an all gates open scenario that uses a pump for diversions (and is therefore not reliant on a certain elevation to divert water in a canal).
Action I.3.4: Measures to Compensate for Adverse Effects of Interim Operations on Green Sturgeon Action I.3.5. Measures to Compensate for Adverse Effects of Interim Operations on Spring-Run	Not represented in CalSim-II modeling. CalSim-II modeling assumes all gates are open all the time.
Action I.4. Wilkins Slough Operations	Not represented in CalSim-II as a specific NMFS RPA. The current minimum flow at Wilkens Slough ranges from 3,250-5,000 cfs based on the ag allocation.
Action I.5. Funding for CVPIA Anadromous Fish Screen Program (AFSP)	Not represented in CalSim-II modeling.

Table 2-2. SLWRI 2012 Version CalSim-II Assumptions for NMFS and USFWS RPA (contd.)

NFMS[1] AND USFWS[2] RPAs STANDARD	REPRESENTATION IN THE SLWRI 2012 VERSION CALSIM-II MODEL
Action Suite I.6: Sacramento River Basin Salmonid Rearing Habitat Improvements	
Action I.6.1. Restoration of Floodplain Rearing Habitat	Not represented in CalSim-II modeling.
Action I.6.2. Near-Term Actions at Liberty Island/Lower Cache Slough and Lower Yolo Bypass	Not represented in CalSim-II modeling.
Action I.6.3. Lower Putah Creek Enhancements	Not represented in CalSim-II modeling.
Action I.6.4. Improvements to Lisbon Weir	Not represented in CalSim-II modeling.
Action I.7. Reduce Migratory Delays and Loss of Salmon, Steelhead, and Sturgeon at Fremont Weir and Other Structures in the Yolo Bypass	Not represented in CalSim-II modeling. Freemont Weir is modeled as existing conditions.
II. AMERICAN RIVER DIVISION	
Action II.1. Lower American River Flow Management	Represented in CalSim-II as written in the RPA.
Action II.2. Lower American River Temperature Management	Not represented in CalSim-II modeling. Temperature targets cannot be represented directly in CalSim-II.
Action II.3. Structural Improvements	Not represented in CalSim-II modeling.
Action II.4. Minimize Flow Fluctuation Effects	Not represented in CalSim-II modeling.
Action II.5. Fish Passage at Nimbus and Folsom Dams	Not represented in CalSim-II modeling.
Action Suite II.6. Implement the Following Actions to Reduce Genetic Effects of Nimbus and Trinity River Fish Hatchery Operations	
Action II.6.1. Preparation of for Steelhead	Not represented in CalSim-II modeling.
Action II.6.2. Interim Actions Prior to Submittal of Draft Hatchery Genetic Management Plan for Steelhead	Not represented in CalSim-II modeling.
Action II.6.3: Develop and Implement Fall-Run Chinook Salmon Hatchery Management Plans for Nimbus and Trinity River Fish Hatcheries	Not represented in CalSim-II modeling.
III. EAST SIDE DIVISION	
Action III.1.1. Establish Stanislaus Operations Group for Real-Time Operational Decision-Making As Described in These Actions and Implementation Procedures	Not represented in CalSim-II modeling.
Action III.1.2. Provide Cold Water Releases to Maintain Suitable Steelhead Temperatures	Not represented in CalSim-II modeling. Temperature targets cannot be represented directly in CalSim-II.
Action III.1.3. Operate the East Side Division Dams to Meet the Minimum Flows, as Measured at Goodwin Dam	Represented in CalSim-II as written in the RPA for wet, above normal and below normal years.

Table 2-2. SLWRI 2012 Version CalSim-II Assumptions for NMFS and USFWS RPA (contd.)

NFMS[1] AND USFWS[2] RPAs STANDARD	REPRESENTATION IN THE SLWRI 2012 VERSION CALSIM-II MODEL
Action Suite III.2. Stanislaus River CV Steelhead Habitat Restoration	
Action III.2.1. Increase and Improve Quality of Spawning Habitat with Addition of 50,000 Cubic Yards of Gravel by 2014 and with a Minimum Addition of 8,000 Cubic Yards Per Year for the Duration of the Project Actions	Not represented in CalSim-II modeling.
Action III.2.2. Conduct Floodplain Restoration and Inundation Flows in Winter Or Spring to Inundate Steelhead Juvenile Rearing Habitat on One- to Three-Year Schedule	Not represented in CalSim-II modeling.
Action III.2.3. Restore Freshwater Migratory Habitat for Juvenile Steelhead By Implementing Projects to Increase Floodplain Connectivity and to Reduce Predation Risk During Migration	Not represented in CalSim-II modeling.
Action III.2.4. Evaluate Fish Passage at New Melones, Tulloch, and Goodwin Dams	Not represented in CalSim-II modeling.
IV. DELTA DIVISION	
Action Suite IV.1 Delta Cross Channel Gate Operation, and Engineering Studies of Methods to Reduce Loss of Salmonids in Georgiana Slough and Interior Delta	
Action IV.1.1 Monitoring and Alerts to Trigger Changes in DCC Operations	Not represented in CalSim-II modeling
Action IV.1.2 DCC Gate Operation	Represented in CalSim-II using a calculated probability of flushing flows. Probability potentially reduces # days of gates open from D1641 standard. Water quality at Rock Slough resulting from RPA standard gate closure is assessed; if salinity standard is not met then exports are capped at 2000 cfs and gates can be open up to the D1641 standard number of days.
Action IV.1.3 Consider Engineering Solutions to Further Reduce Diversion of Emigrating Juvenile Salmonids to the Interior and Southern Delta, and Reduce Exposure to CVP and SWP Export Facilities	Not represented in CalSim-II modeling
Action Suite IV.2 Delta Flow Management	
Action IV.2.1 San Joaquin River Inflow to Export Ratio	Phase II Inflow to export ratio is represented in CalSim-II as written. The April and May Vernalis flow period is represented as either VAMP or the Merced Agreement depending on the level of development used.
Action IV.2.2 Six-Year Acoustic Tag Experiment	Not represented in CalSim-II modeling
Action IV.2.3 Old and Middle River Flow Management	Not represented in CalSim-II modeling. Assumption is that OMR standards in USFWS Actions 1-3 will satisfy this requirement.
Action IV.3 Reduce Likelihood of Entrainment Or Salvage at the Export Facilities	Not represented in CalSim-II modeling
Action Suite IV.4 Modifications of the Operations and Infrastructure of the CVP and SWP Fish Collection Facilities	Not represented in CalSim-II modeling

Table 2-2. SLWRI 2012 Version CalSim-II Assumptions for NMFS and USFWS RPA (contd.)

NFMS[1] AND USFWS[2] RPAs STANDARD	REPRESENTATION IN THE SLWRI 2012 VERSION CALSIM-II MODEL
Action IV.4.1 Tracy Fish Collection Facility Improvements to Reduce Pre-Screen Loss and Improve Screening Efficiency	Not represented in CalSim-II modeling
Action IV.4.2 Skinner Fish Collection Facility Improvements to Reduce Pre-Screen Loss and Improve Screening Efficiency	Not represented in CalSim-II modeling
Action IV.4.3 Tracy Fish Collection Facility and the Skinner Fish Collection Facility Actions to Improve Salvage Monitoring, Reporting and Release Survival Rates	Not represented in CalSim-II modeling
Action IV.5 Formation of Delta Operations for Salmon and Sturgeon Technical Working Group	Not represented in CalSim-II modeling
Action IV.6 South Delta Improvement Program—Phase I (Permanent Operable Gates)	Not represented in CalSim-II modeling.
V. FISH PASSAGE PROGRAM	
Near-Term Fish Passage Actions	Not represented in CalSim-II modeling.
Long-Term Fish Passage Actions	Not represented in CalSim-II modeling.
USFWS RPA STANDARD	
Action 1: Adult Migration and Entrainment (First Flush)	Represented in CalSim-II modeling.
Action 2: Adult Migration and Entrainment	Represented in CalSim-II modeling. For Action 2, the RPA specifies that the standard can be -1250, -3500 or -5000 cfs, but CalSim-II only models -3500 or -5000.
Action 3: Entrainment Protection of Larval Smelt	Represented in CalSim-II modeling.
Action 4: Estuarine Habitat During Fall	Represented in CalSim-II modeling as written for September-November, but condition to release any storage gained in Nov is not modeled.
Action 5: Temporary Spring Head of Old River Barrier and the Temporary Barrier Project	Represented in CalSim-II modeling. HORB is assumed to not be installed during April and May.
Action 6: Habitat Restoration	Not represented in CalSim-II modeling.

Notes:

[1] The CalSim-II modeling assumptions related to the NMFS RPA are from the Representation of National Marine Fisheries Service Biological Opinion Reasonable and Prudent Alternative Actions for CALSIM II Planning Studies (DWR 2010)

[2] The CalSim-II modeling assumptions related to the USFWS RPA are from the Representation of U.S. Fish and Wildlife Service Biological Opinion Reasonable and Prudent Alternative Actions for CalSim II Planning Studies Technical Memo (DWR 2010)

Key:
AFSP = Anadromous Fish Screen Program
BO = Biological Opinion
cfs = cubic feet per second
CVP = Central Valley Project
CVPIA = Central Valley Project Improvement Act
D-xxxx = State Water Resources Control Board Water Right Decision No. xxxx
DCC = Delta Cross Channel
HORB = Head of the Old River Barrier
IFIM = Instream Flow Incremental Methodology
NMFS = National Marine Fisheries Service
OMR = Old and Middle River
RBDD = Red Bluff Diversion Dam
RPA = Reasonable and Prudent Alternative
SLWRI = Shasta Lake Water Resources Investigation
SWP = State Water Project
USFWS = U.S. Fish and Wildlife Service

Reconsultation processes for the 2008 USFWS and 2009 NMFS BOs have resulted in some uncertainty in future CVP and SWP operational constraints. In response to lawsuits challenging the 2008 and 2009 BOs, the District Court for the Eastern District of California (District Court) remanded the BOs to USFWS and NMFS in 2010 and 2011, respectively, and subsequently ordered reconsultation and preparation of new BOs. These legal challenges may result in changes to CVP and SWP operational constraints if the revised USFWS and NMFS BOs contain new or amended RPAs.

Despite this uncertainty, the 2008 and 2009 BOs issued by the fishery agencies contain the most recent estimate of potential changes in water operations that could occur in the near future. Because the RPAs contained in the 2008 and 2009 BOs have the potential to significantly impact SWP/CVP operations and potential benefits of the SLWRI, they have been implemented in this analysis.

Two-Step Simulation

CalSim-II modeling of the SLWRI was conducted using a two-step model, with a CONV (conveyance) step and then a TXFR (transfer) step. For each water year in the 82-year simulation, CalSim-II models the first step, CONV, for 12 months, then models the next step, TXFR, for the same 12 months using initial conditions from the CONV step. The CONV step implements all CVP and SWP operations and regulatory requirements (except transfers), including operation of the enlarged portion of Shasta Reservoir. The TXFR step then adds transfer operations (including Cross Valley Canal (CVC) wheeling and Joint Point of Diversion) into the model simulation, creating the final model results.

Operating Rules for the SLWRI

Operations of Shasta Reservoir depend on conditions in Trinity Lake, Whiskeytown Lake, and Keswick Reservoir. This section describes selected assumptions of the EIS CalSim-II studies related to operational rules for these lakes and reservoirs. Figure 2-1 presents a schematic of the CalSim-II study in the vicinity of Shasta Reservoir. Node 4 represents the existing Shasta Reservoir; Node 44 represents the additional storage component resulting from a Shasta Dam enlargement.

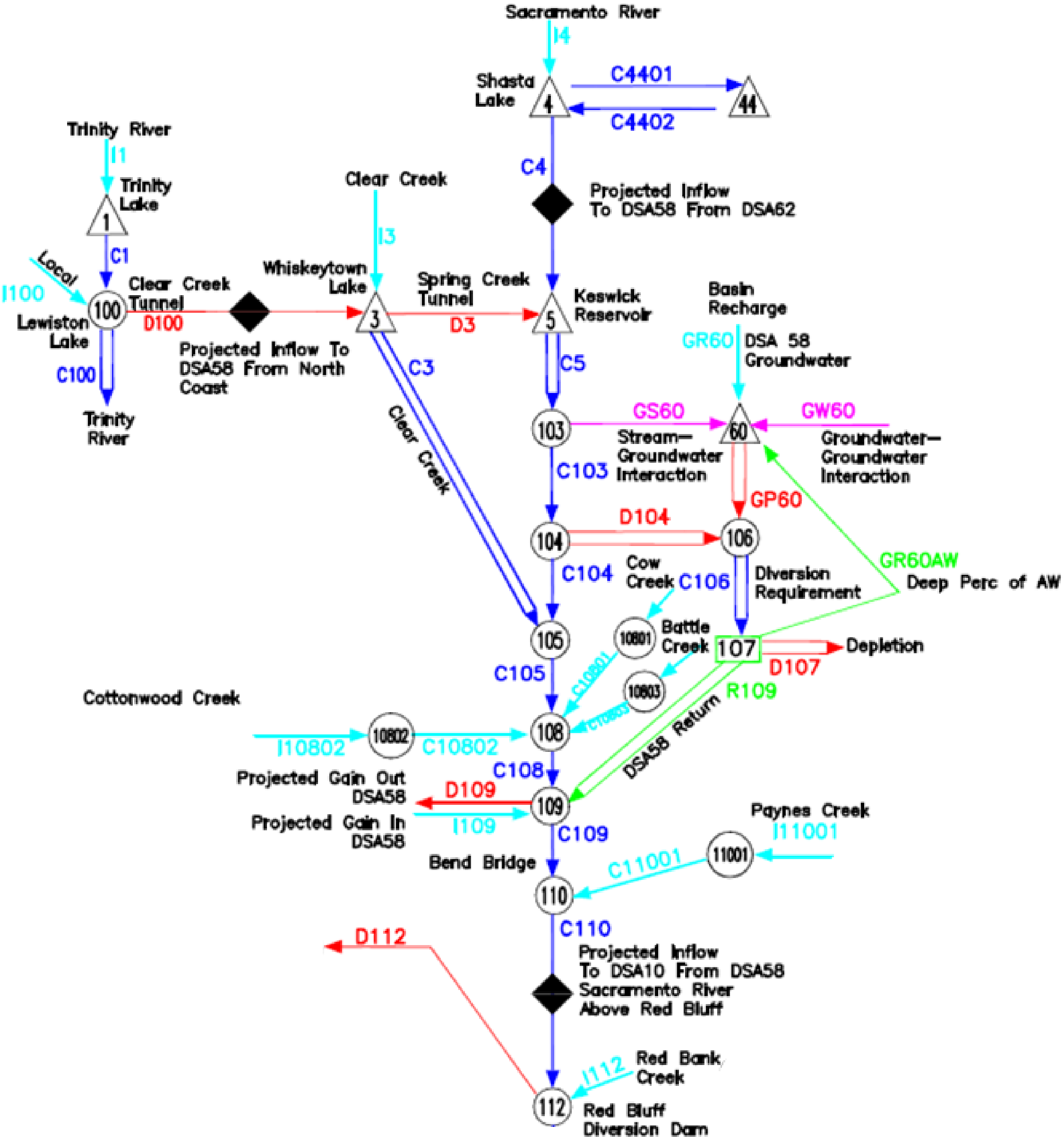

Figure 2-1. CalSim-II Schematic for SLWRI Primary Study Area, Including Shasta Reservoir and Sacramento River to Red Bluff

The 2008 USFWS BO and 2009 NMFS BO include requirements for Sacramento River flows and temperature at various locations, Shasta Reservoir carryover storage, operational restrictions at Red Bluff Diversion Dam (RBDD), and X2 flow requirements. Shasta Reservoir operations must address these issues. Since CalSim-II lacks temperature simulation capability, additional cold-water releases from Shasta Reservoir were used as a surrogate for meeting temperature requirements.

Highlights of operational rules in the CalSim-II existing and future condition studies for the SLWRI include the following:

- **Shasta Reservoir operation** – Under existing and future No-Action conditions, Shasta Reservoir capacity is 4,552,000 acre-feet, with a maximum objective release capacity of 79,000 cubic feet per second (cfs). Storage levels are lowest by October, providing sufficient flood protection and capture capacity during the following wet months. The storage target gradually increases from October to full pool in May. Then, storage is withdrawn for high water demand (municipal, agricultural, fishery, and water quality uses, etc.) during the summer.

- **Imports from the Trinity River watershed** – Since 1964, Trinity River water has been imported into the Sacramento River basin through Clear Creek and Spring Creek tunnels (capacities of 3,300 cfs and 4,200 cfs, respectively). After meeting the monthly minimum instream flow requirement below Lewiston Lake, and a variable Trinity Lake end-of-September minimum storage target, Trinity River water is diverted into Whiskeytown Lake. Monthly diversions are based on the beginning-of-month storage in Shasta Reservoir and Trinity Lake. For example, imports can be as much as 3,300 cfs for July to September when Trinity Lake storage is high and Shasta Reservoir storage is low. Whiskeytown Lake receives inflow from Clear Creek. After making releases to meet the minimum flow requirement downstream from Whiskeytown Dam, water is diverted through Spring Creek Tunnel to Keswick Reservoir.

- **Minimum flow requirement below Keswick Dam** – The minimum flow requirement below Keswick Dam is based on a combination of State Water Board Water Rights Order 90-5 requirements, predetermined Central Valley Project Improvement Act (CVPIA) 3406(b)(2) flows, and Action I.2.2 in the 2009 NMFS BO. From May through September, the minimum flow is always 3,250 cfs. In other months, the minimum flow requirement varies from 3,250 cfs to 4,500 cfs.

- **Minimum flow requirement below the Red Bluff Pumping Plant (RBPP)** – The monthly value of minimum flow below the RBPP is a lookup value based on the Shasta index.[1] The requirement (taken from the previous water resources planning model, PROSIM (Process Simulation), FWQ_b203.dat file) varies from 3,000 cfs to 3,900 cfs.

- **Flow objective for navigation control point** – The monthly navigational flow objective at Wilkins Slough is between 3,250 cfs and

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[1] Hydrologic water year classification according to unimpaired inflow into Shasta Reservoir, defined by the CVP. This index changes in March. The Shasta Index is defined by the contract between Reclamation and the Sacramento River Settlement Contractors.

5,000 cfs, and varies depending on the CVP allocation for agricultural water service contractors. Pumping stations along the Sacramento River use 5,000 cfs as a basis for design; 4,000 cfs is the lowest operable flow limit for some pumps.

Additional Assumptions and Definitions

Additional assumptions for the SLWRI studies for simulating Shasta Reservoir enlargement in CalSim-II include the following:

- For modeling purposes, the additional storage component resulting from raising Shasta Dam was simulated as a separate reservoir, S44, parallel to Shasta Reservoir, S4. The maximum storage in S44 under the different alternatives considered is shown in Table 2-3. Water moves between the two reservoirs through two arcs, C4401 (from S4 to S44) and C4402 (S44 to S4), which have no capacity constraints. During a time step (month), water is only allowed to either flow into or out of S44.

Table 2-3. S44 Storage Volume for SLWRI Alternatives

Alternative	S44 Volume (TAF)
No-Action Alternative	0
Alternative CP1	256
Alternative CP2	443
Alternative CP3	634
Alternative CP4	256[1]
Alternative CP4A	443[2]
Alternative CP5	634

Notes:

[1] Alternative CP4 uses a 256,000 acre-foot enlargement to determine water supply operations, but water temperatures and fishery benefits are computed using a 634,000 acre-foot enlargement. For CalSim-II purposes, the enlargement is only 256,000 acre-feet.

[2] Alternative CP4A uses a 443,000 acre-foot enlargement to determine water supply operations, but water temperatures and fishery benefits are computed using a 634,000 acre-foot enlargement. For CalSim-II purposes, the enlargement is only 443,000 acre-feet.

Key:
CP = Comprehensive Plan
S44 = simulated Shasta storage
SLWRI = Shasta Lake Water Resources Investigation
TAF = thousand acre-feet

- S44 is filled after Shasta Reservoir storage reaches its flood control level (S4_Level5). After S44 is full, water is stored in the Shasta Reservoir flood pool. Water in the Shasta Reservoir flood pool is evacuated first, followed by water in the conservation pool zone (Zone 5), which is below the flood pool. After the S4 storage level reaches S4_Level4 (i.e., Zone 5 is emptied), S44 is drained until empty. Under this reservoir balance logic, flood flow is pumped and stored in S44 during the wet season; in late spring and summer, water in S44 is released to Shasta Reservoir and then to the Sacramento River for allocation.

- Total storage for S44 and S4 is used to calculate the corresponding surface area of the enlarged Shasta Reservoir. The monthly evaporation loss for the enlarged reservoir is equal to the product of the enlarged Shasta Reservoir surface area and monthly Shasta Reservoir evaporation rate. Evaporation is subtracted from storage in S4.

- The lookup table relating Shasta Reservoir storage to Trinity River exports (shasta_level.table) was modified to use the increase in Shasta Reservoir storage. For CP1, Shasta Reservoir storage in Zones 4 and 5 was increased by a volume equivalent to the enlargement volume. For CP2, CP3, and CP5, Shasta Reservoir storage in Zones 3, 4, and 5 was increased by a volume equivalent to the enlargement volume.

The following definitions are used in the SLWRI reservoir operations analysis:

- “Year” is equivalent to a water year, starting in October 1 of the preceding calendar year and ending September 30 of the current calendar year.

- “Monthly” means the average condition for a particular month, except storage, which is end of month.

- “Year-type” is the Sacramento Valley water year hydrologic classification, as defined by the State Water Board in Water Rights Decision No. 1641 (D-1641). The classification consists of five year-types: wet, above normal, below normal, dry, and critical.

- “Impacts” are the differences between CalSim-II results for an alternative and the baseline.

SLWRI Hydrologic Analysis

Primary planning objectives of the SLWRI are as follows:

- Increase survival of anadromous fish in the Sacramento River, primarily upstream from RBPP.

- Increase water supplies and water supply reliability for agricultural, municipal and industrial (M&I), and environmental purposes to help meet future water demands, primarily through enlarging Shasta Reservoir.

As part of the SLWRI Initial Alternatives Information Report (IAIR) (Reclamation 2004), various Shasta Reservoir enlargements and operational changes were identified to address the planning objectives. These measures were combined to form alternatives. Alternatives were simulated with CalSim-II to evaluate hydrologic impacts on the California water supply system (e.g., changes in channel flow rates or water allocation logic). Differences between without-project and with-project conditions represent the hydrologic impacts of the different SLWRI alternatives. These alternatives were further developed and evaluated as part of the Plan Formulation Report (PFR) (Reclamation 2007) and the Preliminary DEIS and Draft Feasibility Report (Reclamation 2011), the DEIS (Reclamation 2013), and have been updated and evaluated for this EIS.

CalSim-II output may be found in Attachment 1 of this Modeling Appendix.

Chapter 3
Temporal Downsizing of CalSim-II Flows for Use in Temperature Modeling

For each alternative, temporal downscaling was performed on the CalSim-II monthly average tributary flows to convert them to daily average flows for SRWQM input. Monthly average flows were converted to daily tributary inflows based on the 1921 through 2003 daily historical record for the following aggregated inflows:

1. Trinity River above Lewiston
2. Sacramento River above Keswick
3. Incremental inflow between Keswick and Bend Bridge (7-day trailing average for inflows below Butte City)
4. Cottonwood Creek (regression with Bend Bridge local flow for 1921 through 1940)

Each of the total monthly inflows specified by CalSim-II was scaled proportionally to one of these four historical records.

Trinity Reservoir inflows were proportioned based on Historical Record No. 1. Whiskeytown and Shasta reservoirs were proportioned based on Historical Record No. 2. (Note that Whiskeytown inflow refers to Clear/Whiskey Creek unregulated flow and not inflow from the Clear Creek Tunnel.) The downscaled reservoir inflows occasionally resulted in minor violations of normal reservoir operation constraints. Since the violations occurred infrequently, and were less than 2 percent of the reservoir volume constraint, they were ignored.

Incremental local inflows above Bend Bridge have two components. The Cottonwood Creek flow (explicitly defined in CalSim-II as I108) was proportioned based on Historical Record No. 4. All other projects gains (I109) were distributed by Historical Record No. 3. Within SRWQM, these project gains were partitioned as shown in Table 3-1.

Table 3-1. Tributary Inflows to the Sacramento River Between Keswick and Bend Bridge

River Mile	Tributary	Percent of Flow Between Keswick and Bend Bridge (excluding Cottonwood Creek) (CalSim-II I108)
292	Clear Creek Local	7
285	Churn Creek	7
280	Cow Creek	42
277	Bear+Ash Creeks	17
273	Anderson Creek	4
271	Battle Creek	23

Since reservoir outflow and diversion rates are a function of CalSim-II operating assumptions, historical flow patterns are not meaningful. Consequently, monthly flows were simply smoothed for a better transition at the end of the month. Initially, flows were defined without regard for reservoir volume constraints or downstream minimum flows.

As flows are redistributed within the month, the minimum flow constraint at Keswick and Red Bluff may be violated. In such cases, operation modifications are required for daily flow simulation to satisfy minimum flow requirements. Minimum Sacramento River flow constraints imposed on CalSim-II at Keswick and Red Bluff are satisfied by the following:

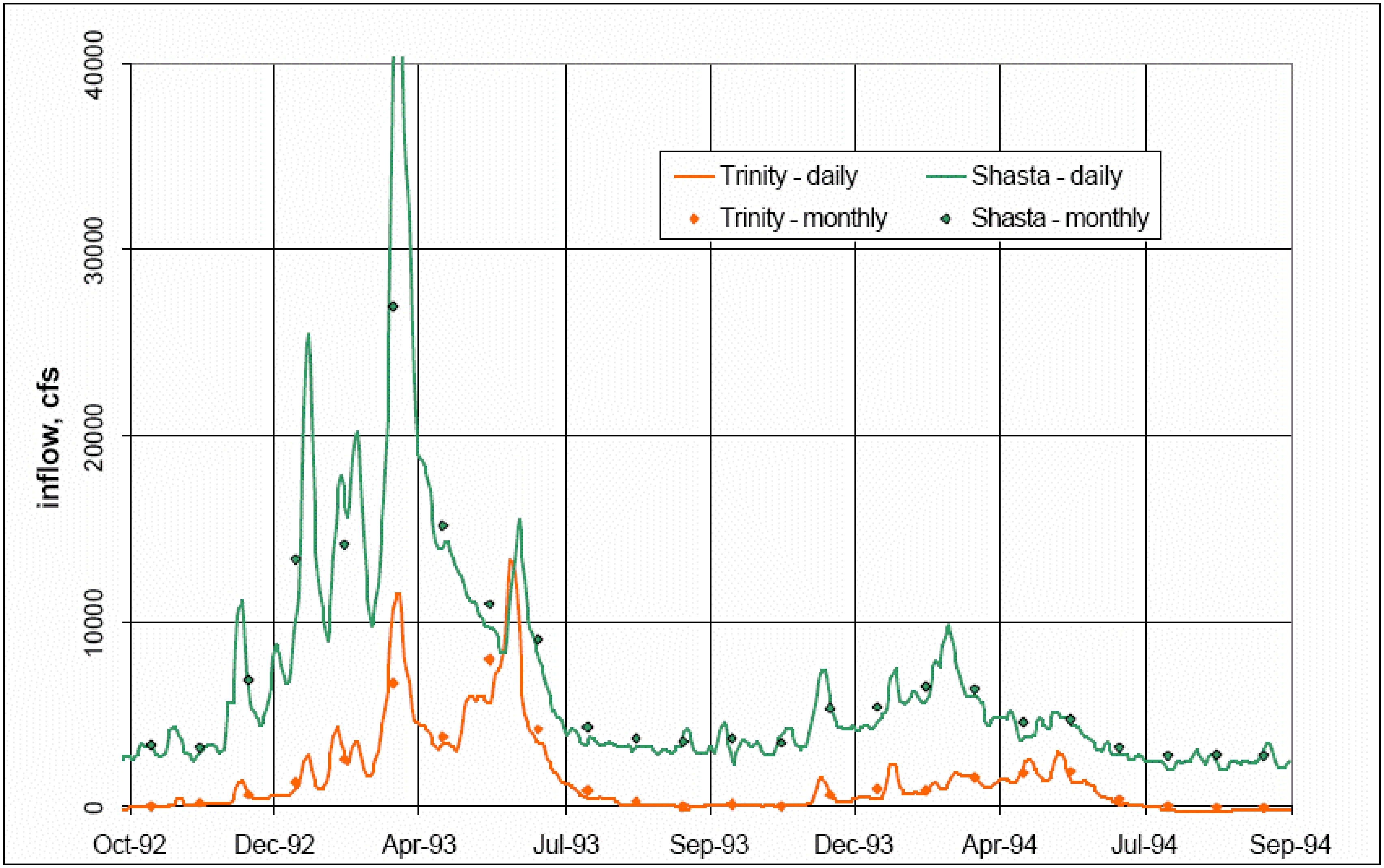
1. Redistribute Tehama-Colusa Canal (TCC) and Glenn-Colusa Canal (GCC) withdrawals up to the capacity of the conveyance facilities.

2. Reallocate Shasta Reservoir outflows maintaining monthly outflow volume.

3. Increase Shasta Reservoir releases if Steps 1 and 2 cannot meet minimum flow requirements (excess release volumes are made up in later months when Shasta Reservoir releases are in excess of minimum flows).

Diversions such as the Anderson-Cottonwood Irrigation District (ACID), Glenn-Colusa Irrigation District (GCID), and Tehama-Colusa Canal Authority (TCCA) were defined as point withdrawals for input to SRWQM. Miscellaneous project gains were combined and assumed as diffuse inflows or withdrawals in SRWQM.

Figure 3-1 shows example results of temporal downscaling of simulated reservoir inflows from CalSim-II for water years 1993 and 1994.



Source: U.S. Department of the Interior, Bureau of Reclamation, 2003

Figure 3-1. Trinity and Shasta Reservoirs CalSim-II Simulated Monthly Inflows and Downscaled Daily Inflows

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Chapter 4
Sacramento River Water Temperature Model

Introduction

SRWQM was developed and calibrated for simulating reservoir and river temperatures at Shasta, Trinity, Lewiston, Whiskeytown, Keswick and Black Butte reservoirs and the Trinity River, Clear Creek, the upper Sacramento River from Shasta to Knights Landing, and Stony Creek. The model simulates mean daily reservoir and river temperatures, with the objective of estimating project impacts on water temperature, under both existing and future conditions.

For model calibration, historical flows from the U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE), and Reclamation data sources were input to the model. Meteorological data from the California Irrigation Management Information System (CIMIS) and the National Weather Service, and ambient water temperatures from DWR, Reclamation and California Data Exchange Center (CDEC) also were input. Similar data sources were used for model validation. All flow data were daily averaged and meteorology and inflow temperatures were defined at 6-hour intervals. All temperature simulations used 6-hour time steps with daily average flows.

SRWQM is implemented in the HEC-5Q platform which is an integral component of the Temperature Modeling System (TMS) (USBR-TMS) software developed previously (Reclamation 2003). Therefore, calibration of the temperature model supports the HEC-5Q application within the TMS.

Further alternative operations, based on CalSim-II hydrologic inputs and outputs, were performed using the upper Sacramento River model. A preprocessor program (described in Chapter 3) was developed to convert CalSim-II monthly averages into daily values based on historical hydrologic patterns and operation constraints. Meteorology and inflow temperatures were correlated with historical air temperatures and extrapolated to the entire 1921 through 2003 CalSim-II simulation period.

Only the calibration and validation of the upper Sacramento River model will be discussed in this appendix. The model output is provided in Attachment 2 of this appendix.

Background

Reclamation initiated development of the USBR-TMS software package under an earlier contract. The USBR-TMS includes flow and temperature simulation capability and provides graphical display options for model output viewing and interpretation. The HEC-5Q model is an integral component of the USBR-TMS. The SRWQM data set provides flow and temperature simulation capability for the Sacramento River system above Knights Landing, as described earlier in this introduction. Under the current phase of this work, the water temperature model has been further developed, including modification of HEC-5Q code and data to better represent the upper Sacramento River system, with emphasis on temperature control device (TCD) operation and the SLWRI, and using HEC-5Q modeling capability to enhance procedures for determining controlled releases in CalSim-II.

Model Description

The water quality simulation module (HEC-5Q) was developed so that temperature, and conservative and nonconservative water quality constituents could be readily included as considerations in system planning and management. Using system flows computed by HEC-5, HEC-5Q computes the distribution of temperature in the reservoirs and in stream reaches. HEC-5Q is designed for long-term simulations of flow and temperature using daily average hydrology and 6-hour meteorology. A 6-hour time step approximates diurnal variations in temperature. For the upper Sacramento River system, flow and temperature within the Colusa and Yolo bypasses were not simulated because temperature control is not a priority during flood control operation.

HEC-5Q can be used to evaluate options for coordinating reservoir releases among projects to examine the effects on flow and water quality at specified locations in a system. Examples of applications of the flow simulation model include examination of reservoir capacities (e.g., impacts of the proposed enlarged Shasta Reservoir) for flood control, hydropower, and reservoir release requirements to meet water supply and instream flow requirements (e.g., CalSim-II operation scenarios). The model can be used in applications including evaluation of instream temperatures and constituent concentrations at critical locations in a system, or examination of the potential effects of changing reservoir operations or water use patterns on temperature or water quality constituent concentrations. Reservoirs equipped with selective withdrawal structures can be simulated using HEC-5Q to determine operations necessary to meet water quality objectives downstream. For this project, the TCD algorithm was modified to operate the Shasta Dam spillway, flood control outlets, and TCD gates to meet tailwater temperature targets.

External heat sources and sinks that were considered in HEC-5Q were assumed to occur at the air-water interface, and at the sediment-water interface. The method used to evaluate the net rate of heat transfer used the concepts of equilibrium temperature and coefficient of surface heat exchange. The equilibrium temperature is defined as the water temperature at which the net rate of heat exchange between the water surface and overlying atmosphere is zero. The coefficient of surface heat exchange is the rate at which the heat transfer process progresses. Total heat flux is a function of the difference between the equilibrium temperature and ambient temperature. All heat transfer mechanisms, except short-wave solar radiation, are applied at the water surface. Short-wave radiation penetrates the water surface and may affect water temperatures several meters below the surface. The depth of penetration is a function of adsorption and scattering properties of the water, as affected by particulate material (e.g., phytoplankton and suspended solids). Since no particulate parameters are simulated, the seasonal definition of light attenuation must include the effect of all particulate parameters. Heat exchange with the bottom is a function of conductance and the heat capacity of the bottom sediment.

Model Representation of the Physical System

For this application of HEC-5 and HEC-5Q, rivers and reservoirs making up the upper Sacramento River system were represented as a network of reservoirs and streams, and discretized into sections within which flow and water quality were simulated. Control points (CP) represent reservoirs and selected stream locations. Flows, elevations, volumes, etc., were computed at each CP.

The upper Sacramento River model extends from Shasta Dam and Trinity Dam to Knights Landing, and includes the following components:

- Trinity Dam
- Trinity River to Lewiston (approximately 10 miles)
- Lewiston Dam
- Clear Creek Tunnel
- Whiskeytown Dam
- Spring Creek Tunnel
- Shasta Dam
- Keswick Dam
- Sacramento River (approximately 218 miles)
- Clear Creek below Whiskeytown Dam (approximately 17 miles)
- RBDD with seasonal operation constraints
- Black Butte Dam
- Stony Creek below Black Butte Dam (approximately 24 miles)

A schematic of the SRWQM is shown in Figure 4-1.

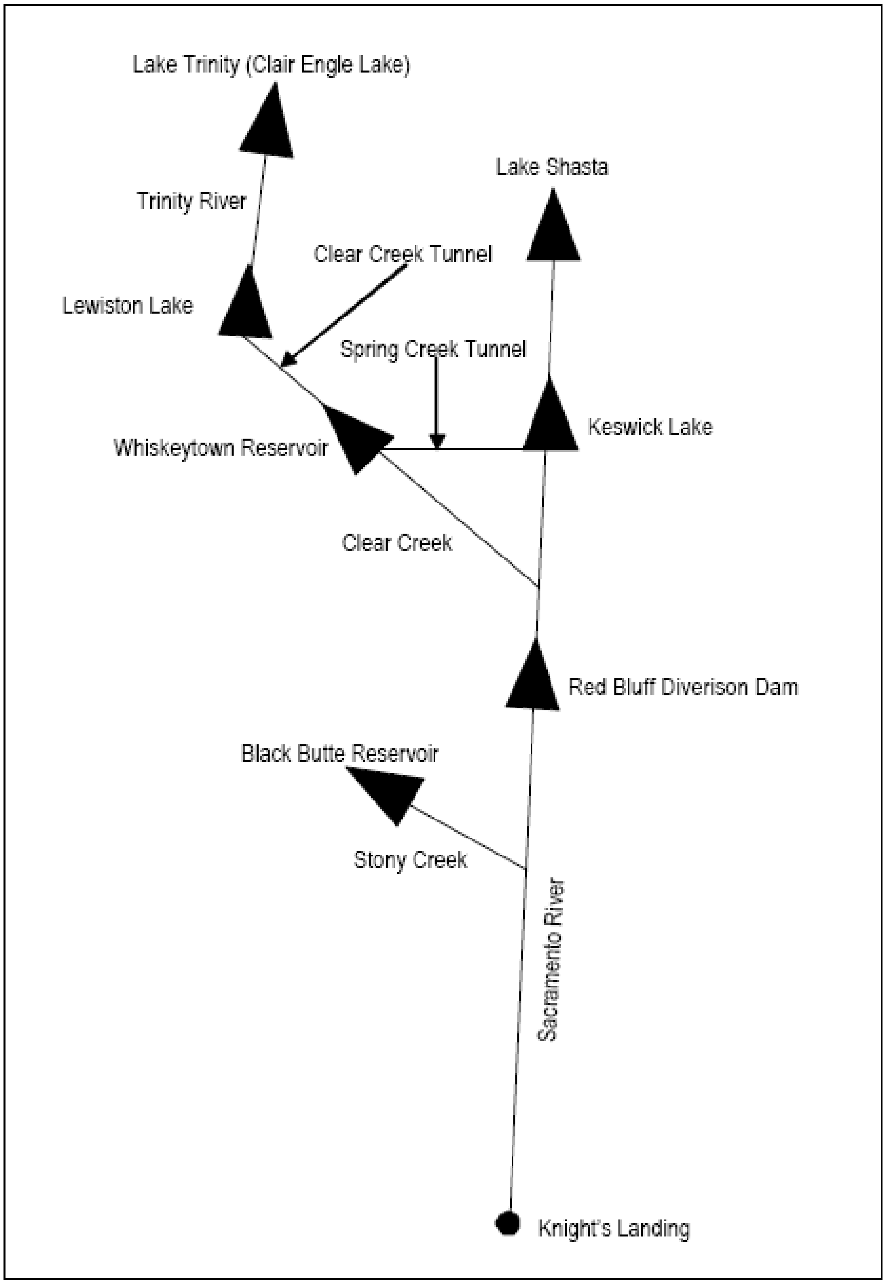


Figure 4-1. Schematic of the SRWQM

In HEC-5, flows and other hydraulic information are computed at each CP. In the HEC-5 context, CPs represent individual reservoirs and locations on river reaches (e.g., gauging stations, stream confluences, major tributaries, etc.). Within HEC-5Q, stream reaches are partitioned into computational elements to compute spatial variations in water temperature between CPs. Reservoirs are partitioned into vertical and/or longitudinal computational elements to represent significant thermal gradients. Within each element, uniform temperature is assumed; therefore, element size determines spatial resolution. Model representation of streams and reservoirs is summarized below.

Model Representation of Reservoirs

For the upper Sacramento River model, Shasta, Trinity, Whiskeytown, and Black Butte reservoirs are geometrically discretized and represented as vertically segmented water bodies with 3.28-foot-thick layers. In Whiskeytown Reservoir, the Oak Bottom Curtain near the Judge Francis Carr Powerhouse tailrace is represented in the model by lowering entrainment. The lowered entrainment limits mixing with the warmer surface waters, thus mimicking the effect of the curtain. The Spring Creek Intake Tunnel Curtain is represented by model geometry and variables. The intake structure is limited to a low-level intake only, to reproduce the effect of only flow from below the curtain reaching the intake.

Lewiston and Keswick reservoirs are represented as vertically layered and longitudinally segmented reservoirs. Lewiston has nine segments, each with nine layers. Keswick has 13 segments each with five layers. RBDD is represented as a longitudinally segmented reservoir with two segments and seasonal elevation constraints. In Lewiston, the Clear Creek Intake Tunnel Curtain is implicitly represented by the calibrated model parameters (i.e., withdrawal elevation and area representative of area below the curtain).

Vertically Segmented Reservoirs

Vertically stratified reservoirs are represented conceptually by a series of 1 dimensional horizontal slices or layered volume elements, each characterized by an area, thickness, and volume. The aggregate assemblage of layered volume elements is a geometrically discretized representation of the reservoir. The geometric characteristics of each horizontal slice are defined as a function of the reservoir’s area-capacity curve. Within each horizontal layer (or “element”), the water is assumed fully mixed with all isopleths parallel to the water surface, both laterally and longitudinally. External inflows and withdrawals occur as sources or sinks within each element and are instantaneously dispersed and homogeneously mixed throughout the layer from the headwaters of the impoundment to the dam. Consequently, simulation results are most representative of conditions in the main reservoir body and may not be indicative of temperature and water quality in the vicinity of major tributary inflows or in shallow regions near the lakeshore. It is not possible to model longitudinal variations in water quality constituents using the vertically segmented configuration. This simplification of the Lewiston and Keswick reservoirs is justified since the observed profile data show little temperature variation throughout either reservoir (profile data are recorded at different locations within each reservoir and do not vary significantly).

The allocation of the inflow to individual elements is based on the relative densities of the inflow and the reservoir elements. Flow entrainment is considered as the inflowing water seeks the level of like density.

Vertical advection is one of two transport mechanisms used in HEC-5Q to simulate transport of water quality constituents between elements. Vertical transport is defined as the interelement flow that results in flow continuity.

An additional transport mechanism used to distribute water quality constituents between elements is effective diffusion, representing the combined effects of molecular and turbulent diffusion, and convective mixing or the physical movement of water due to density instability. Wind and flow-induced turbulent diffusion and convective mixing are the dominant components of effective diffusion in the epilimnion.

Longitudinally Segmented Reservoirs

Longitudinally segmented reservoirs are represented conceptually as a linear network of a specified number of segments or volume elements. Length and the relationship between width and elevation characterize the geometry of each reservoir segment. The surface areas, volumes, and cross-sectional areas are computed from the width relationship.

Longitudinally segmented reservoirs can be subdivided into vertical elements, with each element assumed fully mixed in the vertical and lateral directions. Branching of reservoirs is allowed. For reservoirs represented as layered and longitudinally segmented, all cross sections contain the same number of layers and each layer is assigned the same fraction of the reservoir cross-sectional area. Therefore, the thickness of each element varies with the width-versus-elevation relationship for each element. The model performs a backwater computation to define the water surface profile as a function of the hydraulic gradient based on flow and Manning’s equation.

External flows, such as withdrawals and tributary inflows, occur as sinks or sources. Inflows to the upstream ends of reservoir branches are allocated to individual elements in equal proportions because the cross-sectional area of all layers is equal. Other inflows to the reservoir are distributed in proportion to the local reservoir flow distribution. External flows may be allocated along the length of the reservoir to represent dispersed nonpoint source inflows such as agricultural drainage and groundwater accretions.

Vertical variations in constituent concentrations can be computed for the layered and longitudinally segmented reservoir model. Mass transport between vertical layers is represented by net flow determined by mass balance and by diffusion.

Vertical flow distributions at dams are based on weir or orifice withdrawal. The velocity distribution within the water column is calculated as a function of the water density and depth using the USACE Waterways Experiment Station (WES) weir withdrawal or orifice withdrawal allocation method.

A uniform vertical flow distribution is specified at the upstream end of each reservoir. Velocity profiles within the body of the reservoir may be calculated as flow over a submerged weir, or as a function of a downstream density profile. Submerged weirs or orifices may be specified at the upstream face of the dams. Linear interpolation is performed for reservoir segments without specifically defined flow fields.

Selective Withdrawal Outlet Structures

For reservoirs equipped with selective withdrawal structures, the flow and water quality simulation models can be used to determine the most appropriate withdrawal location and flow rate to achieve the temperature and water quality objectives at downstream CPs. The port selection algorithm of the water quality module uses nonlinear mathematical optimization techniques to determine appropriate port openings and flow rates to satisfy downstream water quality objectives, subject to the different system hydraulic constraints. The solution method is described in the HEC-5 Appendix on Water Quality Analysis (USACE 1998).

CP target values can be specified for several water quality constituents. The water quality routine uses linear optimization to calculate the reservoir release necessary to meet the water quality objectives with the gate operation criteria, and then recalculates the downstream CP water quality using the new reservoir release data. For the purposes of this study, all temperature targets were specified for the tailwater.

The HEC-5Q model also provides for releases through flood control gates and over the spillway during periods when the total outflow exceeds the combined capacity of all other outlets. In representing the Shasta Dam flood control gates, the flow allocation hierarchy is from the highest elevated gate to lowest elevated gate in an attempt to conserve the cold-water pool. Flow is allocated to each gate up to its capacity before the next gate is opened. Although the gate selection algorithm does not compute these releases, the temperature of the water released is considered in the gate selection procedure.

The selective withdrawal algorithm was modified to represent the specific characteristics of the Shasta Dam TCD, and embedded in HEC-5Q. Flood control gates were operated when flows exceeded the capacity (18,750 cfs) of the TCD gates and penstock. TCD gates were operated to achieve temperature targets given flood control, penstock, and leakage flows.

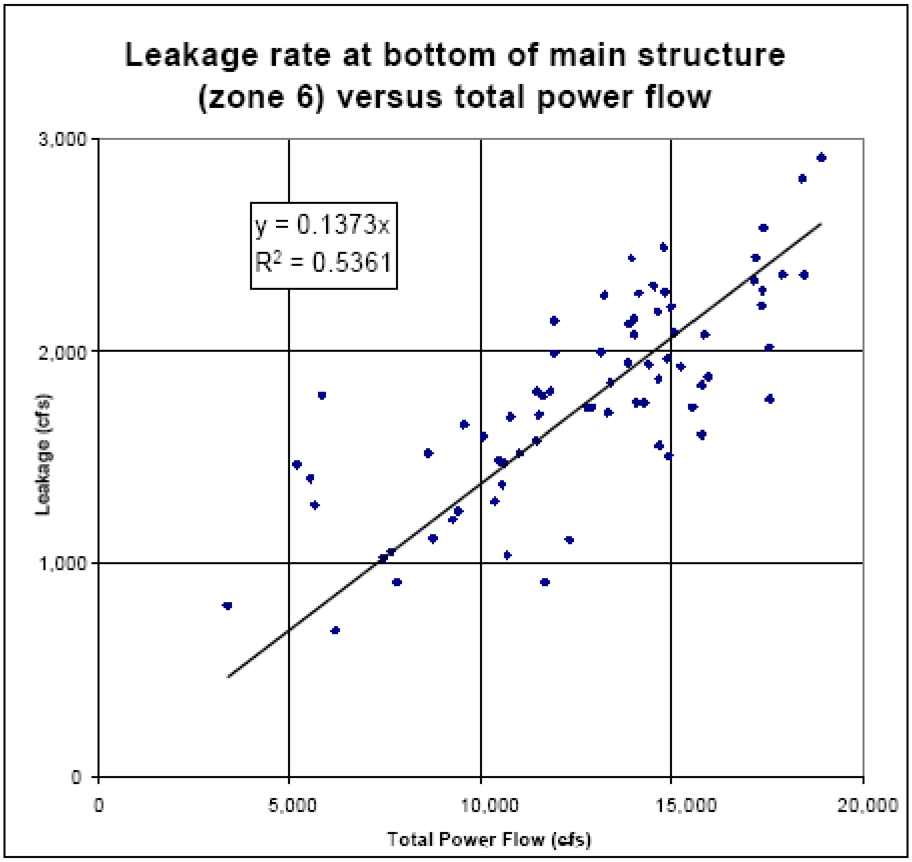
The Shasta Dam TCD algorithm is transparent under nonupper Sacramento River model applications. The TCD option is triggered by inserting a control record into the HEC-5Q data set. The record takes the form of “Shasta Dam TCD opp TCD_opp.log” where the latter part is an output file. The output file contains a summary of the TCD operation, including gate and leakage flows and temperatures. A second project-specific record that controls the beginning date of TCD operation takes the form of “Shasta Dam TCD date 11Mar1999.” Before this date, all withdrawals are assumed to occur at the penstock level (unless flood control gates are in operation). All outlet geometry data and the relationships that compute leakage and gate flows are hard-coded in the subroutine “SHASTA_TCD.FOR.”

The leakage and gate flow relationships are based on 3-dimensional hydrodynamic model results provided by Reclamation (1999). Model results for 73 operation alternatives were processed to develop relationships between total penstock discharge and the leakage for each of seven different leakage zones. The leakage zones were delineated to represent leakage flows that occur between the elevations listed in Table 4-1. These leakage zones coincide with the 3-dimensional model output summaries. The greatest leakage flow occurs from Zone 6, and includes leakage from below the main TCD structure. Zone 7 leakage is associated with the low-level access structure. A sample plot of leakage versus total power flow for Zone 6 is shown in Figure 4-2.

Table 4-1. Leakage Statistics and Equation Coefficients

Zone	Elevation (feet above mean sea level)	K_f	Average Leakage (cfs)	Absolute Difference, Computed vs. Observed Total Q	
				(cfs)	(percent)
1	Above 1,000 (includes over top)	0.0306	356	133	1.07
2	1,000-945	0.0227	296	163	1.36
3	945-900	0.0066	89	30	0.30
4	900-831	0.0282	366	75	0.65
5	831-804	0.0068	95	10	0.08
6	804-780 (inc. from below main structure)	0.1373	1,785	245	2.36
7	780-750 (leakage of low level access)	0.0047	65	8	0.06
		Total	**3,052**	**664**	**5.20**

Key:
cfs = cubic feet per second
K_f = slope
Q = leakage



Source: Upper Sacramento River Water Quality Modeling with HEC-5Q: Model Calibration and Validation. U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-2. Shasta Dam Leakage Rate at Bottom of Gate Structure (Zone 6) Versus Total Power Flow

The leakage is computed by a linear function relating leakage to total generation flow (i.e., $Q = K_f * Q_p$, where Q is the leakage flow, K_f is the slope, and Q_p is the total penstock (power) flow.) Values of K_f are listed in Table 4-1. The table also includes the average leakage rate, average absolute difference between the 3-dimensional model flow, and regression flows by zone. The difference is expressed in cfs and as a percentage of the total penstock flow. The average total difference between the HEC-5Q model TCD approximation and 3 dimensional model leakage is 5.2 percent of the total power flow.

No assessment of the accuracy of the 3-dimensional model is made herein; therefore, it is difficult to assess the ramifications of the 5.2 percent difference between the two approaches. However, once the leakage rates and associated temperatures are determined, the temperature target (objective) is adjusted by thermal balance so that any inaccuracies in the leakage computation are compensated for in the gate operation.

Residual total gate flow (power flow less leakage) is dependent on the location of the target temperature in the water column relative to gate locations. If the target is elevation 1,000 feet above mean sea level, all flow goes through the upper gate. If the target temperature is below 804 feet, all flow goes through the bottom gate. At intermediate locations, the following relationships between proportional discharges from adjacent gates were developed from the 3-dimensional model results (note that only two gate levels are used to assign outflow fractions):

Target is between middle and upper gate:
$Qg = Nt * 0.18 * Qm + Nm * Qm$ ($R^2 = 0.09$)

Target is between middle and penstock gate:
$Qg = Np *(467 + 0.476) * Qm + Nm * Qm$ ($R^2 = 0.87$)

Target is between lower and penstock gate:
$Qg = Np *(690 + 0.127) * Qb + Qb$ ($R^2 = 0.83$)

where

Qg = residual total gate flow (power flow less leakage)

Qm = flow through middle gate

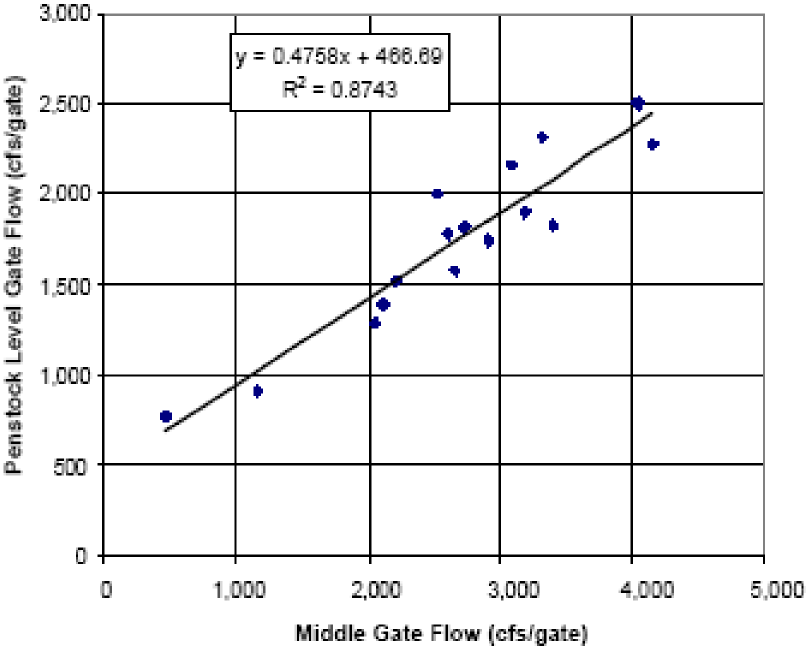
Qb = flow through the lower gate

Nt = number of upper gates

Nm = number of middle gates

Np = number of penstock gates

The R^2 value for each regression relationship is listed above. The R^2 value for the relationship defining upper and middle gate flow split is very poor. However, the ratio of upper gate flow to middle gate flow is only 0.18, indicating that it is difficult to pass much water through the upper gates when the middle gates are open. The R^2 values for the other regression relations indicate there is a strong correlation between the number of open gates and relative flow at the two gate elevations. Figure 4-3 shows the relationship developed between penstock level gate flow and middle gate flow.



Source: Upper Sacramento River Water Quality Modeling with HEC-5Q: Model Calibration and Validation. U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-3. Shasta Dam Penstock Level Gate Flow Versus Middle Gate Flow

Within the TCD algorithm, all combinations of gate openings (Nt, Np, and Nm, varying between one and five gates) were computed for the two gate levels that bracket the adjusted target temperature. The gate setting that resulted in the smallest departure from the target was selected. If the leakage-adjusted target temperature was beyond the available temperature (above the top gate temperature or below the bottom gate temperature), all of the flow was allocated to the upper or lower gate location. The resulting combined discharge temperatures for all gate and leakage flows were then computed using the WES outflow algorithm.

The quality of fit between computed Shasta Dam tailwater temperatures and target tailwater temperatures is a function of the simulated Shasta Reservoir temperatures and the operation of the Shasta Dam TCD. It is believed that the quality of the Shasta Reservoir temperature calibration (profiles and tailwater) attests to the adequacy of the TCD for alternative evaluation.

Model Representation of Streams

In HEC-5Q, a reach of a river, stream, or canal is represented conceptually as a linear network of segments or volume elements. The length, width, cross-sectional area, and a flow-versus-depth relationship characterize each element. Cross sections are defined at all CPs and at intermediate locations when data are available. The flow-versus-depth relationship is computed as a function of slope and channel geometry, or is developed external to HEC-5Q using available cross section data, field observations, and appropriate hydraulic computation. For this study, the flow-versus-elevation input option was used (the flow-versus-depth relation is developed externally, as described below). Linear interpolation between input cross section locations is used to define the hydraulic data for each element.

SRWQM cross sections are based on RMA2 model cross sections and RMA2 simulated flow, elevation, and volume results. The RMA2 model of the upper Sacramento River was originally developed and calibrated by the University of California – Davis (UC Davis) and refined through work sponsored by USGS. To develop flow versus depth relations from this model, a series of simulations was performed with a range of constant inflows at the upstream boundary. Flow depths were then extracted from the model results to correspond to the different flow rates that defined the SRWQM cross section data. The accuracy of the SRWQM cross section is, therefore, a function of the accuracy of the RMA2 calibration. The RMA2 calibration is not assessed herein.

Flow rates are calculated at stream CPs by HEC-5 using one of several available hydrologic routing methods. For the upper Sacramento River project, all flows were routed using hydrologic routing based on attenuation of hydrographs through the system. The routing coefficients result in the flow routing times listed in Table 4-2. Within HEC-5, incremental local flows (i.e., inflow between adjacent CPs) are assumed deposited at the CP. Within HEC-5Q, the incremental local flow may be subdivided into components and placed at different locations within the stream reach (i.e., that portion of the stream bounded by the two CPs). A flow balance is used to determine the flow rate at all element boundaries.

Table 4-2. Flow Routing Times

Location	Flow Routing Time (hours)
Keswick Dam	0
Cow Creek	5
Bend Bridge	9
Red Bluff Diversion Dam	12
Woodson Bridge	20
GCID Intake	22
Stony Creek	26
Butte City	32
Moulton Weir	35
Colusa Weir	40
Tisdale Weir	50
Knights Landing	62

Key:
GCID = Glenn-Colusa Irrigation District

Inflows or withdrawals may include any point or nonpoint flow. Distributed flows such as groundwater accretions and nonspecific agricultural return flows are defined on a rate-per-mile basis.

For simulation of water quality, the tributary locations and associated water quality are specified. To allocate components of the diversion flow balance, HEC-5Q performs a calculation using any specified withdrawals, inflows, or return flows, and distributes the balance uniformly along the stream reach. Only point inflows were considered during this application.

Once interelement flows are established, the water depth, surface width and cross-sectional area are computed at each element boundary, assuming normal flow (or the user-specified flow versus elevation table) and downstream control (i.e., backwater). Stream elements approximately 1 half-mile in length were used in this study.

Hydrologic Boundary Conditions

SRWQM inputs include initial reservoir volumes, inflows, and releases, and tributary inflows, diversions, accretions, and depletions. Historical flows from USGS, USACE, and Reclamation data sources were used to develop boundary conditions.

Temperature Boundary Conditions Input Data

HEC-5Q requires that flow rates and water quality be defined for all inflows. Inflow rates may be defined explicitly or as a fraction of the incremental local flow to the CP.

Water temperature was simulated by SRWQM using tributary stream inflow temperatures developed from DWR, Reclamation, and CDEC daily average ambient stream temperature data.

Tributary inflow temperatures were computed at 6-hour intervals as a function of the typical seasonal variation (same for all years) and 6-hour equilibrium temperature (variable by year and tributary inflow rate). This approach allows for the seasonal effects of snowmelt runoff and the daily variation in meteorology. Tributary inflow temperatures were based on the following ambient data sources:

- **Shasta Reservoir inflow** – flow-weighted temperatures of the three major tributaries
- **Trinity Lake inflow** – Trinity River above Trinity Lake (provided by Mike Deas)
- **Whiskeytown Reservoir external boundary (primarily Clear Creek) –** Sacramento River at Delta (no ambient data were available for Whiskeytown tributaries)

- **Sacramento River tributary (warm) –** Thomes Creek
- **Sacramento River tributary (moderate) –** Cow Creek
- **Sacramento River tributary (cool) –** Battle Creek

The three major tributaries to Shasta Reservoir, the Sacramento River, McCloud River, and Pitt River, were aggregated into one input to be compatible with CalSim-II flow delineation. Flows from the three tributaries were combined and flow-weighted average temperatures were computed. Data were available at hourly intervals or less during the periods and numbers of days listed in Table 4-3.

Trinity inflow temperatures are the flow-weighted average of Trinity River, East Fork Trinity River, and Stuart's Fork Trinity River. Data were available at hourly intervals or less during the periods and numbers of days listed in Table 4-3.

Table 4-3. Reservoir Inflow Data Availability

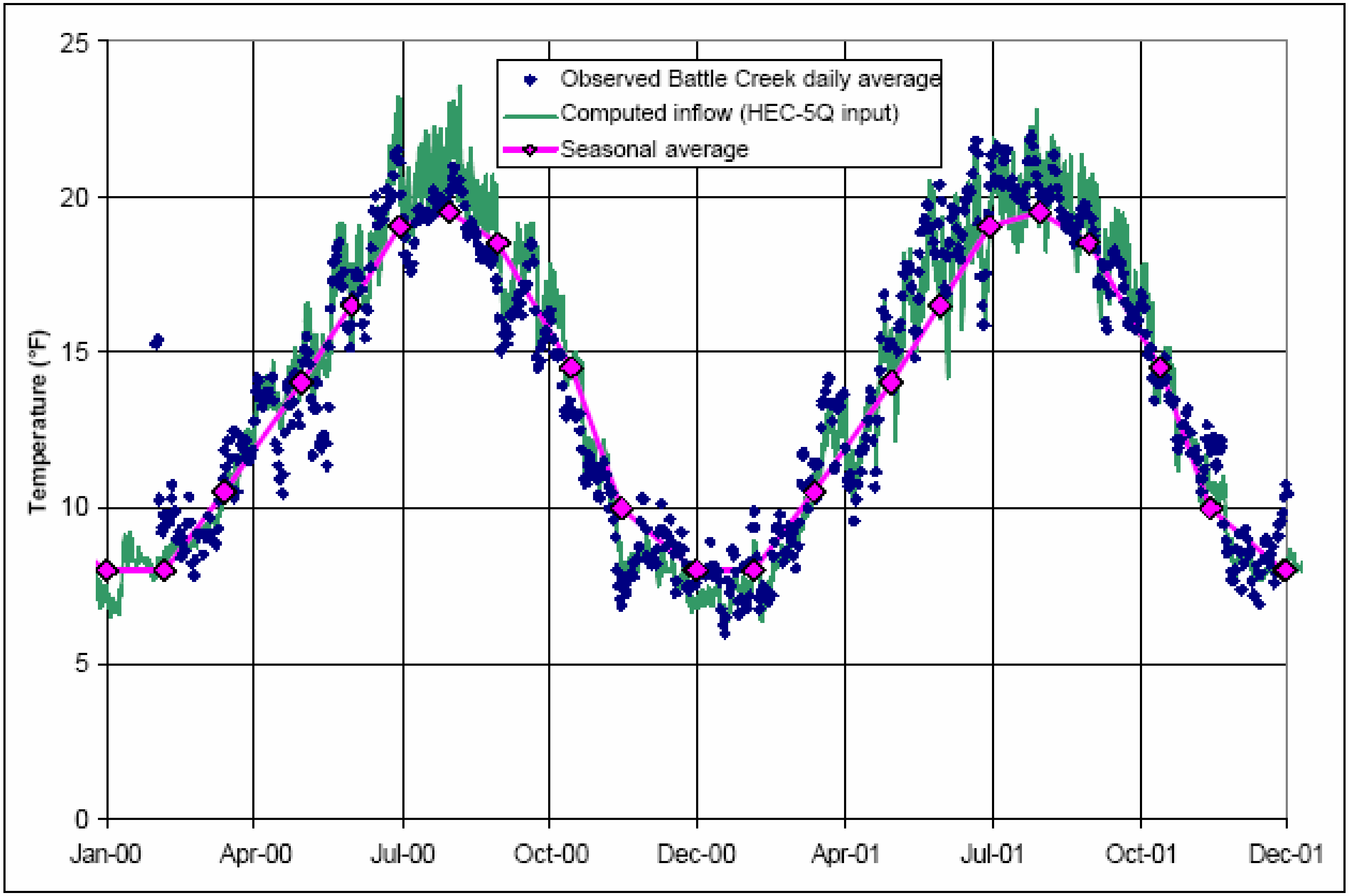
Tributary	Available Reservoir Inflow Data		
	Start	End	No. of Days
Sacramento River	Feb-90	Jun-01	3,418
McCloud River	May-90	Jun-01	3,481
Pitt River	Nov-89	Jun-01	3,913
Stuart's Fork Trinity River	Apr-00	Jun-02	586
East Fork Trinity River	Apr-00	Jun-02	714
Trinity River	Apr-00	Jun-02	711

Temperature data for many of the Sacramento River tributaries were so similar that instead of using all available data for model input, three representative data sets were chosen (warm, moderate, and cool) and each tributary was assigned one of the three. This reduced model input and eliminated the need for interpolating and extrapolating for missing data in multiple data sets. For streams with no data available for comparison, one of the three representative data sets was assigned based on location and watershed characteristics. All minor Sacramento River tributaries, their temperature assignments, and available temperature data are listed in Table 4-4.

Table 4-4. Sacramento River Tributary Temperature Assignments and Data Availability

Sacramento River Tributary	Temperature Assignment	Available Temperature Data		
		Start	End	No. of Days
Clear Creek accretions	moderate			0
Churn Creek	moderate			0
Cow Creek	moderate	Nov-97	Dec-00	1,045
Bear and Ash creeks	moderate			0
Cottonwood Creek	moderate	Aug-97	Oct-00	629
Battle Creek	cool	Jun-98	Jan-02	784
Paynes Creek	cool	Aug-97	Dec-00	1,022
Reeds Creek	warm			0
Red Bank Creek	warm	Jan-98	Jan-02	575
Antelope Creek	cool	Nov-97	Dec-00	1,069
Elder Creek	warm	Jan-98	Jan-02	682
Mill Creek	moderate	Jun-96	Dec-99	581
Thomes Creek	warm	Mar-98	Aug-00	795
Deer Creek	moderate	Jun-97	Nov-00	873
Jewett Creek	warm			0
Pine Creek	moderate			0
Big Chico Creek	moderate	Jun-97	Mar-00	553
Accretions above Butte Creek	warm			0
Butte Creek	warm			0
Colusa Drain	warm	Sep-97	Feb-01	1,181

Figure 4-4 shows daily average, seasonal distribution, and computed tributary inflow temperature for Battle Creek. This plot is intended to show typical temporal variations between computed and observed inflow temperatures. This method provides a link between meteorology and inflow tributary rate, and temperature, so that the limited observed ambient temperature data set can be extrapolated over the entire simulation period. The variable nature of the inflow temperature is important since it impacts river temperatures during storm events unrelated to reservoir release temperatures. It also impacts the distribution of inflows to reservoirs (density effects) and determines the volume of available cool-water resources for river temperature control during the summer and fall seasons.



Source: Upper Sacramento River Water Quality Modeling with HEC-5Q: Model Calibration and Validation. U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-4. Daily Average, Seasonal Average, and Computed Tributary Inflow Temperature for Battle Creek

Meteorological Data

Meteorological data were available from CIMIS and the U.S. Weather Service (USWS) at several locations within the Sacramento Valley. The Gerber station was selected as the primary CIMIS meteorological data record because it is located towards the northern end of the Sacramento Valley where temperature changes within the river are of major concern. This station has a long data record (1985 through 2000) with very few missing data. Temperatures from CIMIS data were extrapolated based on USWS long-term daily maximum and minimum air temperatures and precipitation data back to 1921.

A relationship was developed between the maximum and minimum temperatures at the Gerber CIMIS station and two USWS stations. The relationship with the USWS station at Orland was used from July 1948 through 1985. Before that date, the USWS station at Davis was used because it was the nearest station with data dating back to 1921.

The extrapolation procedure consisted of searching the Gerber CIMIS data record to find the air temperature range that most closely matched the adjusted USWS maximum and minimum air temperatures. Candidate CIMIS records were limited to 2 days before or after the USWS day; thus, up to 5 days from each of the 16 years of CIMIS data (a total of 80 days) were available for assignment to each day of the 1921 through 1985 period. From 1985 on, unadjusted CIMIS data were used.

Hourly air temperature, wind speed, relative humidity, and cloud cover were then used to compute equilibrium temperatures and exchange rates at 6-hour intervals for input to SRWQM. During model calibration, equilibrium temperatures and exchange rates were scaled to reflect ambient conditions such as increased wind speed over open lake water and riparian shading for stream reaches.

Temperature Model Calibration

SRWQM was calibrated for the period of January 1998 through November 2002 using temperature time series field observations at numerous locations in the upper Sacramento River; tailwater temperature time series at Shasta, Lewiston, Keswick, and Black Butte dams; temperature time series at Spring Creek Powerhouse and Stony Creek at TCC; and temperature profile observations in Shasta, Trinity, Lewiston, and Whiskeytown reservoirs. The following temperature data sets were used:

- CDEC water temperature time series
- DWR water temperature time series

- Reservoir temperature profiles (Shasta, Trinity, Lewiston, and Whiskeytown) provided by Reclamation
- USACE Black Butte Reservoir temperature profiles

The hydrology, meteorology, and inflow water quality conditions described in the previous section were assumed.

The intent of the model calibration exercise was to adjust model parameters to minimize differences between the daily average computed and observed data, and demonstrate that the model adequately represents the thermal responses of the upper Sacramento River stream and reservoir system. Calibration emphasized warmer periods.

The results of the calibration effort are presented as plots of computed and observed temperature time series and reservoir temperature profiles. A simulation of 1998 is used to establish the initial conditions for simulation of TCD operations to meet downstream temperature targets beginning in the spring of 1999; therefore, reservoir temperature profile plots are provided from 1999 on.

SRWQM Calibration Results

The following sections briefly describe calibration results for reservoirs and streams.

Reservoir Temperature Calibration Results

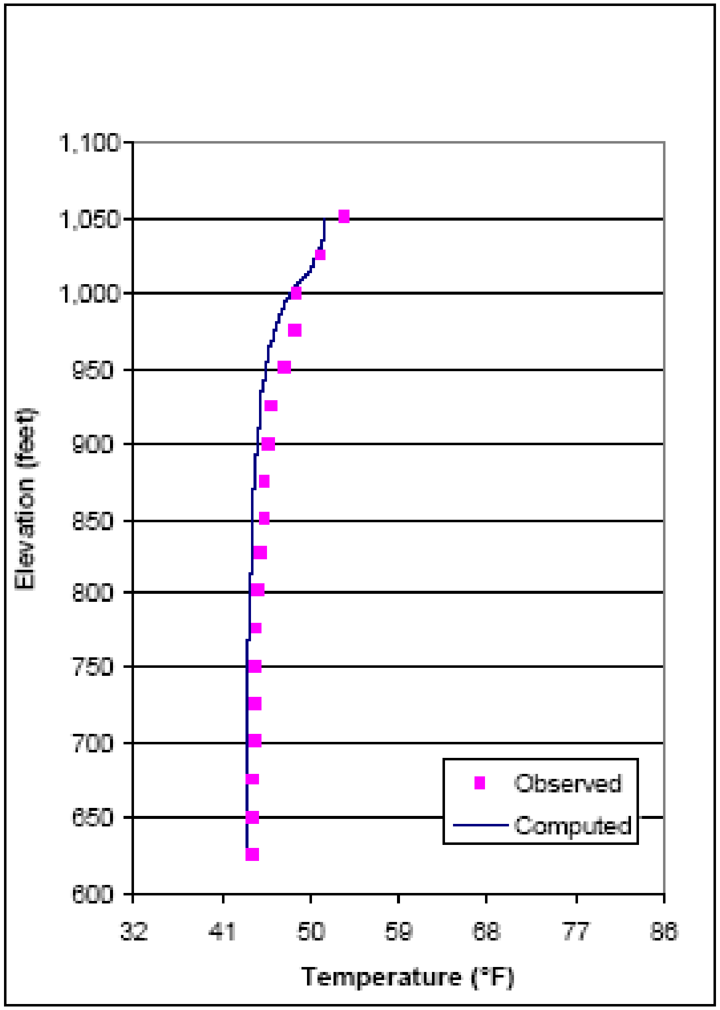
Computed and observed vertical reservoir temperature profiles are plotted for numerous dates during 1999 through 2002 in Figures 4-5 through 4-52.

Shasta Reservoir profiles are plotted in Figures 4-5 through 4-20. There is excellent agreement between computed and observed data for all of the profiles. In several of the profiles, there is a 2 degrees Fahrenheit (°F) to 4°F difference between computed and observed surface temperatures. These discrepancies are normally due to the approximation of the meteorological conditions and, in some cases, may be due to a slight time offset between computed and observed surface temperatures. However, these deviations do not appear to affect temperatures lower in the reservoir nor do they affect tailwater temperatures. The temperatures below the epilimnion are controlled by withdrawal location and the temperature of inflows during the higher runoff period. Once the reservoir becomes well stratified, the water column is very stable and the water at depth is essentially isolated from the surface, thereby minimizing the impacts of the surface temperature discrepancies.

Whiskeytown Reservoir profiles are plotted in Figures 4-21 through 4-36. The calibrated mixing coefficients reflect current facilities that include the temperature control curtain near the Clear Creek Tunnel discharge and modifications to the Spring Creek Tunnel intake structure. Computed values are generally in good agreement with observed profile data. Note that several observed profiles are included and show the slight variability of temperatures within the reservoir. Discrepancies in temperatures may be influenced by the operation of the Oak Bottom Curtain near the Judge Francis Carr Powerhouse tailrace. Additionally, the Spring Creek Intake Tunnel Curtain has undergone repair within the last 5 years. During this time, large sections of the curtain were removed for extended periods. This could also explain some of the discrepancies in the Whiskeytown Reservoir profiles. The emphasis of the Whiskeytown Reservoir calibration was on an accurate prediction of the Spring Creek Tunnel discharge temperature (see Figure 4-55) and the discrepancies noted do not appear to adversely impact the discharge temperature calibration.

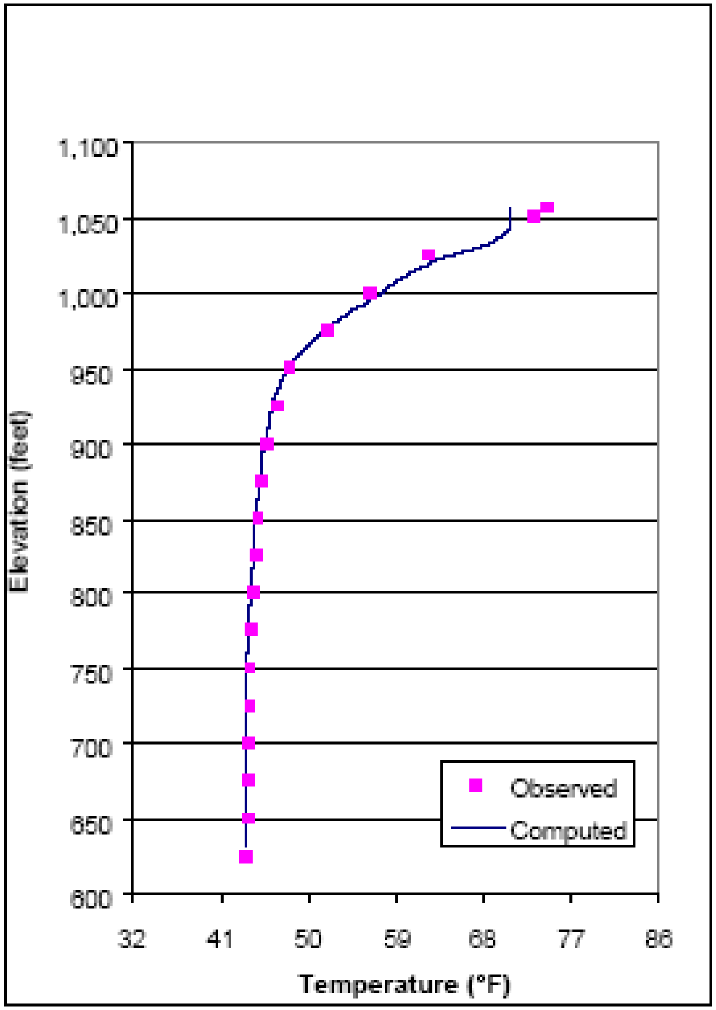
Trinity Reservoir temperature profiles are shown in Figures 4-37 through 4-44. Computed values are in excellent agreement with observed data for all of the profiles. The only notable deviations occur on September 20, 1999, when the computed surface temperature is approximately 2°F warmer than observed, and on July 27, 2000, when the computed surface temperature is approximately 4°F warmer than observed. Surface temperatures are within 1°F or less of observed for all other profiles.

Lewiston Reservoir temperature profiles are shown in Figures 4-45 through 4 52. Computed temperature profiles tend to be 0°F to 2°F cooler than observed. Discrepancies in temperatures may be influenced by the presence of the Clear Creek Intake Tunnel Curtain. Lewiston Reservoir temperatures were not adjusted to correct for this minor discrepancy because it would have adversely affected the calibration of Spring Creek Powerhouse temperatures.



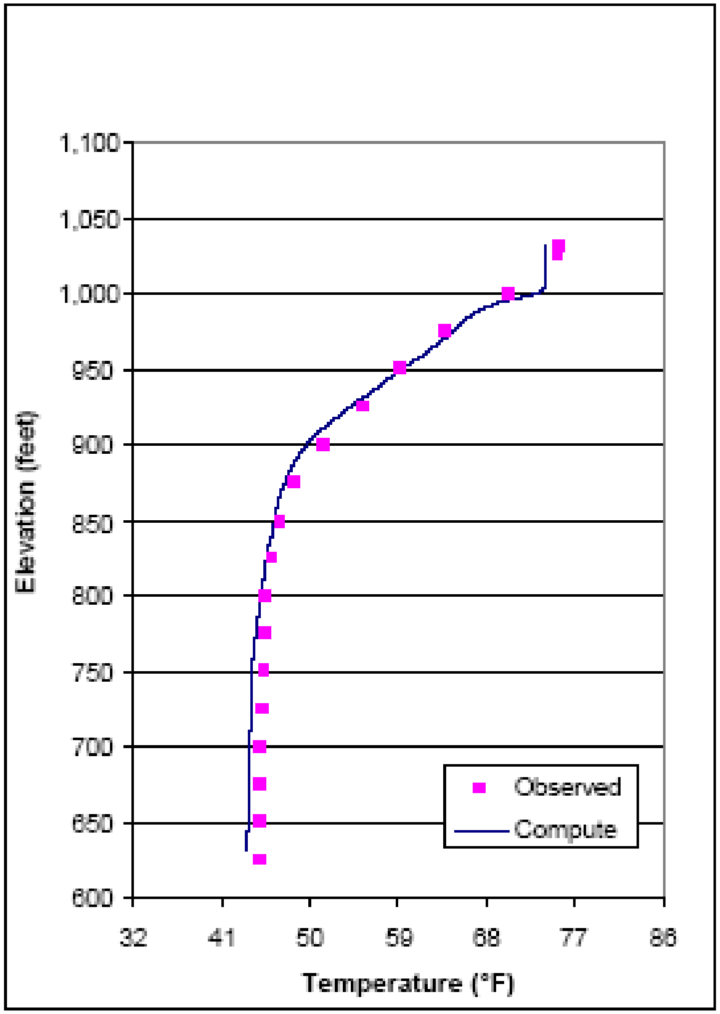
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-5. Computed and Observed Temperature Profiles in Shasta Reservoir on April 13, 1999



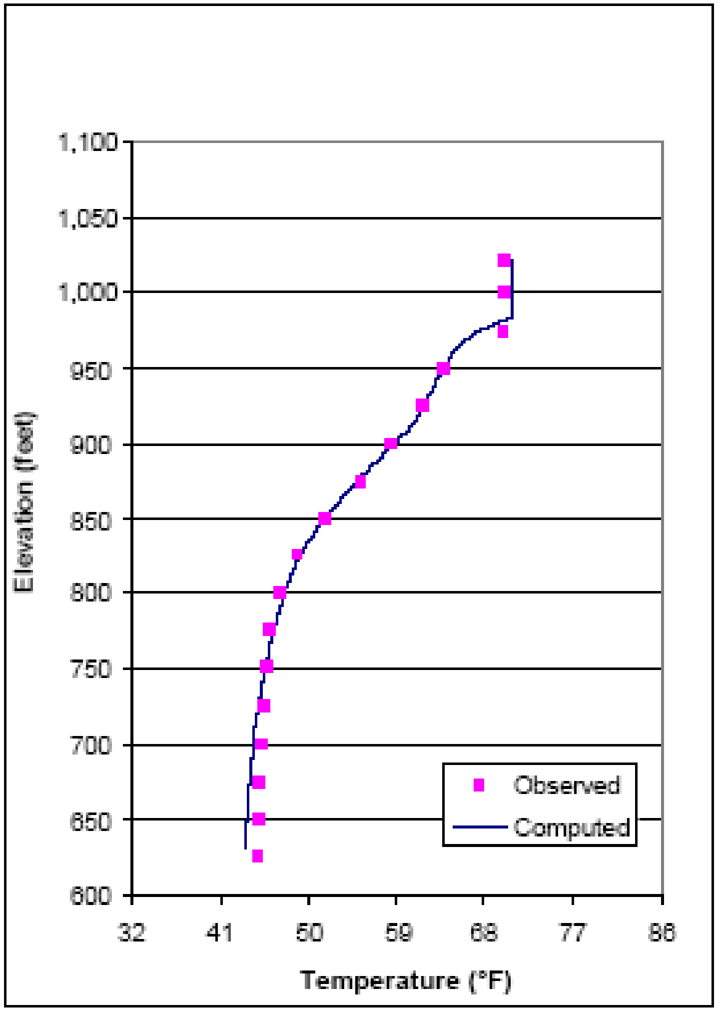
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-6. Computed and Observed Temperature Profiles in Shasta Reservoir on June 18, 1999



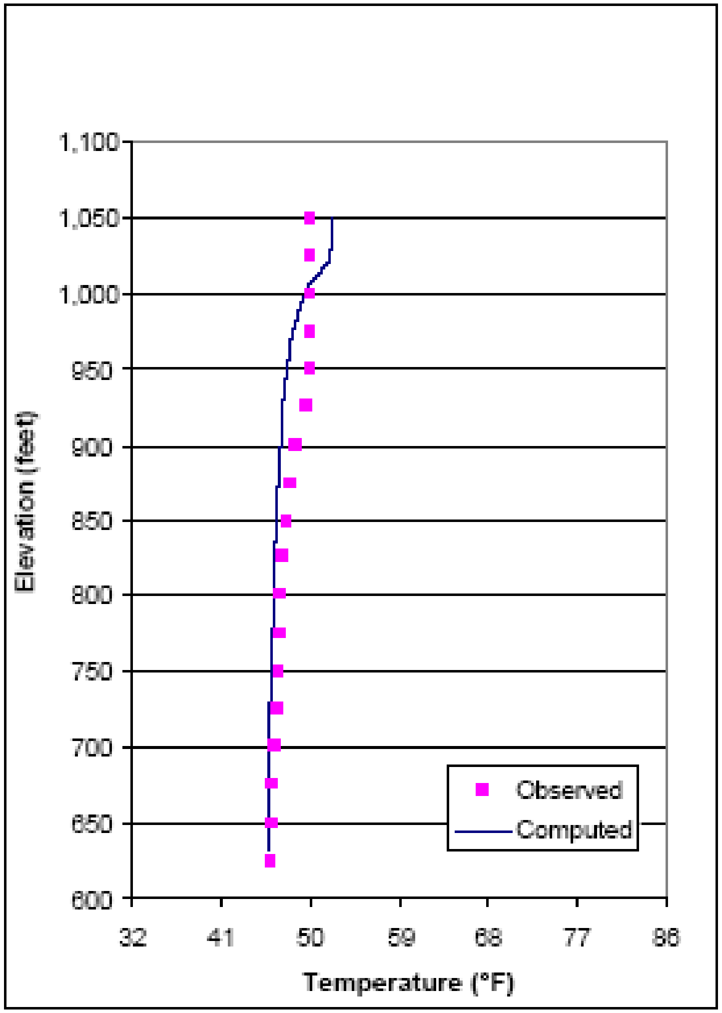
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-7. Computed and Observed Temperature Profiles in Shasta Reservoir on August 13, 1999



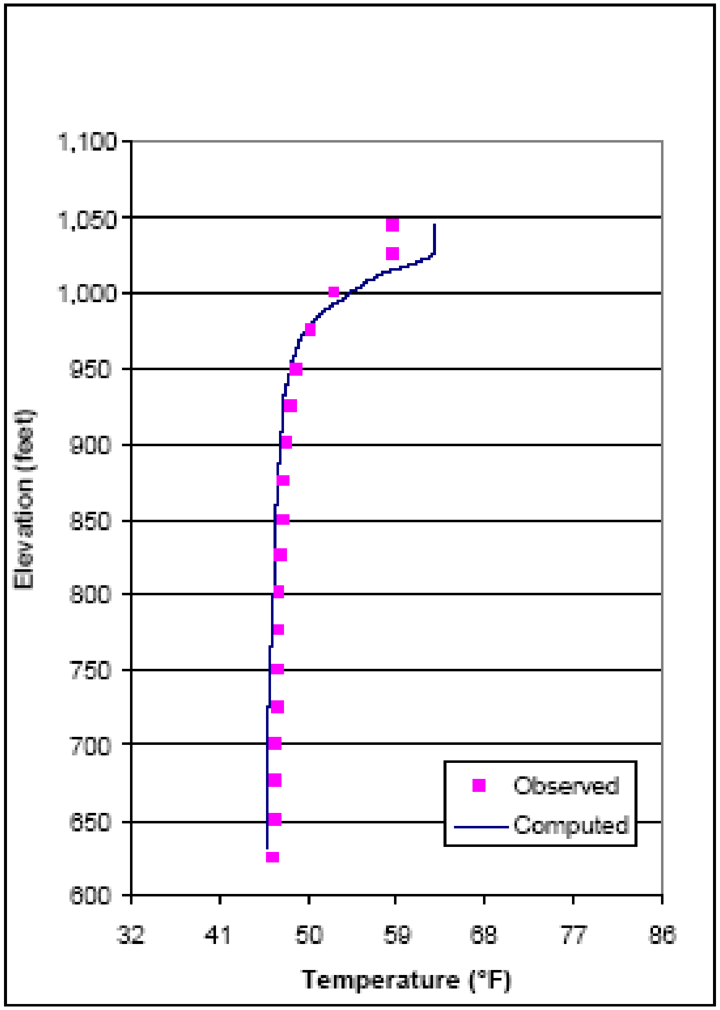
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-8. Computed and Observed Temperature Profiles in Shasta Reservoir on October 1, 1999



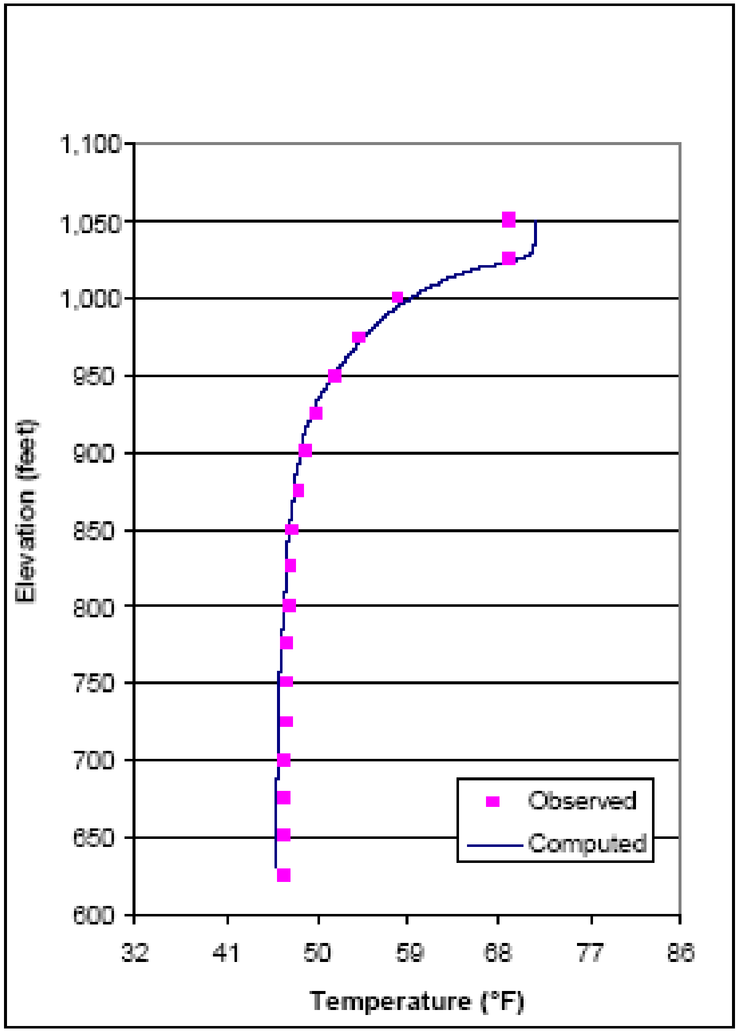
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-9. Computed and Observed Temperature Profiles in Shasta Reservoir on February 16, 2000



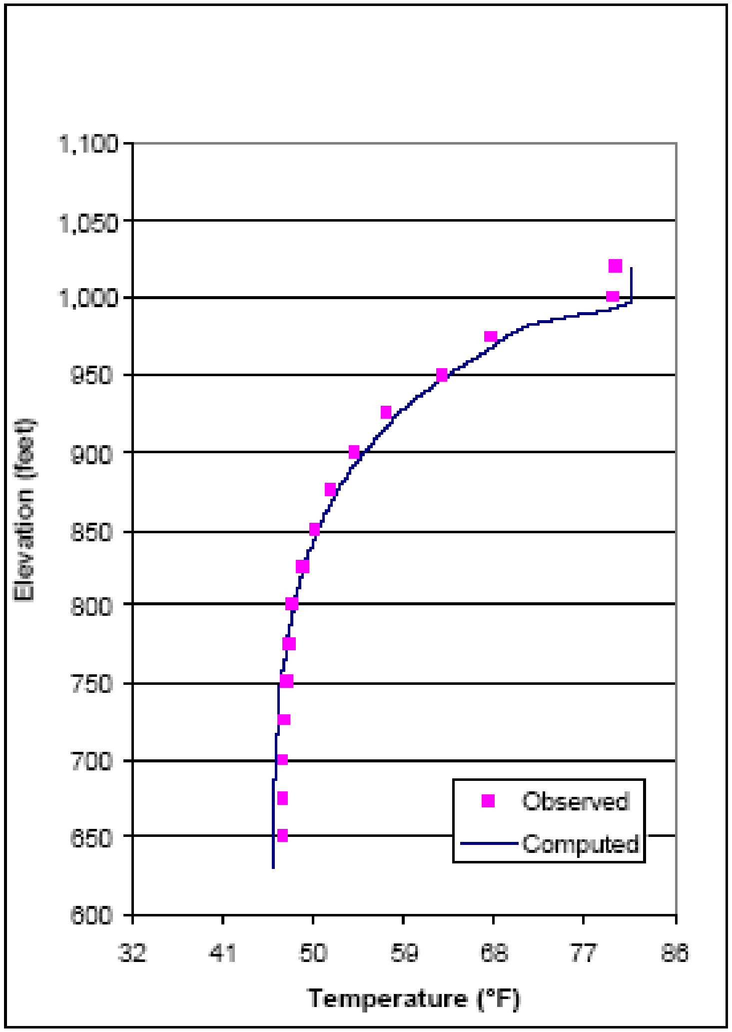
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-10. Computed and Observed Temperature Profiles in Shasta Reservoir on April 14, 2000



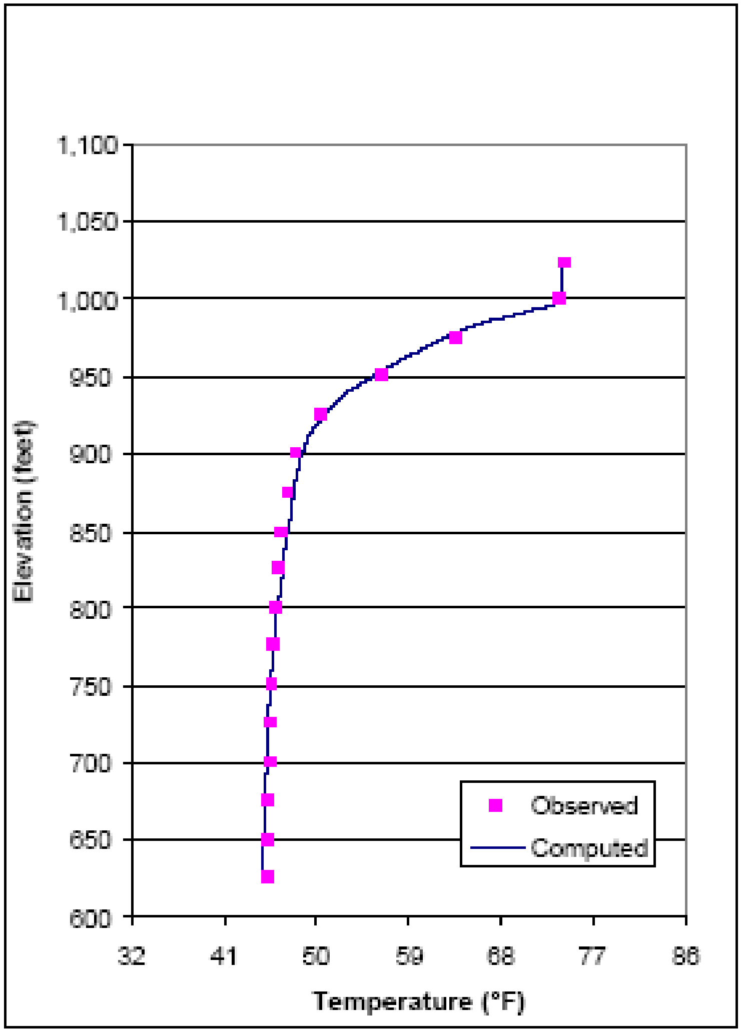
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-11. Computed and Observed Temperature Profiles in Shasta Reservoir on June 6, 2000



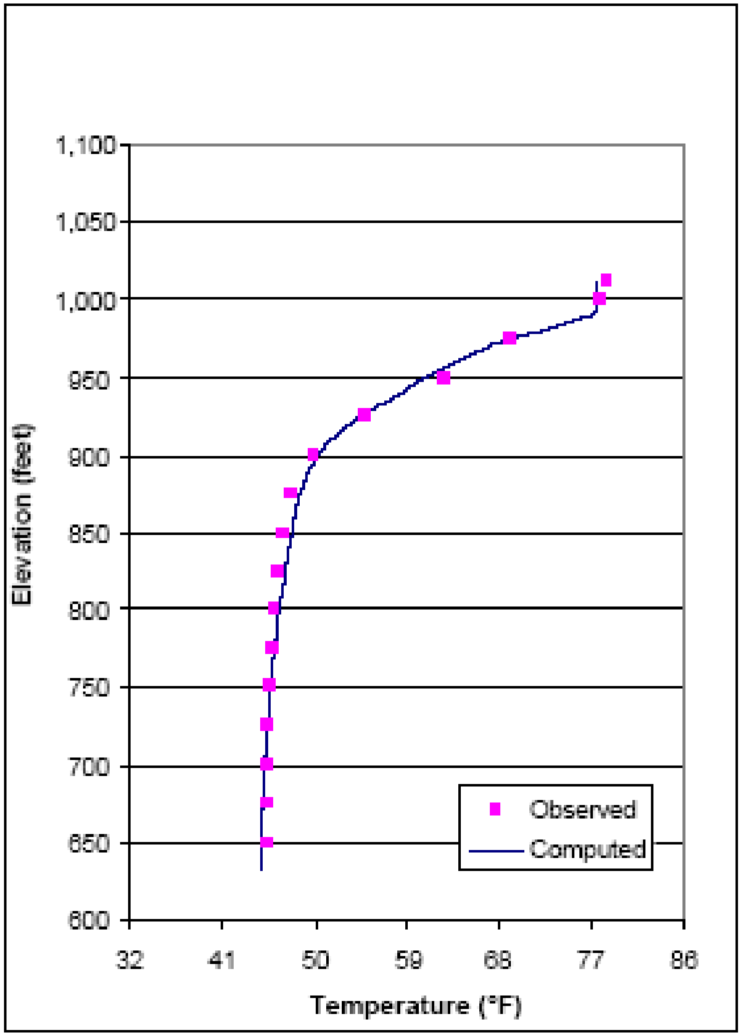
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-12. Computed and Observed Temperature Profiles in Shasta Reservoir on August 4, 2000



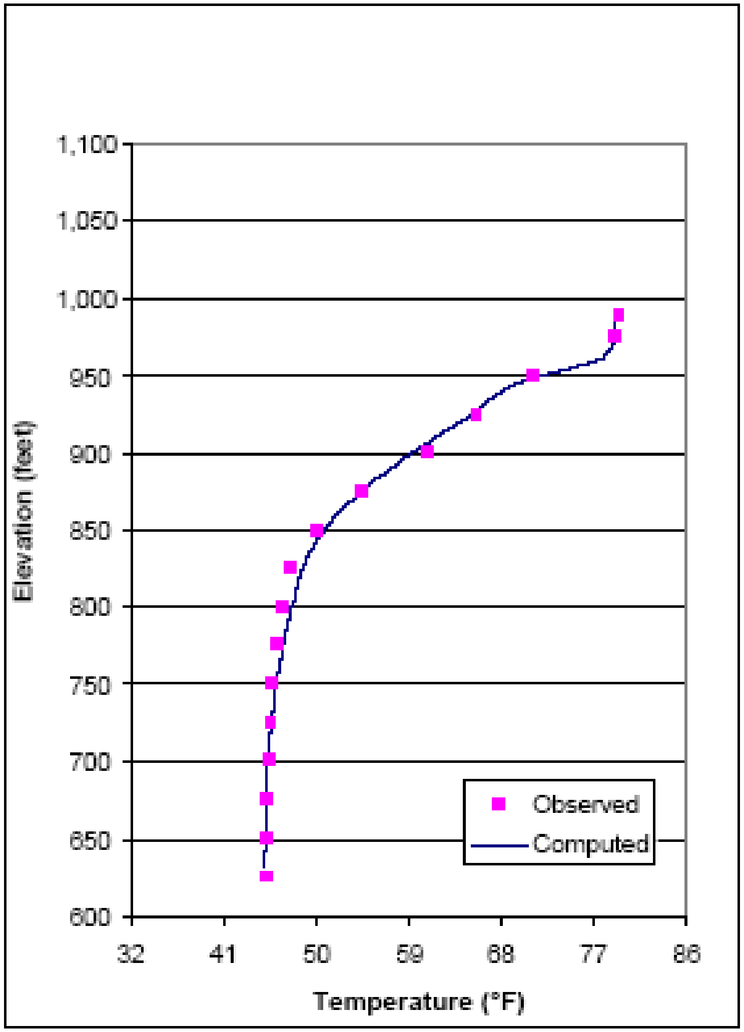
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-13. Computed and Observed Temperature Profiles in Shasta Reservoir on June 25, 2001



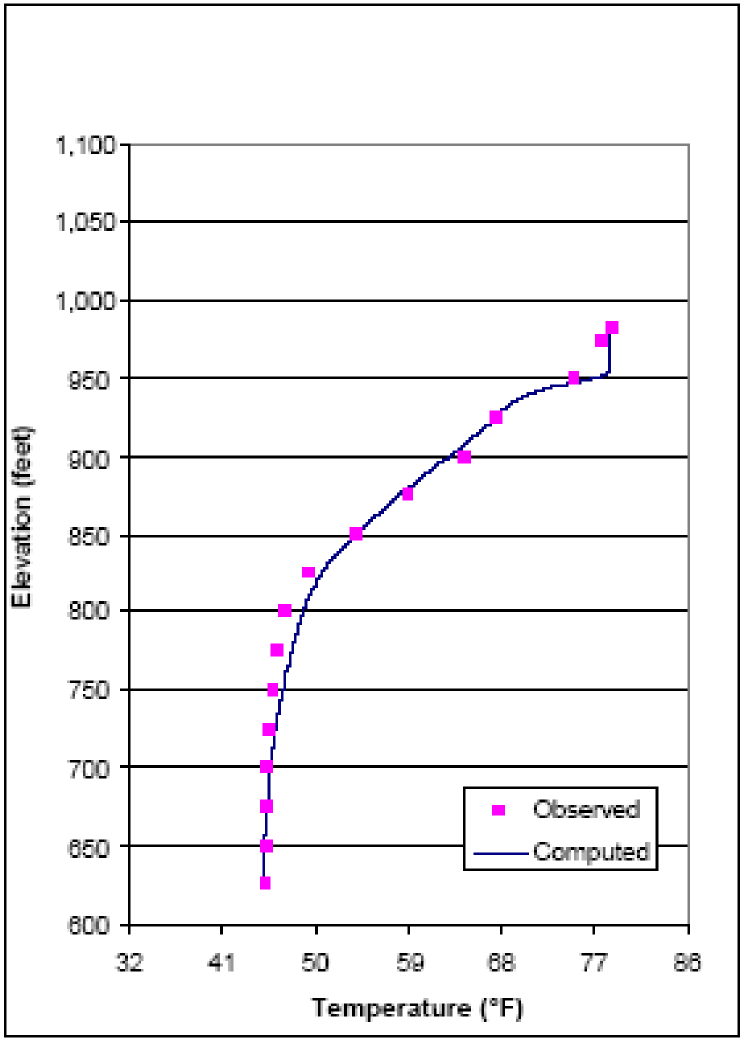
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-14. Computed and Observed Temperature Profiles in Shasta Reservoir on July 11, 2001



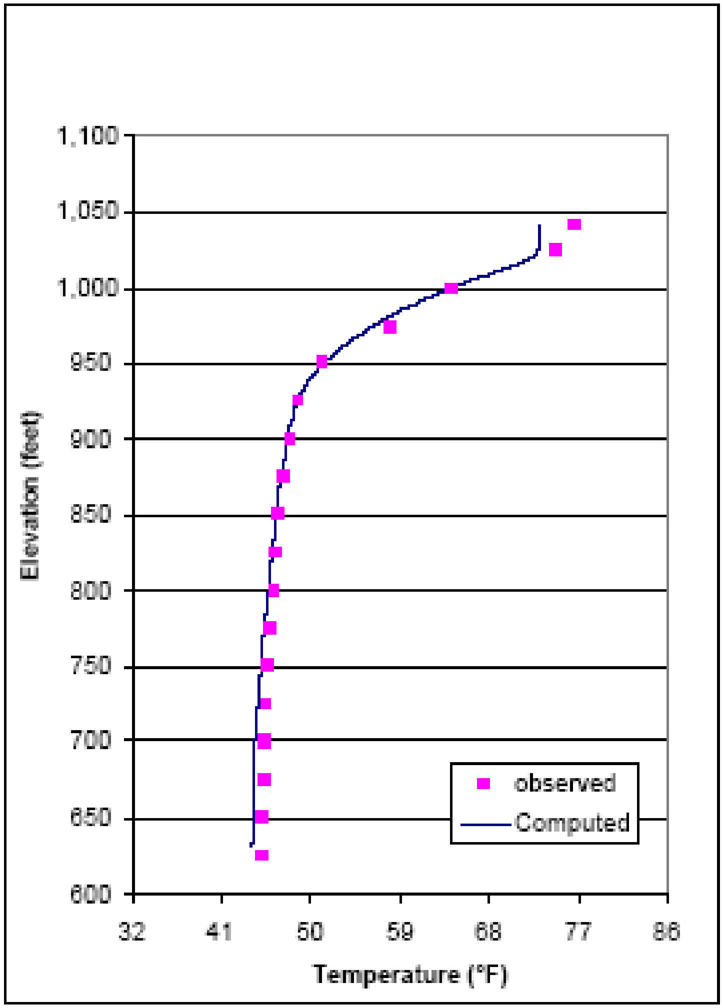
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-15. Computed and Observed Temperature Profiles in Shasta Reservoir on August 9, 2001



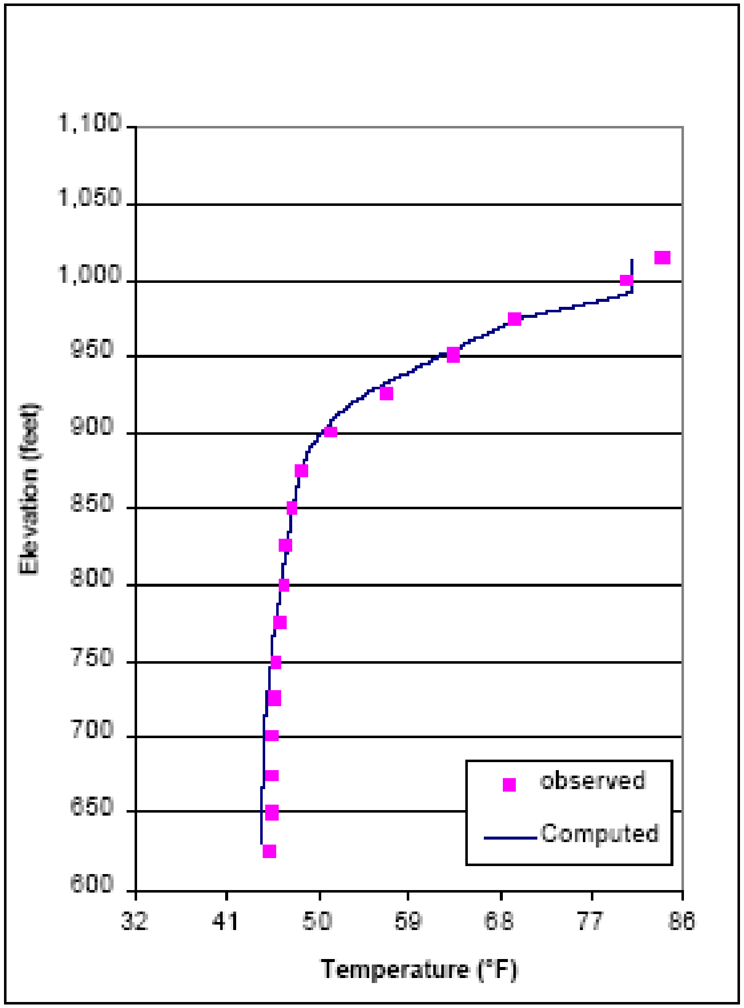
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-16. Computed and Observed Temperature Profiles in Shasta Reservoir on August 21, 2001



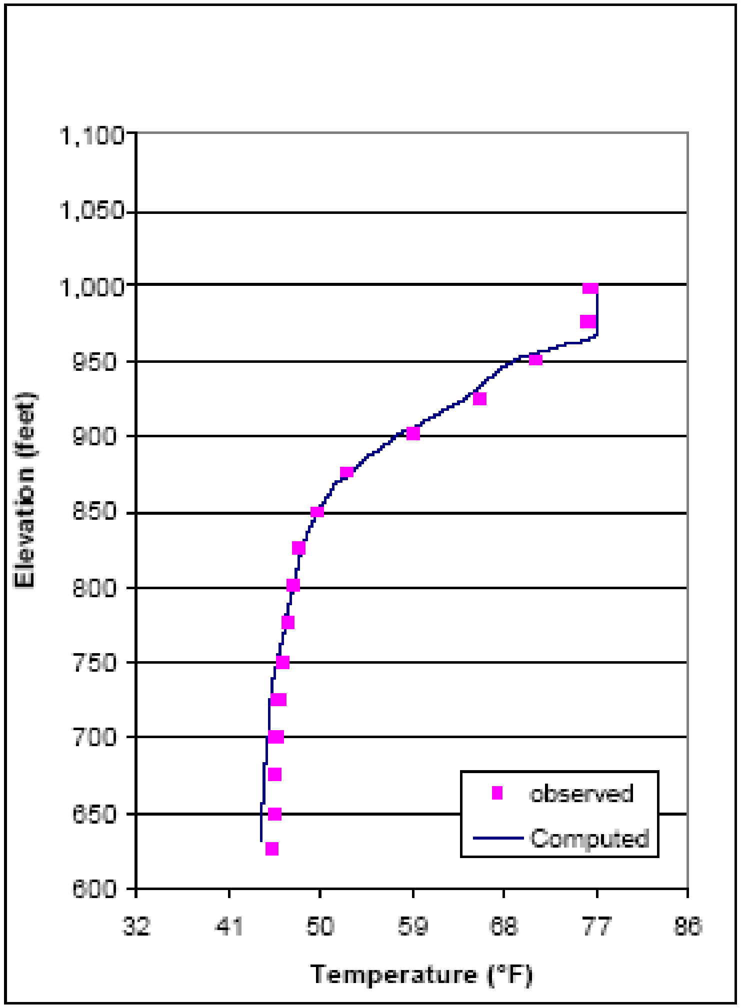
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-17. Computed and Observed Temperature Profiles in Shasta Reservoir on June 24, 2002



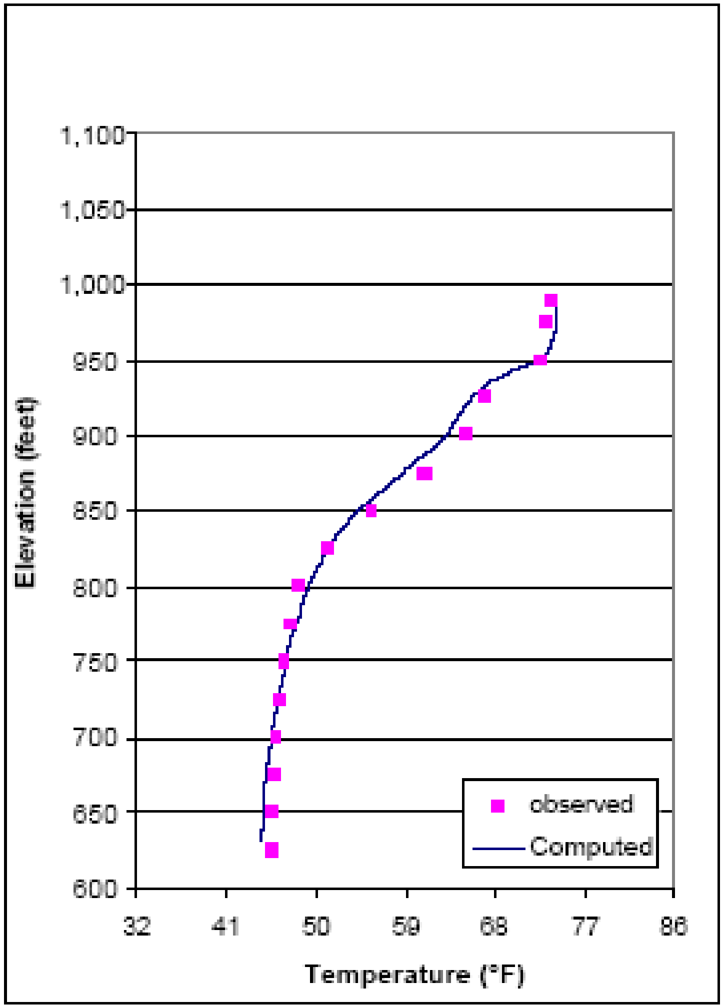
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-18. Computed and Observed Temperature Profiles in Shasta Reservoir on July 29, 2002



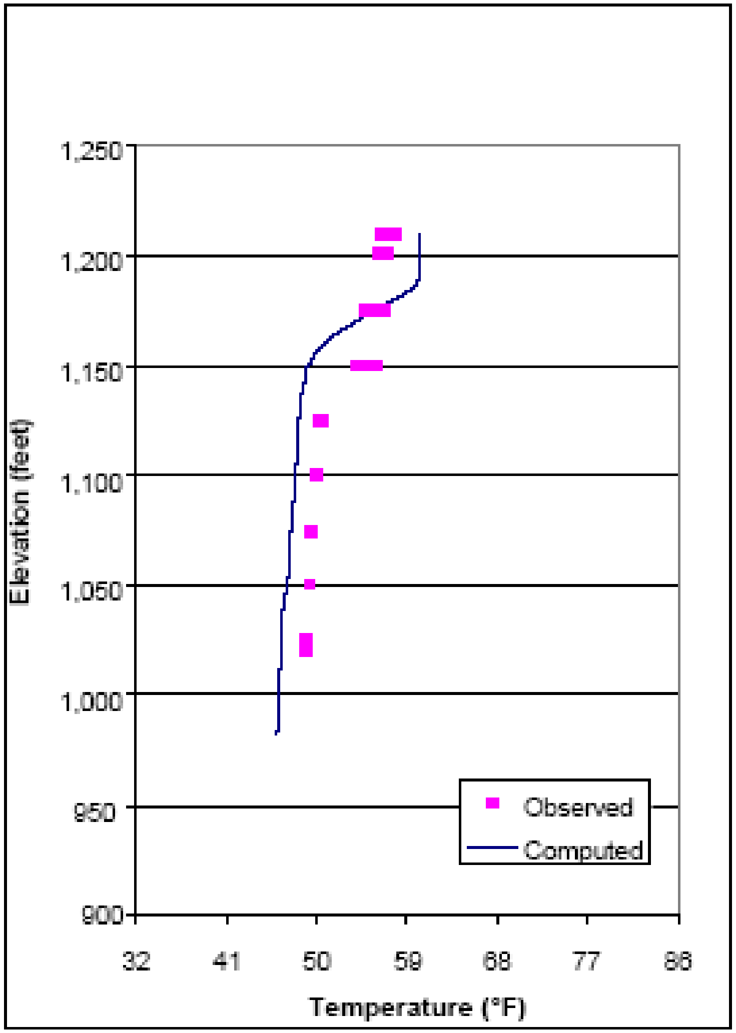
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-19. Computed and Observed Temperature Profiles in Shasta Reservoir on August 28, 2002



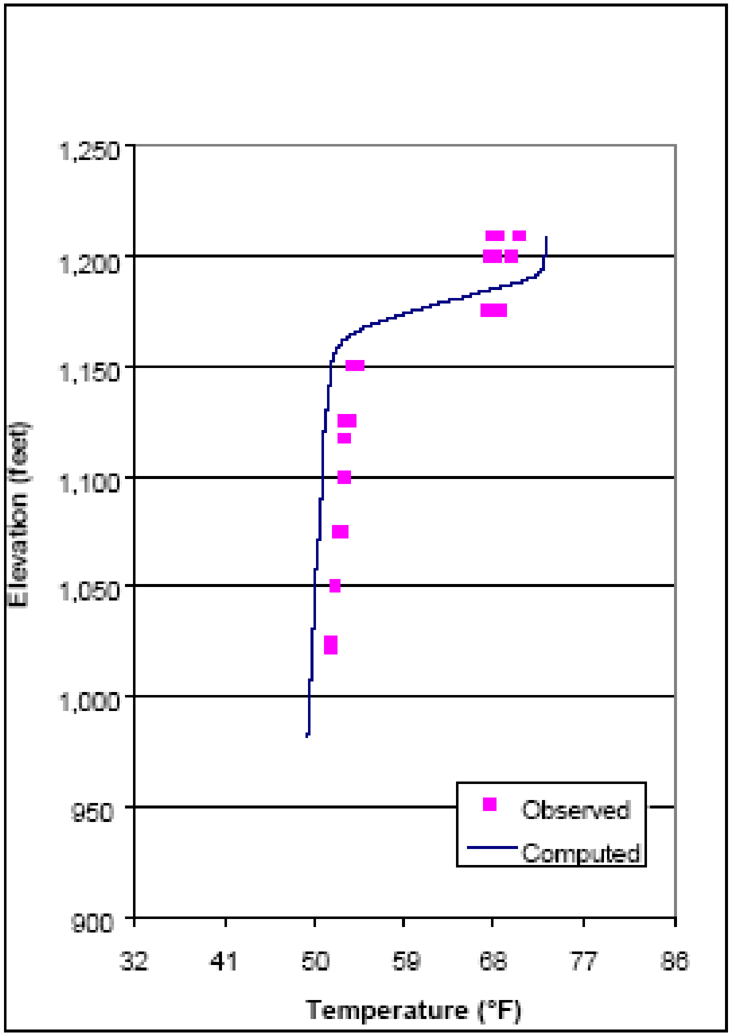
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-20. Computed and Observed Temperature Profiles in Shasta Reservoir on September 23, 2002



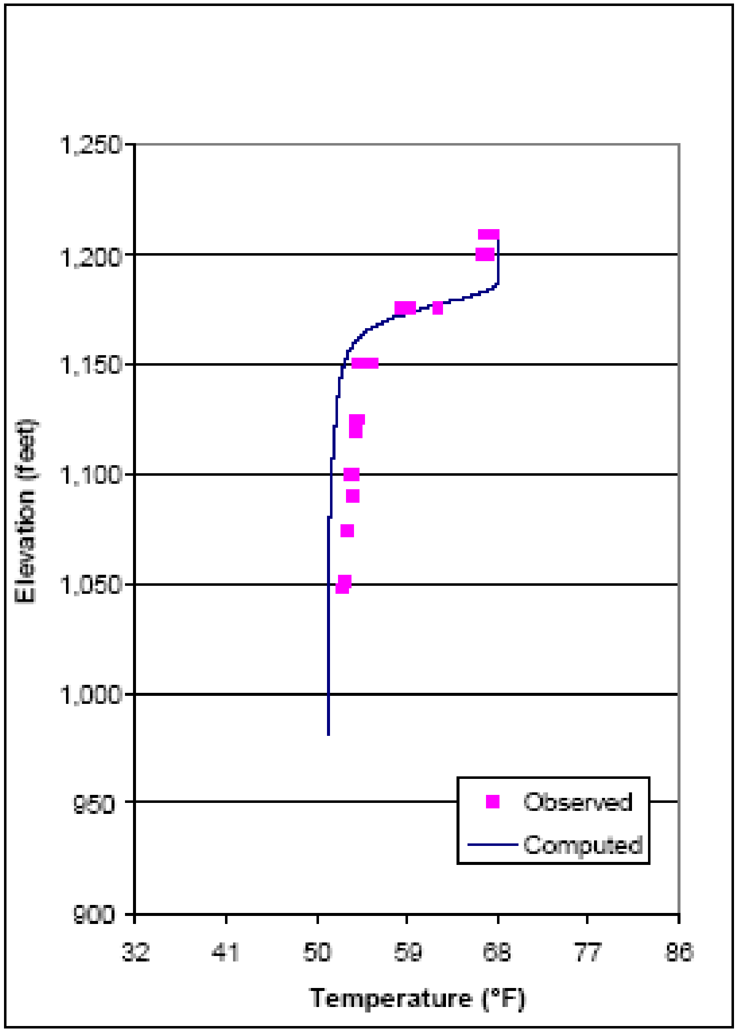
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-21. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on May 12, 1999



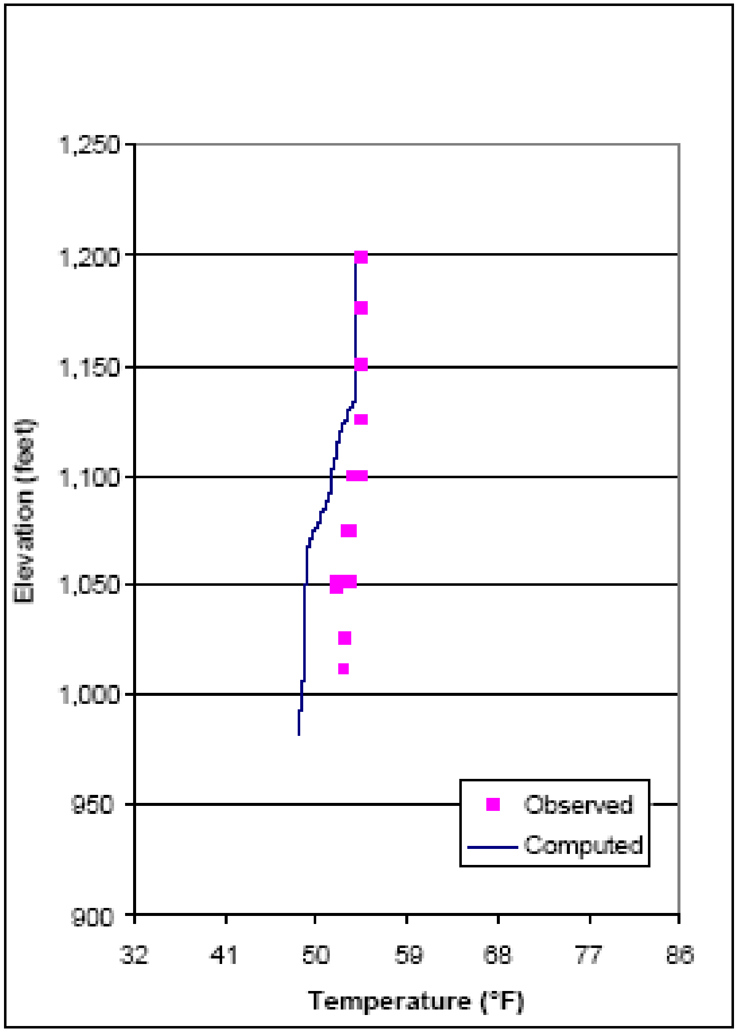
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-22. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on July 7, 1999



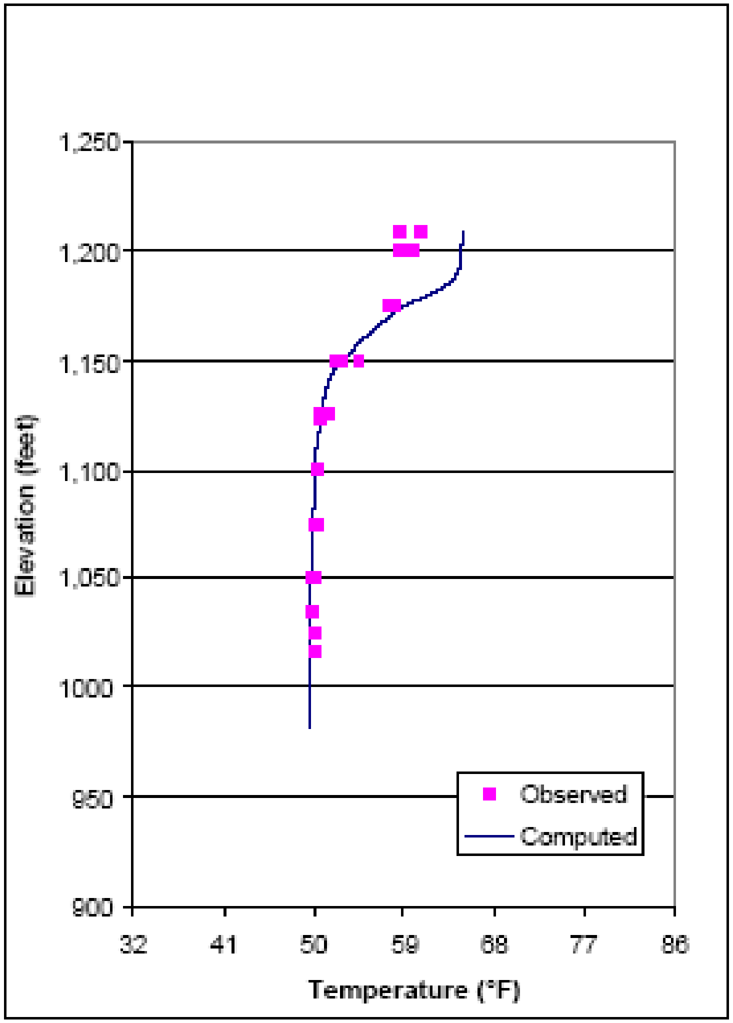
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-23. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on September 30, 1999



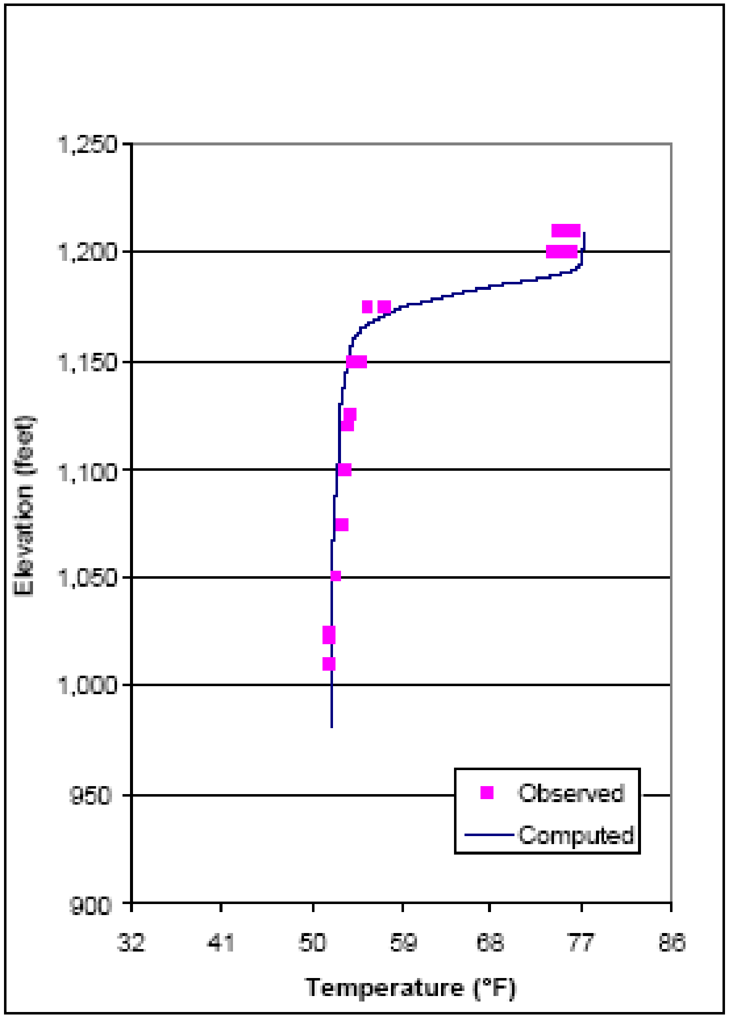
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-24. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on November 22, 1999



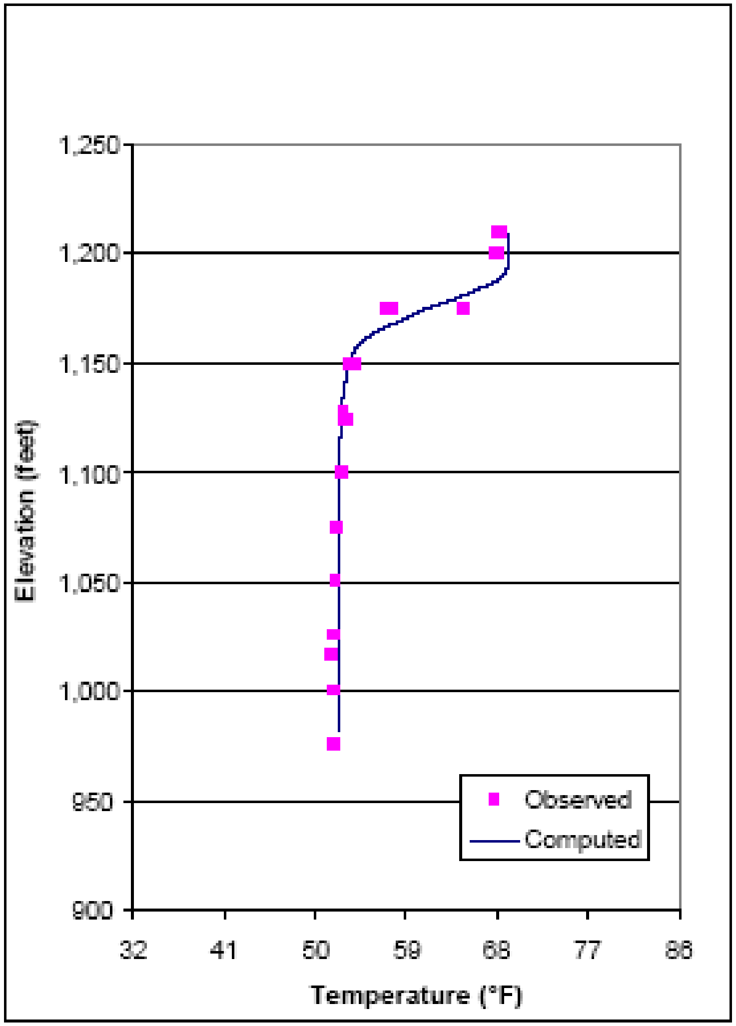
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-25. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on May 19, 2000



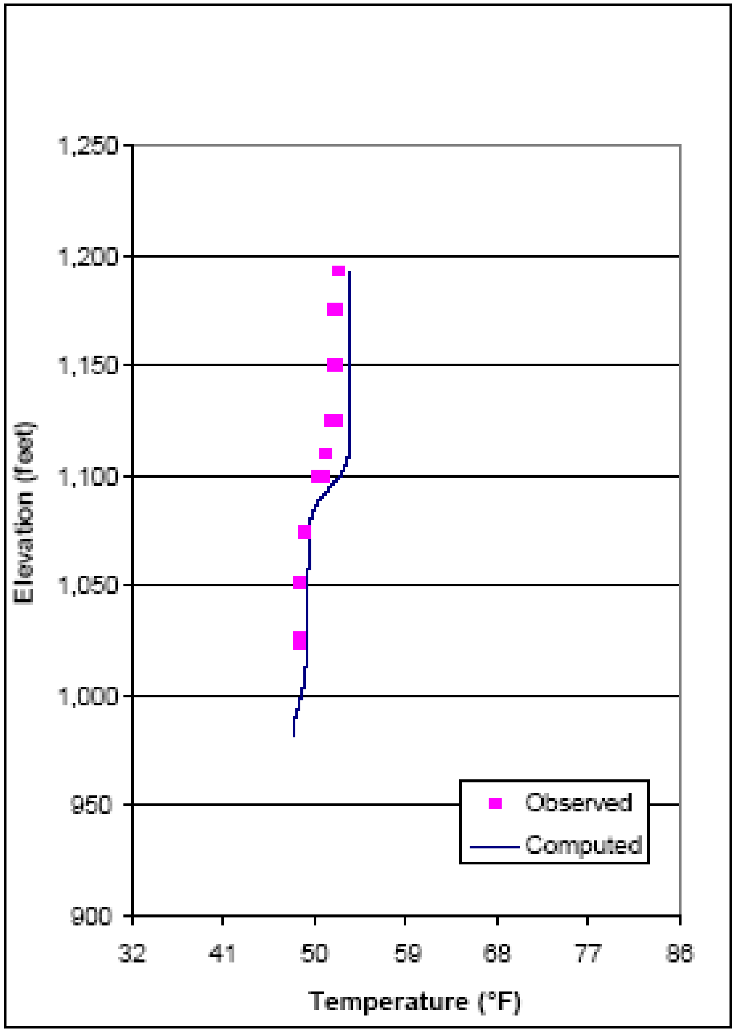
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-26. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on July 18, 2000



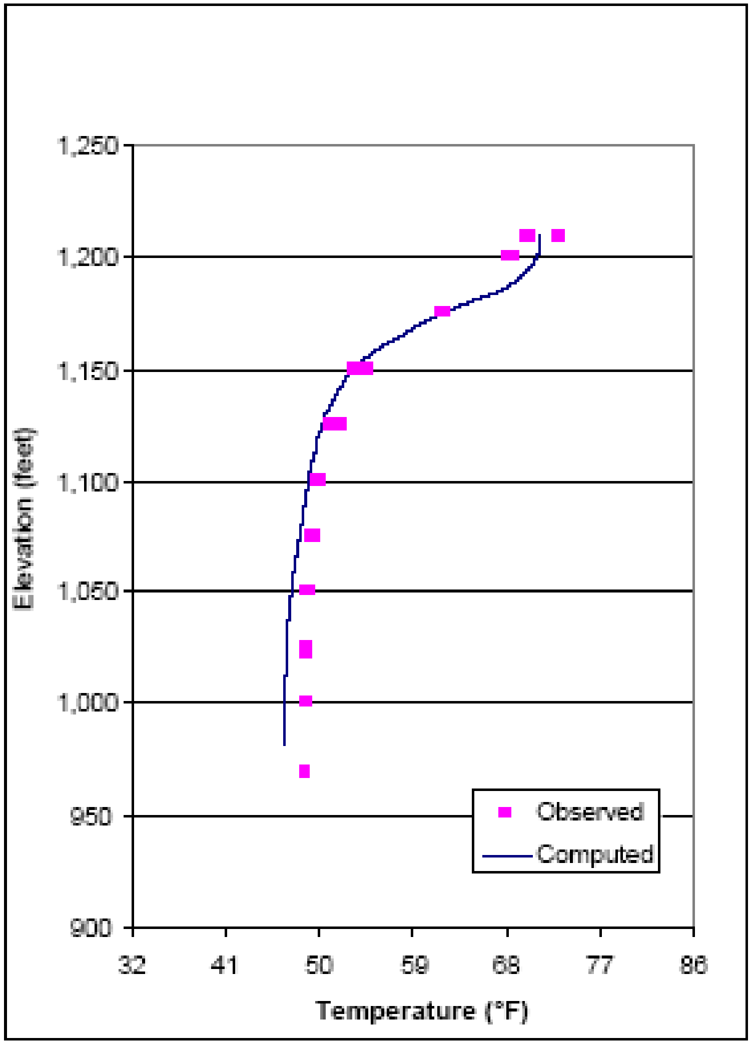
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-27. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on September 13, 2000



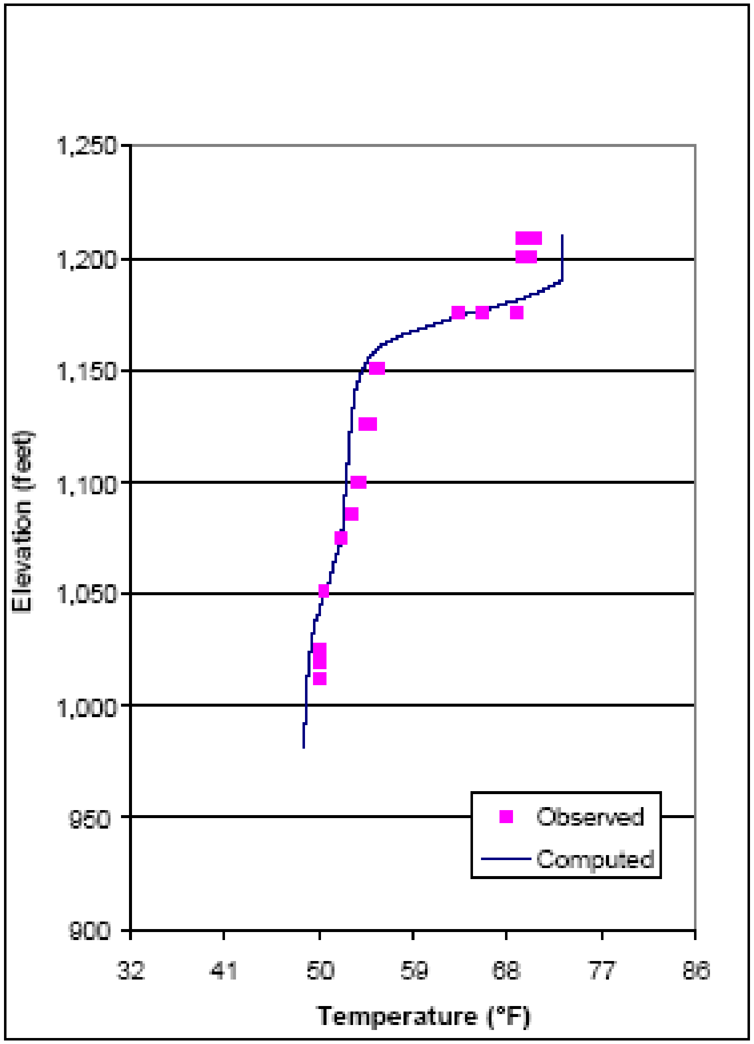
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-28. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on November 27, 2000



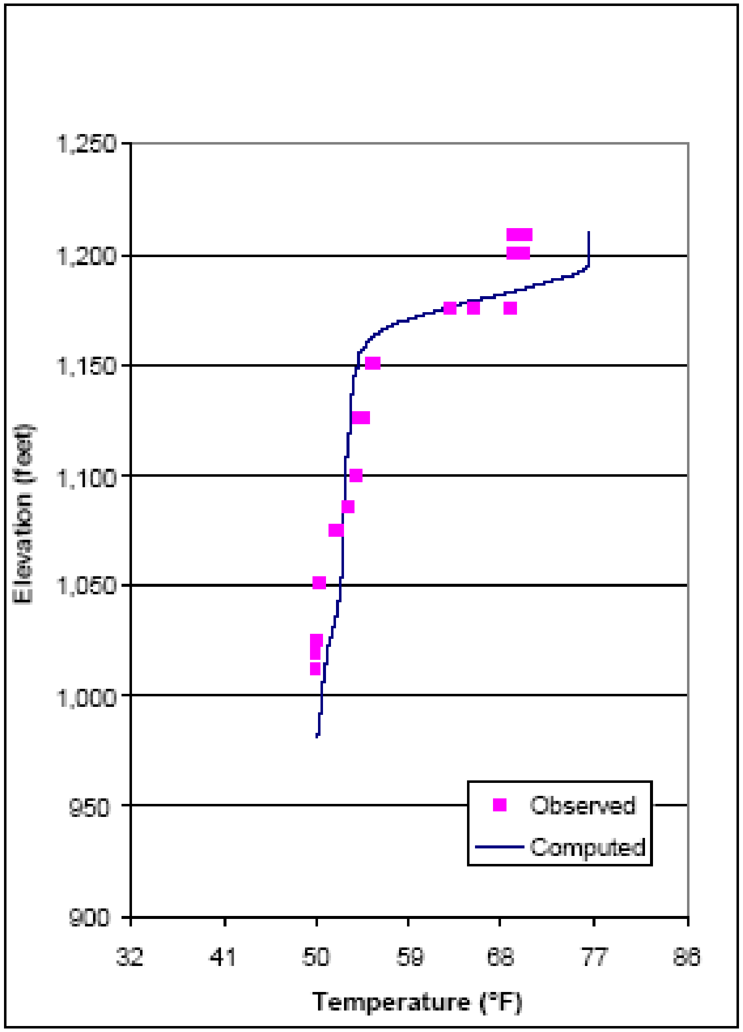
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-29. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on May 23, 2001



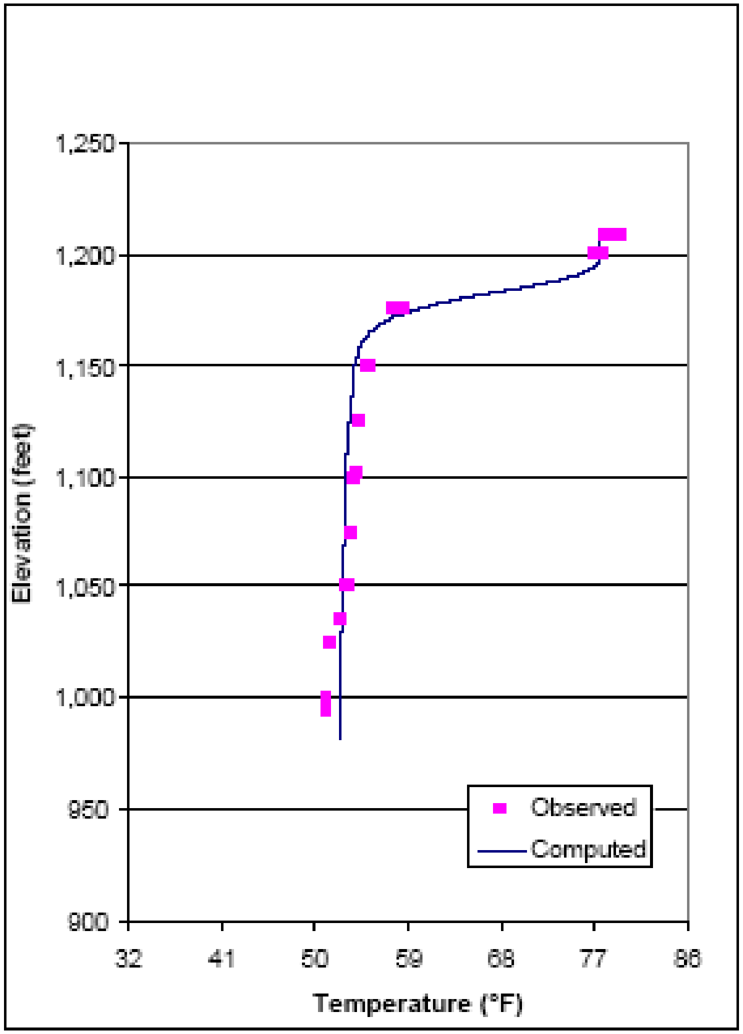
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-30. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on June 25, 2001



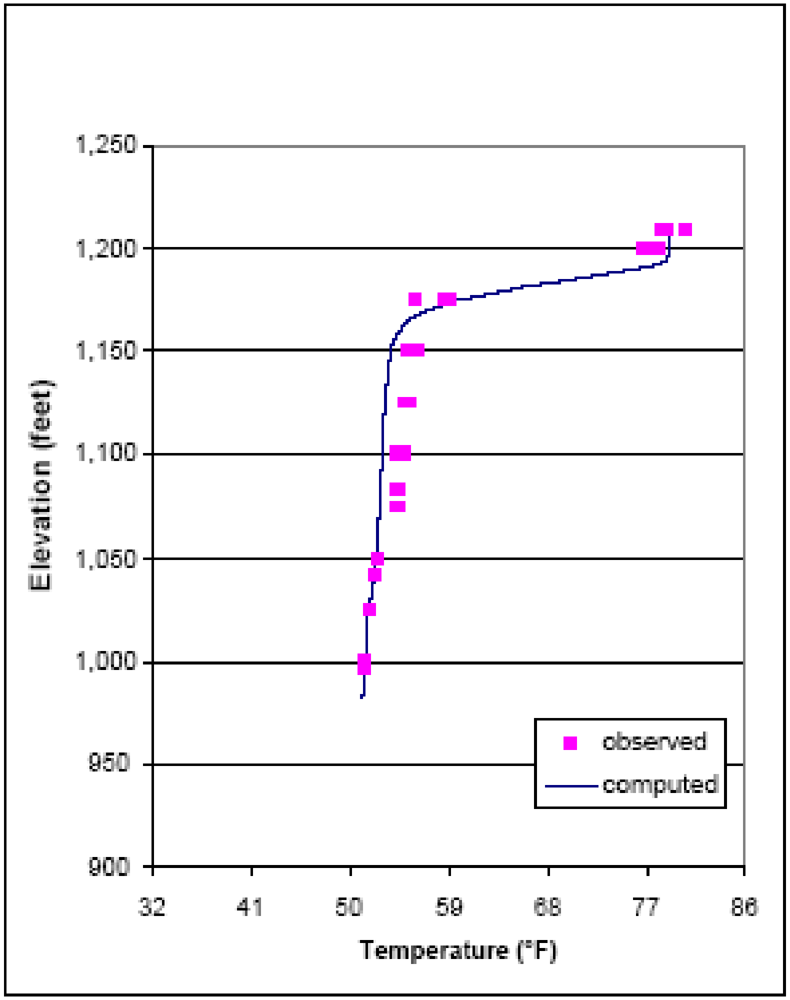
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-31. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on July 11, 2001



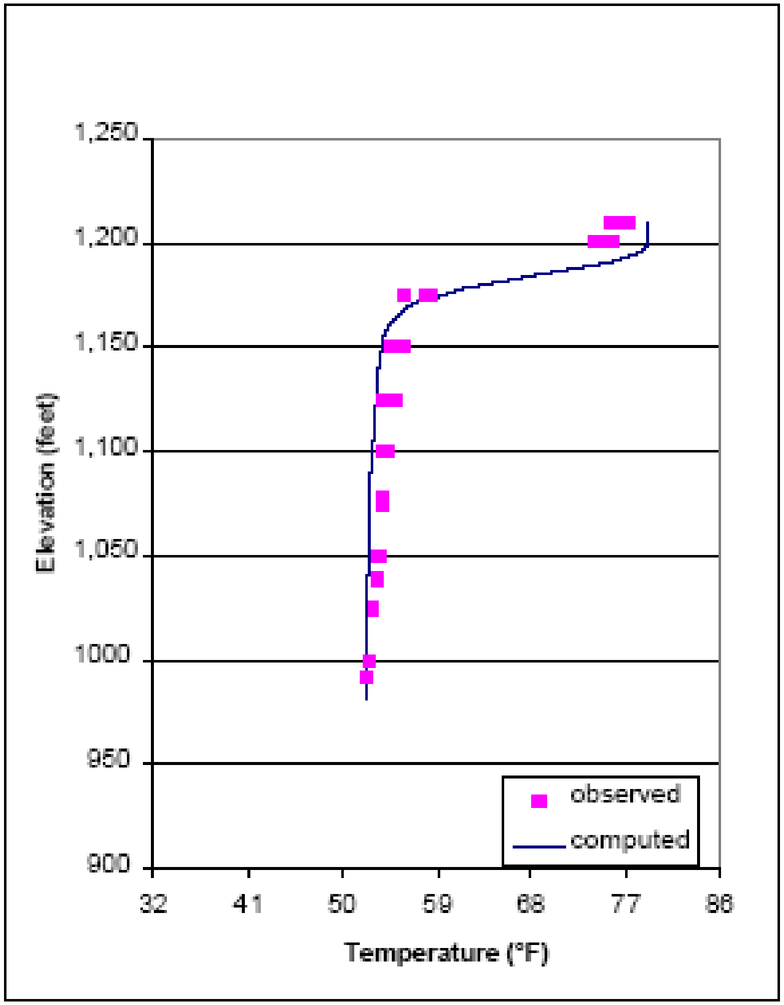
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-32. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on August 9, 2001



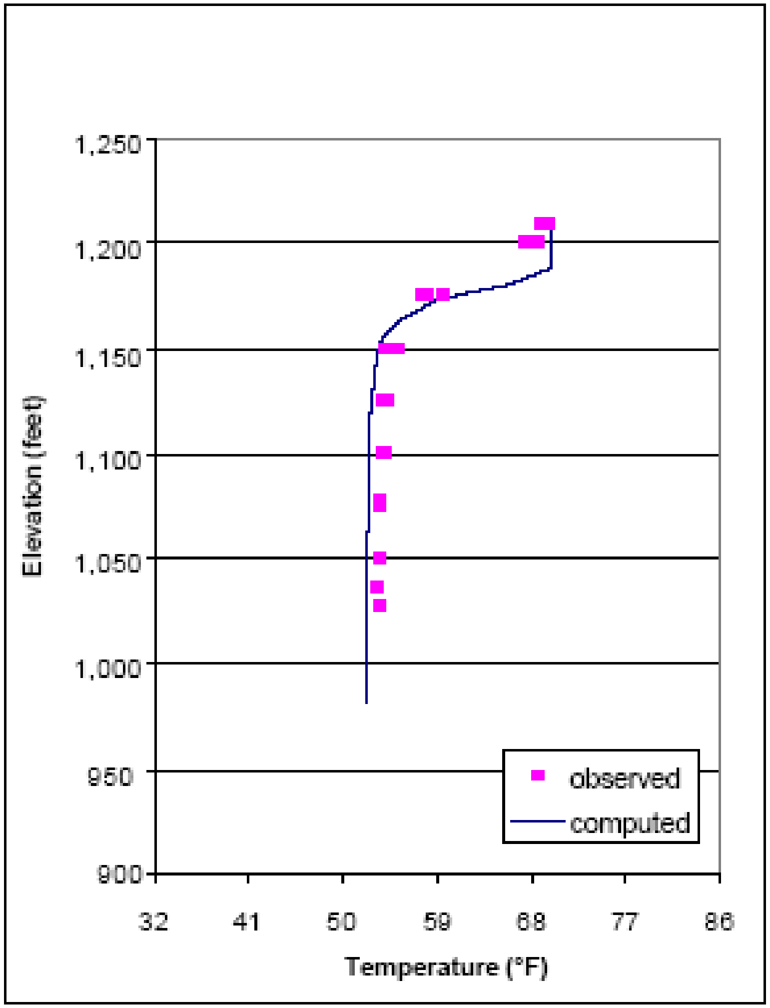
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-33. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on July 25, 2002



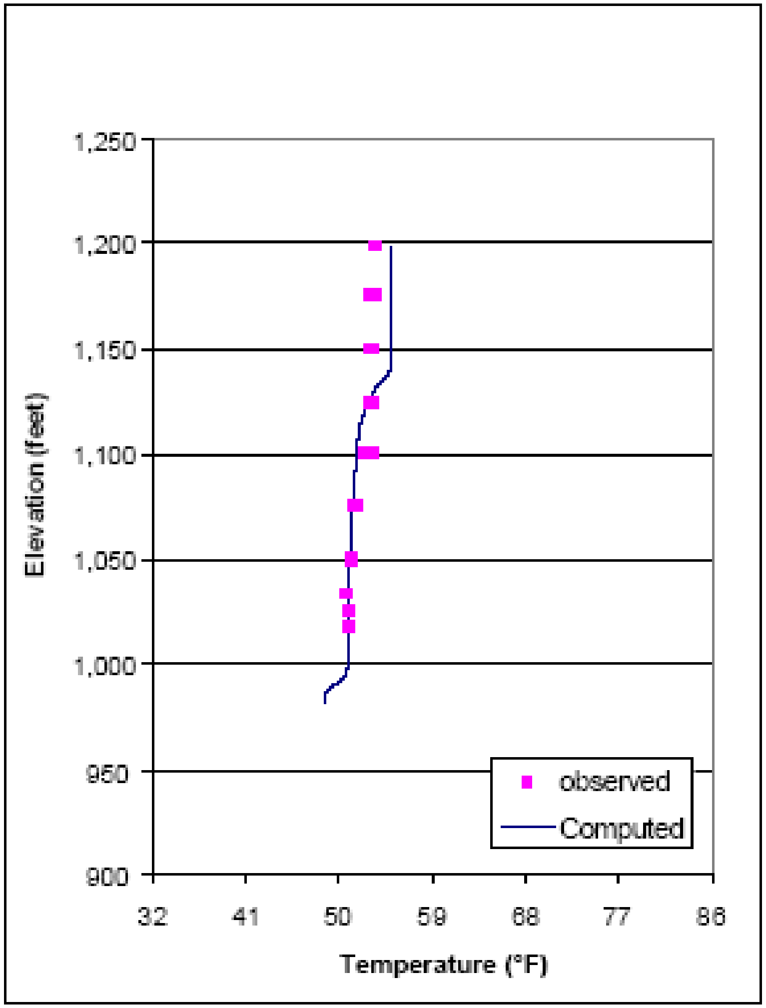
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-34. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on August 15, 2002



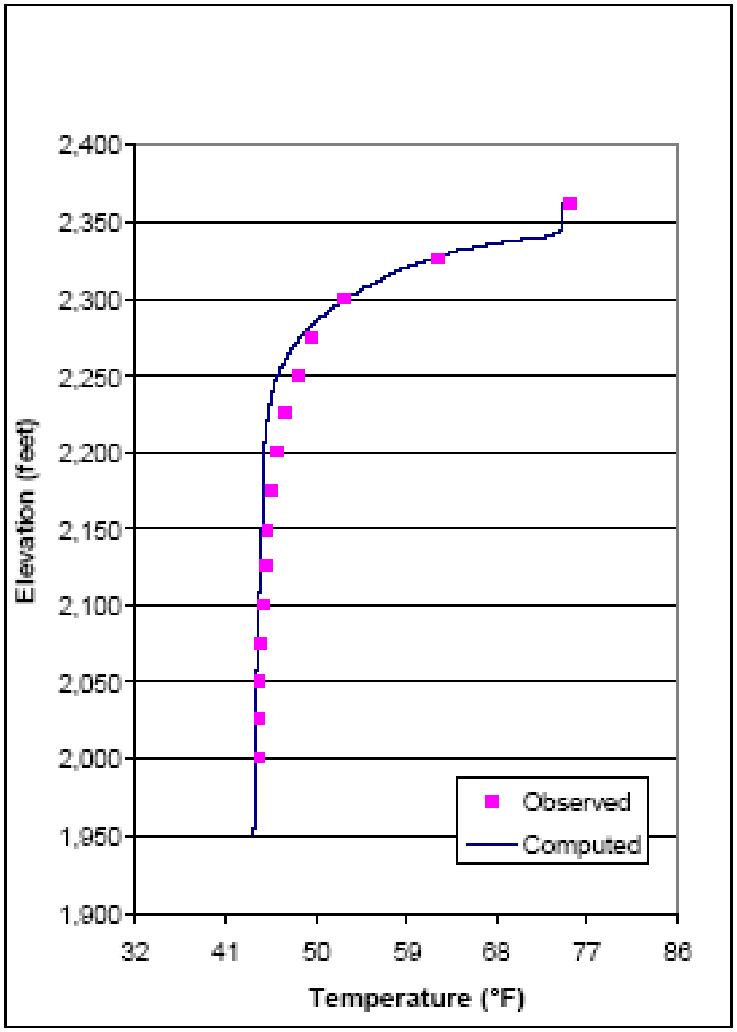
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-35. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on September 19, 2002



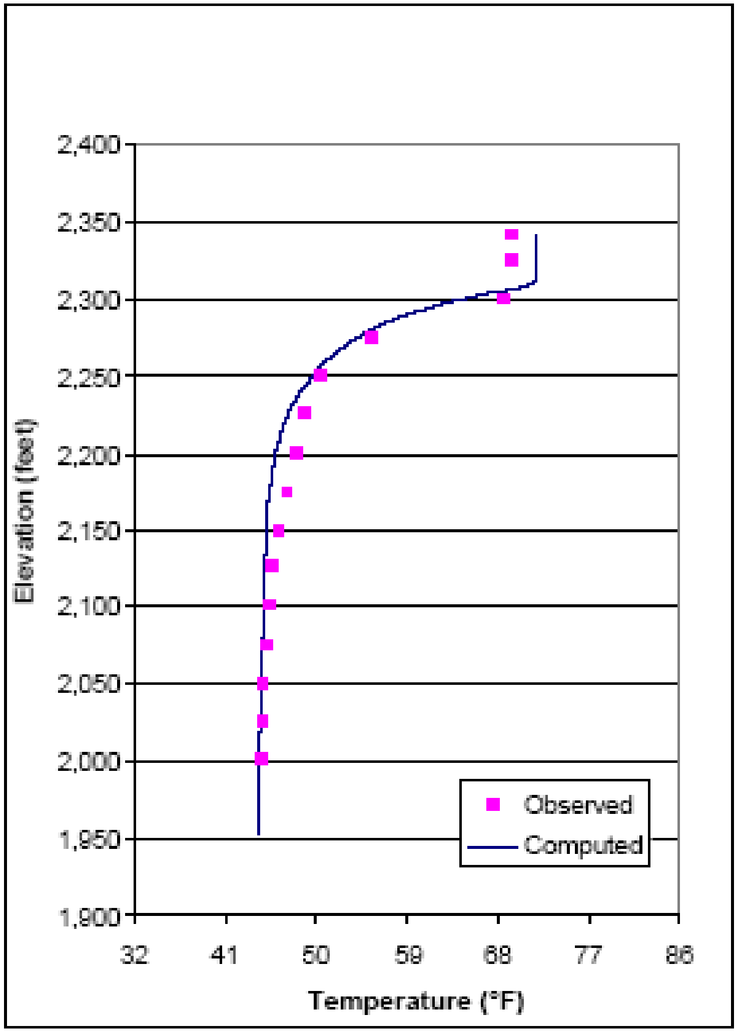
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-36. Computed and Observed Temperature Profiles in Whiskeytown Reservoir on November 26, 2002



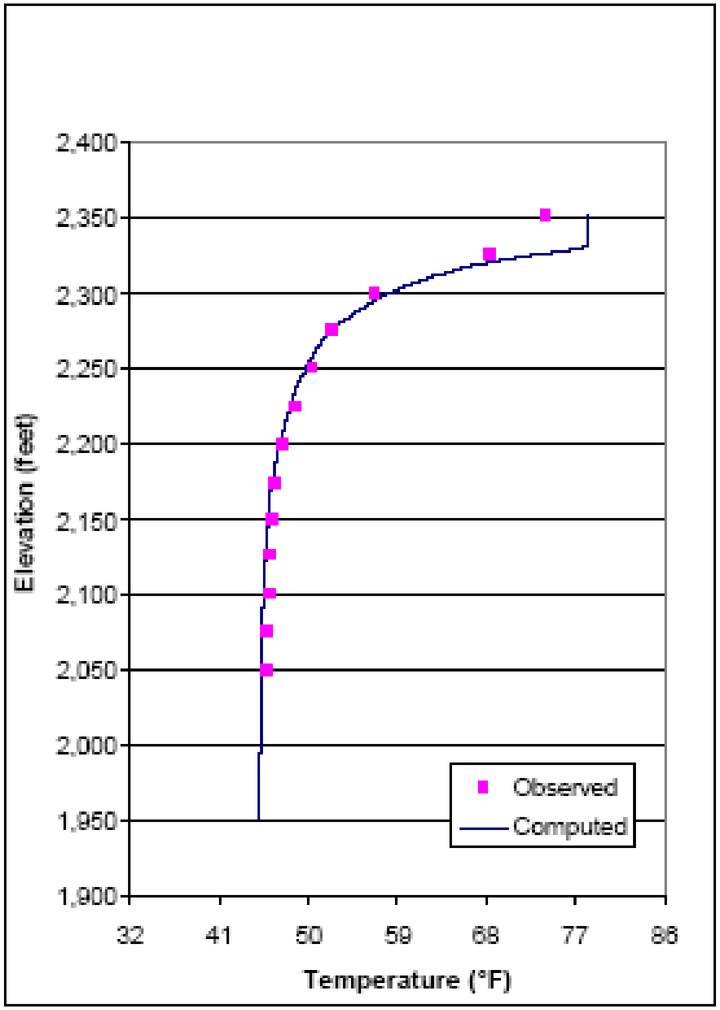
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-37. Computed and Observed Temperature Profiles in Trinity Reservoir on July 14, 1999



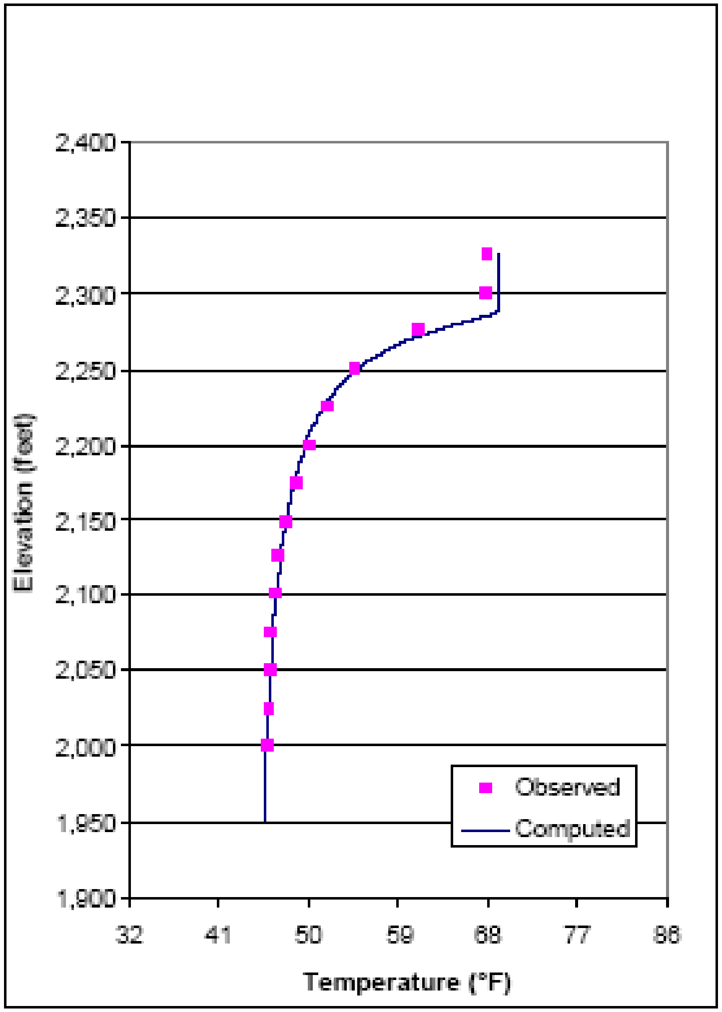
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-38. Computed and Observed Temperature Profiles in Trinity Reservoir on September 20, 1999



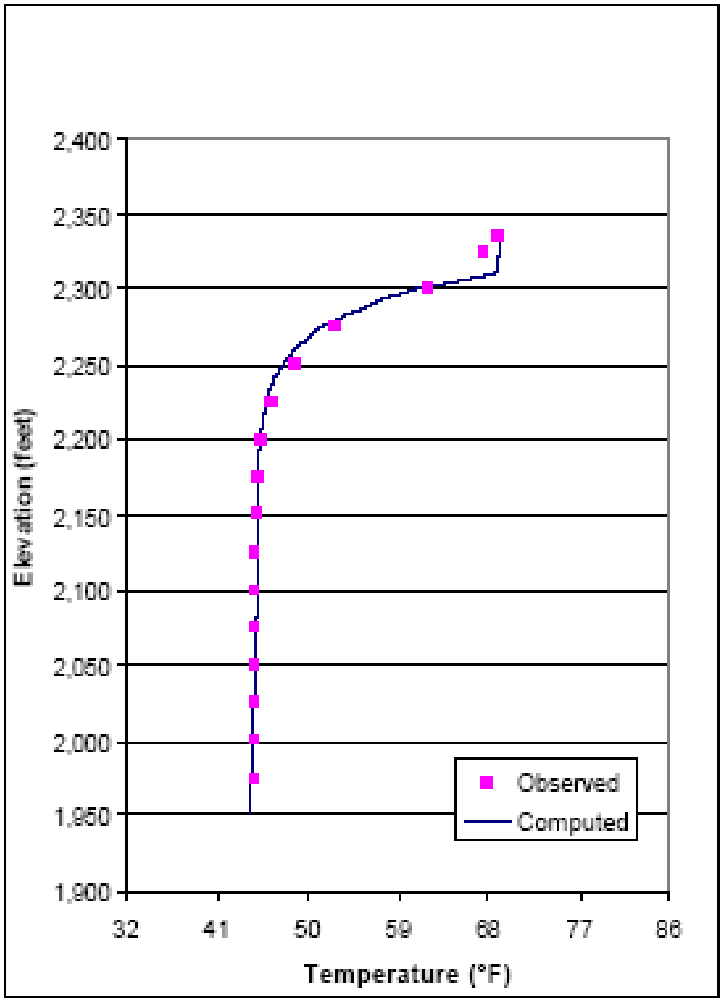
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-39. Computed and Observed Temperature Profiles in Trinity Reservoir on July 27, 2000



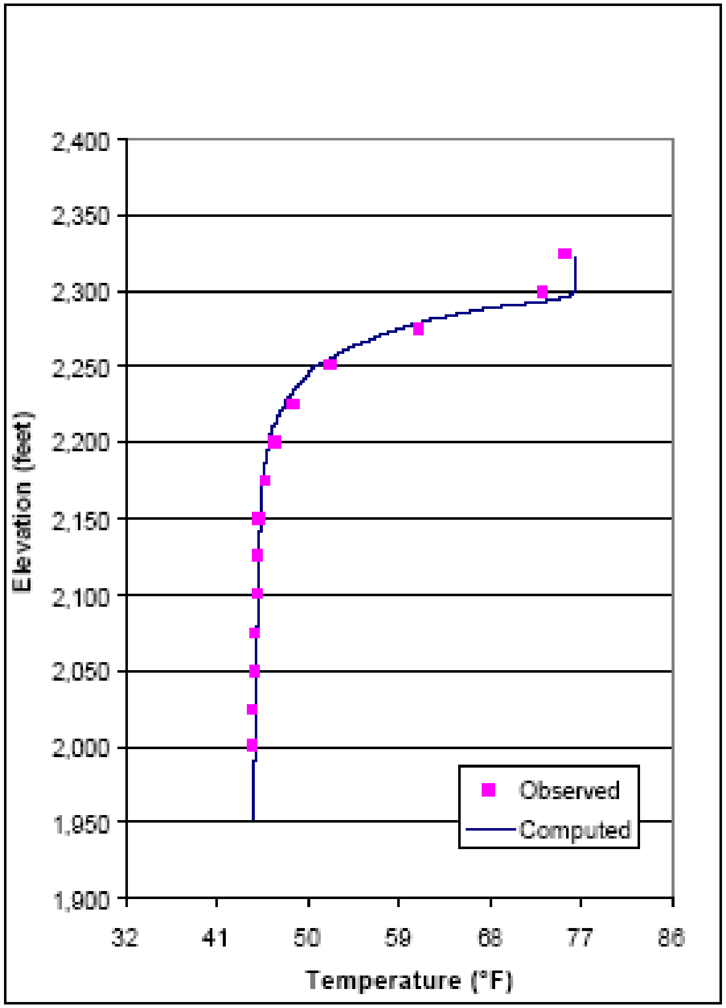
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-40. Computed and Observed Temperature Profiles in Trinity Reservoir on September 29, 2000



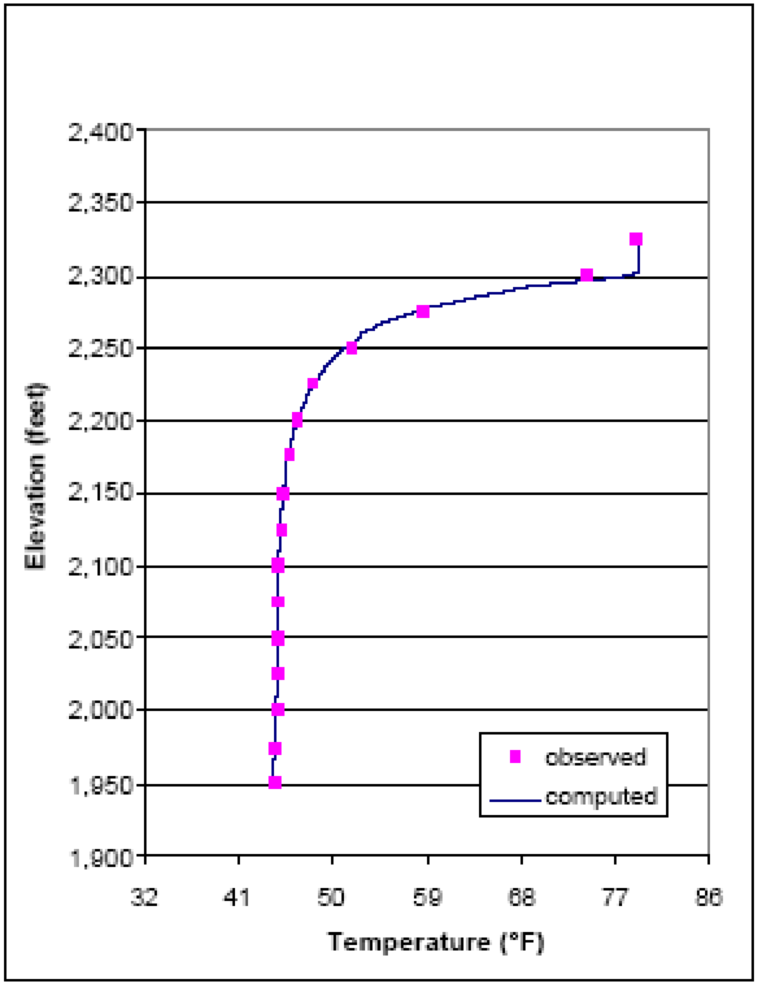
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-41. Computed and Observed Temperature Profiles in Trinity Reservoir on June 28, 2001



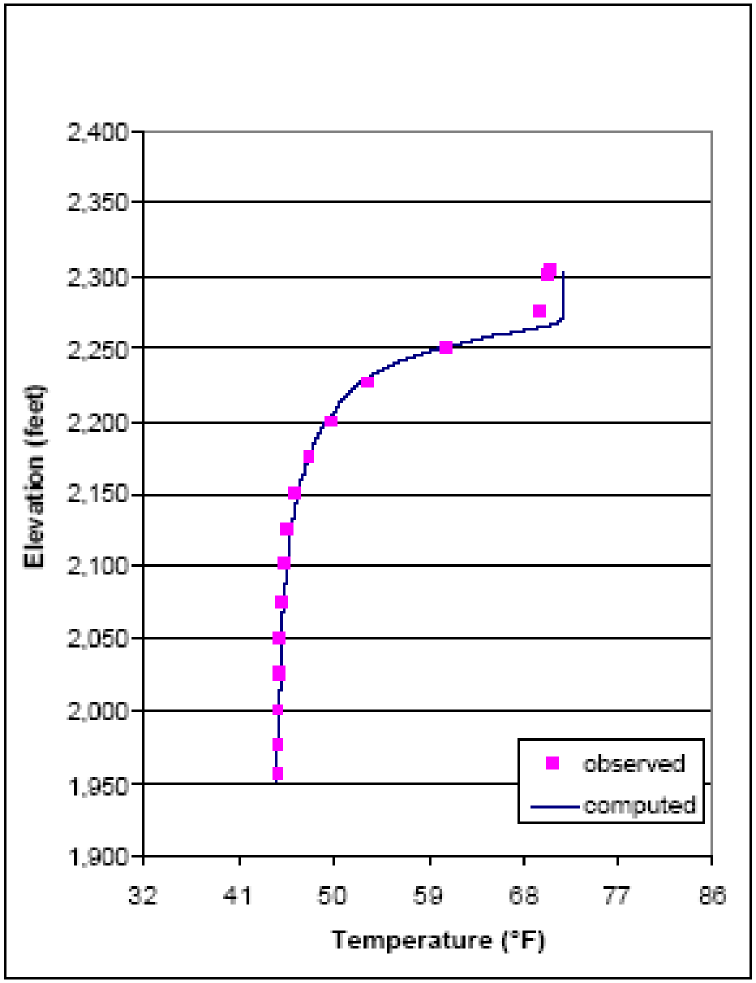
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-42. Computed and Observed Temperature Profiles in Trinity Reservoir on July 31, 2001



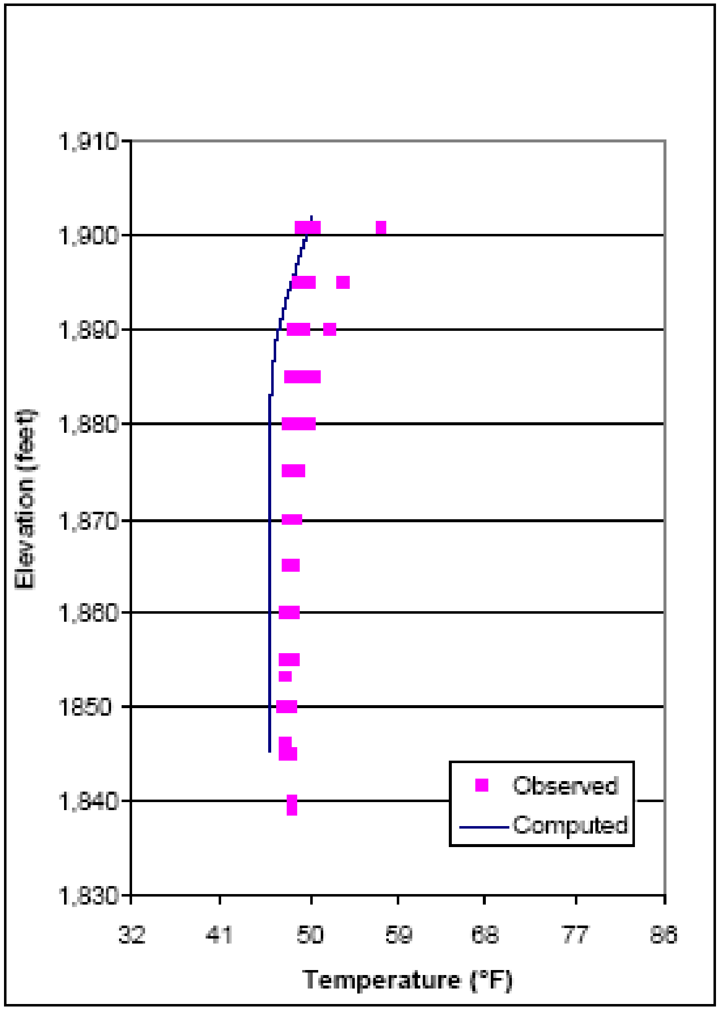
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-43. Computed and Observed Temperature Profiles in Trinity Reservoir on July 30, 2002



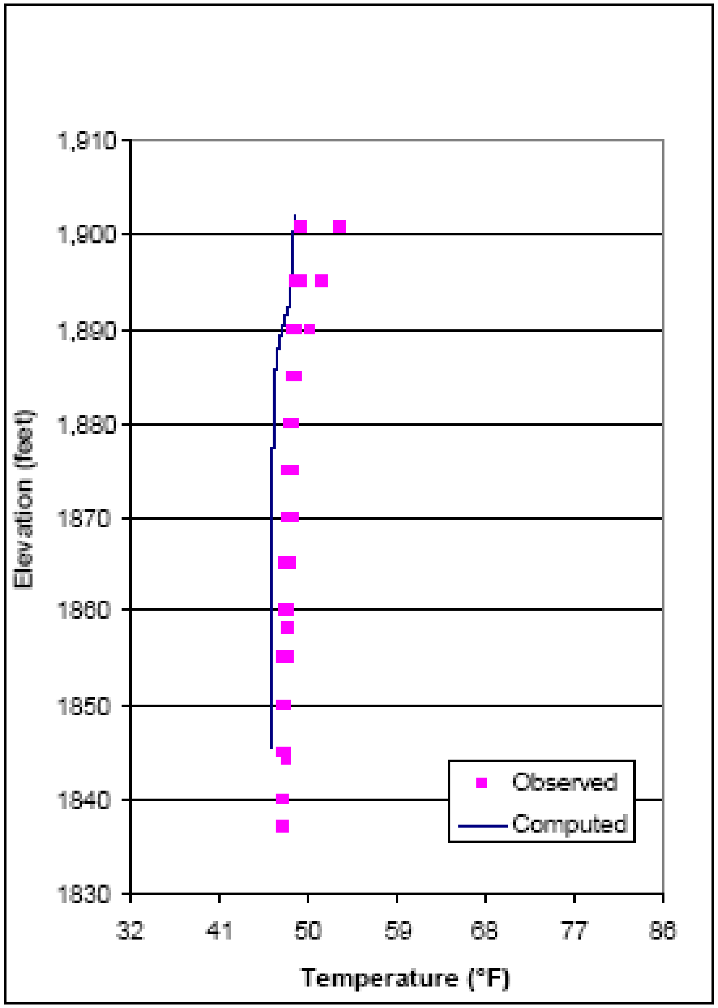
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-44. Computed and Observed Temperature Profiles in Trinity Reservoir on September 26, 2002



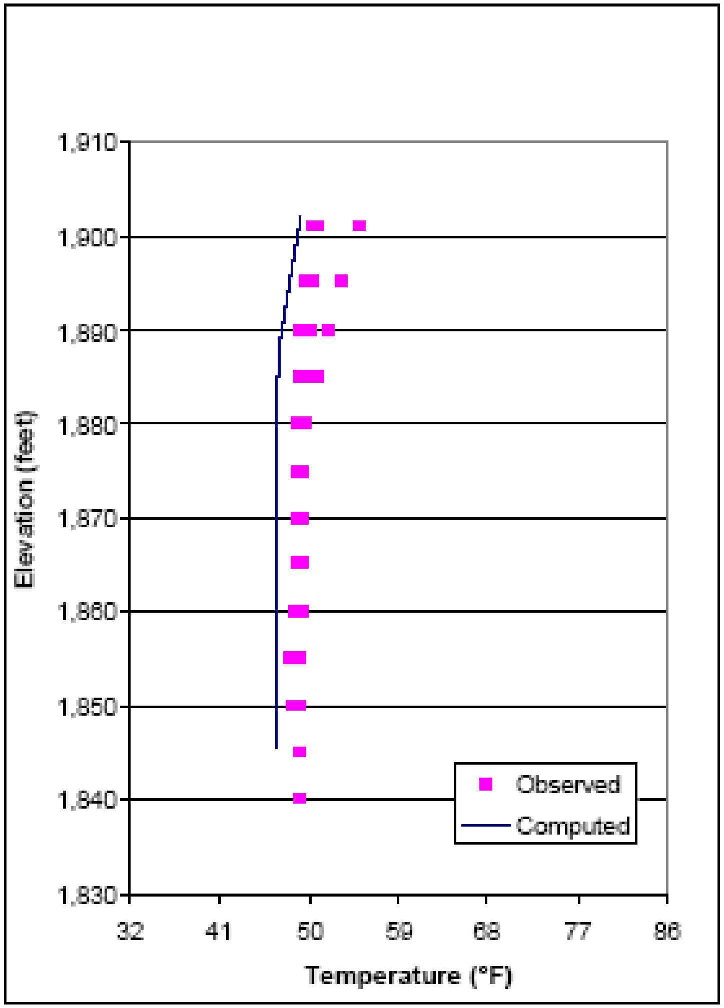
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-45. Computed and Observed Temperature Profiles in Lewiston Reservoir on July 14, 1999



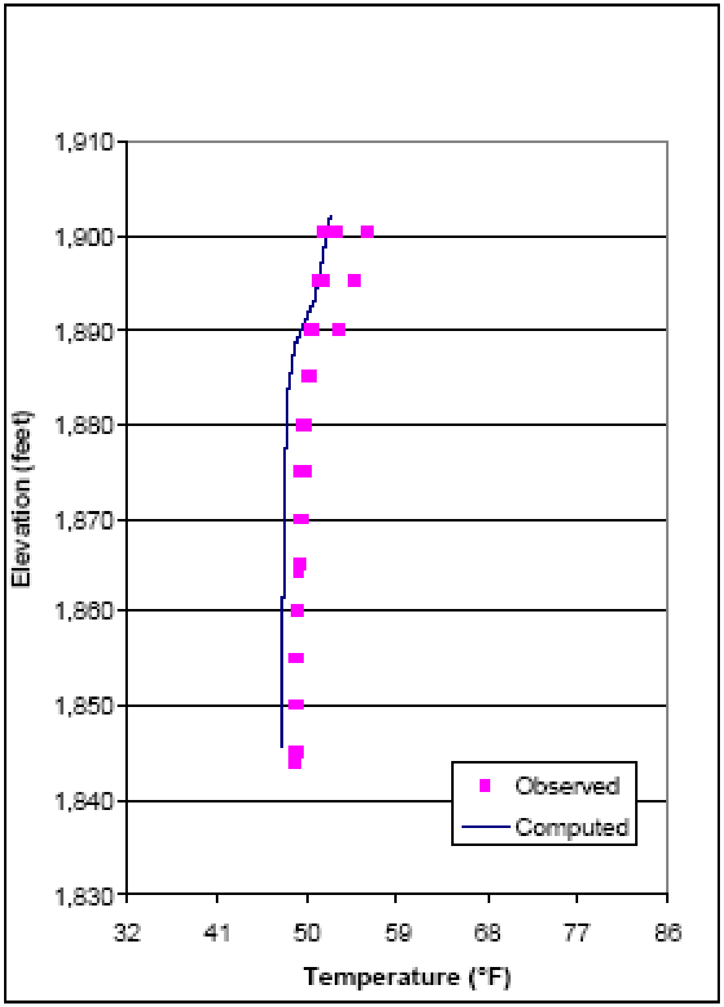
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-46. Computed and Observed Temperature Profiles in Lewiston Reservoir on September 20, 1999



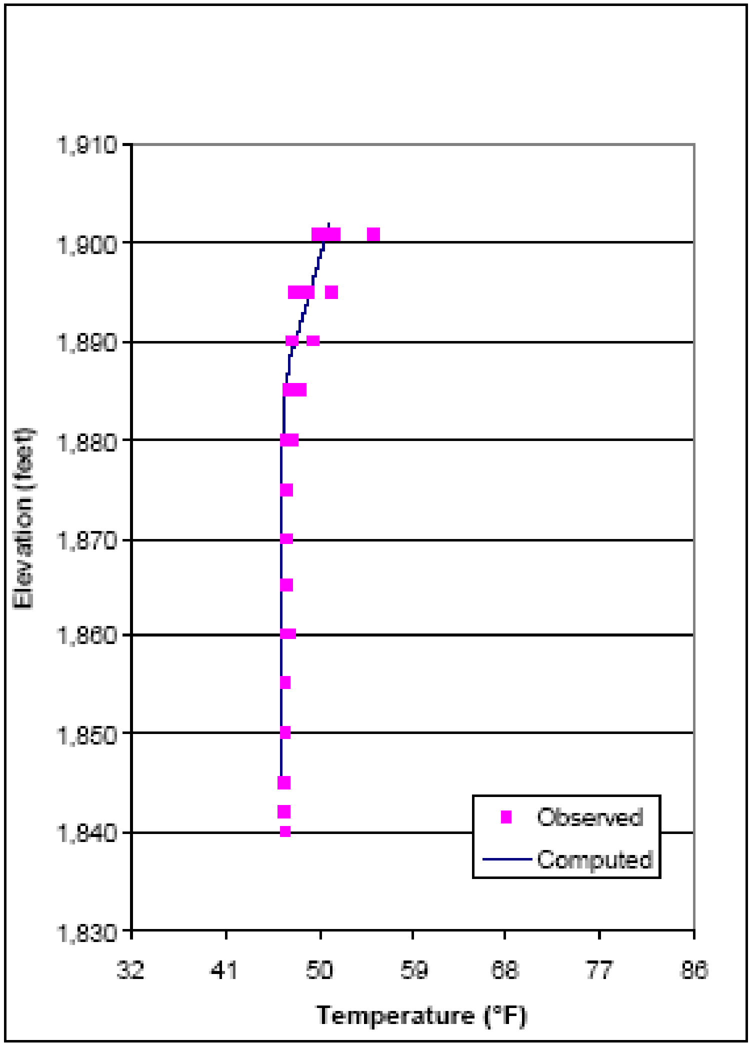
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-47. Computed and Observed Temperature Profiles in Lewiston Reservoir on July 27, 2000



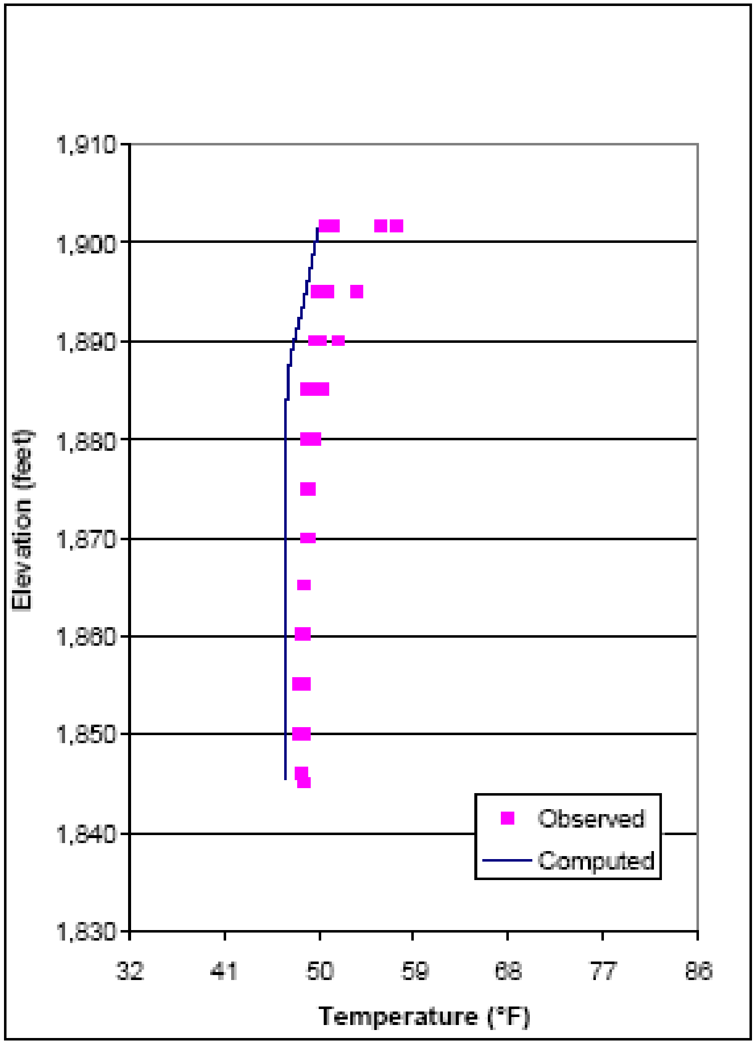
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-48. Computed and Observed Temperature Profiles in Lewiston Reservoir on September 29, 2000



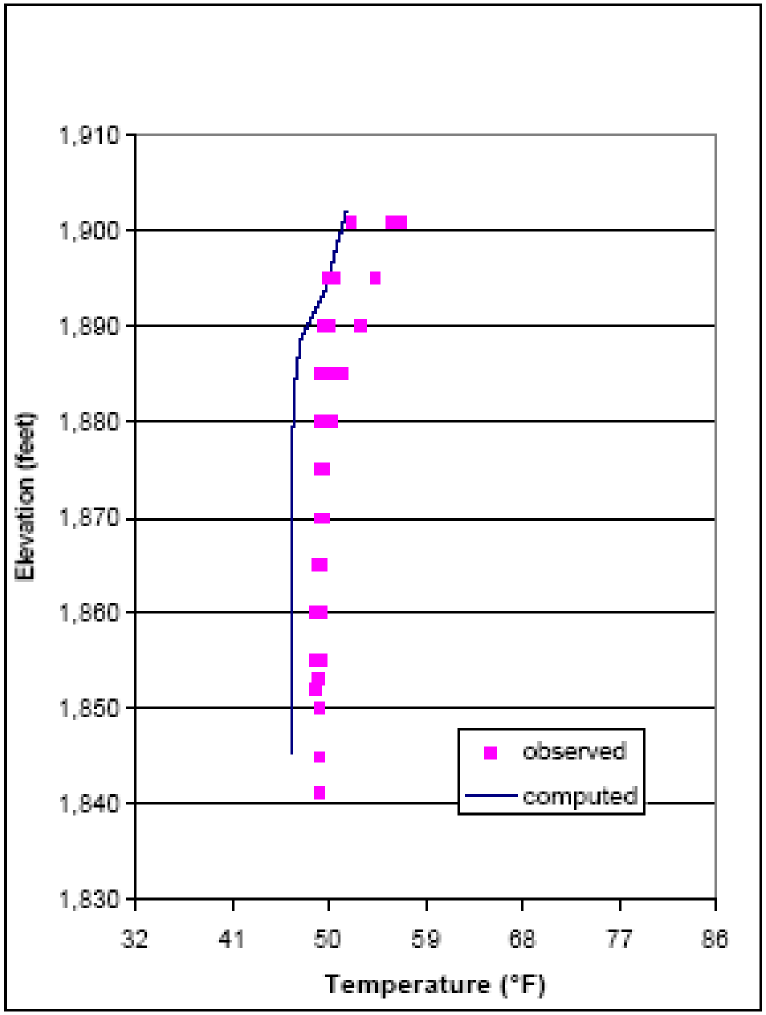
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-49. Computed and Observed Temperature Profiles in Lewiston Reservoir on June 28, 2001



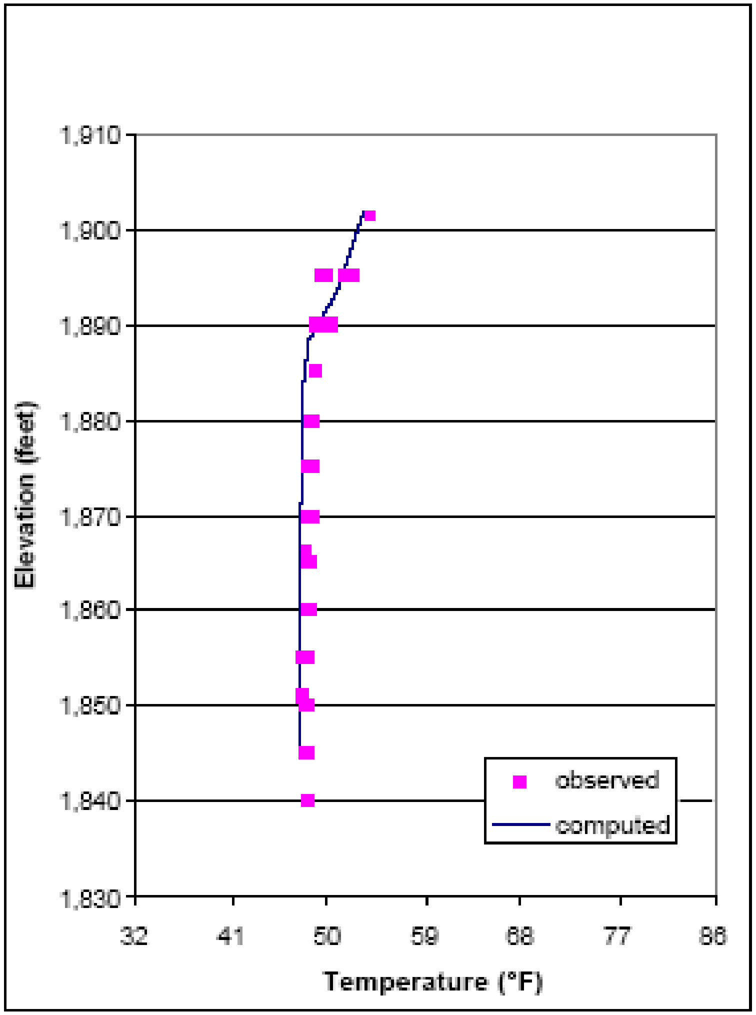
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-50. Computed and Observed Temperature Profiles in Lewiston Reservoir on July 31, 2001



Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-51. Computed and Observed Temperature Profiles in Lewiston Reservoir on June 19, 2002



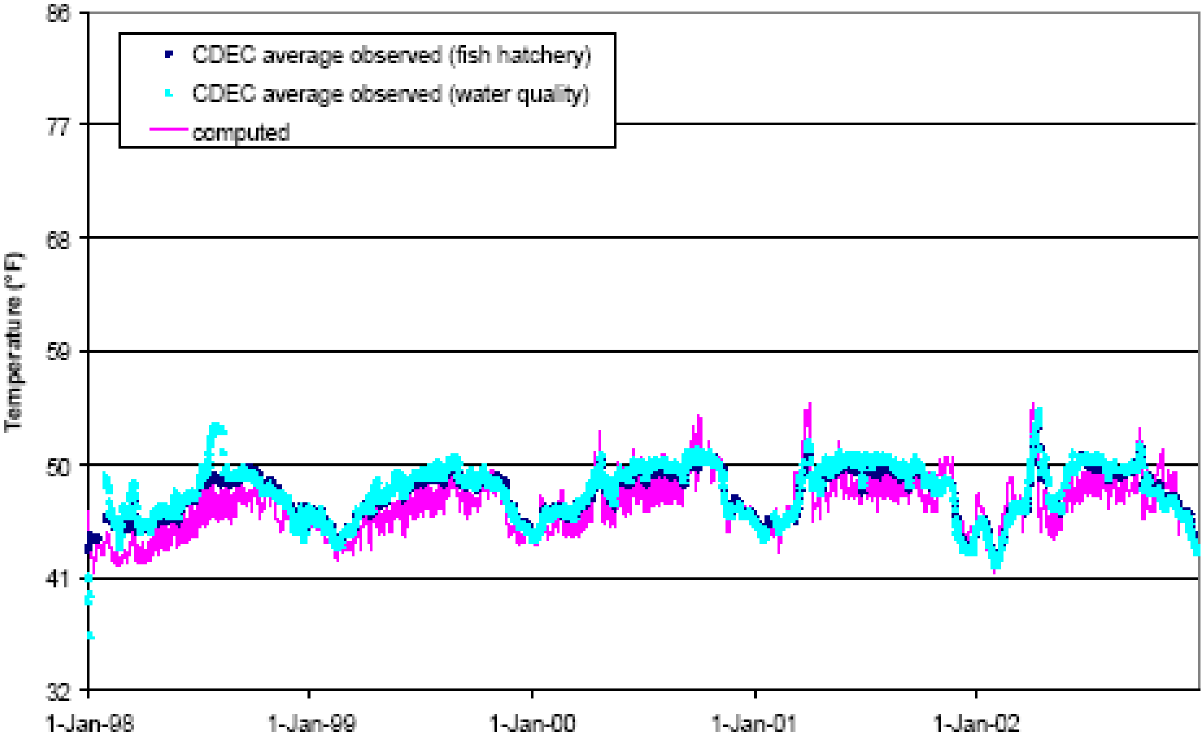
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-52. Computed and Observed Temperature Profiles in Lewiston Reservoir on August 28, 2002

Stream Temperature Calibration Results

Time series of computed and observed temperatures for locations throughout the upper Sacramento River system are plotted in Figures 4-53 through 4-61 and summarized in Table 4-5. Computed values are plotted at 6-hour intervals at the following times: 00:00, 06:00, 12:00 and 18:00. Observed data are plotted as daily average values.

Computed temperatures are generally within 1°F or less of average observed data for each of the reservoir tailwaters and in the Sacramento River down to Tehama. In the Sacramento River at Woodson Bridge, down to Colusa Basin Drain (the farthest downstream data location), computed temperatures are within 2°F or less of average observed data. Larger discrepancies between computed and observed data occur at the Black Butte Dam tailwater and in Stony Creek. This is the result of the limited data available for configuring Black Butte Reservoir in the model.



Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

Figure 4-53. Computed and Observed Mean Daily Water Temperatures at Lewiston Fish Hatchery

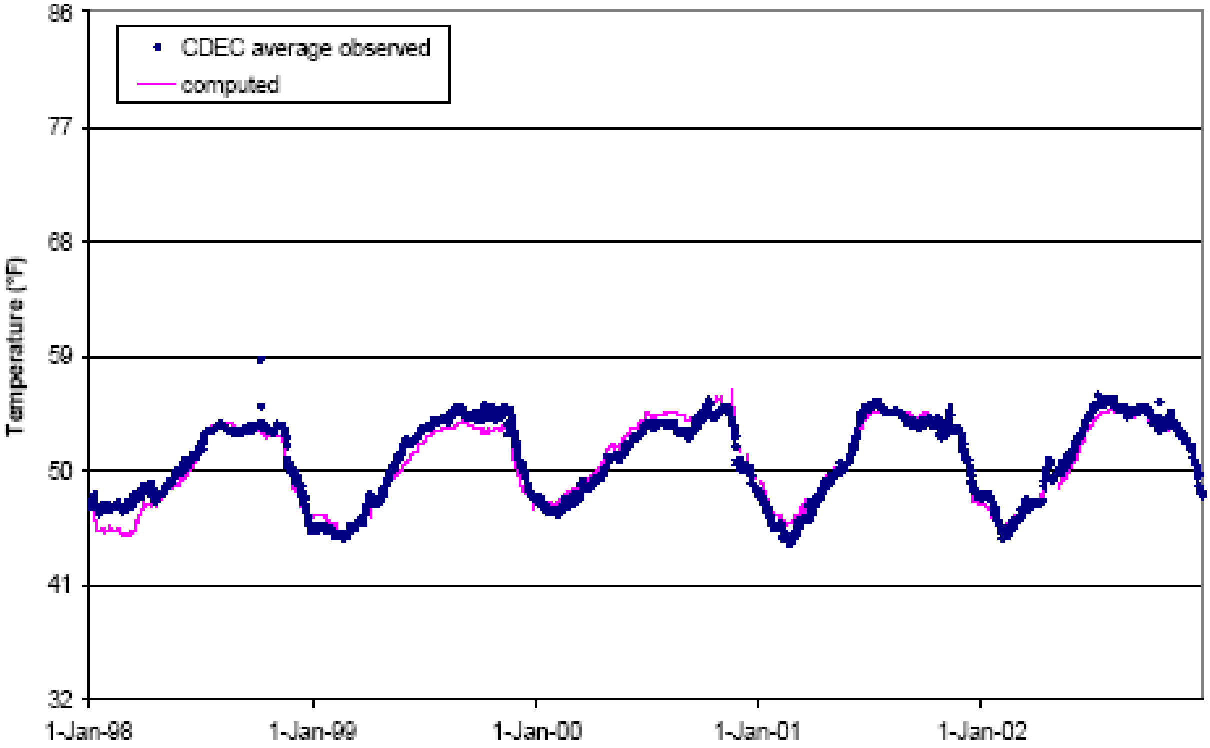


Figure 4-54. Computed and Observed Mean Daily Water Temperatures at Spring Creek Powerhouse

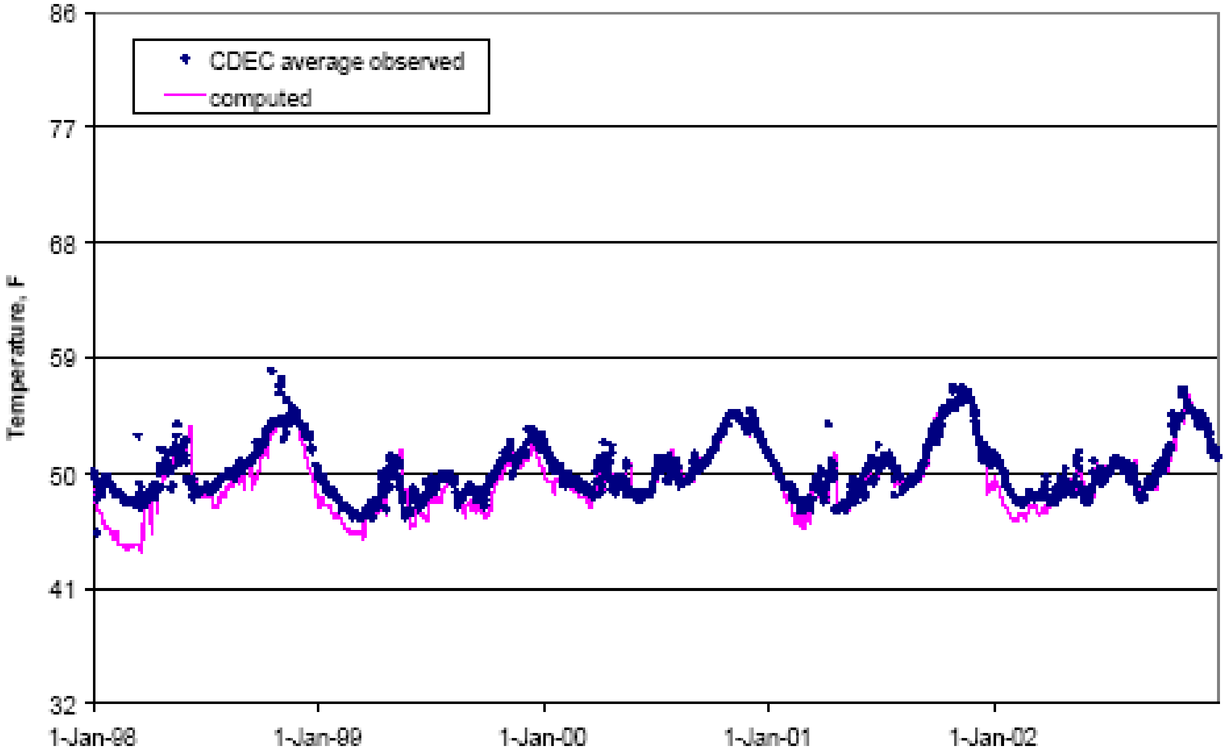


Figure 4-55. Computed and Observed Mean Daily Water Temperatures in Sacramento River Below Shasta Dam

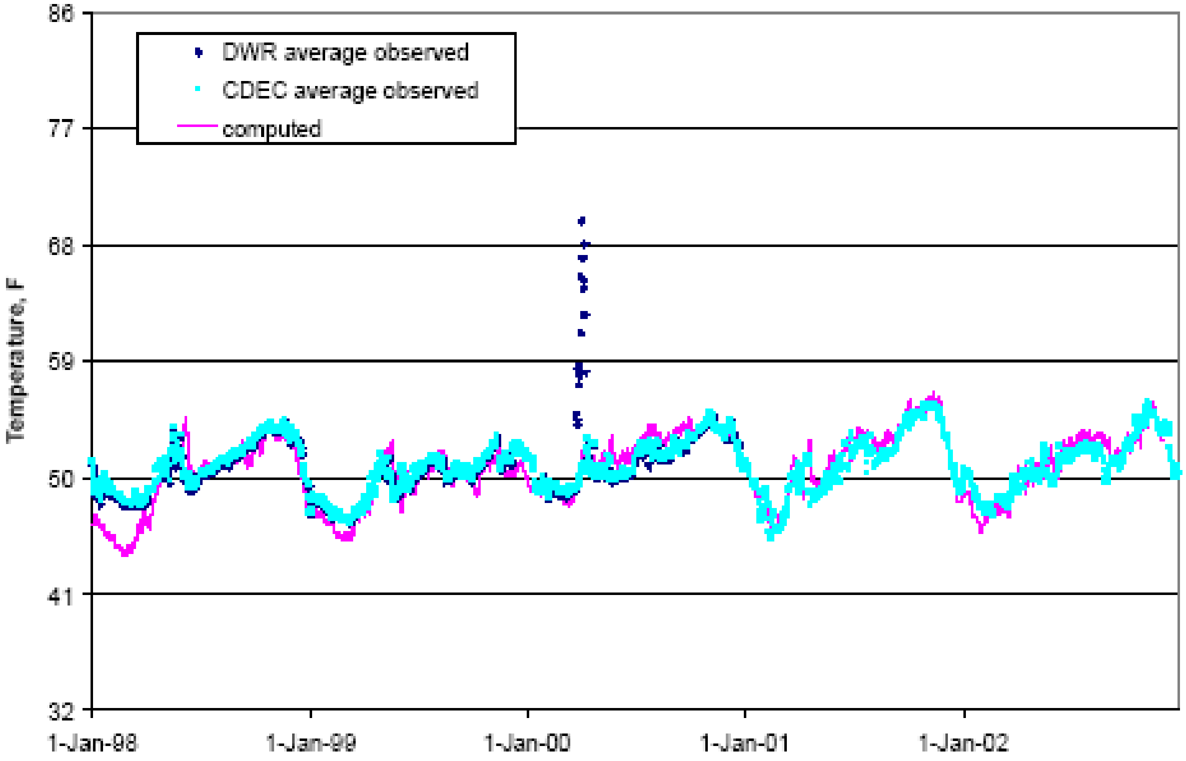


Figure 4-56. Computed and Observed Mean Daily Water Temperatures in Sacramento River Below Keswick Dam

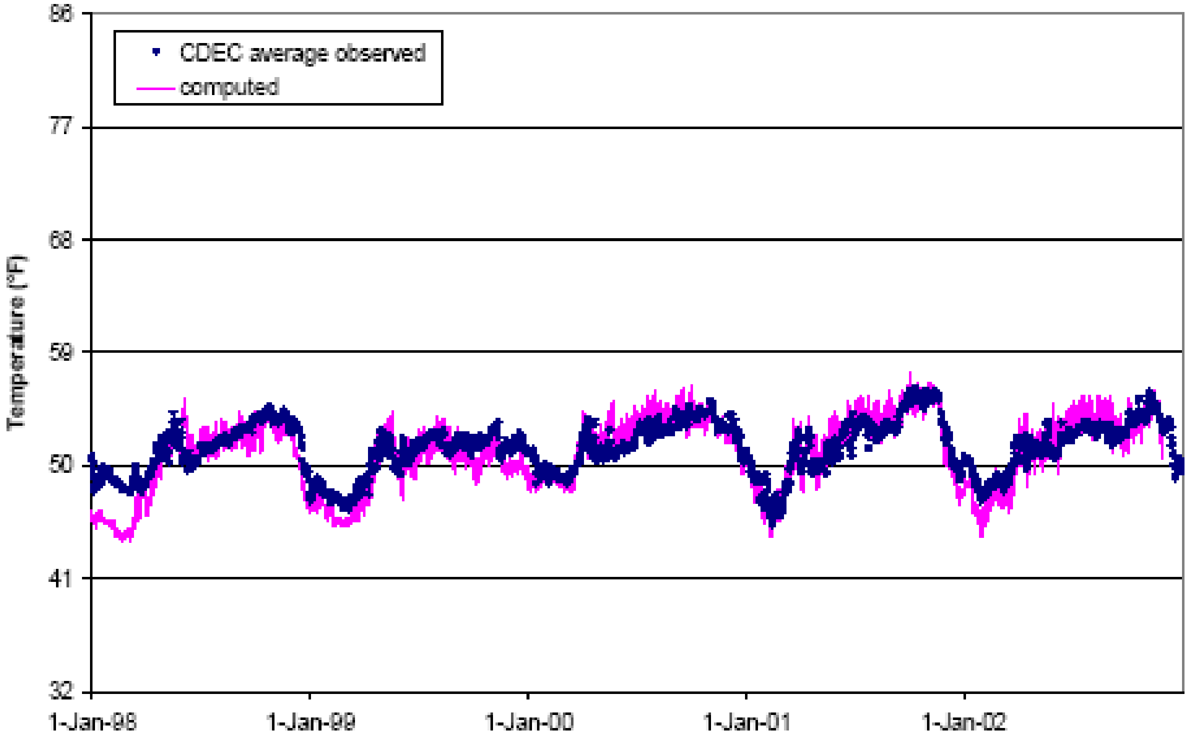


Figure 4-57. Computed and Observed Mean Daily Water Temperatures in Sacramento River Clear Creek (Bonneview)

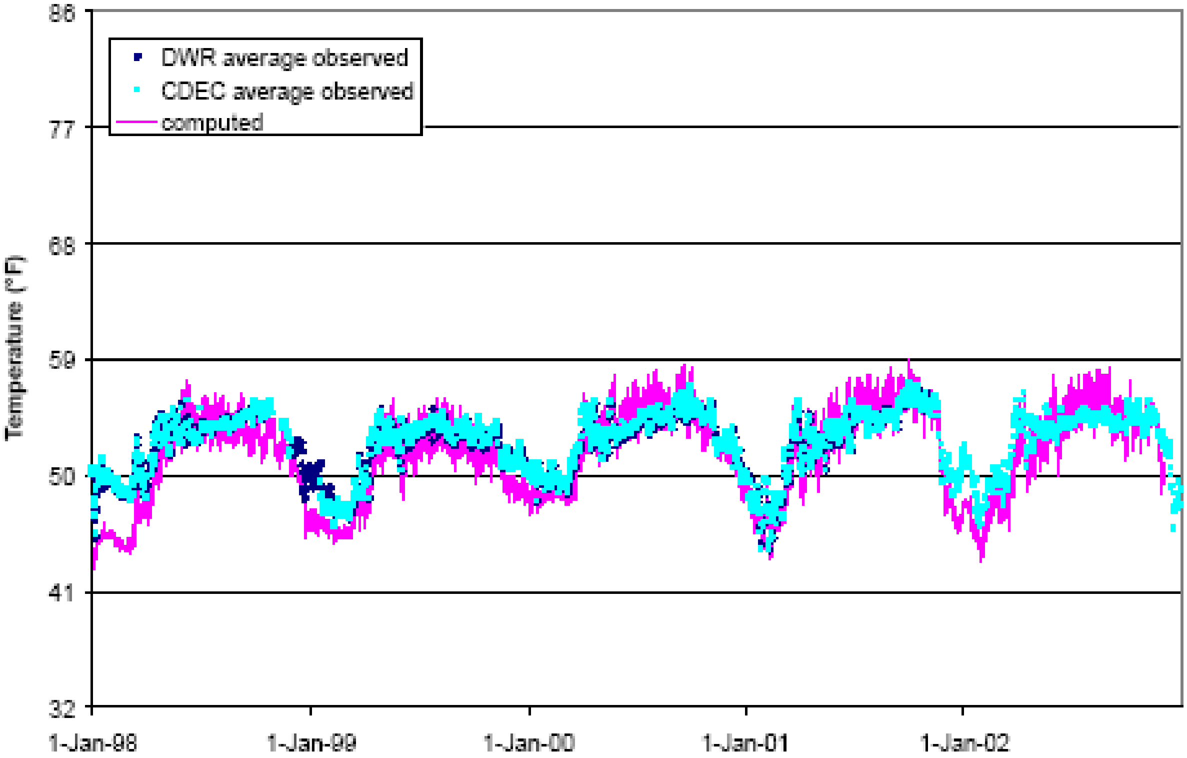


Figure 4-58. Computed and Observed Mean Daily Water Temperatures in Sacramento River at Balls Ferry

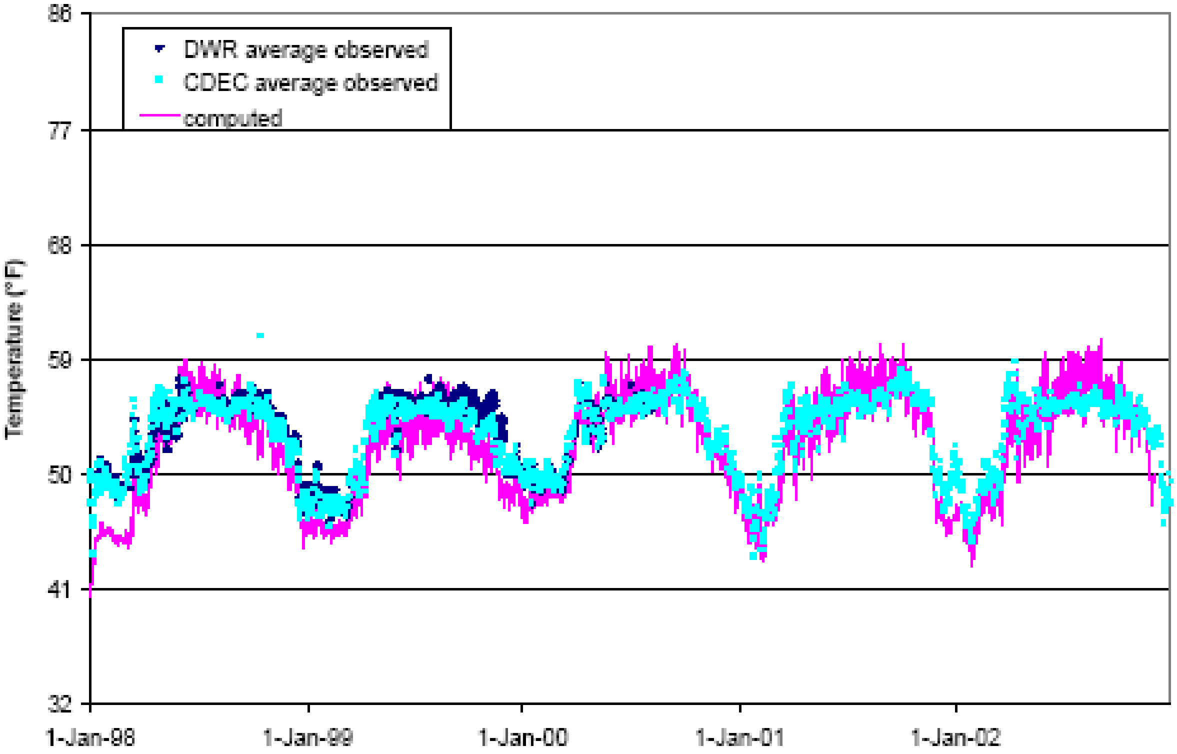


Figure 4-59. Computed and Observed Mean Daily Water Temperatures in Sacramento River at Jellys Ferry

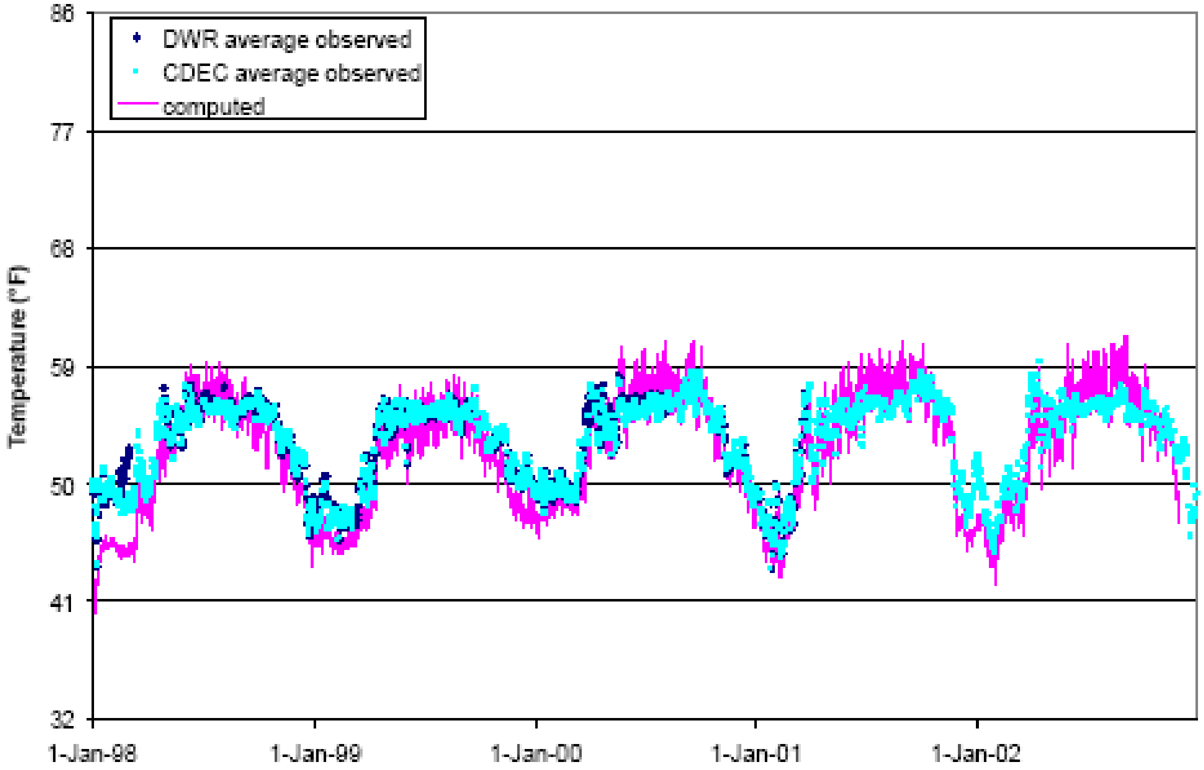


Figure 4-60. Computed and Observed Mean Daily Water Temperatures in Sacramento River at Bend Bridge

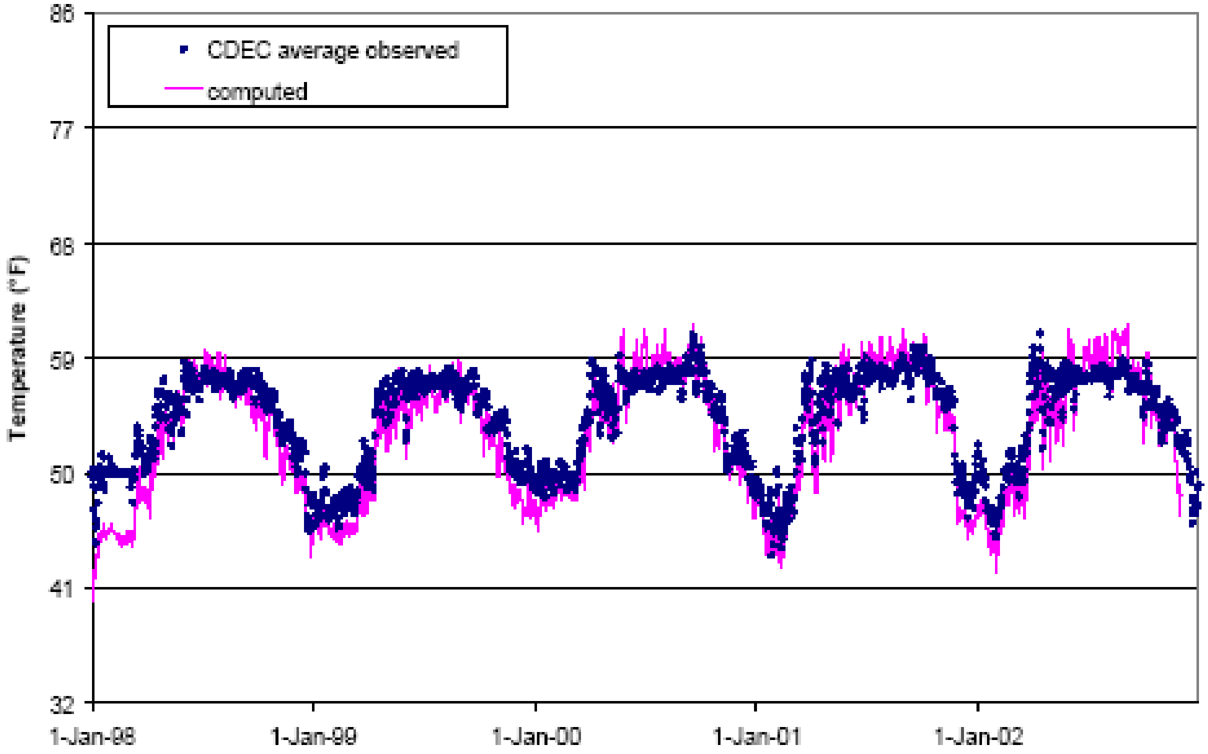


Figure 4-61. Computed and Observed Mean Daily Water Temperatures in Sacramento River at Red Bluff Diversion Dam

Table 4-5. Summary of Stream Temperature Calibration Results

Figure	Location	Description
4-53	Lewiston Fish Hatchery	Average computed temperatures are zero to 1°F lower than average observed temperatures.
4-54	Spring Creek Powerhouse	Computed temperatures are within 1°F of average observed data throughout most of calibration period.
4-55	Sac. R. below Shasta Dam	Computed temperatures are within 1°F of average observed data throughout most of the calibration period.
4-56	Sac. R. below Keswick Dam	Computed temperatures are within 1°F of average observed data throughout most of the calibration period.
4-57	Sac. R. at Clear Creek	Average computed temperatures are within 1°F or less of average observed data throughout the calibration period.
4-58	Sac. R. at Balls Ferry	Average computed temperatures are within 1°F or less of average observed except during January 1999 and January 2002 when there was up to a 2°F difference.
4-59	Sac. R. at Jellys Ferry	Average computed temperatures are within 1°F or less of average observed data throughout the calibration period.
4-60	Sac. R. at Bend Bridge	Average computed temperatures are within 1°F or less of average observed data throughout most of the calibration period.
4-61	Red Bluff Diversion Dam	Average computed temperatures are within 1°F or less of average observed data throughout the calibration period except during December of 1999, 2000, and 2002 when there was as much as 2°F difference.

Key:
ºF = degrees Fahrenheit
Sac. R. = Sacramento River

Temperature Model Validation

The SRWQM temperature model validation was performed for the period of January 1990 through January 1997. There was no Shasta TCD during this period. The model used historical Shasta Dam penstock and flood control outlet flows for this period, which are shown in Figure 4-62. Model results were compared with temperature time series field observations at numerous locations in the upper Sacramento River; tailwater temperature time series at Shasta, Lewiston, and Keswick dams; temperature time series at Spring Creek Powerhouse; and temperature profile observations in Shasta Reservoir. CDEC time series data, and Shasta Reservoir temperature profile data provided by Reclamation were used for comparison with computed temperatures. The emphasis of the validation effort was to ensure that the Sacramento River model performed in a reasonable fashion during the low flow hydrologic conditions of the early 1990s. Shasta Reservoir profiles were included to demonstrate that the model adequately represents pre-TCD conditions. Profiles for the other reservoirs were not included since there were no structural changes to their release structures.

The hydrology, meteorology, and inflow water quality conditions previously described were assumed, with the exception that ambient water temperature data to develop tributary stream inflow temperatures were only available from CDEC.

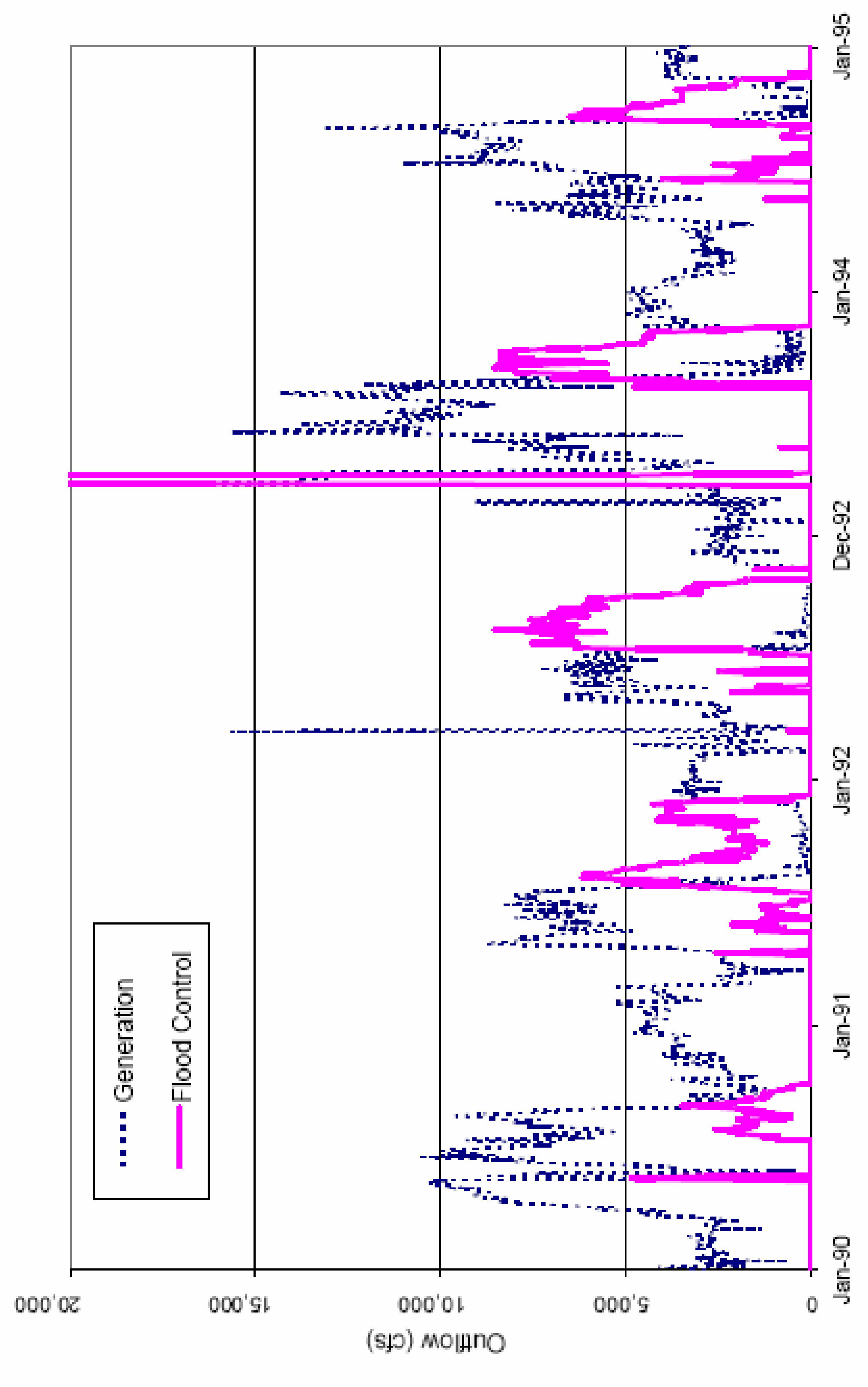


Figure 4-62. Shasta Dam Penstock and Flood Control Outlet Flows During 1990 to 1995 Sacramento River Temperature Control Operation

The intent of the model validation exercise was to verify that the calibrated model adequately represents thermal responses of the upper Sacramento River stream and reservoir system.

The results of the validation effort are presented as plots of computed and observed stream temperature time series and Shasta Reservoir temperature profiles.

SRWQM Validation Results

The following sections briefly discuss the validation results.

Shasta Reservoir Temperature Calibration Results

Computed and observed vertical reservoir temperature profiles for Shasta Reservoir are plotted for two dates (nearest to July 1 and mid-September of each year) during 1990 through 1997 in Figures 4-63 through 4-78.

The computed profiles closely match the observed data for all of the profiles. In several of the profiles, there is a 2°F to as much as 7°F difference between computed and observed surface temperatures. This is similar to the surface temperature discrepancies noted in the calibration results. Again, these discrepancies are likely due to the approximation of the meteorological conditions and, in some cases, may be due to a slight time offset between computed and observed surface temperatures. However, these deviations do not appear to affect temperatures lower in the reservoir nor do they affect tailwater temperatures.

Stream Temperature Validation Results

Computed and observed temperature time series for selected locations throughout the upper Sacramento River system are plotted in Figures 4-79 through 4-85. Computed values are plotted at 6-hour intervals at the following times: 00:00, 06:00, 12:00, and 18:00. Observed data are plotted as daily average values.

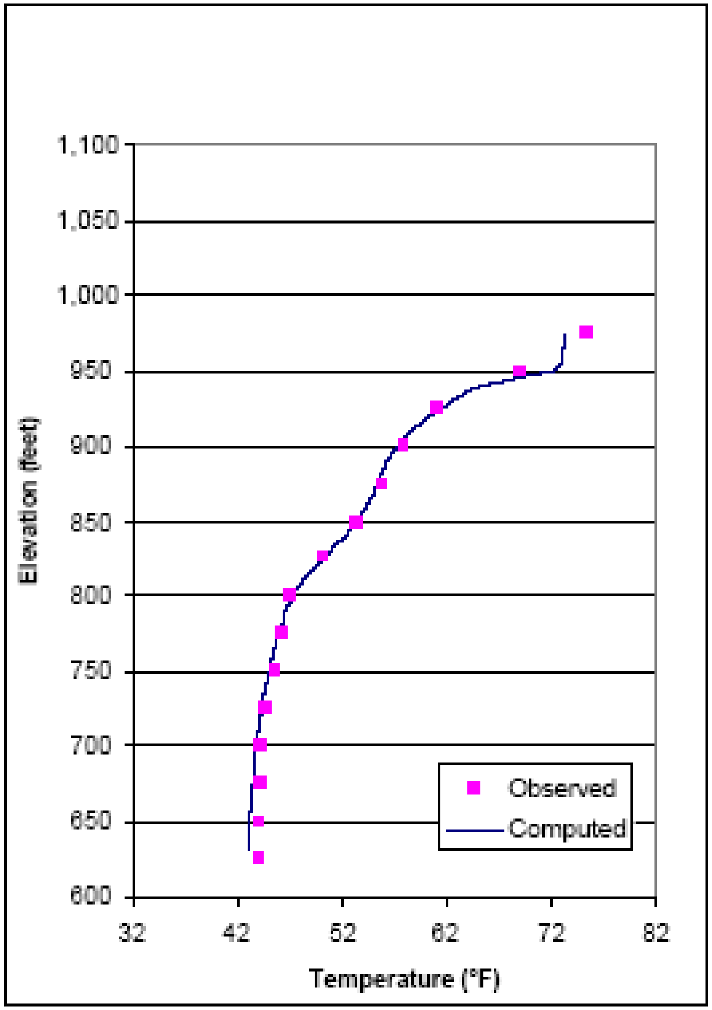


Figure 4-63. Computed and Observed Temperature Profiles in Shasta Reservoir on July 5, 1990

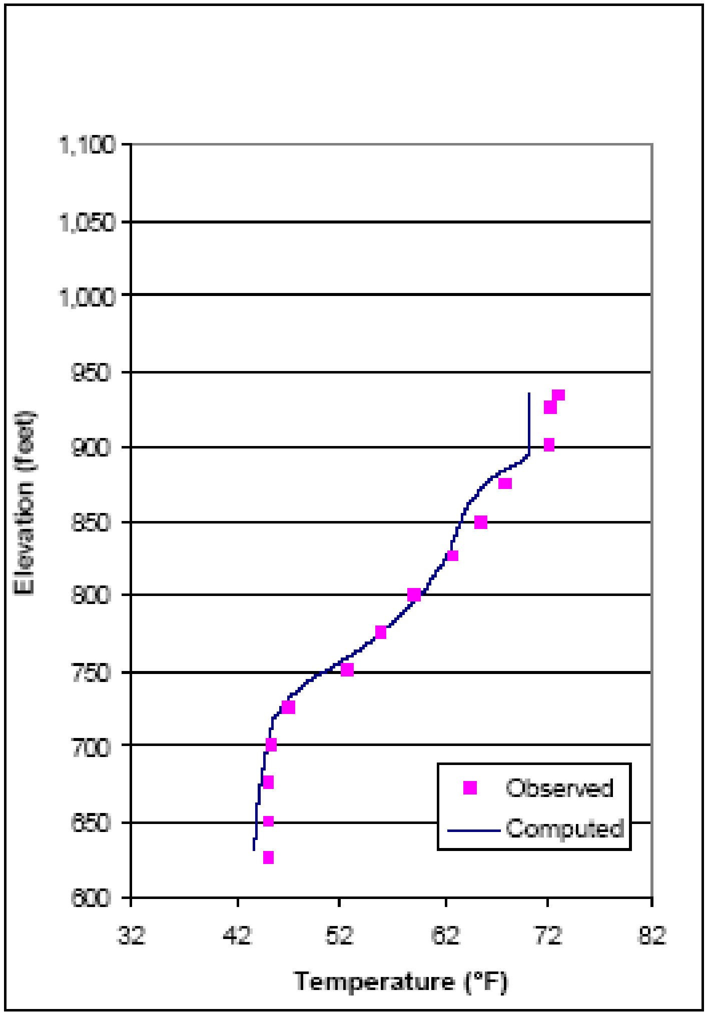


Figure 4-64. Computed and Observed Temperature Profiles in Shasta Reservoir on September 21, 1990

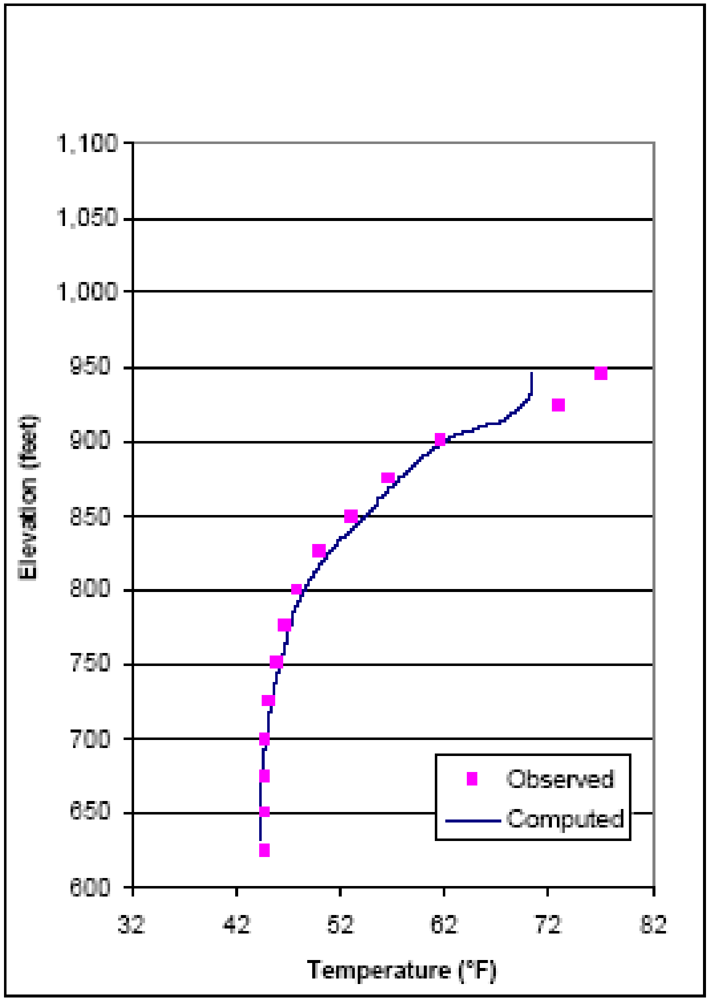


Figure 4-65. Computed and Observed Temperature Profiles in Shasta Reservoir on July 3, 1991

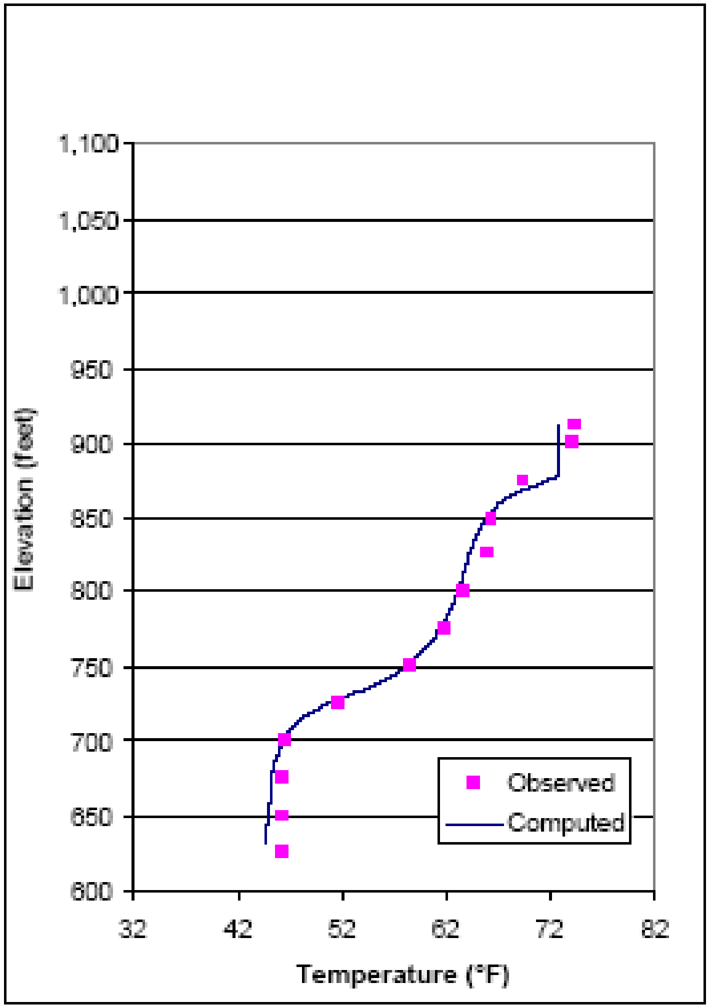


Figure 4-66. Computed and Observed Temperature Profiles in Shasta Reservoir on September 19, 1991

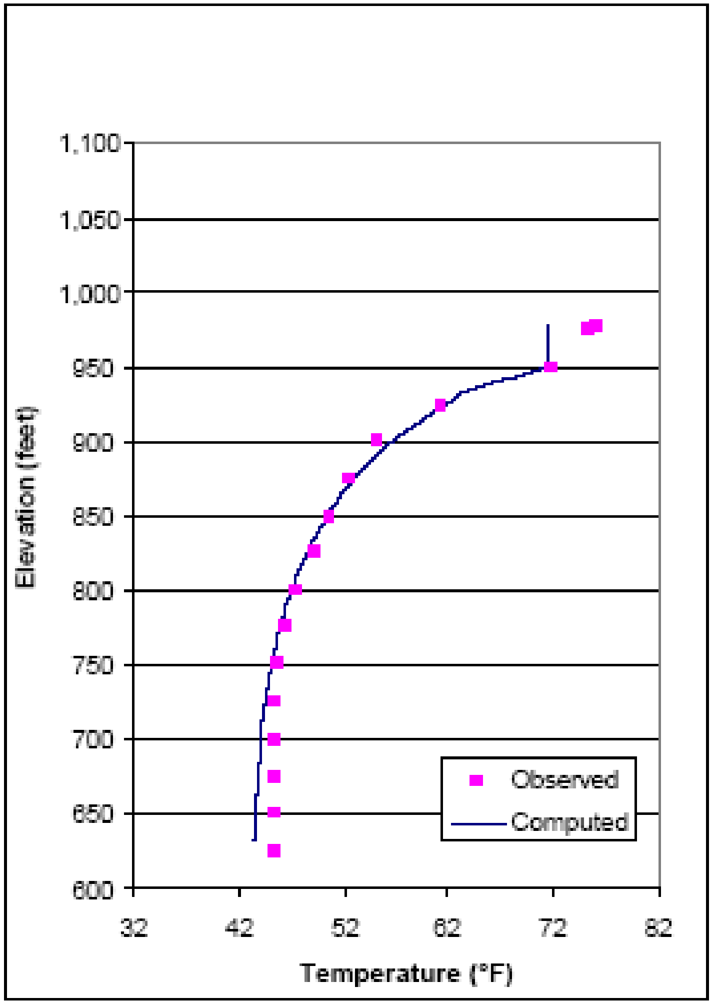


Figure 4-67. Computed and Observed Temperature Profiles in Shasta Reservoir on July 8, 1992

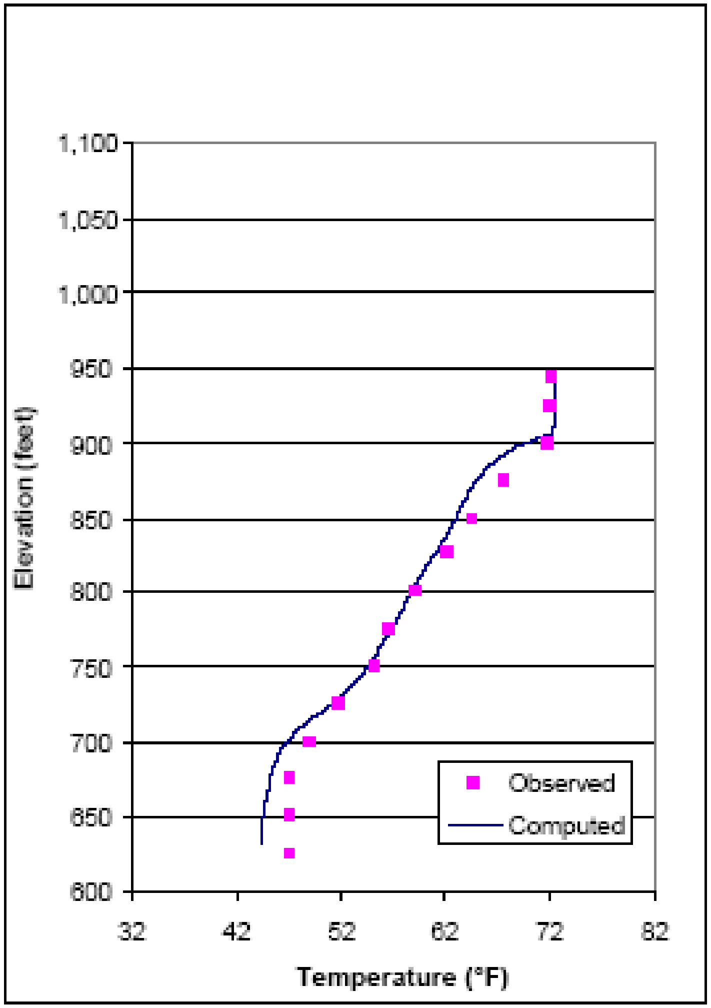


Figure 4-68. Computed and Observed Temperature Profiles in Shasta Reservoir on September 15, 1992

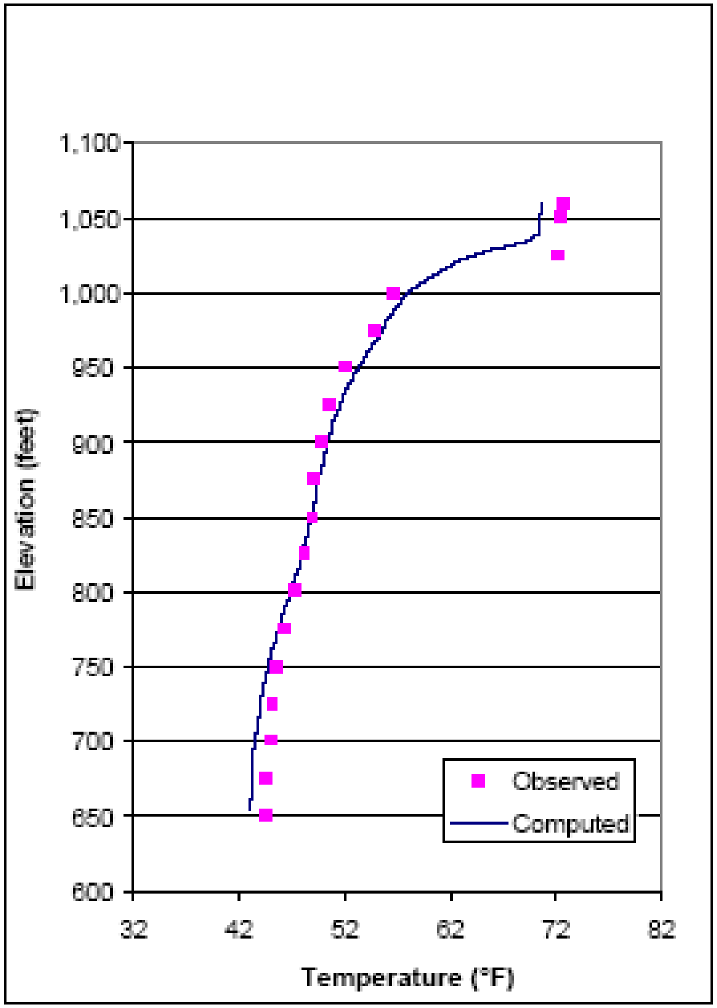


Figure 4-69. Computed and Observed Temperature Profiles in Shasta Reservoir on June 30, 1993

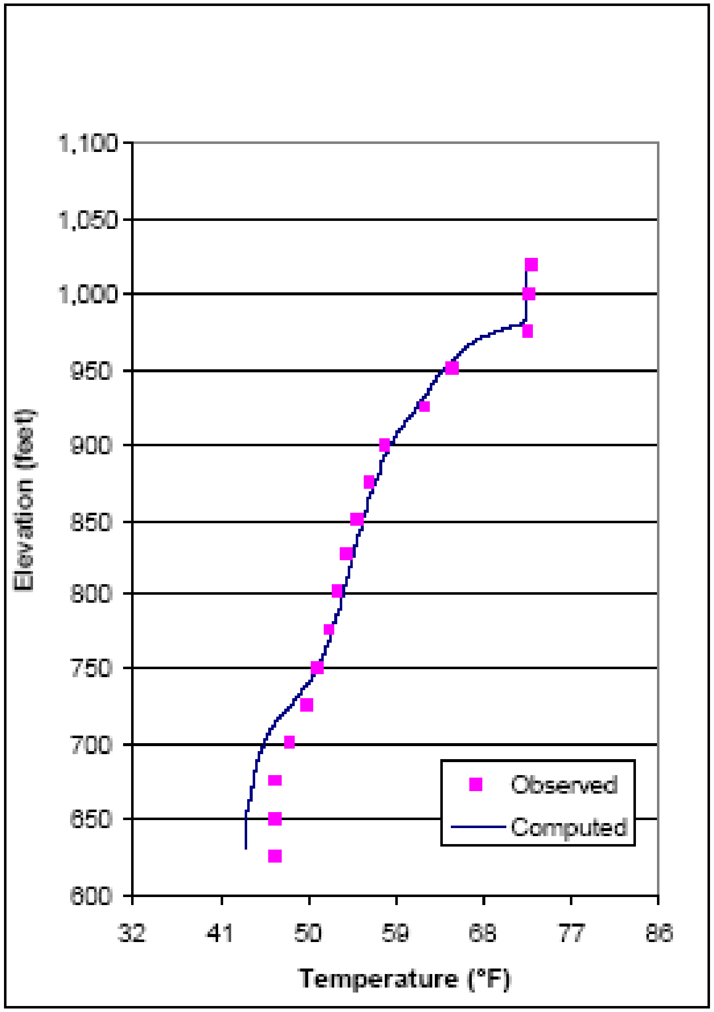


Figure 4-70. Computed and Observed Temperature Profiles in Shasta Reservoir on September 17, 1993

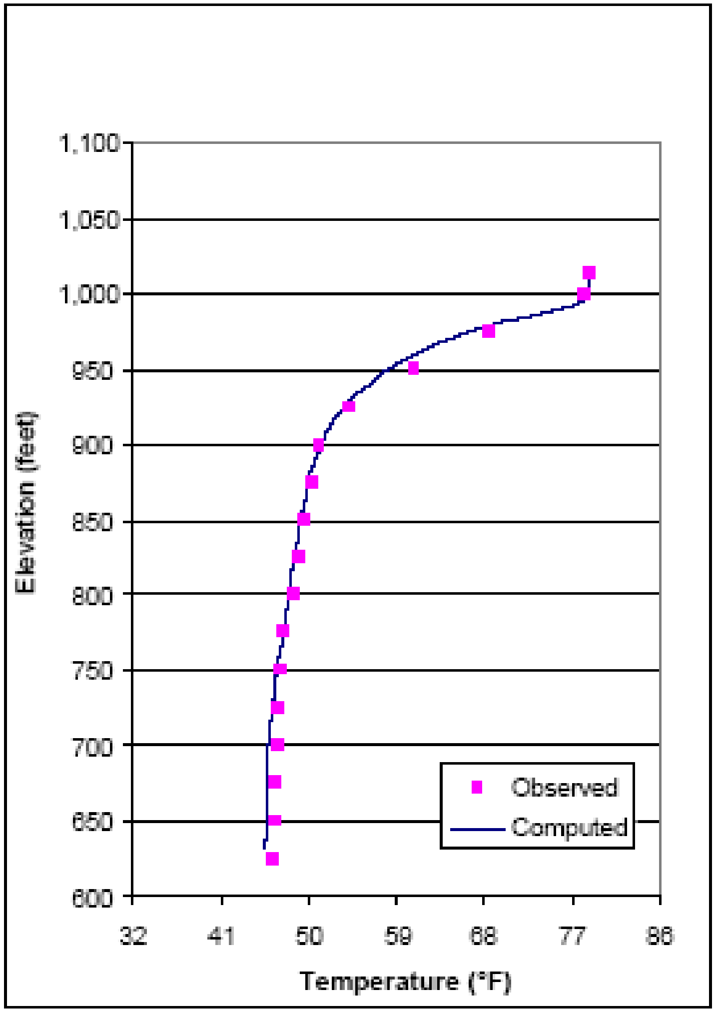


Figure 4-71. Computed and Observed Temperature Profiles in Shasta Reservoir on July 13, 1994

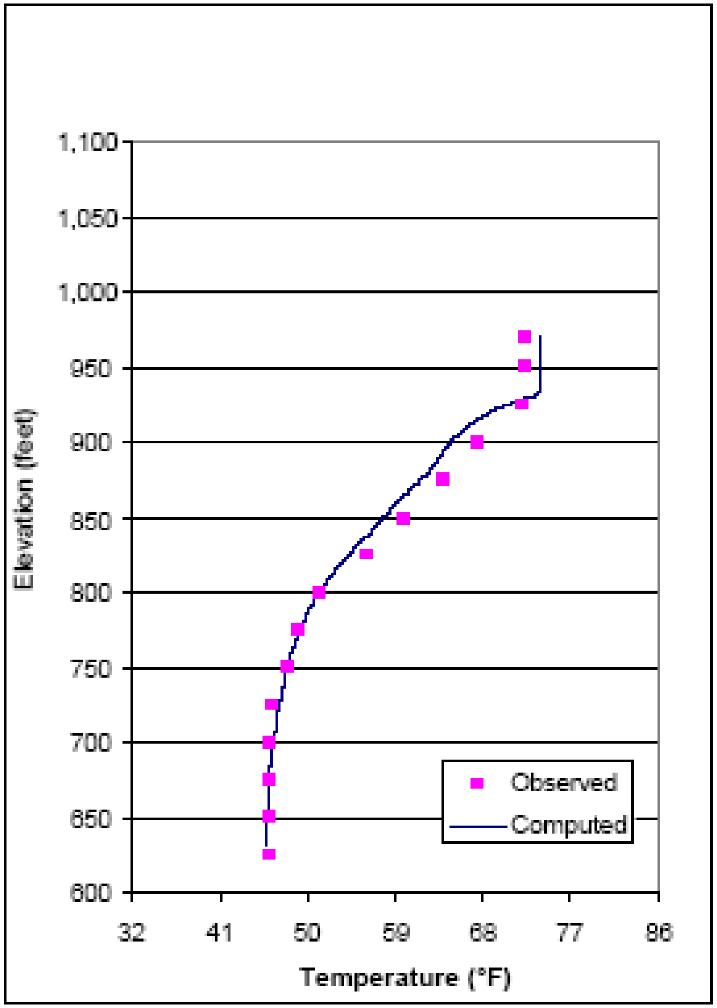


Figure 4-72. Computed and Observed Temperature Profiles in Shasta Reservoir on September 14, 1994

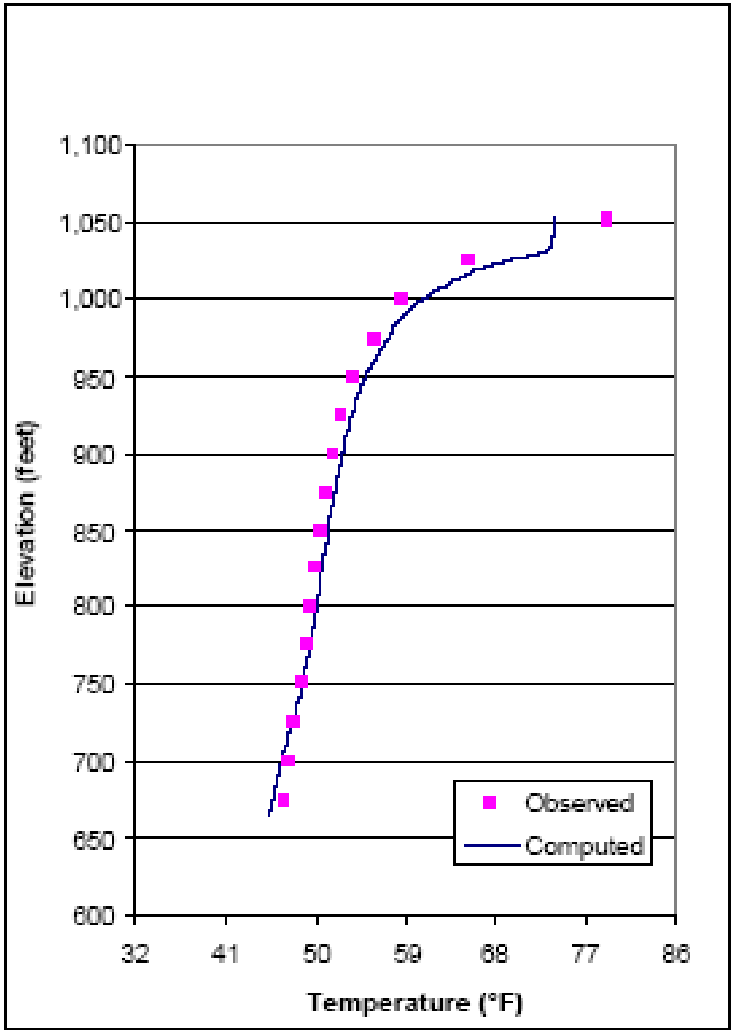


Figure 4-73. Computed and Observed Temperature Profiles in Shasta Reservoir on July 7, 1995

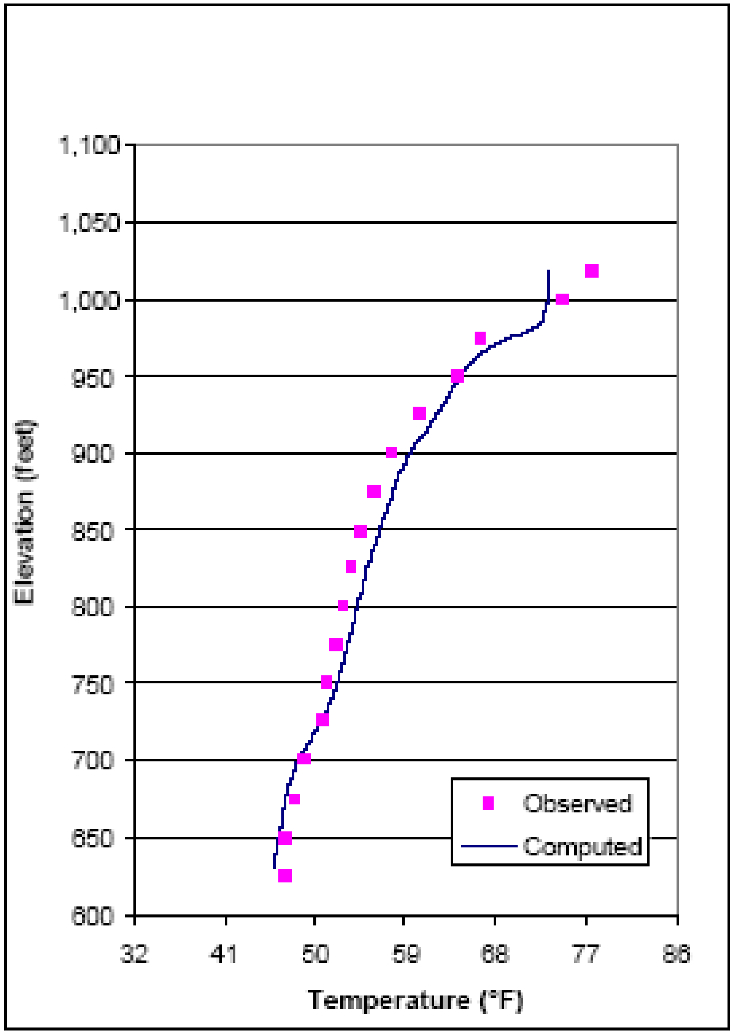


Figure 4-74. Computed and Observed Temperature Profiles in Shasta Reservoir on September 14, 1995

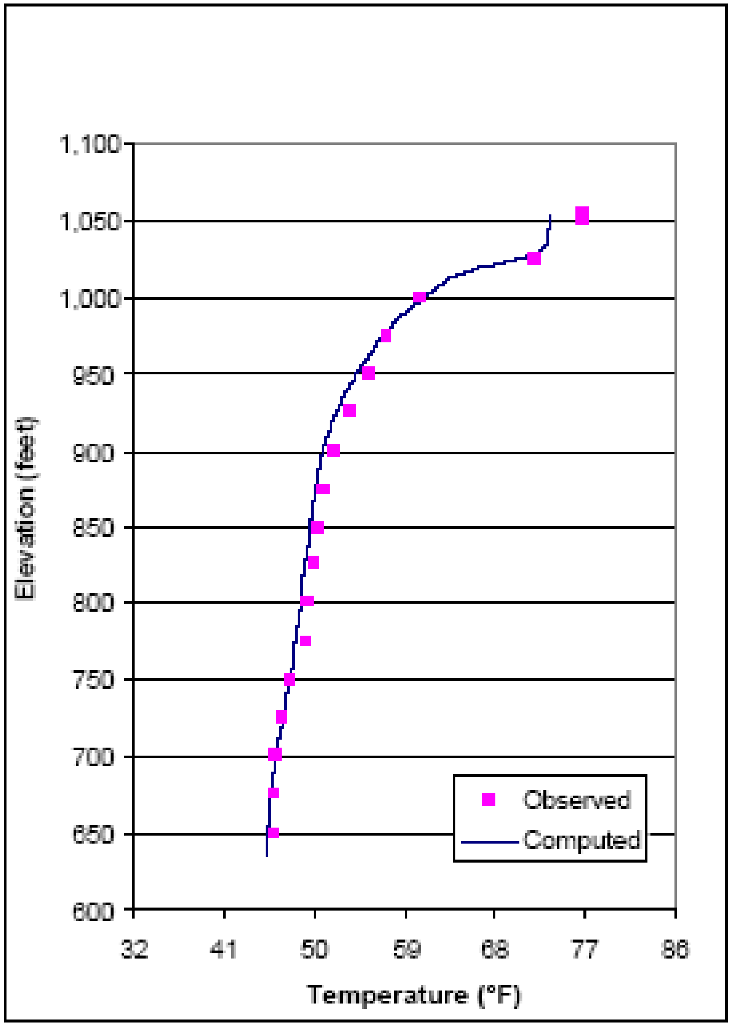


Figure 4-75. Computed and Observed Temperature Profiles in Shasta Reservoir on July 2, 1996

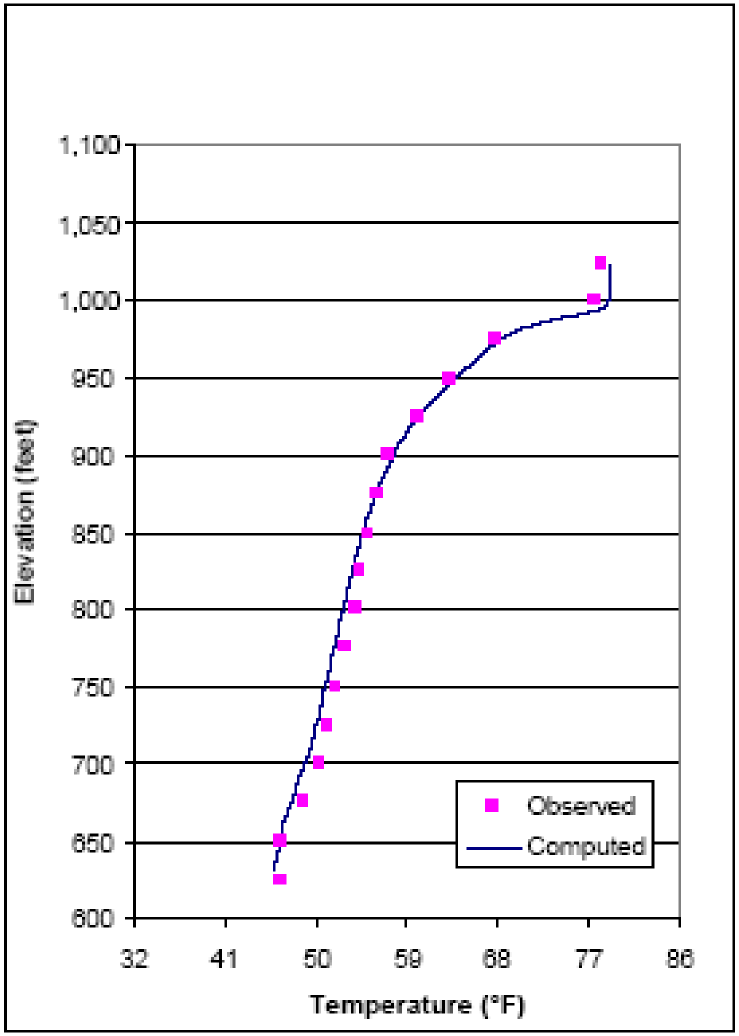


Figure 4-76. Computed and Observed Temperature Profiles in Shasta Reservoir on August 26, 1996

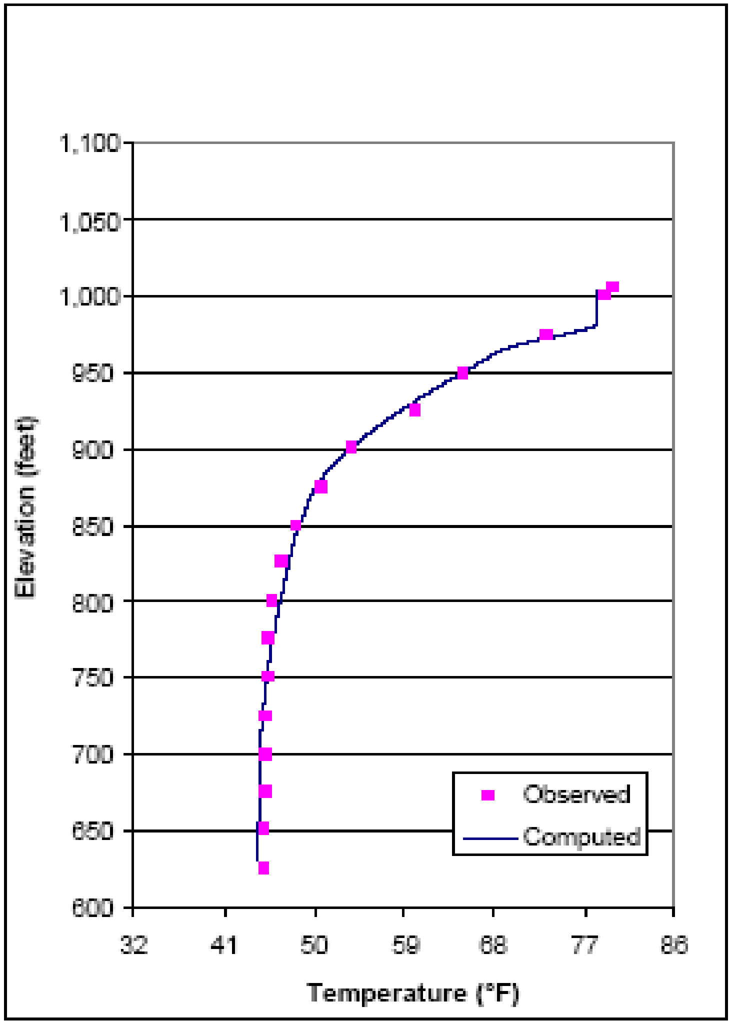


Figure 4-77. Computed and Observed Temperature Profiles in Shasta Reservoir on August 1, 1997

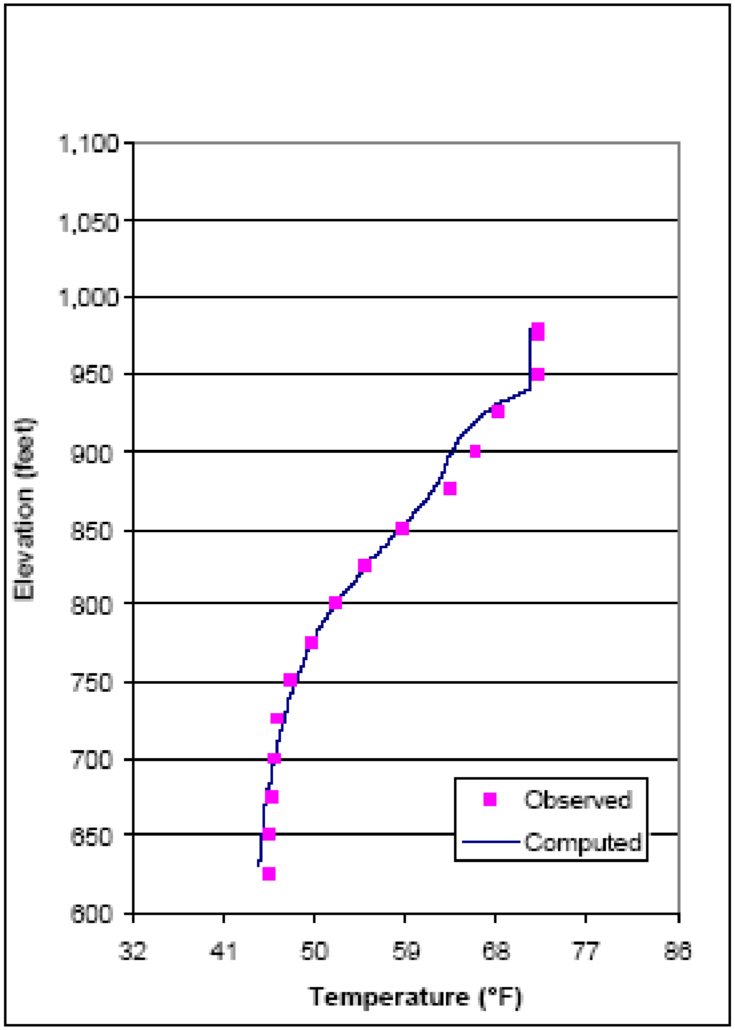


Figure 4-78. Computed and Observed Temperature Profiles in Shasta Reservoir on September 16, 1997

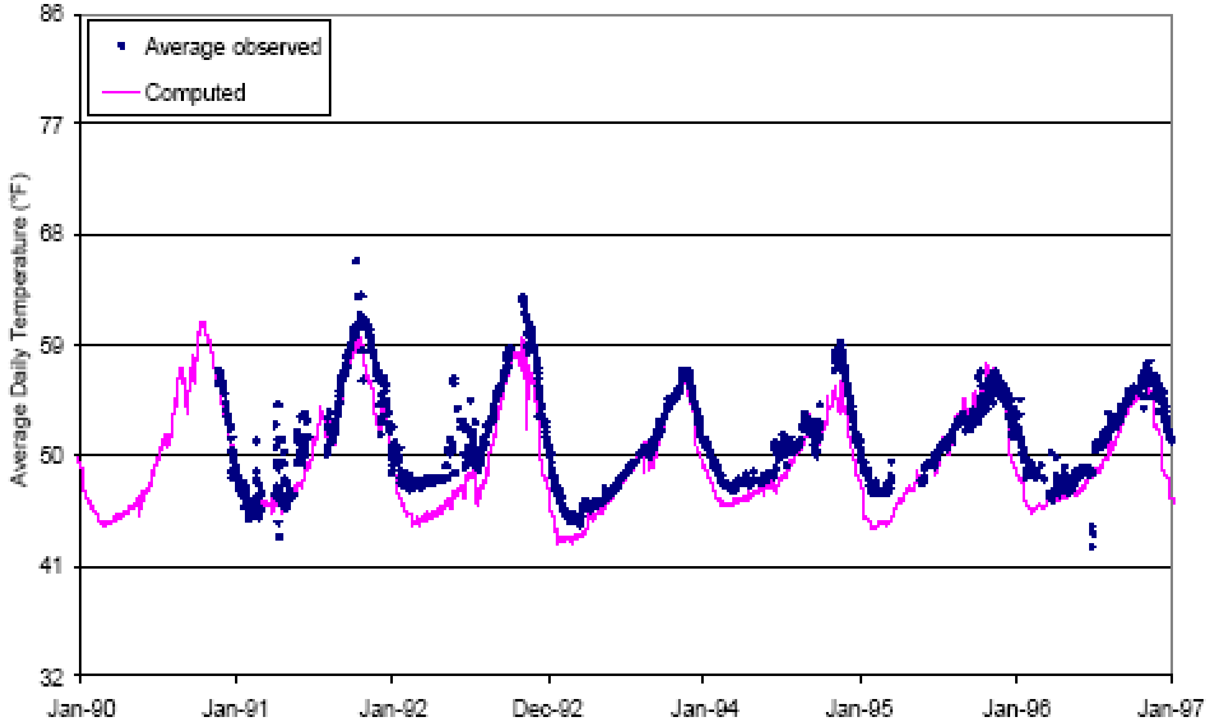


Figure 4-79. Computed and Observed Temperature Time Series in Sacramento River Below Shasta Dam (with observed low level/penstock flow rates and no TCD)

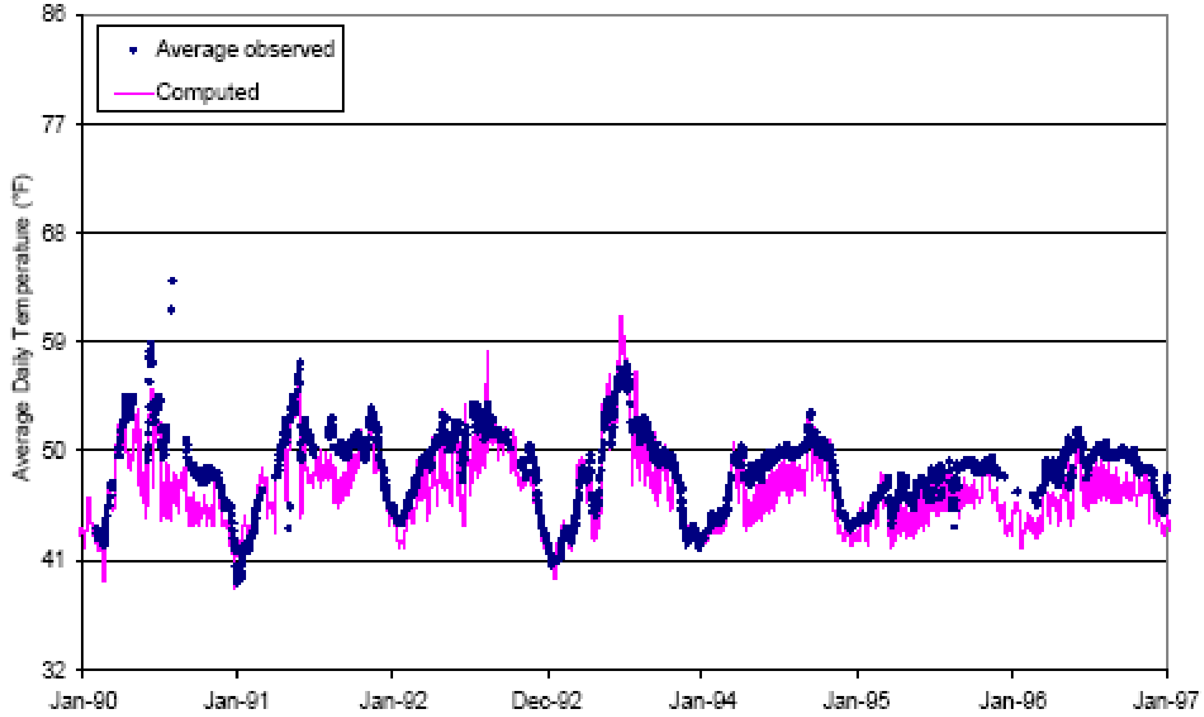


Figure 4-80. Computed and Observed Temperature Time Series in Trinity River at Lewiston

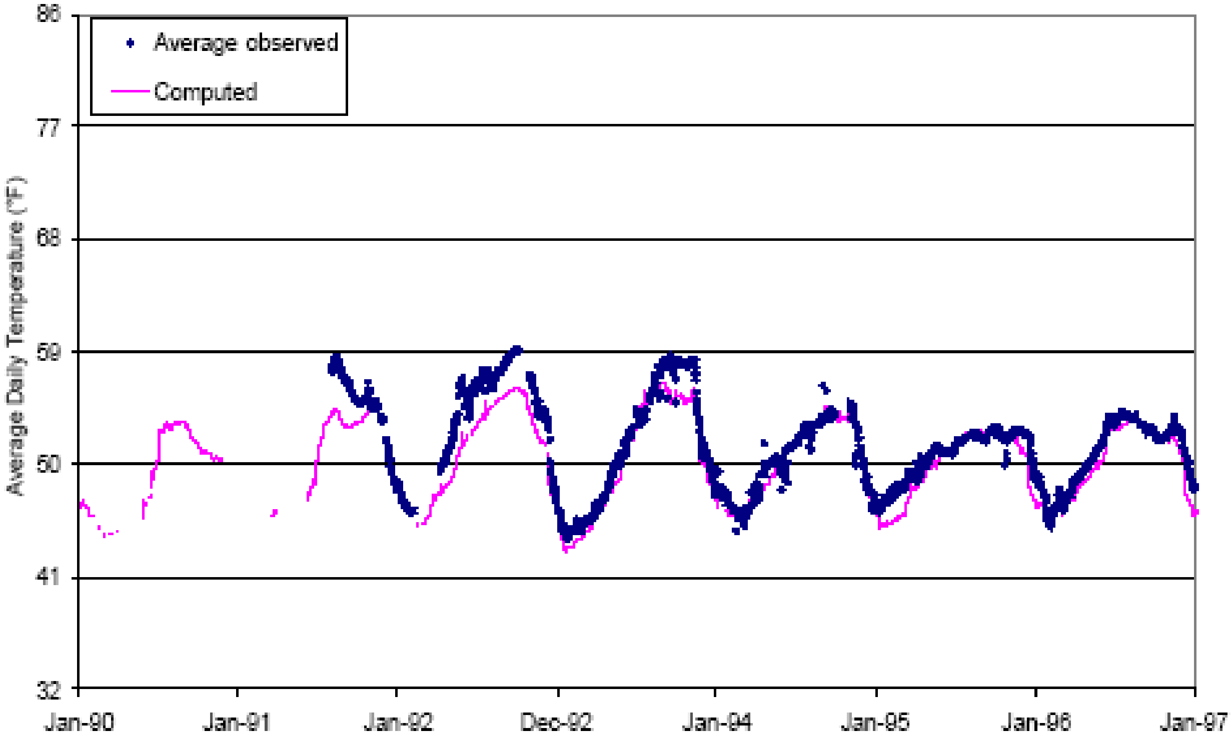


Figure 4-81. Computed and Observed Temperature Time Series in Spring Creek Powerhouse at Keswick

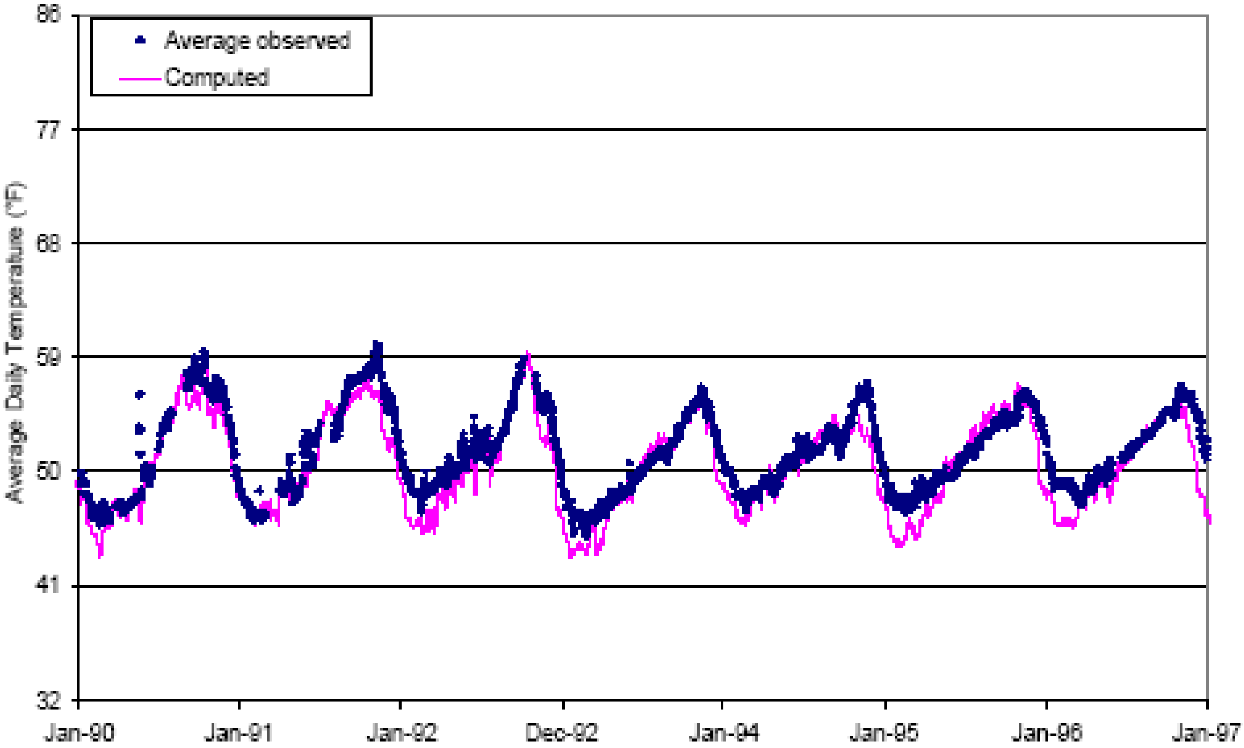


Figure 4-82. Computed and Observed Temperature Time Series in Sacramento River at Keswick

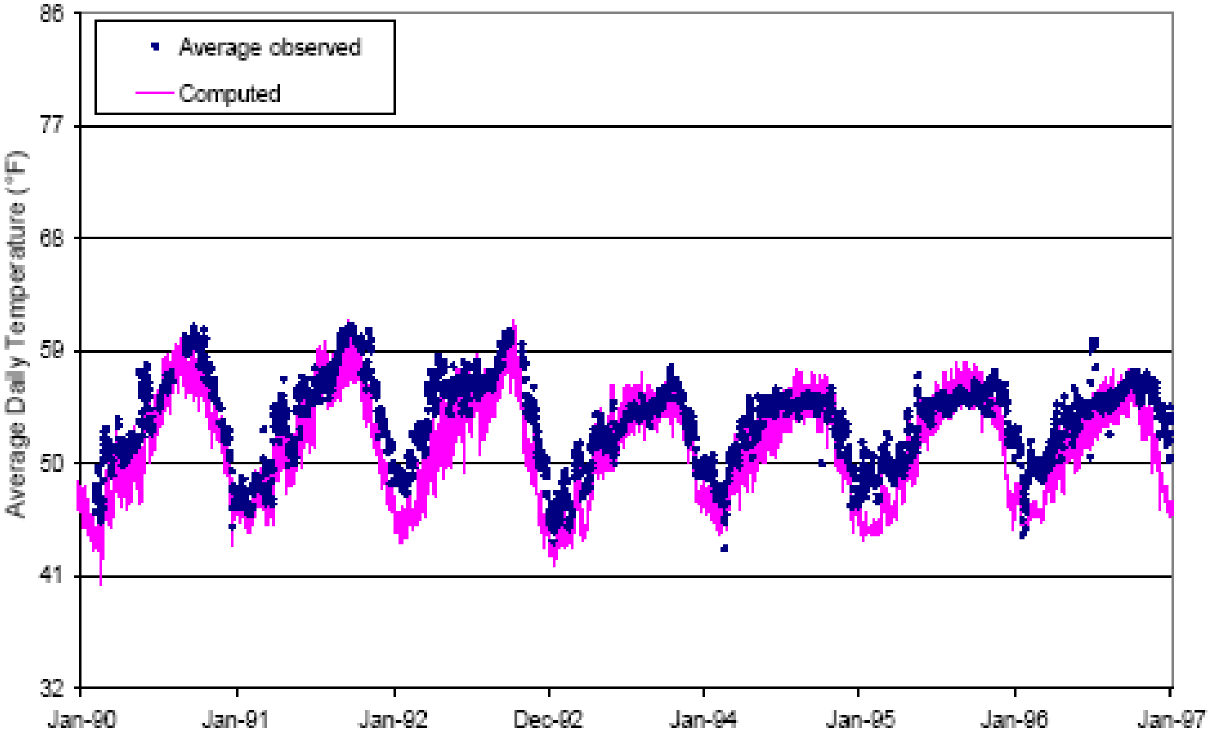


Figure 4-83. Computed and Observed Temperature Time Series in Sacramento River at Balls Ferry

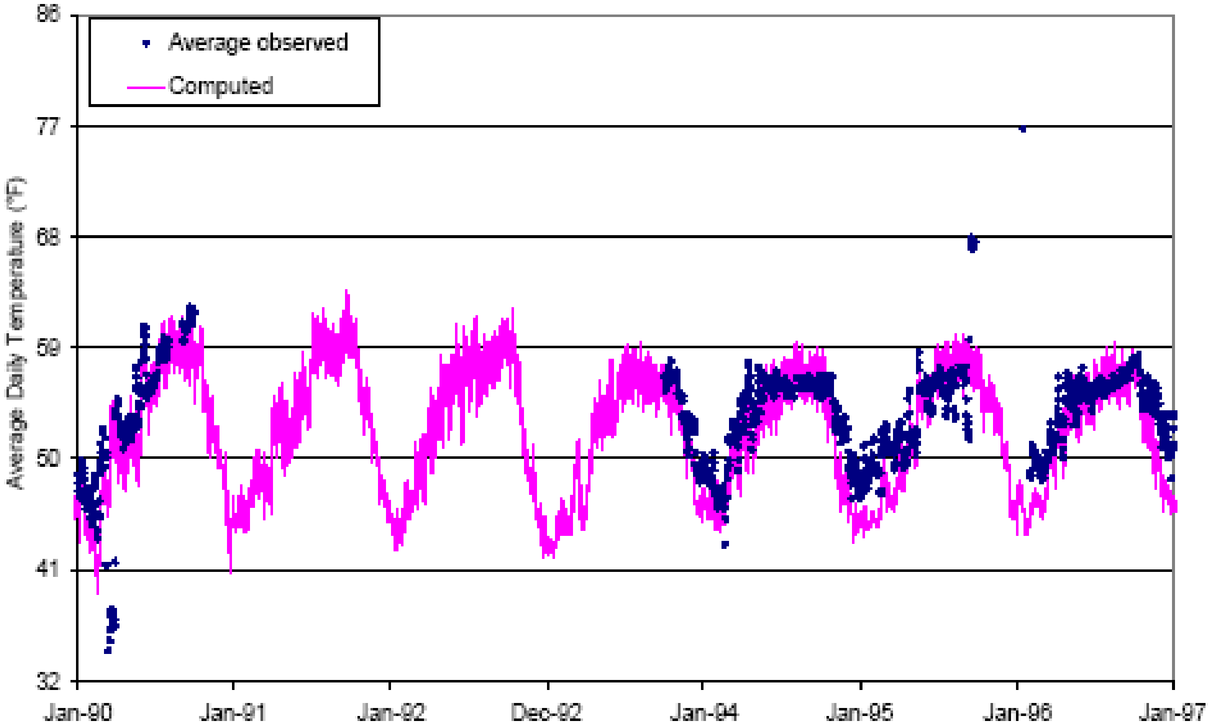


Figure 4-84. Computed and Observed Temperature Time Series in Sacramento River at Bend Bridge

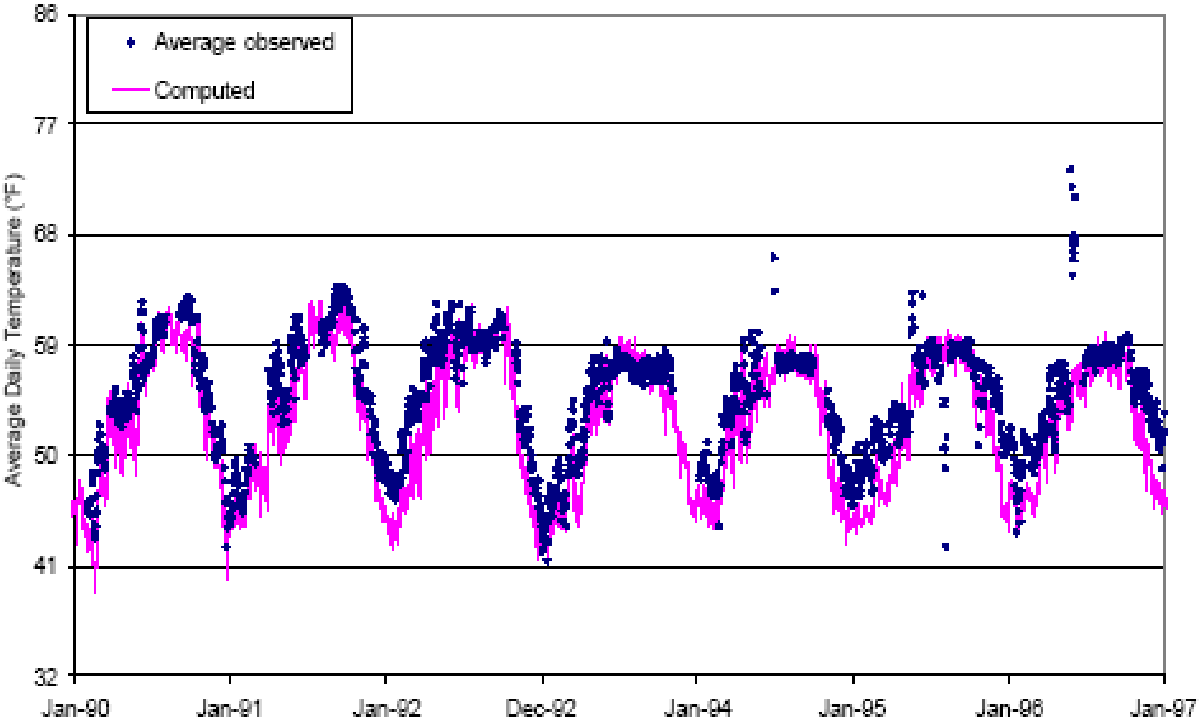


Figure 4-85. Computed and Observed Temperature Time Series in Sacramento River at Red Bluff Diversion Dam

Computed temperatures are generally within 3°F or less of average observed data at each of the locations plotted. Computed temperatures tend to be slightly cooler than observed. The higher summertime temperatures of 1990 through 1992 relative to the 1993 through 1997 temperatures show that the model adequately represents ambient temperature conditions during wet and dry years. Validation results are summarized in Table 4-6.

Table 4-6. Summary of Stream Temperature Calibration Results

Figure	Location	Description
4-79	Shasta Dam tailwater	Computed temperatures as much as 3°F lower than average observed data, with the greatest discrepancies occurring during the winter.
4-80	Trinity River at Lewiston	Computed temperatures are within zero to 2°F of average observed data during the winters and within zero to 3°F of average observed data during the summers.
4-81	Spring Creek Powerhouse	Computed temperatures as much as 3°F below average observed data during the summers of 1991 through 1993, and generally within 1°F or less of average observed data throughout most of rest of the calibration period.
4-82	Sac. R. below Keswick Dam	Computed temperatures are in excellent agreement with average observed data throughout much of the calibration period, and during some periods (particularly in the winter) are as much as 3°F below average observed data.
4-83	Sac. R. at Balls Ferry	Average computed temperatures are within 3°F or less of average observed data throughout the calibration period, with the greatest discrepancies occurring during the winter.
4-84	Sac. R. at Bend Bridge	Average computed temperatures are within 3°F or less of available average observed data throughout most of the calibration period. There are slightly greater discrepancies during winter 1994 – 1995.
4-85	Red Bluff Diversion Dam	Average computed temperatures are generally within 3°F or less of average observed data throughout the calibration period with closest agreement during the summer and fall months, and larger discrepancies during some winter and spring months.

Key:
ºF = degrees Fahrenheit
Sac. R. = Sacramento River

Chapter 5
Anadromous Fish Production Simulation (SALMOD)

Introduction

A deterministic salmon production model, SALMOD, was parameterized and applied to help evaluate streamflow and water temperatures predicted as representative of several scenarios being proposed for raising Shasta Dam on the Sacramento River, California. The model predicts the degree to which changes in river flows and temperatures associated with the project may impact freshwater production potential for the four runs of Chinook salmon (*Oncorhynchus tshawytscha*) that inhabit the Sacramento River. Model simulations were used to evaluate the relative change in production, as compared to a baseline level of production, across 82 years representing a range of hydrologic and meteorological conditions, under both existing and future demand levels.

This model application is an outgrowth of previously described work on both the Sacramento and Klamath rivers, although neither model has been quantitatively calibrated. Specific parameter requirements, data sources, and significant assumptions are discussed in detail. Model uncertainty has been comprehensively highlighted through a sensitivity analysis (SA) that focuses on those model parameters that were both sensitive and uncertain.

There are a number of acknowledged limitations and uncertainties inherent in SALMOD which limit the types of inferences that can be draw from the model. Like any model of a natural system, SALMOD is based on simplified rules and assumptions used to represent and approximate the complex factors that drive real-world conditions, which are of themselves often poorly or incompletely understood. While these assumptions can form a reasonably accurate and useful simulation of natural conditions, they cannot exactly replicate or predict actual conditions. These required simplifications and inherent uncertainties in model inputs naturally lead to uncertainties in the accuracy of model outputs for any individual model run relative to actual, real-world conditions.

In addition, SALMOD relies on output from a sequence of other models (CalSim-II and SRWQM) for its flow and temperature inputs, and these models contain similar simplifications and uncertainties, which further influence the overall accuracy of a single SALMOD model run. For instance, CalSim-II, the best available tool for predicting system-wide water operations throughout the

Central Valley, simplifies the system by assessing flows on a monthly basis and at a relatively coarse geographic scale, while fish populations are affected by changes on much finer temporal and geographic scales, so flows must be downscaled using an additional set of assumptions to approximate natural processes.

However, when sufficient data is available, a model like SALMOD can be an invaluable tool for understanding the operation of a complex system and predicting its response to certain types of change. If the modeling assumptions and parameters form a reasonably accurate representation of the relationship between input variables and outputs, and the nature of those relationships will not change between scenarios, the model is valid for comparing between alternatives despite its inherent uncertainty (identical assumptions will influence all scenarios and lead to similar uncertainties/ inaccuracies that cancel out in the process of comparison). As a result, the inferences drawn from the modeling results would not be affected by underestimation or overestimation of mortality that similarly impacts both the no action and action alternatives.

In light of these uncertainties, SALMOD is not used as a predictive tool for explicit population estimation; rather it is used as a comparative tool to evaluate relative change between alternatives. A valid use of the model results is to identify general trends (such as positive or negative responses) and the relative magnitude of impacts (such as percent changes), whereas making inferences about absolute changes in fish production would be an invalid use of the model. In this study, SALMOD is being used on a year-by-year basis, which allows Reclamation, under each year, to evaluate what would happen under the water operations, to each run of Chinook salmon (NMFS assumes steelhead would be similar to late fall-run per their evaluation in the 2009 NMFS BO). The resulting simulated fish production values should be viewed as an index of production for each alternative, which can be used to make relative comparisons between alternatives, and should not be treated as an explicit prediction of absolute numbers of fish production under any alternative.

Similarly, it should be noted that SALMOD is not a life cycle-population dynamics model, but rather a life stage model. SALMOD is intended to be used as an operations and alternatives screening tool, not a rigorous population dynamics model. By keeping the same starting population number, Reclamation is able to make a comparison against each alternative. The identified limitations do not preclude the ability of SALMOD to identify potential effects to Chinook salmon caused by changes in operations. Some of the factors outside of the area of influence of the SLWRI (for instance, ocean conditions) are poorly understood and are themselves subject of both environmental and anthropogenic forces, making them highly uncertain and thus difficult to quantify or even fully anticipate. Ultimately, because SLWRI is only able to improve specific portions of the life cycle of anadromous fish, within a specific section of the Sacramento River, which have been demonstrated to be likely limiting factors to anadromous fish survival, any other portions of the life cycle that may also be limiting factors for anadromous fish survival will have to be addressed by other actions/projects that are outside the purview of the SLWRI. Inclusion of those factors outside of the areas and life stages influenced by this project could obscure the modeling effort and as such, the influence of the project, by introducing significant uncertainty from factors (and life stages) that are not directly influenced by the project. Therefore, the model has been formulated to isolate the effect of the project on anadromous fish survival, by excluding factors outside of the area of influence of the project.

Model output is included in Attachments 3 through14 of this appendix.

Present Study

The SLWRI has two primary goals: water supply reliability and anadromous fish survival. To achieve these goals, along with multiple secondary goals, Reclamation is proposing to evaluate raising Shasta Dam to various heights to determine which alternative best meets the goals. Raising the dam may improve the reservoir's ability to deliver cold water in some years, potentially increasing salmon survival beyond levels provided by the existing TCD. An enlarged Shasta Dam also is likely to alter flow and storage patterns simply because more carryover storage options become available with a larger, manageable reservoir, and because more storage space is available to capture inflows during high flow events.

Chinook salmon stocks from the Sacramento River, especially the listed winter-run, continue to be below their recovery goals (USFWS 1995). For this reason, Reclamation needs to evaluate the effects of potentially raising Shasta Dam on downstream salmonid populations in the Sacramento River.

Hanna (2000) outlined a conceptual process of incorporating a salmon production model into an EIS-related assessment activity. Hanna envisioned proposed hydrologic scenarios advancing through a chain of models. The chain would start with a water-supply/quantity model (e.g., CalSim-II) capable of predicting monthly streamflows and overall mass balance given existing water-management constraints and obligations. The water quantity model's output would be fed into a reservoir and river water quality model (e.g., HEC-5Q) capable of predicting in-reservoir, outfall, and downstream water temperatures given tributary and meteorological inputs. Both streamflows and water temperatures would then be available as inputs for a salmon production model (e.g., SALMOD) to help compare the relative merits, or demerits, of the various scenarios. In this study, a refined version of the SALMOD model was used to help evaluate the potential benefits and costs of various alternatives as part of the ongoing EIS evaluation. Streamflows and water temperatures were derived from Reclamation modeling estimates using the HEC-5Q model (more fully described in the Flow and Water Temperature Data section below).

USGS has previously applied SALMOD for Chinook salmon in the Sacramento River between Keswick Dam and Battle Creek (Kent 1999). SALMOD computes the effects of flow and water temperature on growth and survival of Chinook salmon. Kent (1999) first applied SALMOD to the Sacramento River for fall-run Chinook salmon. Kent's work was expanded to include the other Chinook salmon runs in the Sacramento River and shown to produce production estimates of approximately the correct magnitude and trend (Bartholow 2003). Since the last application of SALMOD on the Sacramento River, much progress has been made on many of the model's basic parameters based on continued literature review and application on the Klamath River in Northern California (Bartholow and Henriksen, 2006). For this study, these new parameter estimates have been incorporated for the Sacramento River, and the study area was extended downstream to the RBPP (previously terminated at Battle Creek). This extended study reach encompasses an area where water temperatures may be more of an issue for spawning and rearing salmon.

Specific Objective of the Present Study

The specific objective of this study was to estimate the effects of water temperature and flows for the various alternatives on salmonids using SALMOD. Effects were evaluated by examining the relative change in overall production estimates generated by SALMOD for each of the four runs of Chinook salmon.

Methods

The modeling environment, including model selection and operation and data requirements, sources of data and parameter values, and important assumptions, is outlined in the following sections. Portions of the text were adapted from Bartholow and Henriksen (2006).

Model Selection

The modeling tools used in this EIS analyses were selected because they are publicly available, have a knowledgeable user community, and are widely accepted for use in similar system wide analysis of resources in the California Central Valley. Despite its acknowledge limitations, SALMOD is the best available tool that is accepted by the resource agencies for predicting project-related outcomes (on a relative, not absolute, basis) for all anadromous fish species in the upper Sacramento River. SALMOD was peer reviewed by Lisa Thompson and Chris Mosser of UC Davis (2011), and the SALMOD model applied for this EIS was developed in coordination with resource agency staff, including Mark Gard (USFWS) and Doug Killam (DFG). It has also been approved for use in several other studies, including the 2008 Biological Assessment on the Continued Long-Term Operations of the CVP and SWP (Reclamation 2008) and resulting 2009 BO and Conference Opinion on the Long-Term Operations of the CVP and SWP (NMFS 2009).

No accepted life-cycle model was available for use at the time the NEPA evaluation for the DEIS was conducted. While the Interactive Object-oriented

Salmon (IOS) model for winter-run Chinook salmon was used in the 2008 Reclamation BA, it was not considered an acceptable tool by NMFS. The tool has since been updated and revised, but there is no proof, as of yet, that it is considered by NMFS or other fisheries experts to be a reliable and acceptable model. NMFS is currently working on a life cycle model, but it was not complete at the time this evaluation was conducted. Therefore, Reclamation used SALMOD as an accepted tool for SLWRI evaluations.

SALMOD (Version 3.8) is a component of the Instream Flow Incremental Methodology (IFIM) (Stalnaker et al. 1995). Another component of the IFIM methodology, specifically the Physical Habitat Simulation System (PHABSIM), has been criticized (e.g., Conder and Annear 1987) as demonstrating no relationship between microhabitat quantification (weighted usable area, or WUA, an index to suitable microhabitat) and fish standing crop. Yet many other researchers persist in developing and using these relationships to relate WUA and standing crop (Capra et al. 1995; Heggenes et al. 1996). Like Stalnaker et al. (1995) and Bovee et al. (1994), Orth (1987) argued persuasively that it is illogical to expect any instantaneous relationship between habitat availability and fish density to hold true. Orth outlined the hypothesis that microhabitat availability may limit fish populations, but episodically, not continuously. In addition, he notes that other factors, such as water temperature, must be included in an analysis. In effect, Orth (1987) said that the PHABSIM models were incomplete. In response, the SALMOD model was constructed to integrate habitat limitations with a population through time and space, both microhabitat and macrohabitat. Note that when reference is made to habitat limitations, this does not necessarily mean that freshwater habitat is the ultimate factor limiting populations. Habitat constraints may simply reduce production while other factors, such as ocean conditions or fishing pressure, may be the ultimate “bottleneck.”

SALMOD was chosen for the study for several reasons, including:

1. SALMOD has been previously used on the upper Sacramento River between Keswick Dam and Battle Creek (Kent 1999; Bartholow 2003)

2. SALMOD has been updated using model parameters and techniques developed for use on the Klamath River and from Sacramento River-specific Chinook salmon information obtained from USFWS and CDFW fisheries biologists (Bartholow 2003). The USGS completed a thorough review and update of model parameters and techniques on the Klamath River that enabled a smooth transfer of relevant model parameters to the Sacramento River (Bartholow and Henriksen 2006)

3. SALMOD has been peer reviewed by Lisa Thompson and Chris Mosser of University of California (UC) Davis (Thompson and Mosser 2011)

4. SALMOD has been approved for use in several other Federal level studies, including the Reclamation's 2008 Long-Term Operation BA for compliance with Section 7 of the ESA (Reclamation 2008) and resulting NMFS 2009 BO (NMFS 2009a)

5. Resource agency personnel agreed that using SALMOD was the appropriate means of evaluating potential conditions after being presented with the model's capabilities by John Bartholow (formerly with the USGS) under contract by Reclamation

General Description of SALMOD

SALMOD simulates population dynamics for salmonids in freshwater; no population dynamics are included for ocean habitat. Though the model is applicable for both anadromous and non-anadromous salmonids, this chapter will only discuss the anadromous life-history implementation for Chinook salmon.[2] The model is fully described in Bartholow et al. (1993; 2001); only an outline of the model is presented here.

The model's premise is that egg and fish mortality are directly related to spatially and temporally variable microhabitat and macrohabitat limitations, which themselves are related to the timing and amount of streamflow and other meteorological variables. SALMOD is a spatially explicit model (Dunning et. al. 1995) in which habitat quality and carrying capacity are characterized by the hydraulic and thermal properties of individual mesohabitats, which serve as spatial computational units in the model. The model tracks a population of spatially distinct cohorts that originate as eggs and grow from one life stage to another as a function of water temperature in a computational unit. Individual cohorts either remain in the computational unit in which they emerged or move, in whole or in part, to nearby units. Model processes include spawning (with redd superimposition), incubation losses (i.e., redd scour or dewatering), growth (including egg maturation), mortality due to water temperature and other causes, and movement (freshet-induced, habitat-induced, and seasonal).

The model is organized around events (Figure 5-1) occurring during a biological year (sometimes known as a production year or brood year), beginning with spawning and typically concluding with fish that are physiologically "ready" (i.e., presmolts) swimming downstream toward the ocean. The model operates on a weekly time step for one or more biological years. Input variables (e.g., streamflow, water temperature, number, and distribution of adult spawners) are represented by their weekly average values. The study area is divided into individual mesohabitat[3] types (e.g., pools, riffles,

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[2] While steelhead are not evaluated directly in SALMOD, effects for late fall-run Chinook salmon are considered representative for steelhead since NMFS, in their 2009 BO, assumed late fall-run Chinook salmon could be used as a surrogate for steelhead because they have similar life history stages, including spawning at the same time of the year (NMFS 2009a).

[3] Microhabitat refers to small-scale physical features defining suitability for fish on a fish's scale, for example 1 meter. In contrast, mesohabitat refers to the character of the channel that defines microhabitat (for example tens of meters).

runs) categorized primarily by channel structure and hydraulic geometry but modified by the distribution of features such as fish cover. Thus, habitat quality in all computational units of a given mesohabitat type changes similarly in response to discharge variation.

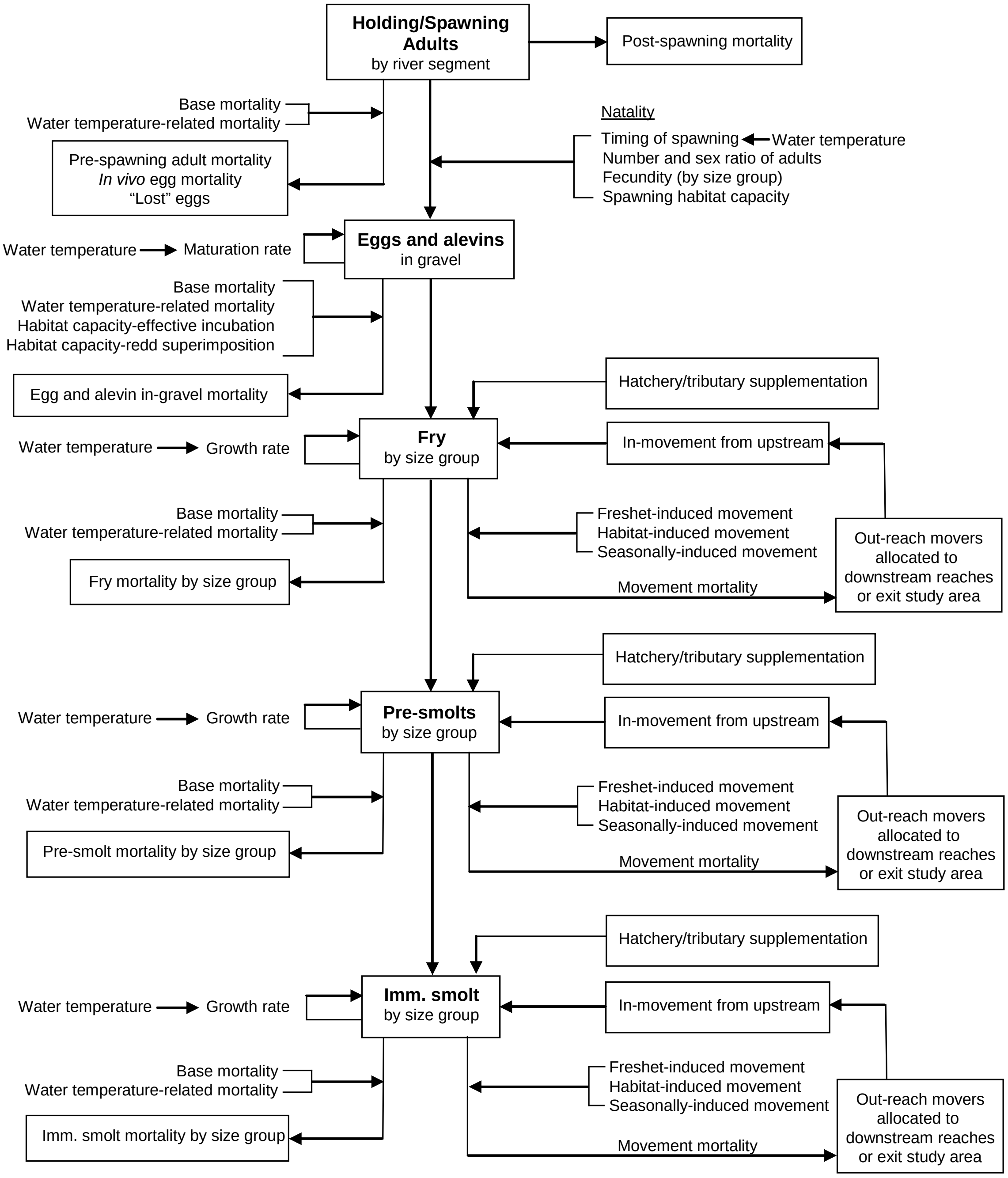


Figure 5-1. Conceptual Illustration of Factors Important in Controlling Salmon Production Throughout SALMOD Biological Year

Fish cohorts are tracked by life stage and size class within the spatial computational units. Streamflow and habitat type determine available habitat area for a particular life stage for each timestep and computational unit. Habitat area (quantified as WUA) is computed from flow: microhabitat area functions developed empirically or by using PHABSIM (Milhous et al. 1989) and River 2D. Habitat capacity for each life stage is a fixed maximum number (or biomass) per unit of habitat area available estimated from literature or empirical data. Thus, the maximum number of individuals that can reside in each computational unit is calculated for each time step on the basis of streamflow, habitat type, and available microhabitat. Fish in excess of the habitat's capacity must move to seek unoccupied habitat elsewhere. Fish from outside the model domain (from stocking, hatchery production, or tributaries) may also be added to the modeled stream at any point in their life cycle.

Models such as SALMOD are attaining confirmation in the scientific literature. For example, Capra et al. (1995) demonstrated that spawning habitat availability reductions over continuous 20-day periods correlate well with production of age zero+ trout. Building on Capra's work, Sabaton et al. (1997) and Gouraud et al. (2001) have further explored the field of limiting factors, both microhabitat and macrohabitat, by using population models markedly similar to SALMOD, with some promising results.

Data and Parameter Sources for SALMOD

There are three primary sources for initial parameter values for Chinook salmon modeling on the Sacramento River. The first is from the Trinity River flow evaluation (USFWS and Hoopa Valley Tribe 1999), which in turn was an outgrowth of the work done by Williamson et al. (1993) and Bartholow et al. (1993). These values were reinforced by Kent (1999) and Bartholow (2003), who applied SALMOD for Chinook salmon on the Sacramento River downstream from Shasta Dam. Both of these applications added credence to parameter values, strengthened confidence in the model's predictive utility, and supplemented the analysis toolbox.

Second, because a full complement of values is never available for any site-specific model application, literature values developed for other rivers or related species are used. By necessity, data were obtained from unpublished material when this was the best source available to represent the life history of Chinook salmon in the Sacramento River. Where relevant, significant assumptions are included when data are borrowed from other species, locales, or runs. A summary of the important model input values and assessment of their relative certainty or uncertainty is also provided.

Third, a great deal of biological information is available on the Sacramento River. Much of this information is found in unpublished reports and databases, but has been used extensively in developing parameters for this modeling effort.

The data input for many of the parameters are sets of paired values. For example, thermal mortality values are described by a set of values for the temperature and corresponding life stage mortality rate (e.g., temperature1, mortality rate1, temperaturen, mortality raten). SALMOD always performs a piece-wise interpolation between user-specified values to derive intermediate results or, if outside the range of supplied values, extends but does not extrapolate the terminal values.

Definition of Model Life History Structure

Life Stage and Size Classes The naming of life stages and size classes is flexible in SALMOD and generally reflects the nomenclature used by local biologists. The egg class covers both eggs and in-gravel alevins (larvae or preemergent fry) with a developmental index roughly dividing the two equally in time. Smolts are referred to as immature solely because these fish may be of a size indicative of a smolt but are not yet tolerant of saltwater, and they are still many kilometers from the ocean. Table 5-1 lists the class attributes chosen for the Sacramento River and is a modification of the categorization used on the Trinity and Klamath rivers.

Table 5-1. Life Stage and Size Class Naming and Break Points

SALMOD Life Stage	Other Names for Life Stage	Development Index (0 to 1.0) for Eggs, Length Class (mm) for Juveniles		
			Min	Max
Eggs	• Eggs		0.0	0.6
	• Alevins		0.6	1.0
Fry	• Yolk-sac fry	F1 =	30	40
	• Fry	F2 =	40	60
Presmolts	• Parr	P1 =	60	70
	• Silvery parr	P2 =	70	80
		P3 =	80	100
Immature smolts	• Smolts	S1 =	100	150
		S2 =	150	200
		S3 =	200	269

Key:
mm = millimeters

Weight: Length Data

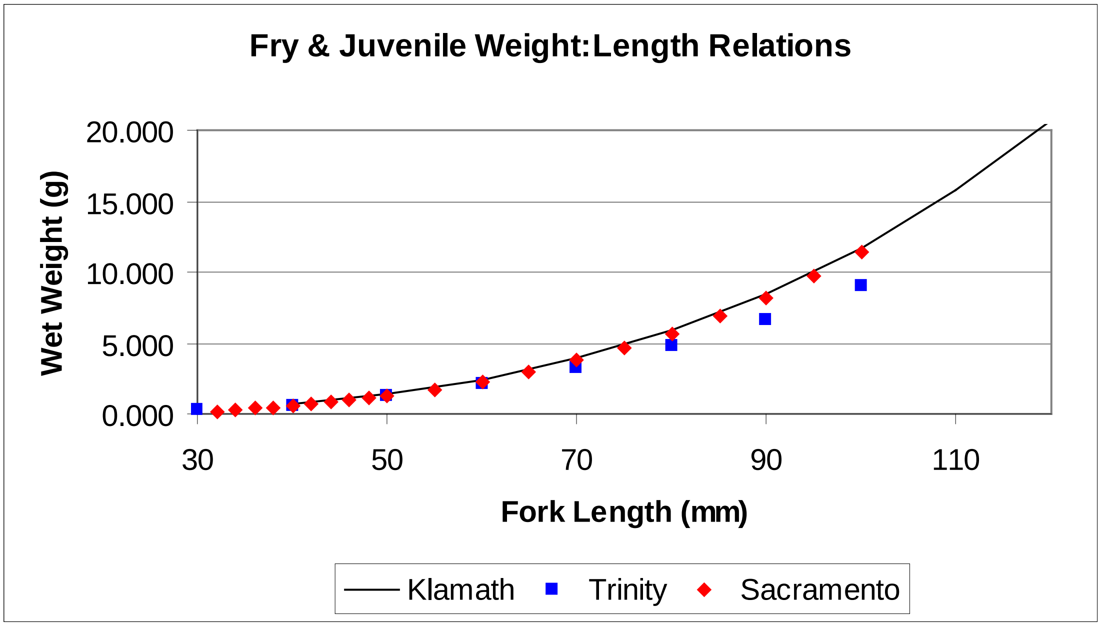
Kent (1999) used a formula based on a cubic regression of fork length and wet weight developed for naturally reared fall-run Chinook salmon with lengths between 30 and 100 millimeters (mm). A cubic regression was used because the length and weight relationship for fish is approximately cubic (Busacker et al. 1990):

$$WW(g) =$$

$$-0.67 + 0.0282FL - 0.000491FL2 + 0.0000141FL^3 \text{ (R unspecified)}$$

where WW = wet weight (grams) and FL = fork length (mm)

Figure 5-2 contrasts weight:length relations for three California rivers for the length ranges from which the data were derived. Variability in the wet weight of individual fish of the same fork length may be due to true variation in weights or may simply be explained by differences among individuals in fullness of the stomach or presence of water in the buccal (mouth) cavity. Nonetheless, it might be reasonably concluded that Sacramento River and Klamath River Chinook salmon have better condition factors than those from the Trinity River, at least for the time periods from which these fish were collected and relations developed. Klamath River fish may be slightly heavier than Sacramento River fish of the same length, diseased juveniles (often found on the Klamath River) can appear to have higher condition factors (Bartholow and Henriksen 2006).



Source: Data from Bartholow and Henriksen (in press)

Figure 5-2. Weight:Length Relations for the Sacramento and Other Rivers

The weight:length relationship is used in SALMOD to convert from one metric to the other. Fish grow in body mass (weight) and are then assigned the appropriate length. The exception to this is if fish lose weight; if so, they retain their previous length, but must regain lost weight to add length. The weight:length relationship supplied to SALMOD for the Sacramento River is detailed in Table 5-2.

Table 5-2. Weight:Length Relationship for Sacramento River Fall-Run Chinook Salmon

Weight (g)	Fork Length (mm)	Weight (g)	Fork Length (mm)
1.112	48	11.34	100
1.275	50	15.258	110
1.742	55	20.008	120
2.3	60	40.1	150
2.961	65	92	200
3.734	70	310.5	300
4.632	75	1,437.5	500
5.663	80	3,944.5	700
6.839	85	5,888	800
8.17	90	12,000	900

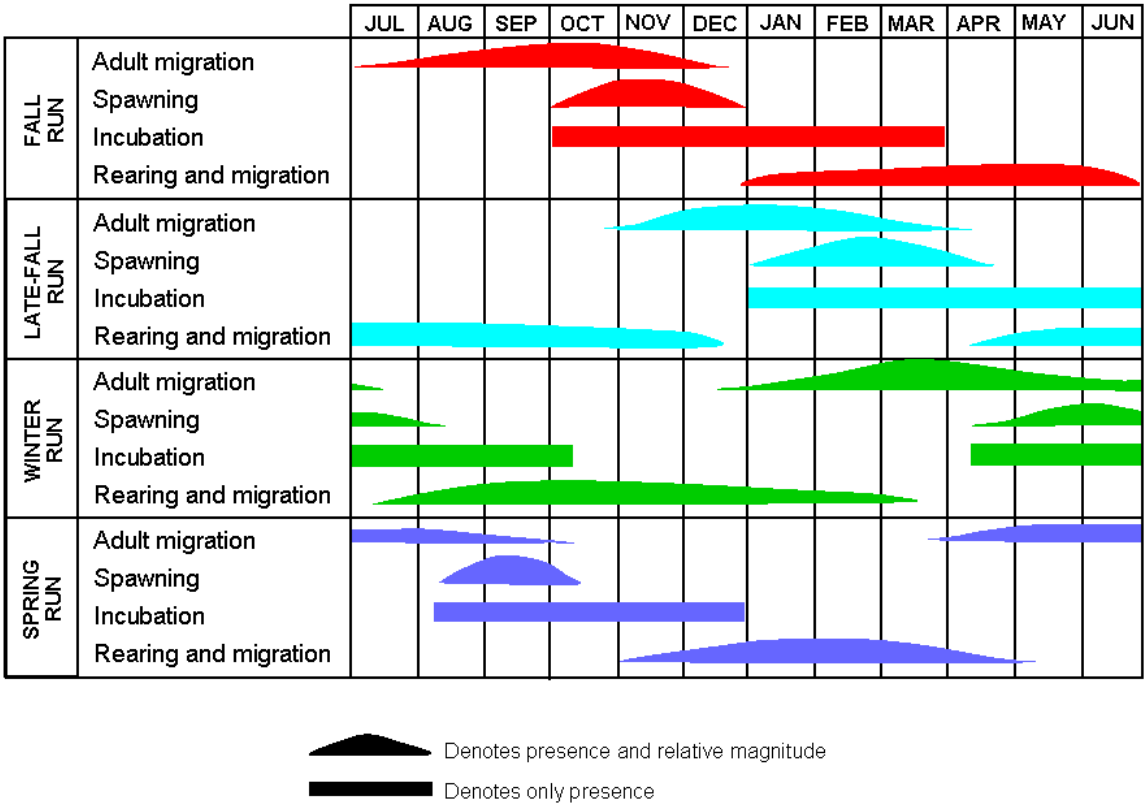
Note:

The number of decimal points reflects the need to convert back and forth accurately and should not be construed to imply precision.

Key:
g = grams
mm = millimeters

General Biological Year Timing SALMOD is a weekly time step model that, when used for an anadromous species with a single season in freshwater, most frequently begins with the onset of spawning and continues through the duration of outmigrating juveniles. For the Sacramento River, four distinct runs of Chinook salmon are of concern, each with different life history timing. Although it is theoretically possible to construct a single SALMOD model incorporating all runs (each as a separate "species"), it is advisable not to let the spawning season for any "species" span 2 “biological” years. For this reason, four distinct SALMOD data sets were constructed, each with different simulation timing and each uniquely named.

Sacramento River Chinook salmon life history timing is illustrated in Figure 5-3 (Vogel and Marine, 1991). Figure 5-3 and Table 5-3 were derived from this source and became the essentially fixed timing template for the model’s treatment of each run’s biological year. Some compromises were necessary to best fit run-specific timing into the capabilities of the model. Not all sources may agree with Vogel and Marine. For example, Frank Fisher (CDFW) created a "Race Designation Chart" (unpublished) that tends to show a much more protracted rearing period than Vogel and Marine. In addition, Healey (1994) argues that the various runs in the Sacramento River have no unique phenotype but rather a gradation of characteristics that can be related to and named. Others may argue that no true spring-run Chinook salmon spawn in the mainstem Sacramento River. This study, however, uses Vogel and Marine (1991). It is also assumed that most of the juveniles of each run will emigrate as ocean-type Chinook salmon (migrate to the ocean during their first year) if they are physiologically ready, although stream-type Chinook salmon (migrate to the ocean during their second year) likely exist in some cold-water tributaries, such as Deer and Mill creeks, and even Butte Creek on occasion (Brannon et al. 2004), and are shown to pass the RBPP in small numbers (DFG 2011).



Source: Vogel and Marine 1991.

Figure 5-3. Approximate Timing of Various Runs of Chinook Salmon

Simulation time steps referenced in SALMOD's input files are simply by chronological week number (Table 5-3). Note that simulation processes are initiated on the first day of the week, but simulation results are tabulated on the last day. This can be a cause for confusion when reviewing the output.

Table 5-3. Correspondence Between SALMOD Weekly Time Step and Biological Year for Each of the Four Runs of Chinook Salmon

Simulation Week	Fall-Run	Late Fall-Run	Winter-Run	Spring-Run
1	2-Sep	3-Dec	4-Feb	6-May
2	9-Sep	10-Dec	11-Feb	13-May
3	16-Sep	17-Dec	18-Feb	20-May
4	23-Sep	24-Dec	25-Feb	27-May
5	1-Oct	31-Dec	4-Mar	3-Jun
6	8-Oct	7-Jan	11-Mar	10-Jun
7	15-Oct	14-Jan	18-Mar	17-Jun
8	22-Oct	21-Jan	25-Mar	24-Jun
9	29-Oct	28-Jan	1-Apr	1-Jul
10	5-Nov	4-Feb	8-Apr	8-Jul
11	12-Nov	11-Feb	15-Apr	15-Jul
12	19-Nov	18-Feb	22-Apr	22-Jul
13	26-Nov	25-Feb	29-Apr	29-Jul
14	3-Dec	4-Mar	6-May	5-Aug
15	10-Dec	11-Mar	13-May	12-Aug
16	17-Dec	18-Mar	20-May	19-Aug
17	24-Dec	25-Mar	27-May	26-Aug
18	31-Dec	1-Apr	3-Jun	2-Sep
19	7-Jan	8-Apr	10-Jun	9-Sep
20	14-Jan	15-Apr	17-Jun	16-Sep
21	21-Jan	22-Apr	24-Jun	23-Sep
22	28-Jan	29-Apr	1-Jul	1-Oct
23	4-Feb	6-May	8-Jul	8-Oct
24	11-Feb	13-May	15-Jul	15-Oct
25	18-Feb	20-May	22-Jul	22-Oct
26	25-Feb	27-May	29-Jul	29-Oct
27	4-Mar	3-Jun	5-Aug	5-Nov
28	11-Mar	10-Jun	12-Aug	12-Nov
29	18-Mar	17-Jun	19-Aug	19-Nov
30	25-Mar	24-Jun	26-Aug	26-Nov
31	1-Apr	1-Jul	2-Sep	3-Dec
32	8-Apr	8-Jul	9-Sep	10-Dec
33	15-Apr	15-Jul	16-Sep	17-Dec
34	22-Apr	22-Jul	23-Sep	24-Dec
35	29-Apr	29-Jul	1-Oct	31-Dec
36	6-May	5-Aug	8-Oct	7-Jan
37	13-May	12-Aug	15-Oct	14-Jan
38	20-May	19-Aug	22-Oct	21-Jan
39	27-May	26-Aug	29-Oct	28-Jan
40	3-Jun	2-Sep	5-Nov	4-Feb
41	10-Jun	9-Sep	12-Nov	11-Feb
42	17-Jun	16-Sep	19-Nov	18-Feb
43	24-Jun	23-Sep	26-Nov	25-Feb
44	1-Jul	1-Oct	3-Dec	4-Mar
45	8-Jul	8-Oct	10-Dec	11-Mar
46	15-Jul	15-Oct	17-Dec	18-Mar
47	22-Jul	22-Oct	24-Dec	25-Mar
48	29-Jul	29-Oct	31-Dec	1-Apr
49	5-Aug	5-Nov	7-Jan	8-Apr
50	12-Aug	12-Nov	14-Jan	15-Apr
51	19-Aug	19-Nov	21-Jan	22-Apr
52	26-Aug	26-Nov	28-Jan	29-Apr

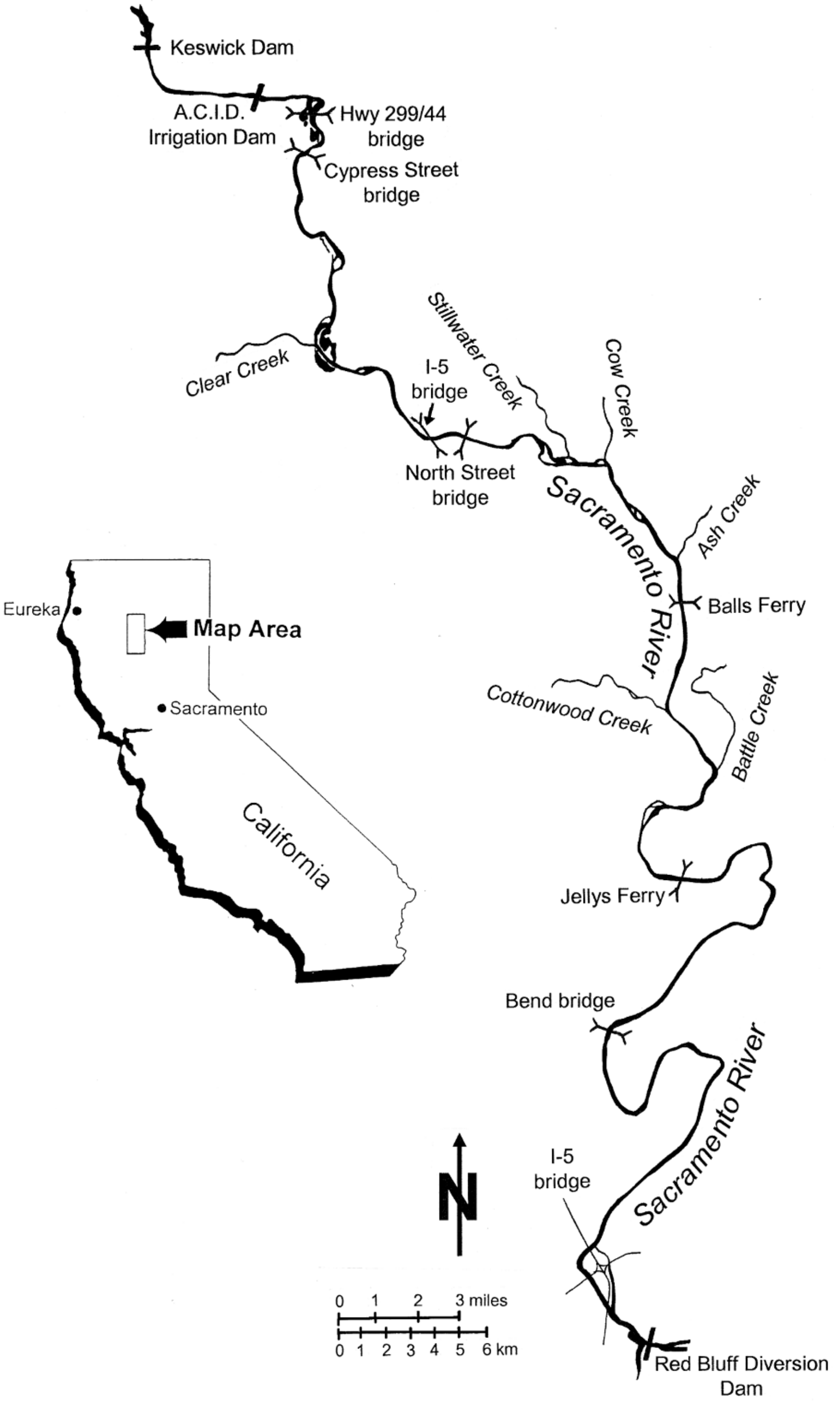
Physical Data

Study Area The study area for this analysis covers an 85-kilometer (km) (53-mile) stretch of the Sacramento River from Keswick Dam to just upstream from the RBPP at a latitude of approximately 40.5°N (Figure 5-4). Keswick Dam forms the current upstream boundary of anadromous migration in the Sacramento River, and the RBPP marks the current downstream limit of habitat that has been consistently classified by mesohabitat type, and evaluated using PHABSIM or a similar tool. The study area terminates at this point because at the time of model development the RBDD (at the site of the current RBPP) was operated with spillway gates that altered the inundation pool's hydraulics. This pool was not modeled for habitat value.

Flow and Water Temperature Data The upper Sacramento River temperature model was used to evaluate the potential impacts of each alternative on the Shasta cold-water pool volume, and on river temperatures. The water temperature model used for the alternatives analysis used mean daily flows and consisted of an HEC-5Q reservoir and river water temperature model developed and calibrated for the upper Sacramento River system. The model includes Shasta, Trinity, Lewiston, Whiskeytown, Keswick and Black Butte reservoirs and the Trinity River, Clear Creek, the upper Sacramento River from Shasta to Knights Landing, and Stony Creek. A preprocessor program was developed to convert CalSim-II monthly average flows into daily values based on historical hydrologic patterns and operation constraints. The meteorology and inflow temperatures were correlated with historical air temperatures and extrapolated to include the entire 1922 through 2003 CalSim-II simulation period.

One set of Shasta Dam tailwater temperature targets was applied for operation of the TCD. Temperature targets were therefore not optimized yearly or by alternative. Although the temperature model cannot accurately simulate certain aspects of the actual operation's strategies used when attempting to meet temperature objectives, especially on the upper Sacramento River, the model results are still useful for general comparison of alternatives. In addition, modeled TCD operation is reasonably consistent with historical operations.

Flow (in cfs) and water temperature (in degrees Celsius (°C)) time series values derived from the HEC-5Q model were received from Reclamation for each scenario analyzed (RMA 2003). Data were in the form of a database of values for each day corresponding to the weekly average conditions for that day forward. Data covered the period of October 1, 1921, through September 30, 2003, a total of 82 water years. Data were extracted from this database appropriate for each run and each scenario.



Note:

Ranges from Keswick Dam to the Red Bluff Diversion Dam. Shasta Dam lies approximately 14.5 kilometers (9 miles) upstream from Keswick Reservoir, off this detailed map.

Figure 5-4. Salmon Production Model Study Area in Northern California

Because each run has an individually defined biological year (Table 5-4), decisions about when to begin the record for each run were made to reduce potential confusion. Table 5-4 illustrates how these data were organized by calendar year. One potential disadvantage to the approach used is for winter-run Chinook salmon. Their simulated biological year begins in February and ends in January. SALMOD will report the results for that biological year as of the January calendar year, even though the bulk of the winter-run's outmigration may have occurred the previous calendar year. Another consequence is that the SALMOD model can only be run for 81 biological years (1922 to 2003) because some data values at the beginning and end of the record cannot be used, given the staggered life history.

Table 5-4. Illustration of Flow and Temperature Data Extraction from the HEC-5Q Model Database and "Line Up" Across Four Chinook Salmon Runs

Month	Initial Calendar Year	Fall	Late Fall	Winter	Spring	Month	Last Calendar Year
10	1921					10	2000
11	1921					11	2000
12	1921					12	2000
1	1922					1	2001
2	1922			Begin		2	2001
3	1922			v		3	2001
4	1922			v		4	2001
5	1922			v		5	2001
6	1922			v	Begin	6	2001
7	1922			v	v	7	2001
8	1922			v	v	8	2001
9	1922	Begin		v	v	9	2001
10	1922	v		v	v	10	2001
11	1922	v		v	v	11	2001
12	1922	v	Begin	v	v	12	2001
1	1923	v	v	End	v	1	2002
2	1923	v	v		v	2	2002
3	1923	v	v		v	3	2002
4	1923	v	v		v	4	2002
5	1923	v	v		End	5	2002
6	1923	v	v			6	2002
7	1923	End	v			7	2002
8	1923		v			8	2002
9	1923		v			9	2002
10	1923		v			10	2002
11	1923		End			11	2002
12	1923					12	2002

Note:
Month 10 is October.

Note that this evaluation did not deal directly with flow ramping. However, ramping criteria are expected to minimize or eliminate impacts to steelhead and spring-run Chinook salmon fry and juveniles from stranding and dewatering. Ramping flows occur primarily at night when fish typically are more active and less likely to become isolated in pools or side channels. In addition, releases are reduced at slow rates over several nights, allowing adequate opportunities for fish to pass from shallow, near-shore areas and pools into the mainstem of the river. Stranding of winter-run Chinook salmon fry is not expected to be significant since large flows from Shasta Dam are usually stabilized by May. Regardless of expectations, with SALMOD's weekly flows, potential ramping effects are not considered.

Mesohabitat Sequence and Segmentation

Microhabitat refers to the collection of physical characteristics (depth, velocity, substrate, cover) that determine suitability of a given river's "space" for fish of a given life stage (e.g., adults, juveniles), essentially on a square meter or finer scale. By contrast, mesohabitat refers to larger channel forms such as riffles, pools, or runs that tend to respond similarly to changes in flow. It has been argued that collecting data for a PHABSIM microhabitat study was best done at the mesohabitat unit (also known as a channel geomorphic unit) level; microhabitat is characterized by multiple samples of each mesohabitat type within each subsegment. SALMOD carries this process further by retaining the exact sequence and length of each mesohabitat type as computational units within the model.

One of SALMOD's inputs is a description of mesohabitats for the study area. This list is arranged from upstream to downstream and tabulates the sequence of mesohabitat types and their length. Each habitat in the list becomes a computational unit for the SALMOD model. The list ends with a table giving the longitudinal boundaries of where flows and water temperatures change in the model, referred to as segments. Although the flows and temperatures are supplied as separate input files, the list at the end of the habitat sequence denotes which computational units belong to which flow and temperature segments. Also, although flow and temperature segments need not be congruent with each other, they were for this application.

The habitat description developed by Kent (1999) extended from Keswick Dam to Battle Creek; subsequently, USGS contracted with the Sacramento office of USFWS to extend the mesohabitat description from Battle Creek to the inundation pool that was created by the RBDD at the time (at the site of the current RBPP). At that time, flash boards were in place intermittently, and the inundated habitat within the inundation pool had not been satisfactorily measured hydraulically. Thus, the study area terminated at the downstream end of the free-flowing river.

It was apparent that the mesohabitat delineation compiled by Kent, and the new delineation developed by USFWS, overlapped slightly. To resolve this overlap, coordinates for the beginning and end of the Battle Creek to Red Bluff section of the river were measured from the habitat map provided by USFWS (Gard 1995, 2003) using ARCGIS (v. 9.0). The distance from Keswick Dam to the beginning of the section from Battle Creek to Red Bluff was computed using Maptech Terrain Navigator software. These distances were used to determine the overlap between the upper and lower river descriptions. The old upper section computational units contained in the overlap were removed, as appropriate. The lower section computational units were then added to the remaining upper section units.

Next, the newly described habitat units from Battle Creek to Red Bluff were evaluated and converted to a sequential list of mesohabitats. However, a given river reach may have been typed in such a manner that a given habitat type only covered one-half of the river’s width, while the other one-half was another habitat type. Areas around islands were often mapped as complex habitat mosaics. Although the habitat was realistically described by USFWS, SALMOD is not capable of representing this level of habitat complexity, complicating the translation process.

Fifty-six habitat polygons were processed in sequence, from the most upstream polygon to the most downstream polygon. River length was measured for each habitat polygon representing a distinct segment of the river. This was done by tracing the centerline of the river from the upstream boundary to the downstream boundary using the ARCGIS v. 9.0 measurement tool. A single computational unit with the length measured was thus created for river segments containing a single habitat polygon.

For those segments containing habitat mosaics, a multistep process was used to divide the reach into sequential computational units. The total area for the reach was computed as the sum of the habitat areas for all constituent polygons. The length for each computational unit was computed as the ratio of the habitat polygon’s area to the reach area times the reach length. Computational units were ordered according to the upstream-to-downstream position of their respective habitat polygons. Where internal polygons were not near the edge of the river reach, the parent polygon was split, their areas estimated, and computational units were created with the parent units on the upstream and downstream side of the internal units. Side channels were treated as if they were internal to the river reach, and added as sequential computational units.

In total, 61 computational units were created from the original 56 habitat polygons, covering 22.27 miles of the river. This process preserved each unique habitat type and continues to reflect the diversity of habitats available and their approximate length. However, it does not reflect the true complexity around islands and may not reflect the exact sequence of habitat types encountered by a migrating salmonid. For example, if a juvenile took a right-channel path around an island, the habitat types encountered would be different from those experienced by a juvenile taking the other channel.

A table of flow and temperature segment descriptions was provided by Reclamation. These segments were developed from Reclamation's HEC-5Q model application and reflect approximate locations where tributaries are accounted for, or other "compliance" points. Within each segment, flows and temperatures are assumed to be homogeneous. The ACID diversion is the only major diversion within the study area. Balls Ferry, Jellys Ferry, and Bend Bridge are temperature compliance points on the Sacramento River.

Table 5-5 was used to develop estimates of river kilometers to assign the flow and water temperature segment boundaries. This was accomplished by measuring the distances for each named segment on USGS topographic maps using Maptech Terrain Navigator software. These distances were compared with delineated computational unit boundaries. Some of the new or previously existing computational units were split in two so that the flow and water temperature segment boundaries approximately coincided with computational unit boundaries.

Table 5-5. Flow and Water Temperature Segmentation for the Study Area

Segment Number	Length (miles)	Flow and Temperature Segments
1	3.5	Keswick Dam to ACID Diversion Dam
2	2.0	ACID Diversion Dam to Hwy 299/44 Bridge
3	7.5	Hwy 299/44 Bridge to Clear Creek
4	4.5	Clear Creek to Churn Creek
5	4.4	Churn Creek to Cow Creek
6	2.8	Cow Creek to Bear and Ash Creeks
7	1.1	Bear and Ash Creeks to Balls Ferry Bridge
8	2.7	Balls Ferry Bridge to Anderson Creek
9	0.5	Anderson Creek to Cottonwood Creek
10	1.7	Cottonwood Creek to Battle Creek
11	4.8	Battle Creek to Jellys Ferry Bridge
12	5.8	Jellys Ferry Bridge to Bend Bridge Gage
13	7.4	Bend Bridge Gage to Paynes Creek
14	10.3	Paynes Creek to Red Bluff Diversion Dam

Key:
ACID = Anderson-Cottonwood Irrigation District
Hwy = Highway

Finally, all computational units greater than 500 meters (m) long were split so that the maximum length of any computational unit was 500 m. This was done because SALMOD moves fish from center to center of adjacent computational units. Long computational units might result in unrealistically high movement mortality. Constraining the maximum computational unit length overcomes, or at least minimizes, this potential problem. In total, the stream habitat description resulted in 279 computational units from Keswick to Red Bluff

Diversion Dam, where the stream description was truncated, approximately 85 km (53 miles) in length.

Assigning Habitat Descriptions to Computational Units In SALMOD, each mesohabitat must have a corresponding estimate of the amount of WUA available throughout a range of flows for each life stage. Kent (1999) had compiled estimates of WUA for fall-run Chinook salmon for each mesohabitat type from hydraulic data collected in a 1990s study by DWR, but updated to include new habitat suitability criteria from USFWS. Bartholow (2003) expanded the analysis to include the other three runs, and slightly modified the same scheme that Kent had developed to include new information regarding which specific computational units did or did not appear to support spawning, and for a limited amount of run-specific spawning WUA estimates, both with the assistance of Mark Gard (USFWS, Sacramento). The result was a tri-part naming scheme–type:subtype:spawning or no spawning.

Habitat types received from USFWS were Bar Complex Riffle, Bar Complex Run, Bar Complex Glide, Bar Complex Pool, Flatwater Riffle, Flatwater Run, Flatwater Glide, Flatwater Pool, Side Channel Riffle, Side Channel Run, Side Channel Glide, and Side Channel Pool. These types are defined in Table 5-6 along with their habitat assignment to readily available and previously applied typing.

Table 5-6. Definitions of Habitat Types Received from the U.S. Fish and Wildlife Service for Mesohabitats Downstream from Battle Creek

Name	Characteristics
Bar complex	Submerged and emergent bars are the primary feature, sloping cross-sectional channel profile.
Flatwater	Primary channel is uniform, simple, and without gravel bars or channel controls, fairly uniform depth across channel.
Side channel	Carrying less than 20 percent of total flow.
Pool	Primary determinant is downstream control – thalweg gets deeper going upstream from bottom of pool. Fine and uniform substrate, below average water velocity, above average depth, tranquil water surface.
Glide	Primary determinants are no turbulence (surface smooth, slow, and laminar) and no downstream control. Low gradient, substrate uniform across channel width and composed of small gravel or sand/silt, depth below average and similar across channel width (but depth not similar across channel width for Bar Complex Glide), below-average water velocities, generally associated with tails of pools or heads of riffles, width of channel tends to spread out, thalweg has relatively uniform slope going downstream.
Run	Primary determinants are moderately turbulent and average depth. Moderate gradient, substrate a mix of particle sizes and composed of small cobble and gravel, with some large cobble and boulders, above-average water velocities, usually slight gradient change from top to bottom, generally associated with downstream extent of riffles, thalweg has relatively uniform slope going downstream.
Riffle	Primary determinants are high gradient and turbulence. Below-average depth, above-average velocity, thalweg has relatively uniform slope going downstream, substrate of uniform size and composed of large gravel or cobble, change in gradient noticeable.

Most of the habitats downstream from Battle Creek were bar complexes with a few side channels, which, in turn, were further subtyped and translated easily into Kent's glides (Subtype 1), runs (Subtype 2), riffles (Subtype 3), and pools (Subtype 4). In a few cases, when no equivalent type was readily available, categorization was based on the best assumption. For example, Kent (1999) had no side channel glide; therefore, flatwater was used in its place. For each habitat type downstream from Battle Creek, spawning WUA estimates were used from USFWS for each run (USFWS 2005b). Thus, the WUA estimates collected directly in the Battle-Creek-to-RBPP segment of the study area were not used, except spawning, because no assuredly comparable habitat types were identified. Inspection of USFWS (2005a; b) reveals that there is not likely to be much difference in at least the qualitative shape of the WUA relative to discharge curves for other life stages. However, this approach may not have captured the correct amount of habitat available in this segment.

Detailed redd counts were available that could have been used to delineate spawning/no spawning computational units (Gard 1995, 2003), as was done in the previous model application. It was assumed that all computational units with spawning habitat were spawnable.

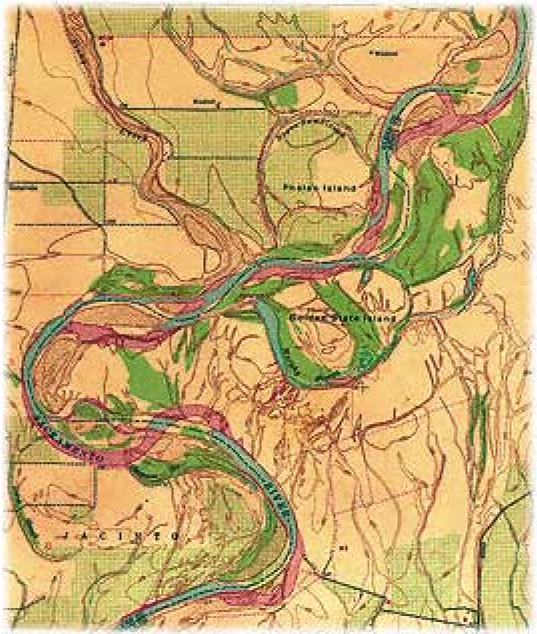
Microhabitat (WUA) Estimates for SALMOD Kent (1999) and Bartholow (2003) did not have WUA estimates for egg incubation habitat. Instead, they assumed that egg incubation habitat was essentially identical to spawning habitat by making them equivalent in SALMOD's WUA input file. On consultation with Mark Gard (USFWS), it became apparent that this assumption was likely responsible for overestimating egg incubation losses due to presumed redd scour. This is because SALMOD "remembers" the amount of spawning habitat available when each set of redds is constructed in each computational unit. If the egg incubation habitat declines in a unit due to changes in flow during the incubation period, SALMOD assumes a proportionate loss in egg incubation habitat. Such an assumption is reasonable when flows decline, potentially dewatering redds constructed at high flows, but the reverse is less logical. WUA for spawning in the Sacramento River peaks at relatively low flows (approximately 2,000 to 5,000 cfs). If flows exceed this range and WUA decreases, SALMOD would predict bed scour. But true bed scour is unlikely until very high flows are encountered.

A more reasonable way to treat egg incubation habitat is to assume that as long as eggs are "kept wet regardless of depth," they suffer no mortality until true scouring flows occur. Because the Sacramento River channel is generally quite large, scouring flows are unlikely to occur until discharge is similarly large. It is assumed that bed scour is likely above 50,000 cfs, given gravel displacement observations recorded by Bigelow (1996), and that significant bed-changing events occur above 60,000 cfs. Therefore, egg incubation WUA was derived directly from the estimated spawning WUA by retaining the rising limb of the spawning curve with increasing discharge, but then holding the maximum WUA value constant with increasing flow. This is equivalent to keeping the eggs wet regardless of depth. This maximum value was truncated when flows exceeded 50,000 cfs, linearly reducing the habitat value to zero at 60,000 cfs because of the increasing probability of redd-destroying bed scour or entombment.

Zero habitat above 60,000 cfs assumes that redd scour or entombment causes 100 percent egg mortality. Lapointe et al. (2000) estimated that scour would indeed “destroy” a redd, but they also estimated that flooding would scour a maximum of only 20 percent of a Canadian Shield stream. However, according to USGS (2006), this method only considered “net scour,” that is, what had changed from preflood to postflood. Such a technique risks ignoring the during-flood maximum scour extent. Montgomery et al. (1999) speculate a much higher mortality when scouring occurs at only modest egg burial depths (e.g., 80 percent at 30 centimeters (cm)). Note that SALMOD’s weekly time step may underestimate the frequency of scour from daily peak flow events, especially if those flows were derived from CALSIM’s monthly flow model.

There are two assumptions to note regarding the treatment of physical micro/mesohabitat. First, in assessing the effects of alternative flows and water temperatures on different life stages of salmon, it is assumed that the salmon do not use – or compete for – the same microhabitat at the same time. Although more than one juvenile life stage (e.g., fry and presmolts) of more than one run may be present in the Sacramento River at the same time, juvenile Chinook salmon use progressively deeper and faster water as they grow. Therefore, it is reasonable to assume that there is minimal competitive interaction. The same holds true with the assumption that juveniles are not competing with those of other species (e.g., steelhead). Obviously, these are ecological niche assumptions that could be strengthened or challenged by additional research.

Second, the quantification of WUA as a function of discharge is static. That is, it is assumed that none of the flows simulated result in changes to channel geometry, substrate composition (gravel quantity or quality), or cover availability. The Sacramento River does change its channel morphology (Figure 5-5), but the assumption is that such changes for this application are tantamount to dynamic equilibrium; that is, habitat types remain in approximately the same proportion before and after channel-changing events.



Credit: US Geological Survey

Note:
See http://www.forester.net/ec_0005_river.html and http://www.sacramentoriverportal.org/big_chico/1_40.pdf.

Figure 5-5. Illustration of Channel Change Along the Mainstem Sacramento River

Model Processes

Spawning

Spawner Characteristics SALMOD requires the specification of the number and attributes of adults to “seed” the model. A sex ratio is assigned of 48 percent spawning females to all other returning adults or grilse (Kent 1999).

The SALMOD model may be inappropriate in situations when the number of spawners is quite small. SALMOD relies on being able to treat many rate values (e.g., base mortality) as average values. When the number of fish in each cohort is small (less than 500), random events (attributable to either environmental stochasticity or individual fish variability) not captured by the model can play a larger, more stochastic role in survival than SALMOD “expects.” When spawner numbers are low (e.g., spring-run Chinook salmon 1992 to 2003 average), even more attention to model uncertainty is encouraged and other models, such as population viability analysis (PVA), might be more appropriate than SALMOD. However, it is unclear whether PVA would include detailed enough provision for altered flows and water temperatures to distinguish among scenarios.

Fecundity SALMOD uses a simple relationship for the number of eggs per gram of spawning female weight. Kent (1999) stated that the ratio he used was taken from Coleman National Fish Hatchery Lot History Reports, from the hatchery’s annual reports for fiscal years 1970 to 1997. This value is currently scaled to 5,000 eggs for a 12-kilogram (kg) fish.

It is assumed that Kent was referring to fall-run Chinook salmon. NMFS (no date) has noted that winter-run Chinook salmon have a lower fecundity (average of 3,353 eggs per female) than most other Chinook salmon populations, including Central Valley fall-run Chinook salmon (average of 5,498 eggs per female). Because of this potentially lowered reproductive potential, winter-run fecundity was reduced to 60 percent of that of the other runs.

Redd Area and Superimposition SALMOD calculates the amount of spawning habitat required each week for the number of female spawners ready to spawn, given the value supplied for the area of an average redd's egg pocket. The model also calculates the probability of redd superimposition for previously constructed and undefended redds (McNeil 1967) by knowing the area already occupied by preexisting redds. The model does not allow superimposition of redds created within one weekly time step; in effect, this means that redds are defended for one week.

A female spawner typically excavates multiple egg pockets by repeatedly digging in an upstream direction and depositing newly swept material on top of downstream egg pockets; the total area of disturbance may be more than 10 square meters (Neilson and Banford 1983). However, input values to SALMOD specify the approximate area of only the egg pockets for its calculation of superimposition mortality. The egg pocket refers to that area where deep streambed disturbance is at a maximum, indicative of essentially complete destruction of any previously deposited eggs. The egg pocket area is typically a value much smaller than the total area of disturbance. A value of 4.5 square meters (Bartholow 2003) was chosen after consultation with Mark Gard (USFWS).

SALMOD can simulate superimposition by using three distinct probability algorithms. For this application, the “avoidance” option was selected to reduce the assumed redd egg pocket area to 2 square meters in deference to California Department of Fish and Wildlife’s (CDFW) (formerly known as the California Department of Fish and Game (CDFG)) concerns. These changes, in effect, allow more spawners to use the same amount of spawning habitat with less superimposition.

Spatial and Temporal Distribution of Spawners SALMOD allocates adult spawners to designated segments of the river at the beginning of each simulation year; these segments may be defined differently from the flow and temperature division points described previously. Required data include the number of adults spawning in each section of river, the proportion of female spawners to nonspawners, and their weights, information typically available from carcass and/or redd counts. The values in Table 5-7 were used to seed the study area for each simulation year to clearly distinguish the effects of flow and water temperature, as opposed to escapement, in estimating salmon production. Note that the spatial distribution of spawners is assumed to be essentially the same with higher spawner numbers as it has been in the past with lower returns.

Table 5-7. Assumed Distribution of Spawners in Eight Spawning Segments Throughout the Study Area

Spawning Segment Number	Description	Cumulative Distance from Keswick (meters)	Proportion Spawning			
			Fall	Late Fall	Winter	Spring
1	Keswick to ACID	5,791	0.103	0.345	0.418	0.045
2	ACID to Highway 44 Bridge	9,025	0.062	0.153	0.205	0.191
3	Highway 44 Bridge to Airport Road Bridge	28,810	0.111	0.228	0.354	0.317
4	Airport Road Bridge to Balls Ferry Bridge	41,411	0.192	0.183	0.019	0.176
5	Balls Ferry Bridge to Battle Creek	49,207	0.129	0.056	0.001	0.106
6	Battle Creek to Jellys Ferry Bridge	56,538	0.188	0.021	0.001	0.151
7	Jellys Ferry Bridge to Bend Bridge	71,413	0.136	0.010	0.002	0.015
8	Bend Bridge to Red Bluff inundation zone	84,828	0.078	0.005	0.000	0.000
	Totals		**1.0**	**1.0**	**1.0**	**1.0**

Note:
Original location data covering years 2001 to 2005 were from data supplied by Reclamation. It was assumed that there were no redds in the Red Bluff inundation zone.
Key:
ACID = Anderson – Cottonwood Irrigation District

Spawn timing in SALMOD is set to occur regularly within a certain time window and is not specifically a function of streamflow or habitat availability, although it does depend on water temperature being within a certain range. If outside the specified bounds, fish that are ready to spawn will wait for the next time step and reevaluate the temperature. Some biologists believe that spawn timing may be more a function of habitat availability than water temperature. Although spawning in SALMOD does not directly respond to a habitat cue, limited spawning habitat will result in the spawners above the spawning habitat's capacity shedding their eggs or dying unspawned. Thus, SALMOD does indirectly consider habitat availability.

The model does not account for “green” spawners directly, but does so indirectly by allocating spawning activity through time based on "new" redds identified in the redd counts. Thus, it does not matter if spawning occurs only in 1 week or is spread out over 2 months or more. The model is told what proportion of adults is "ready" to spawn each week of the designated period. These proportions will hold unless other factors preclude spawning, such as temperatures being too high (they wait) or not enough spawning habitat even with superimposition (the adults shed their eggs and die). Adult mortality will be discussed later, but adults may suffer pre-spawn mortality from various causes (e.g., high water temperatures).

Spawn timing in this model application (Table 5-8) was identical to Bartholow (2003) and directly mimics the overall phenology shown in Table 5-8.

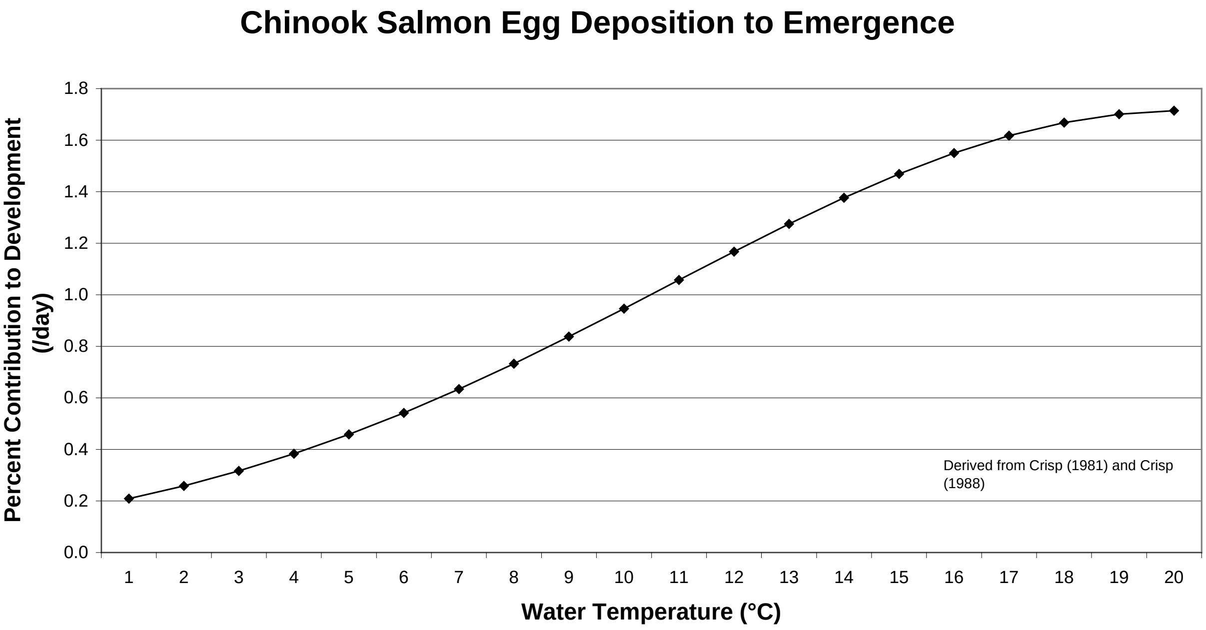
Table 5-8. Date and Fraction of Adults Converted to Spawners in Each Week of Their Respective Spawning Periods

Spawning Week	Fall-Run		Late Fall-Run		Winter-Run		Spring-Run	
1	1-Oct	0.02	7-Jan	0.02	15-Apr	0.02	12-Aug	0.12
2	8-Oct	0.06	14-Jan	0.06	22-Apr	0.06	19-Aug	0.13
3	15-Oct	0.12	21-Jan	0.12	29-Apr	0.12	26-Aug	0.15
4	22-Oct	0.16	28-Jan	0.16	6-May	0.16	2-Sep	0.16
5	29-Oct	0.20	4-Feb	0.20	13-May	0.20	9-Sep	0.20
6	5-Nov	0.13	11-Feb	0.13	20-May	0.13	16-Sep	0.08
7	12-Nov	0.08	18-Feb	0.08	27-May	0.08	23-Sep	0.06
8	19-Nov	0.07	25-Feb	0.07	3-Jun	0.07	1-Oct	0.05
9	26-Nov	0.06	4-Mar	0.06	10-Jun	0.06	8-Oct	0.05
10	3-Dec	0.05	11-Mar	0.05	17-Jun	0.05		
11	10-Dec	0.04	18-Mar	0.04	24-Jun	0.04		
12	11-Dec	0.01	25-Mar	0.01	1-Jul	0.01		
Total		1.00		1.00		1.00		1.00

Egg Development and Juvenile Growth

Egg Development Rate

After deposition, eggs incubate and hatch in approximately 6 to 12 weeks depending on local river temperatures. Alevins remain in the gravel for an additional period, living off the still-attached yolk sac and emerge when 100 percent of the development accumulation is reached. A quadratic equation was used to calculate each day's thermal contribution from deposition to hatch (Crisp 1981). The resulting rate values were decreased to 60 percent to approximate the time from hatch to emergence (a slight modification of Crisp 1988), as used by Bartholow (2003). The resulting rate function supplied to SALMOD is shown in Figure 5-6. This function shows that eggs will mature more rapidly at 10°C (50 (°F) than at 2°C (35.6°F). Note that thermal accumulation begins with egg deposition and does not account for any ova maturation that may have occurred *in vivo*.



Note:
Each week adds to the percent development until 100 percent is reached.

Figure 5-6. Egg and Alevin Development Rate as a Function of Mean Weekly Water Temperature

Minimum Emergence Temperature

SALMOD does not allow fry to emerge from the gravel until mean weekly water temperature exceeds a user-specified threshold. Previous applications have used a minimum of 8°C (46.4°F) based on work on Atlantic salmon (Jensen et al. 1991), although it is known that in-gravel feeding for Chinook salmon alevins may still be underway (Heming et al. 1982). Verifying this relationship is problematic on the Sacramento River because trapped fry may have originated in warmer, spring-fed tributaries, biasing any estimate of true emergence temperature. Bartholow and Henriksen (2006) carefully examined a variety of data sources for the Klamath River and concluded that an emergence value of around 7°C or 8°C (44.6°F or 46.4°F) was not unreasonable.

There may indeed be a threshold emergence temperature, although it might vary from river to river or area to area. However, the suite of simultaneous environmental cues is difficult to decouple, and most likely fish will synchronize spawn timing to “optimize” production, with the development rate being purely mechanistic. Chinook salmon can feed in the gravel and remain there after their yolk is absorbed if conditions make moving out of the gravel unsuitable.

Because of this uncertainty, the minimum emergence temperature was set to 6°C (42.8°F) until more mainstem-specific evidence may be brought to bear on the issue. SALMOD has no upper temperature threshold. If temperatures are too hot, fry will die due to thermal mortality.

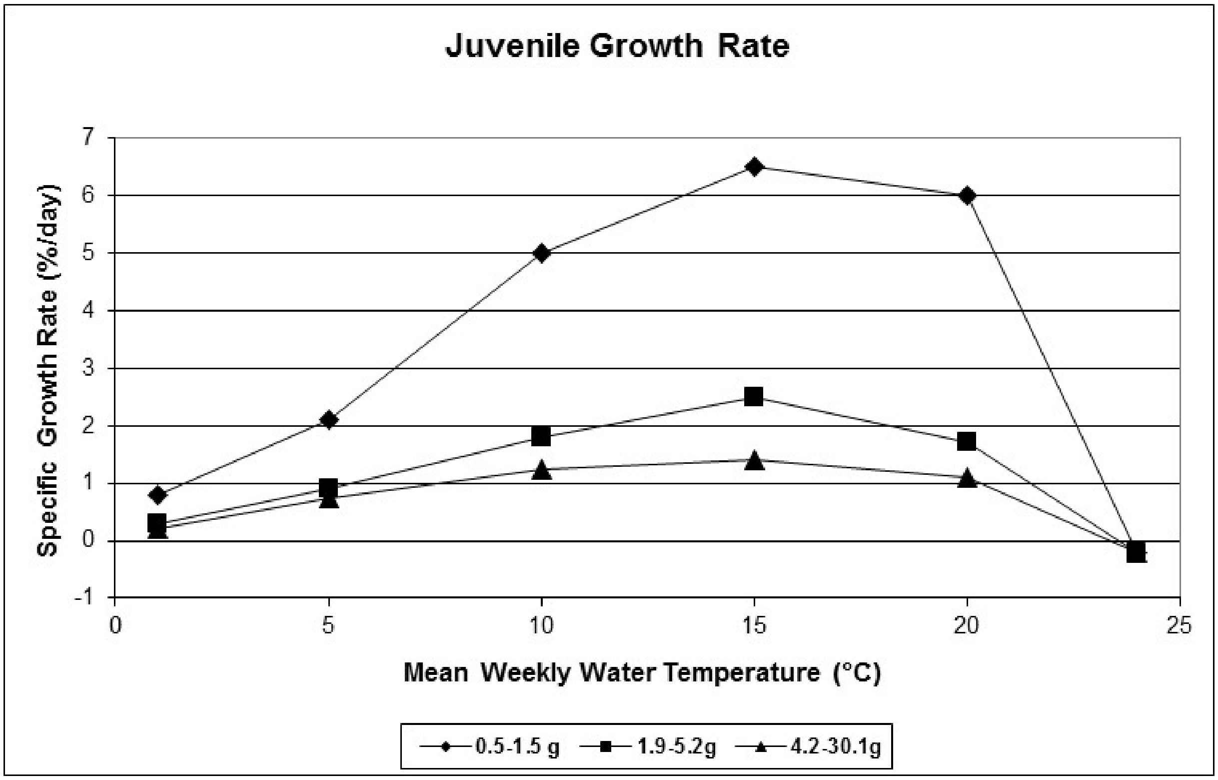
Emergent Length

Eggs incubate after deposition and hatch after 6 to 12 weeks, depending on water temperatures. Alevins remain in the gravel for an additional period, living off the still-attached yolk sac. The average weight of a fry on emergence from the gravel was given by Kent (1999) as 0.275 grams (g), equivalent to a 34 mm fish. Bartholow (2003) imposed a ± 4 mm deviation from this initial value, estimated from data shown in Vogel and Marine (1991), and this value is used for this application.

Juvenile Growth Rates

Growth rates for juvenile fish are important because the size that fry and presmolts achieve provides a competitive advantage to all subsequent life stages, being correlated with survival, smoltification, and reproductive success (Dill et al. 1981; Holtby and Scrivener 1989; Quinn and Peterson 1996). Growth rate is the most frequently reported measure of fish health (Sullivan et al. 2000), as it appears to integrate the full range of physiological responses to water temperature. In SALMOD, growth is (almost) solely a function of mean weekly water temperature. Although the weekly time step has been questioned regarding its adequacy in handling thermal mortality, a mean weekly temperature approach for growth appears well justified. Several authors have investigated the effects of fluctuating temperatures on growth. Fortunately, a time-weighted mean provides essentially the same results as integration over much smaller time increments (Sullivan et al. 2000).

Growth as a function of water temperature for juvenile life stages was obtained from Shelbourne et al. (1973) and is the same function used on the Trinity and Klamath rivers. Note that this function (Figure 5-7) assumes a constant food supply with juveniles fed to excess. It is not known whether the Sacramento River downstream from Keswick is nutrient-rich, but simulated growth results from Bartholow (2003), at least for fall-run Chinook salmon, did not suggest that the SALMOD model was either over- or underestimating juvenile growth. The growth rates are consistent with findings from Marine and Cech (2004), who did not observe significant reductions in juvenile growth rates until daily temperatures, either means or maxima, exceeded 20°C (68°F).



Note:
Values are from Shelbourne et al. (1973).

Figure 5-7. Juvenile Growth Rates for Different Weight Fish as a Function of Mean Weekly Water Temperature

There is one exception to the statement that growth is solely a function of water temperature. SALMOD can control whether fish that are forced to move because of a habitat/density constraint will be allowed to grow or not. There is scant literature to support one view or the other, but Titus and Mosegaard (1991) concluded that newly emerged trout fry that successfully established feeding territories grew well in contrast to those forced into downstream movement. In fact, they characterized the emigrants as “starved” on the basis of otolith measurements. For this reason, SALMOD is set to allow growth only for juveniles not forced to move, the assumption being that energy is preferentially expended by movers in search for new territory and is not available for growth. In contrast, SALMOD is set to allow growth during volitional seasonal downstream movement (discussed in the following section), as reported by Mikulich and Gavrenkov (1986).

Movement and Associated Mortality

Seasonal Movement Timing and Attributes

SALMOD moves juveniles a specified distance downstream through a specified time period. The assumption is that these fish are physiologically "ready" and that some combination of external timing cues (e.g., water temperature, discharge) triggers downstream volitional movement of (pre)smolts (McDonald 1960; Bjornn 1971).

Bartholow (2003) used Vogel and Marine's (1991) timing chart to estimate times for the bulk of outmigration for presmolts and immature smolts (not fry) of each run. However, it was found that under many circumstances, with the larger number of adult spawners and generally cooler water temperatures, too many fry (less than 60 (mm)) could remain in the study area even after 52 weeks of the biological year. For this reason, the outmigration period was extended throughout the biological year, as shown in Table 5-9. Through the outmigration period, the proportion of each life stage actively moving was assumed to increase through time from 30 to 95 percent, while the corresponding mortality rate associated with this movement was assumed to decrease through time from 1.5 to 1 percent, a lower rate than previously used because higher rates had been questioned on the Klamath River.

Table 5-9. Time Windows for Outmigration for Presmolts and Immature Smolts

Run	Time Period
Fall-run	27-May to 26-August
Late fall-run	26-August to 26-November
Winter-run	29-October to 28-January
Spring-run	28-January to 29-April

Note that SALMOD does not adjust movement distance based on the river's discharge, as has been documented for the Columbia and Snake rivers (Berggren and Filardo 1993). This is an area of potential improvement in the model, although reasonable estimates of travel time would be needed relative to discharge for the juvenile life stages. Movement rates found by Berggren and Filardo (1993) would not be applicable because in that study, movement rates were computed for fish moving through impoundments.

Freshet Movement

Freshet movement was used initially in the model for the Trinity River but was discontinued because of lack of direct evidence for movement stimulus, and is currently disabled for the Sacramento River.

Freshets (sudden increases in discharge) have been associated with displacement of fry in some rivers (Irvine 1986; Saltveit et al. 1995). It is not clear whether such displacement is due to volitional movement, is entirely involuntary, or some combination of the two. Nor is it clear whether the stimulus is discharge, turbidity, temperature, or some combination (note that a water temperature “signal” may not occur in regulated rivers immediately downstream from sizable impoundments). SALMOD can displace juvenile life stages according to user-specified parameters governing the proportion of fish moved per weekly time period, the distance they are displaced downstream, and any associated mortality. Currently, there are three options for defining a freshet: (1) when the current time step flow is greater than or equal to twice the previous time step flow or is greater than or equal to twice the average of the previous three flows, (2) when the current time step flow is greater than or equal to twice the previous time step's flow and is greater than or equal to twice the average of the three previous time step flows, or (3) user-specified in the *Flow.Dat* input file. Note that a corollary to the previous discussion is that a lack of freshet stimulations may “encourage” juveniles to remain longer in freshwater than they might otherwise (Irvine 1986). Future application of SALMOD should more closely examine the evidence for or against simulating freshet-induced movement.

Base Mortality Rates

Base, or background, rates of mortality cover all causes of death not otherwise modeled by SALMOD. For example, "normal" or “background level” predation falls into this category, as would mortality because of chronically low dissolved oxygen egg survival, unscreened diversions, and the like. The fractional rates used came from the calibrated Trinity River model and are identical to those used previously on the Sacramento River (Bartholow 2003). The weekly base mortality rates were eggs, 0.035; fry, 0.025; presmolts, 0.025; and immature smolts, 0.025. The adult rate was 0.002 based on judgment.

Thermal Mortality Rates

Thermal effects on salmon have long been recognized as important on the Sacramento River. Thermal concerns span the range from (1) physiological changes, including direct or indirect mortality, growth rate, embryonic development, and susceptibility to parasites and disease, (2) changes to behavior, including seeking special habitat such as thermal refugia, altering feeding activity, shifting fish spatial distributions, and altered species interaction, (3) changes to periodicity, including duration of incubation, onset of spawning, onset of migration, and gonad maturation, and (4) interaction with other water quality constituents, including dissolved oxygen. Most of the temperature focus on West Coast rivers has been on high temperatures, with both the Central Valley of California and the Columbia River receiving the largest share of attention.

Thermal mortality values for SALMOD reflect 7-day exposure-related effects of water temperature. Acute mortality is generally defined as anything up to 96 hours, but SALMOD’s 7-day (168-hour) time step encompasses both acute and longer-term (chronic) mortality. The reason that SALMOD uses mean weekly water temperatures instead of maximum daily temperatures is a growing consensus that chronic, sublethal temperatures are often more significant than acute lethal temperatures, with the effects being both cumulative and positively correlated with the duration and severity of exposure (Ligon et al. 1999). Brett (1956) concludes that sublethal thermal stress is as decisive as lethal temperatures to survival. Sublethal effects are also associated with suboptimal growth rates, reduced swimming performance and associated predation, increased disease risk, and impaired smoltification (EPA 2003; Marine and Cech 2004).

SALMOD deals with thermal mortality by life stage, which is egg and alevin, fry, juvenile, and adult. There is also a special *in vivo* category for eggs inside female spawners. Literature suggests that exposure of eggs to high temperatures *in vivo* may not directly kill the eggs, but rather result in unviable fry that have high mortality. SALMOD, however, calculates *in vivo* mortality as if it occurred pre-spawn. (Note that *in vivo* egg mortality is calculated independently of other adult mortality; if an adult female dies for any reason, her eggs also die.)

Egg Thermal Mortality Rates

Work done by USFWS and Reclamation to evaluate the effectiveness of adding temperature control to Shasta Dam on the Sacramento River provided the basis for egg and embryo (including *in vivo* egg) mortality rates used in SALMOD. For this project evaluation, Reclamation built a salmon mortality model parameterized with values supplied by USFWS (Richardson and Harrison 1990) in collaboration with CDFW. The exact origin of the rate values supplied by Richardson and Harrison is somewhat obscure, but they cite Hinze et al. (1956) and Boles (1988), among others.

However, USFWS calculated what is called "crude" mortality rates because for most, but not all, of the rates presented (Table 5-10), USFWS divided the percent mortality by the number of days in the reference period to obtain average daily mortality. Crude mortality rates would not be correct for SALMOD or similar models because the model's mortality rates operate sequentially. For example, the egg mortality rate given by the USFWS (Richardson and Harrison 1990) for a temperature of 61°F is 80 percent at 15 days. Using the USFWS "crude" averaging method resulted in an average daily rate of 5.33 percent (USFWS reports 5.3 percent). But if this crude rate were applied for 15 consecutive days, the resulting mortality rate would be as follows:

5-day mortality (M15) = 1 - (1 - 0.0533)15 = 1 - 0.44 = 0.56

This rate is far different from the 80 percent USFWS expected and SALMOD requires.

Table 5-10. Calculation of Mean Weekly Mortality Rate as a Function of Mean Daily Water Temperature (diel fluctuations of 3°F) for Chinook Salmon

Temp (°F)	Temp (°C)	Given Egg Mortality (%/days)[1]	Given Egg Avg. Mortality (%/day)	Given Sac-Fry Mortality (%/days)	Egg Mortality (frct/day)[3]	Sac-Fry Mortality (frct/day)	Egg Mortality (frct/week)	Sac-Fry Mortality (frct/week)	Geometric Mean Mortality (frct/week)
<56	13.33	Natural[2]	0.00	Natural	0.000	0.000	0.000	0.000	0.000
57	13.89	8 / 24	0.40	Natural	0.003	0.000	0.024	0.000	0.016
58	14.44	15 / 22	0.70	Natural	0.007	0.000	0.050	0.000	0.034
59	15.00	25 / 20	1.25	10 / 14	0.014	0.007	0.096	0.051	0.081
60	15.56	50 / 12	4.16	25 / 14	0.056	0.020	0.333	0.134	0.272
61	16.11	80 / 15	5.30	50 / 14	0.102	0.048	0.528	0.293	0.460
62	16.67	100 / 12	8.30	75 / 14	0.319	0.094	0.932	0.500	0.867
63	17.22	100 / 11	9.00	100 / 14	0.342	0.280	0.947	0.900	0.934
64	17.78	100 / 7	14.00	NA	0.482	NA	1.000	NA	1.000

Notes:

Values on the left side of the table were given by Richardson and Harrison (1990); those shaded on the right are the replacement calculations.

[1] Percent mortality for the number of days indicated.

[2] Natural implies not elevated above normal background levels.

[3] Mortality expressed as a fraction.

Key:
°C = degrees Celsius
°F = degrees Fahrenheit
frct = fraction
NA = not applicable

The values reported by Richardson and Harrison (1990) were corrected using a formula to calculate what is called an "absolute" or "instantaneous" mortality rate, and then those rates were converted to the reference time period, namely 1 week for SALMOD. The same example is used for illustration:

$$M = 1 - (1 - M_n)^{1/n}$$

where

n is the number of days in the reference period, thus:

$$M_1 = 1 - (1 - M_{15})^{1/15} = 1 - (1 - 0.8)^{1/15} = 1 - 0.898 = 0.102$$

Then a 7-day mortality rate would be calculated as follows:

$$M_7 = 1 - (1 - 0.102)^7 = 1 - 0.472 = 0.528$$

Regrettably, the 100 percent mortalities for temperatures over 62°F given in Richardson and Harrison (1990) present a challenge for this technique. To account for this, a 1 percent survival is assumed for mathematical convenience.

Thus, a single-day mortality rate that would result in 99 percent mortality at 12 days could be calculated as follows:

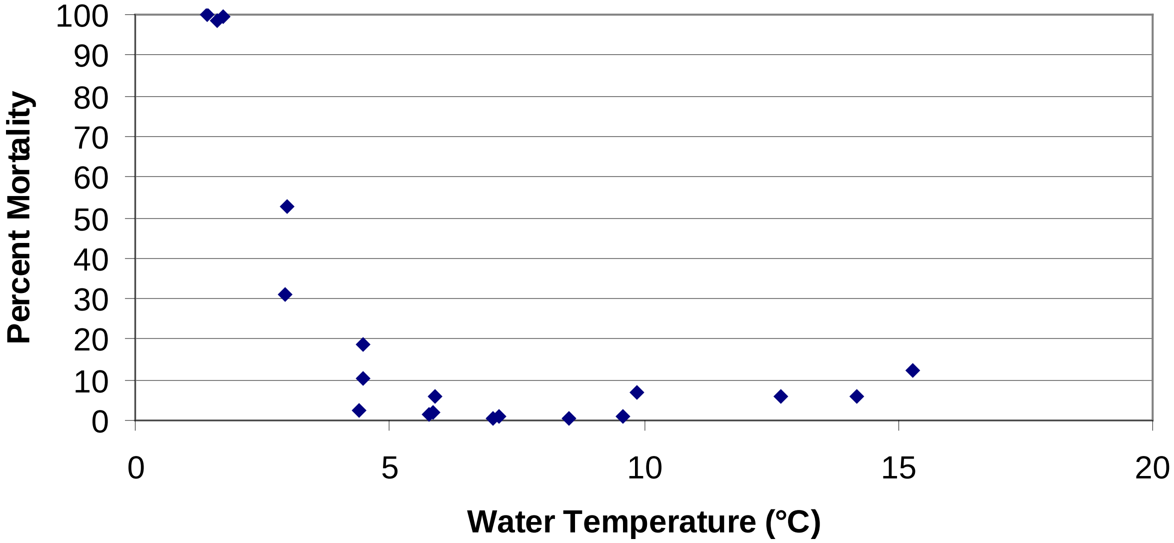
$$1 - (1 - M_1)^{12} = 0.99$$

$$1 - M_1 = 0.01^{1/12}$$

$$M_1 = 1 - 0.6812 = 0.3187$$

Also, the mortality rates Richardson and Harrison (1990) used for eggs and sac fry (embryos) were averaged to be consistent with the combined life history simulated in SALMOD for the Sacramento River. This was done by first calculating the absolute weekly mortality rate for both egg and sac-fry. These two rates were averaged by taking the geometric mean of their respective survival rates (analogous to what was done above). Weighting the two survival rates by their respective durations somewhat complicates this. That is, the egg stage lasts about two-thirds of the whole egg-alevin life stage whereas the sac-fry stage lasts about one-third. Thus, these two survival rates were weighted accordingly. This method assumes independence, which is probably not true, but a better alternative has not been identified.

With one exception, the last column of Table 5-10 then records the in-gravel egg mortality rates used in the model. Richardson and Harrison (1990) did not evaluate temperatures below 13°C (55.4°F), but Combs and Burrows (1957) supply relevant data for egg mortality under low constant water temperatures (Figure 5-8). Data from their study indicate substantial mortality below about 4.5°C (41°F). However, these low temperatures do not appear to occur on the Sacramento River, making them irrelevant for this analysis.



Source: Combs and Burrows (1957).

Figure 5-8. Chinook Egg Mortality from Low Constant Water Temperatures

In Vivo Egg Mortality

Donaldson (1990) compiled an extensive list of likely potential effects of stressors (not just water temperature) on sexually maturing adults, including changes in gonad development, changes in the endocrine control system, and changes in gametes, all of which may reduce reproductive success or ultimate recruitment. In SALMOD, these effects due to temperature have been lumped into the *in vivo* egg mortality category. In previous model applications, SALMOD has been parameterized using an *in vivo* mortality rate as a function of water temperature identical to the rate used for in-gravel eggs.

Although not cited by USFWS, probably the strongest evidence for *in vivo* gamete mortality has been presented by Berman and Quinn (1991), and Leitritz and Lewis (1980). In the Berman and Quinn (1991) study, sample size was too small to permit statistical analysis, and disease was an issue. Leitritz and Lewis (1980, p. 33) dealt primarily with hatchery methods, stating that young rainbow trout should be reared at about 15.5°C (60°F) for good growth, but then maturing rainbow trout (and Chinook salmon) should be held at water temperatures not exceeding 13.3°C (56°F), and preferably not above 12.2°C (54°F), for a period of at least 6 months before spawning. Flett et al. (1996) speculated that low egg survival of Coho salmon swimming through warm lake surface water to spawn in tributaries was due to “overripening” in females exposed to high, but not lethal, temperatures. Unfortunately, exact thermal exposure was unknown. Smith et al. (1983) showed that cutthroat trout whose holding temperatures ranged from 2 to 10°C (35.6 to 50°F) produced better quality eggs than those fish held at a constant 10°C (50°F), but the water sources were different.

Because there is a considerable body of published literature that suggests that a real *in vivo* thermal effect exists, a compromise was chosen. It is assumed that in-gravel egg thermal mortality rates apply for *in vivo* eggs, and that adults are behaviorally capable of buffering themselves (and their eggs) from the warmest in-river temperatures. For lack of any other value, the 2.5°C (4.5°F) difference found by Berman and Quinn (1991) for the Yakima River in Washington was used. Because of the uncertainty, this topic should be a priority for future research on the Sacramento River.

Juvenile and Adult Thermal Mortality Rates

Thermal mortality rates for juvenile and adult life stages were derived from Baker et al. (1995), who used coded-wire tag data to conclude that hatchery-raised fall-run Chinook salmon migrating through the Delta had an upper incipient lethal temperature (LT50) of 23.01±1.08°C (73.4±1.9°F). This value is slightly lower than well-recognized laboratory data with established acclimation temperatures but is pragmatically estimated in the field from trawl runs 2 to 5 days after hatchery releases. The Baker et al. (1995) data can be used to estimate a survival curve from a quasi-likelihood function the authors fitted:

$$\text{Survival rate} = 1 / (1 + e^{-a-bT})$$

where

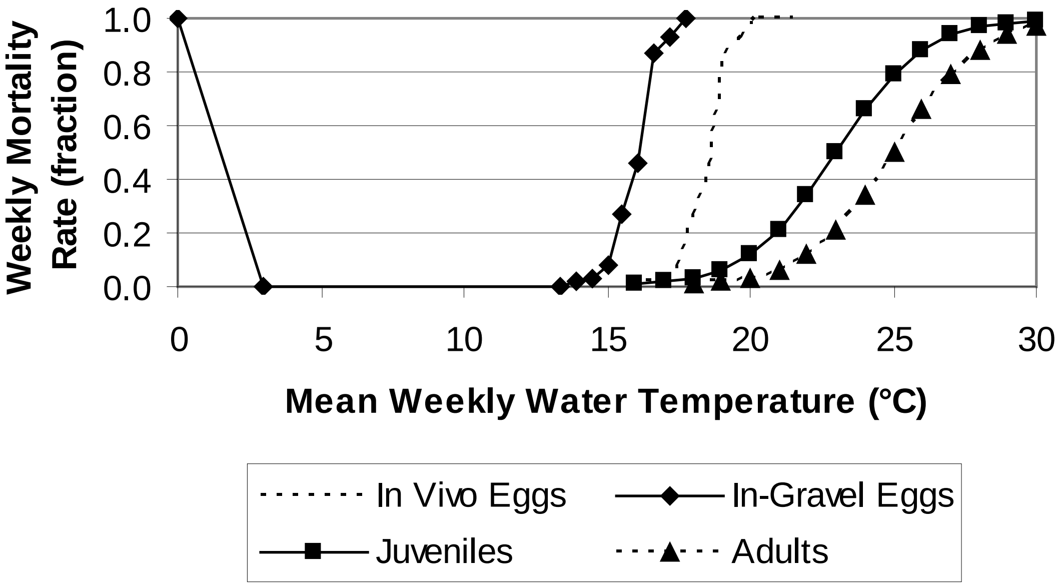
$a = 15.56$

$b = -0.6765$

T = mean daily water temperature for the sampling period

This method is appealing because it avoids problems associated with applying laboratory results to field situations, and has an exposure period roughly equal to SALMOD's. The mortality rates for juveniles derived from Baker at al. (1995) are assumed to also represent adult thermal mortality.

However, as has been discussed for in vivo eggs, adults may also be buffered from ambient thermal mortality. As mentioned previously, the study by Berman and Quinn (1991) demonstrated that adult spring-run Chinook salmon could maintain an average internal body temperature 2.5°C (4.5°F) below ambient river temperatures through a combination of specific cool-water habitat selection and behavioral timing. Although the study was for the Yakima River, at least some areas of cool-water refuges generally associated with tributary mouths are likely to exist in the Sacramento River. For example, Resource Management Associates, Inc. (RMA) (2003), identified Battle Creek, Paynes Creek, and Antelope Creek as “cool,” and Clear Creek, Chum Creek, Cow Creek, Bear and Ash creeks, Cottonwood Creek, Mill Creek, Deer Creek, Pine Creek, and Big Chico Creek as “moderate.” To be consistent with the in vivo mortality compromise, adults are buffered using the same 2.5°C (4.5°F) value. In other words, the model would treat an ambient water temperature of 17.5°C (63.5°F) as if it were only 15°C (59°F) for adults in calculating thermal mortality. The mortality curves used are shown in Figure 5-9.



Notes:
See text for a description of data sources and assumptions. Mortality values used for in vivo eggs and adults have been shifted to the right by 2.5°C (4.5°F) to reflect assumed adult behavioral "thermoregulation."

Figure 5-9. Fall-Run Chinook Thermal Mortality as a Function of Mean Weekly Water Temperature Used in SALMOD Simulations

Verification of Thermal Mortality Rates

Because SALMOD can be sensitive to thermal mortality rates for all life stages, it was appropriate to seek independent verification. Representative values from the literature are provided below. In general, the authors are referring to constant temperature experiments, but occasionally their metrics are not specific, as discussed below.

Healey (1977) examined egg-to-fingerling mortality at the Coleman National Fish Hatchery and concluded that mainstem Sacramento River temperatures should not exceed 14.2°C (57.6°F) to prevent abnormally high (about 80 percent) mortality.

Boles (1988) reviewed thermal requirements for each Chinook salmon life stage. Although not quantified in a manner suitable for direct comparison, his findings include the following: (1) adults held at temperatures in excess of 15.5°C (60°F) exhibited "poor" survival and "reduced" egg viability, (2) eggs incubated at temperatures in excess of 15.5°C (60°F) suffer "high" mortality, (3) eggs incubated in the range of 12.8 to 14.2 (55 to 57.5°F) experienced sac-fry mortality in excess of 50 percent, and(4) fingerlings appear to survive an upper lethal temperature of approximately 25.8°C (78.5°F) for long term exposure.

Marine (1992) explored a wide variety of thermal effects with an emphasis on adults and their progeny. His findings are summarized in Table 5-11.

Table 5-11. Compilation of Published Information and Summary of Observed Relationships Between Water Temperature and Various Attributes of Spawning Performance in Chinook Salmon

Temperature Range	Effect on Adult Salmon and Reproduction	Sources Cited by Marine
< 6°C (< 42.8°F)	Increased adult mortality, retarded gonad development and maturation, infertility.	Leitritz and Lewis (1976); Piper et al. (1982).
10°C to 18°C (50^{0}F to 64.4°F)	Physiological and behavioral optimum temperature range for nongravid adult salmon.	Coutant (1977); Piper et al. (1982); Raleigh et al. (1986).
6°C to 14°C (42.8^{0}F to 57.2°F)	Optimal pre-spawning broodstock survival, maturation, and spawning temperature range.	Leitritz and Lewis (1976); Piper et al. (1982).
15°C to 17°C (59^{0}F to 62.6°F)	For chronic exposure, inferred range of incipient sublethal elevated water temperature for broodstock, increased infertility, and embryonic developmental abnormalities.	See text for derivation of this temperature range.
17°C to 20°C (62.6^{0}F to 68°F)	For chronic exposure, incipient range of upper lethal water temperature for pre-spawning adult Chinook salmon (primarily derived from observations of captive broodstock).	Hinze et al. (1956); Rice (1960); Bouck et al. (1977); and personal communications (see text).
13°C to 27°C (55.4^{0}F to 80.6°F)	Increased pathogenesis of many of the important salmonid disease organisms with potential for impairing reproduction in Chinook salmon.	Fryer and Pilcher (1974); Becker and Fujihara (1978); Post (1987).
25°C to 27°C (77^{0}F to 80.6°F)	Range of highest elevated temperatures observed to be transiently passed through during migrations or tolerated for short-term by adult Chinook salmon.	Moyle (2002); Piper et al. (1982); California Department of Water Resources (1988).

Source: Marine (1992).

Note:

Infers the sublethal elevated temperature range, derived from scientific literature, agency reports, and interviews with fishery biologists and hatchery workers.

Key:
ºC =degrees Celsius
ºF = degrees Fahrenheit

Myrick and Cech (2001) provide a comprehensive review for Central Valley salmon. They conclude that eggs can survive between 1.7 and 16.6°C (35.1 to 61.9°F), but with increased mortality below 4°C (39.2°F) or above 12°C (53.6°F). The chronic upper lethal level is approximately 25°C (77°F) with higher temperatures, up to 29°C (84.2°F), tolerated for short periods. Marine and Cech (2004) provide the latest information for juveniles. They conclude that juvenile fall-run Chinook salmon can withstand chronic (more than 60 days) exposure to temperatures in the range of 21 to 24°C (69.8 to 75.2°F) (with diel fluctuations) and even grow when fed without limit, albeit at reduced rates. At these temperatures, smoltification was impaired, and the smaller fish were at increased vulnerability to predation. Fish reared at 17 to 20°C (62.6 to 68°F) grew well, but experienced variable smoltification impairment and higher predation rates than fish reared at 13 to 16°C (55.4 to 60.8°F). Although Marine and Cech (2004) conclude that the Baker et al. (1995) results likely represented indirect thermal effects as opposed to direct upper incipient lethal thermal effects, for SALMOD's purposes, the distinction is unimportant because thermal mortality covers both direct and indirect effects.

The latest compilation of information appears in information assembled in support of thermal criteria developed by The U.S. Environmental Protection Agency (EPA) primarily for use in total maximum daily load (TMDL) analyses (Poole et al. 2001). This compilation drew heavily from the work of McCullough (1999) and is summarized in Table 5-12.

Table 5-12. Estimates of Thermal Conditions Known to Support Various Life Stages and Biological Functions of Anadromous Salmon

Consideration	Anadromous Salmon	
	Celsius	Fahrenheit
Temperature of common summer habitat use	10 to 17°C	50 to 62.6°F
Lethal temperatures (1-week exposure)	Adults: >21 to 22°C Juveniles: >23 to 24°C	>69.8 to 71.6°F >73.4 to 75.2°F
Adult migration	Blocked: >21 to 22°C	>69.8 to 71.6°F
Swimming speed	Reduced: >20°C Optimal: 15 to 19°C	>68°F 59 to 66.2°F
Gamete viability during holding	Reduced: >13 to 16°C	>55.4 to 60.8°F
Disease rates	Severe: >18 to 20°C Elevated: 14 to 17°C Minimized: <12 to 13°C	>64.4 to 68°F 57.2 to 62.6°F <53.6 to 55.4°F
Spawning	Initiated: 7 to 14°C	44.6 to 57.2°F
Egg incubation	Optimal: 6 to 10°C	42.8 to 50°F
Optimal growth	Unlimited food: 13 to 19°C Limited food: 10 to 16°C	55.4 to 66.2°F 50 to 60.8°F
Smoltification	Suppressed: >11 to 15°C	>51.8 to 59°F

Note:

These numbers do not represent rigid thresholds, but rather represent temperatures above which adverse effects are more likely to occur. In the interest of simplicity, important differences between various species of anadromous salmon are not reflected in this table. Likewise, important differences in how temperatures are expressed are not included (for example, instantaneous maximums, daily averages, etc.).

Finally, Richter and Kolmes (2005) synthesized numeric water temperature criteria on a mean weekly basis as follows: spawning and incubation, 10°C (50°F); juvenile rearing, 15°C (59°F); adult migration, 16°C (61°F); and smoltification, 15°C (59°F). Therefore, no information appears to exist that provides more temperature dose-response quantification than that developed from Richardson and Harrison (1990), Combs and Burrows (1957), and Baker et al. (1995) with the modifications applied. However, it is apparent that much of the emphasis has been on developing thermal standards (thresholds), not examining exposure-related mortality. To corroborate the estimates derived from Baker et al. (1995), the more “classic” approach to calculate mortality, given exposure time and acclimation temperature, was examined. Armour (1991) summarizes parameters for an equation that shows, if evaluated to be greater than 1.0, when mortality is expected to occur:

$$1 \geq (\text{exposure time}_{\text{minutes}}) / (10[a + b^{(\text{temperature °C} + 2\text{°C})}])$$

where

a = 22.9065

b = -0.7611 for an acclimation temperature of 20°C (68°F)

Using this equation and a weekly exposure (10,080 minutes), a temperature of 23°C (73.4°F) is expected to result in 50 percent mortality, in remarkably exact agreement with the Baker et al. (1995) formula (see Figure 5-9). Thus, using multiple lines of evidence, relevant data and accepted methods point to the conclusion that the relationships given in Figure 5-9 are acceptable for modeling.

Uncertainty in Thermal Mortality Rates

Eggs The egg mortality rates derived from hatchery studies could be too high at moderate temperatures because eggs, and presumably embryos, remain buried in approximately 10 to 30 cm of gravel and may be buffered from in-channel water temperatures that would otherwise be too hot, or too cold, for optimum survival. Shepherd et al. (1986) showed that intragravel temperatures approximately 10 cm into the streambed cause parallel but lagged and buffered heating and cooling trends in infiltration-source intragravel water compared with surface water. Such waters were generally 0.5 to 1.0°C (0.9 to 1.8°F) warmer in winter and 0.5 to 1.5°C (0.9 to 2.7°F) cooler in summer, with crossovers around March and October. Hannah et al. (2004) showed that in-gravel incubation temperatures were, on average, 1.97°C (3.6°F) warmer than water column temperatures in a coastal Scottish salmon stream. However, Geist et al. (2002) found that Chinook salmon, unlike chum salmon, in the Columbia River tended to spawn in zones of downwelling water where presumably a redd’s thermal environment would be more like that of the main river. For the Sacramento River, it is assumed (Geist et al., 2002) that intragravel egg temperatures are likely to be little different from main channel water temperatures. This may be an appropriate area for research in the future.

Juveniles and Adults There may be problems using the Baker et al. (1995) technique applied previously. The data were collected from fall-run hatchery fish traversing the sometimes-brackish waters of the San Francisco Bay/Sacramento-San Joaquin Delta (Bay-Delta) system. Fish recoveries were made from mid-water trawls that may bias the interpretation for fish not actively (or passively) outmigrating. There are a variety of mathematical assumptions implicit in the curve fitting that Baker et al. (1995) created. Exposure times were not uniform and may or may not conform to SALMOD's weekly time step. Finally, the data represent only smolts, yet the results have been applied to all juvenile and adult life stages. In spite of these limitations, this approach is a step forward from the more simplistic habitat suitability index (HSI)-type method used in some previous SALMOD applications, and helps avoid using unmodified laboratory-derived data in real world applications (Ligon et al. 1999).

There has always been speculation that California's southerly salmon stocks may exhibit higher thermal thresholds than other West Coast stocks. However, during the course of the literature review, no conclusive evidence that this is true was found. McCullough (1999) investigated the issue of stock-specific thermal adaptation as part of his comprehensive review and found that although there are well recognized genetic adaptations to temperature that appear to tailor the fitness of stocks to their environment, absolute differences are small, generally attributable to morphological distinctions, and never result in a conclusion that thermal standards should be stock-specific. Myrick and Cech (2001) comment that Central Valley Chinook salmon, despite their southerly distribution, do not appear to have any greater thermal tolerance than more northerly runs. Further, thermal tolerance is a function of acclimation history that is an implicit consequence of each unique physical setting and time series of thermal exposure.

In summary, the identified suitable sets of thermal mortality rates for each of the Chinook salmon life stages are adequate, at least initially. Remaining uncertainty leaves some room for adjusting those rates.

Habitat Capacity

SALMOD assumes a relatively fixed "capacity" per unit of available physical habitat for adult and juvenile fish (Chapman 1962, 1966; Mesick 1988; Beechie et al. 1994; Burns 1971). Capacity is computed by knowing the flow in each computational unit, translating that into square meters of available habitat for each life stage, and knowing the maximum biomass or number of individuals for that life stage that can occupy a square meter of optimum habitat. The model moves juvenile and adult fish that exceed capacity to a downstream computational unit.

In previous SALMOD applications, either the maximum number of fish or maximum biomass per unit area was used. On the Trinity River, for example, the biologists preferred the maximum number because it best matched the data they had collected from systematic snorkel observations. Kent (1999) subsequently applied the Trinity River derived values to the initial Sacramento River model but did not calibrate the model. In an earlier study (Bartholow 2005), the maximum biomass approach was used rather than numbers of individuals because (1) it is more consistent with what was understood in terms of bioenergetic requirements, (2) measuring density with numbers per unit area has the problem that two individuals of different body size should not count equally, and (3) because biomass increases as fish grow in length and weight, such growth would result in a somewhat constant "pressure" for some individuals to move (Grant and Kramer 1990; Bohlin et al. 1994; see Grant et al. 1998, for a critique).

Regardless of the technique used, it is apparent that vastly different density estimates in different riverine settings can be obtained, and great care must be used to transfer site-specific density values from another river to the

Sacramento River, unless verified. Density estimates described by Grant and Kramer (1990) were largely from small, “natural” streams; the Sacramento River, with its in-line reservoir, is not natural or small. Further, SALMOD assumes that maximum habitat capacity is per unit of ideal habitat (WUA), and the quality of ideal habitat may not be transferable from small streams to large rivers (Grant et al. 1998). The factor most likely to influence the “currency,” and therefore lack of transferability from one stream to another, is food availability because food productivity is thought to directly affect minimum territory size (Grant et al. 1998). Hume and Parkinson (1987) cite stocking densities as low as 0.3 to 0.7 fry per square meter (fry/m^2) in low productivity British Columbia streams.

USFWS supplied revised site-specific maximum density estimates for the Sacramento River that were used in the previous model application (Gard 1995, 2003). These estimates were based on observations (actually 90 percent of absolute maximum observed) of 106 fry smaller than 60 mm and 200 juveniles larger than 60 mm. In the previous application, an average weight of 0.94 g for fry was used, resulting in approximately 100 g per unit WUA, but experimentation with the current model suggested that it was likely overestimating fry habitat-induced mortality. Fry can be anywhere from 30 to 60 mm, totaling from 20 to 240 grams per square meter (g/m^2) depending on their length; therefore, the maximum biomass density was increased to 250 g/m^2 for this application, in part because CDFW was wary of putting undue emphasis on juvenile habitat limitations, and the previous model (Bartholow 2003) was viewed as likely underestimating production. Table 5-13 reflects the maximum biomass for each life stage used in this Sacramento River application, identical to that used previously by Bartholow (2003), as corrected by Mark Gard (USFWS).

Table 5-13. Maximum Biomass per Unit WUA for Each Life Stage Used in the Sacramento River Application

Life Stage	Maximum Grams/Square Meter/WUA
Fry	250
Presmolts	1,162
Immature smolts	1,162
Adults	52.58

Key:
WUA = weighted usable area

Habitat-Induced Movement Rules

In the event that fry in a computational unit exceed the computed habitat capacity, SALMOD was set to first move the most recent arrivals out of that computational unit under the supposition that moving, nonterritorial fry are more likely to continue to move. In contrast, the model moves the more territorial presmolts and immature smolts with the lowest condition factor first, assuming that more robust fish have a territorial advantage. These two methods operate only within in a life stage category; that is, fry only compete with fry, and so forth. It is possible to set SALMOD to be even more size selective within a life stage. In other words, one could move the smallest, most recently arrived fry first, but that has not been done for this Sacramento River application because it does not appear to affect the results significantly. On the Sacramento River, all habitat-induced movement is set to be downstream only.

Distance Moved Mortality Rate

There is a mortality rate associated with habitat-constrained movement – the farther fish must travel to encounter unoccupied habitat, the greater their mortality. Although this mortality can be quantified in a variety of ways in SALMOD, it is conceptually easiest to specify the maximum distance that can be moved in 1 week before 100 percent mortality, linearly interpolating back to zero mortality at zero distance.

Kent (1999) and Bartholow (2003) used 3 km as the maximum distance regardless of life state/size class on the Sacramento River, relying on an estimate from CDFW. Juveniles that must move more than 3 km in a week due to lack of suitable rearing habitat will die. Assumption for this application was doubled, again because of CDFW’s concerns and the perception that the model as previously constructed was likely underestimating production (Bartholow 2003).

Exogenous Production

Chinook salmon production in the Sacramento River downstream from Keswick is not isolated to the mainstem. Several tributaries and two hatcheries (Battle Creek and Livingston Stone) also produce fish that supplement mainstem production, with those fish entering the mainstem at specific locations during specific time periods. If specified in SALMOD, these additional tributary fish contribute to production along with mainstem fish, undergoing all simulated mainstem events. It should be understood that these tributaries are not simulated as individual streams; rather, the exogenous production has been simulated as constant for each year just like adult mainstem spawners.

For this application, hatchery production information was compiled for the period of 1992 to 2004. Releases were, however, inconsistent between the hatcheries, with some releases made at downstream locations different from their hatchery stream. Because of these inconsistencies, and because most of the releases appeared to be made in a manner that deliberately avoids the peak outmigration period (presumably to avoid the possibility of competition for food and space with natural fish), hatchery production in this application is not included.

Weekly production estimates from Clear Creek, 1998 to 2004, were summarized by USFWS. The data were divided into four average weekly time series, one for each “run.” But according to USFWS personnel, the four categories represented fish length instead of true run. The majority of fish were nominally classified as fall-run Chinook salmon, with the other “runs” representing less than 2 percent of the “fall” fish. An average length for each weekly cohort was computed based on the length:weight conversion formula given previously, and scaled the numbers of fish in an attempt to better match the relative production between mainstem and tributaries. Because similar data for Battle Creek production were unavailable, the Clear Creek values were duplicated when these “fall” fish were added to SALMOD’s input files, as shown in Table 5-14. This was not done for the other runs because the number of fish in the other runs from Clear Creek was comparatively small.

Conceptually, tributaries enter the simulation model’s virtual river at 1 computational unit. Adding 1 week’s tributary contribution to a single computational unit would result in disproportionate crowding in that unit. An alternative would be to distribute these fish for a distance equal to 1 week’s travel time downstream, but this would essentially permit distribution throughout most of the study area. A compromise was selected by assuming that tributary fish would be distributed throughout a 5 km “mixing zone” downstream from each tributary. Juveniles entering the mainstem are treated just like mainstem cohorts; if they are moving seasonally, they will continue to do so.

Summary of Model Parameters and Variables

SALMOD has many input requirements. To the degree possible, evidence-based inputs from Sacramento-River-specific sources were used. However, some values were derived from literature sources, previous model applications, and assumptions. Table 5-15 summarizes these values and, where appropriate, shows which values have been changed from the previous application (Bartholow 2003).

Table 5-14. Scaled Number of "Fall" Chinook Salmon Added to the Fall-Run Chinook SALMOD Model to Represent Tributary Production

Date (month/day)	Week	Number of Fish	Weight (grams)
12/3	14	9,447	0.192
12/10	15	7,972	0.192
12/17	16	10,812	0.233
12/24	17	46,895	0.320
12/31	18	86,050	0.320
1/7	19	134,149	0.367
1/14	20	188,462	0.367
1/21	21	493,681	0.415
1/28	22	472,797	0.415
2/4	23	337,226	0.415
2/11	24	300,265	0.415
2/18	25	385,796	0.466
2/25	26	235,752	0.466
3/4	27	197,219	0.466
3/11	28	128,375	0.519
3/18	29	75,703	0.633
3/25	30	61,695	0.756
4/1	31	20,947	0.890
4/8	32	26,171	0.961
4/15	33	13,945	1.362
4/22	34	12,134	1.846
4/29	35	12,506	2.300
5/6	36	12,945	2.424
5/13	37	14,730	2.424
5/20	38	15,144	2.424
5/27	39	5,492	2.424
6/3	40	2,592	2.683
6/10	41	1,374	3.106
6/17	42	830	3.106
6/24	43	1,023	3.570
7/1	44	513	4.078

Table 5-15. Summary of Important Model Structural Elements, Parameters, Variables, and Potential Calibration Data, with Notes on Their Origin and Status

Element, Parameter, or Variable	Sacramento-River-Specific	Differs from Previous Application	Status
Study area	Yes	Yes	Fixed at present; Keswick to Red Bluff Pumping Plant.
Flow and temperature segments	Yes	Yes	Fourteen segments, matched to hydrology and thermal attributes of the river.
Flow and water temperature values	Yes	Yes	Comes from CALSIM/HEC-5Q. CALSIM deals in monthly flows that have been disaggregated to daily by Reclamation and subsequently aggregated by Reclamation and USGS to weekly means. These transformations may mask peak flows or temperature events. Scenarios are all synthetic, essentially eliminating the opportunity to field-verify model results. Water temperature model (HEC-5Q) also contains uncertainty and known seasonal biases (RMA 2003).
Mesohabitat typing data and sequence	Yes	Yes	Derived from detailed habitat mapping.
PHABSIM WUA quantification	Yes	No	Available, with assumptions. Differences in methods between Kent, DWR, and USFWS, as interpreted by USGS.
Biological year timing	Yes	No	Good.
Life stage nomenclature and size class breakpoints	Yes	No	Good.
Weight:length relationship	Yes	No	Well defined.
Spawning spatial and temporal distribution	Yes	Yes	Well defined, but using multiyear average.
Spawning temperature window	No	Yes	Well defined from literature.
Spawner density and characteristics	Yes	Yes	Reflects run-specific goals.
Fecundity	Yes	Yes, for winter-run only	From Coleman Hatchery and literature.
Redd area and superimposition	Yes	Yes	Well defined, but deliberately reduced estimated superimposition by reducing redd area, using “avoidance” option, and allowing spawning in computational units without recorded redds.
Egg development rate	No	No	From reliable literature.
Emergent length	Yes	No	From field measurements.
Minimum emergence temperature	No	Yes	Reasonable estimate, but called into question on the Klamath River.
Juvenile growth rates	No	No	Well-defined literature values that have worked well on this river.
Freshet movement attributes	Not used on Sacramento River	No	Largely stable flows in dry years may preclude measurement-monitor.
Seasonal movement timing and attributes	Yes for timing but no for distance	Yes	Not well defined.
Base mortality rates	No	No	Values derived from Trinity River.
Thermal mortality rates	Partly	Yes	Composite values from multiple literature sources.
Habitat capacity	Partial	Yes for fry; no for other life stages	Based on extensive sampling.

Table 5-15. Summary of Important Model Structural Elements, Parameters, Variables, and Potential Calibration Data, with Notes on Their Origin and Status (contd.)

Element, Parameter, or Variable	Sacramento-River-Specific	Differs from Previous Application	Status
Habitat capacity movement rules	No	No	Based on literature and previous model.
Distance moved mortality rate	No	Yes	Derived initially from Bill Snider (CDFW), but adjusted.
Exogenous production	Yes	Yes	Derived from Clear Creek; assumed Battle Creek was identical to Clear Creek; other tributaries and hatchery ignored.

Key:
CDFW = California Department of Fish and Wildlife
DWR = California Department of Water Resources
PHABSIM = Physical Habitat Simulation System
Reclamation = United States Department of the Interior, Department of Reclamation
USFWS = United States Fish and Wildlife Service
USGS = United States Geological Survey
WUA – weighted usable area

Sensitivity Analysis

SALMOD is a mathematical model constructed from a series of variable inputs, equations, and parameters that describe and quantify Chinook salmon production potential on the Sacramento River downstream from Keswick Dam. Variables are defined as those external driving factors (flow, water temperature, and spawner seeding density) that vary from time step to time step or year to year. Parameters are essentially fixed values controlling internal model computations. It is important to understand uncertainties in both model variables and parameters, but in this initial SA, model parameters are targeted. Sensitivity to flow and temperature variability will be addressed in another stage of the analysis.

Model parameters are subject to many sources of uncertainty, including errors of measurement, absence of information, and poor or partial understanding of important biological mechanisms. These limitations necessarily tax confidence in model predictions. Good modeling practice requires that the modeler provide an evaluation of his or her confidence in the model, a portion of which involves assessing uncertainties associated with all model inputs.

SA is one tool that can be used to accomplish the following:

- Apportion the relative variation in model output to variation in model inputs, qualitatively or quantitatively
- Identify those parameters in the greatest need of additional empirical data collection
- Identify factors that may prove useful in subsequent model calibration

- Identify insensitive variables that require little further attention
- Establish defensibility in the sense that reviewers are increasingly asking for SA as a component of a thorough modeling analysis

Sensitivity Analysis Methods

General steps followed in conducting an SA for SALMOD on the Sacramento River are as follows:

1. Specify the model output of interest. It is important to select only one or a few of the many outputs produced by a model and identify this as the output of interest. In this case, the key value chosen was the total annual number of Chinook salmon outmigrating downstream from the RBPP. Although biomass could have been chosen, numbers of fish were selected because this would be more widely understood by all stakeholders, and this metric was relied on during subsequent modeling analysis.

2. Select the inputs of interest from the full suite of possibilities, focusing on the most likely sensitive factors. SALMOD has literally many hundreds of input values. If every value were subject to variation, it would be very difficult to make sense of the voluminous results. For this reason, values were grouped into sets that were subsequently treated as single factors. For example, SALMOD has a set of x,y coordinates that describe the relationship between mean weekly thermal exposure and mortality rate for each life stage. Rather than test the sensitivity of each coordinate pair, the whole set of coordinates was shifted “left and right” by 2°C (3.6°F) for each life stage.

3. Choose the amount of variability for the selected factors. There is no single standard technique in performing an SA. Parameter variation is typically specified either as proportionate (e.g., ± 10 percent) or through a “reasonable range” (i.e., from a low to high “probable” or “expected” value). The reasonable range approach was chosen for most parameters, but the proportionate approach was used when no reasonable range could be clearly identified. Note that using both techniques can result in measures of sensitivity that are difficult to compare. For example, adjusting the calendar date of downstream presmolt migration by ±1 week may not be directly comparable to varying the temperature that initiates spawning by ±2°C (±3.6°F) because the units of variation differ. In addition, it should be clear that the variability range for some parameters may have been overestimated and the range for others may have been underestimated, regardless of the approach. A comprehensive list of parameters and the variability assigned to them is given in Table 5-16.

Table 5-16. Considerations in Choosing Sensitivity Variation Range for Each Important Model Constituent

Model Constituent	Uncertainty	Sensitivity Range
Structural Element		
Study area	Downstream fate (including estuary and ocean) is considerable.	None
Flow and temperature segments	Considered minor; segments, well-matched to hydrology and thermal characteristics of the river.	None
Mesohabitat typing data and downstream sequence	Derived from detailed habitat mapping. Any misclassifications considered random.	None
Life stage nomenclature and length class breakpoints	Considered minor. Some investigators may use slightly different values.	None
Initiation of biological year	Some adults may be in study area somewhat before model initiation.	None
Hatchery supplementation	Not included at this time.	None
Tributary supplementation	Is not dynamic across years/conditions. Fall-run Chinook salmon only. Numbers.	±10 percent
	Weight.	±10 percent
Driving Environmental Variables		
Flow and water temperature values	All values from other simulations. Aggregation to weekly time step masks peaks.	None
Parameters		
Q:WUA quantification (life stage-specific)	Considerable. Magnitude (y-axis).	0.5 to 2 times
	Unknown. Flow dependence (x-axis).	Did not vary
Weight:length relationship	Agrees well with other rivers.	None
Spawning initiation temperature	Annual temperatures are generally constrained on the Sacramento River.	± 2°C “shift”
Spawning spatial and temporal distribution	Well-defined, but using multiyear average for all attributes. Distribution through study area.	None
	Initiation timing (x-axis).	± 1 week
	Duration or “peakedness” (x-axis).	± 1 week
Spawner density and characteristics	Number of adults.	± 10 percent
	Sex ratio (actual spawners to nonspawner ratio).	± 10 percent
	Size (weight).	± 10 percent
Fecundity	Could perhaps improve based on more current estimates.	± 10 percent
Redd area	From measured data, but adjusted to minimize superimposition.	± 10 percent
Superimposition option	Set to “avoidance” to minimize superimposition.	Random/Avoidance
Egg development rate	Some uncertainty in hatch to emergent timing.	± 2°C “shift”
Emergent length (weight)	Contains both uncertainty and variability; 34mm	± 10 percent
Minimum emergence temperature	Literature-derived, but for Atlantic salmon. Has been called into question on the Klamath River. Lowered to 6°C.	± 2°C “shift”
Juvenile growth rates (life-stage-specific)	Some uncertainty because values derived from ad lib feeding.	± 2°C “shift”
Freshet movement attributes (life-stage-specific)	Trigger.	NA
	Distance moved.	NA
	Mortality.	NA

Table 5-16. Considerations in Choosing Sensitivity Variation Range for Each Important Model Constituent (contd.)

Model Constituent	Uncertainty	Sensitivity Range
Parameters (contd.)		
Seasonal movement attributes (life-stage-specific)	Initiation timing and subsequent duration.	± 1 week
	Distance moved.	± 10 percent
	Mortality–much uncertainty.	± 10 percent
Base mortality rates (life-stage-specific)	Much uncertainty.	± 10 percent
Thermal mortality rates (life-stage-specific)	Uncertainty due to many causes.	± 2°C “shift”
Habitat capacity (juvenile life-stage-specific)	Uncertainty from multiple causes.	0.5 to 2 times
Habitat capacity movement rules	Several assumptions, but considered fixed assumption of the model.	None
Habitat-related distance moved mortality rate (life-stage-specific)	Much uncertainty. Will vary only the distance to 100 percent mortality.	0.5 to 2 times

Key:
°C = degrees Celsius
mm = millimeters
NA = not applicable
WUA = weighted usable area

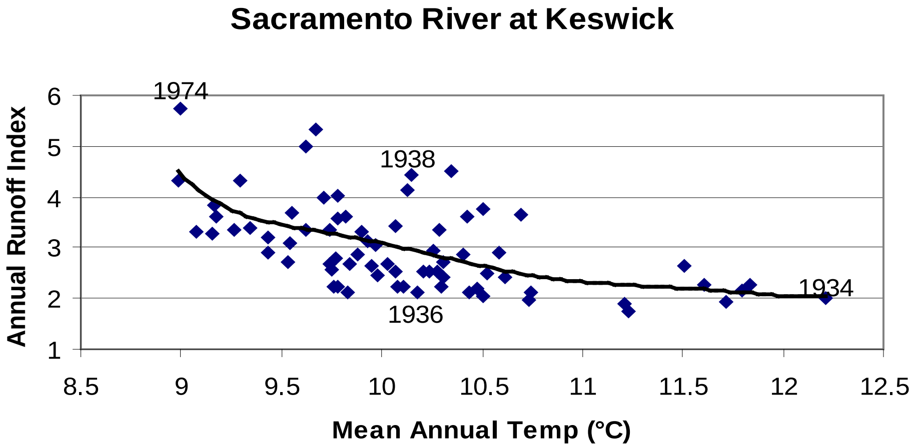
4. Choose variation technique. The simplest and most common SA varies one parameter at a time, executing the model repeatedly to quantify any differences in key model outputs. The next level of complexity calls for variation of more than one parameter at a time, typically from a joint probability distribution that attempts to describe how the parameters might vary in tandem. However, it is often the case that such a joint probability distribution is itself unknown. The single factor approach was chosen because of its simplicity. Under the presumption that all uncertain factors are susceptible to “correct” determination, and have the same cost to remove uncertainty, this so-called first-order SA identifies the factor(s) most deserving of better field or experimental measurement.

5. Generate a matrix showing the maximum sensitivity in model outputs from parameter variation. Again, a simple design was chosen. The initial evaluation begins with the base simulation that contains the current best estimate of parameters. Then two other simulation runs are made, one with the high estimate and one with the low. Computing the biggest absolute change in outmigrant numbers (high minus base or low minus base) provides a measure of the maximum sensitivity for this parameter. In addition, having three points for each parameter (high, base, and low) enables an examination of whether variation in each

parameter causes a linear or nonlinear response. This last point is not discussed further here.

6. Repeat Step 5 for a variety of year-types. Following the philosophy of looking for the maximum possible sensitivity, make sure that a variety of different year-types were examined, from wet to dry and hot to cold. After examining the range of conditions (Figure 5-10) for 4 specific years, wet-cold 1974, wet-average 1938, dry-average 1936, and dry hot 1934 were selected. As before, the maximum sensitivity for each parameter across all nine year-types was chosen.

Repeat across all four runs of Chinook salmon.



Notes:

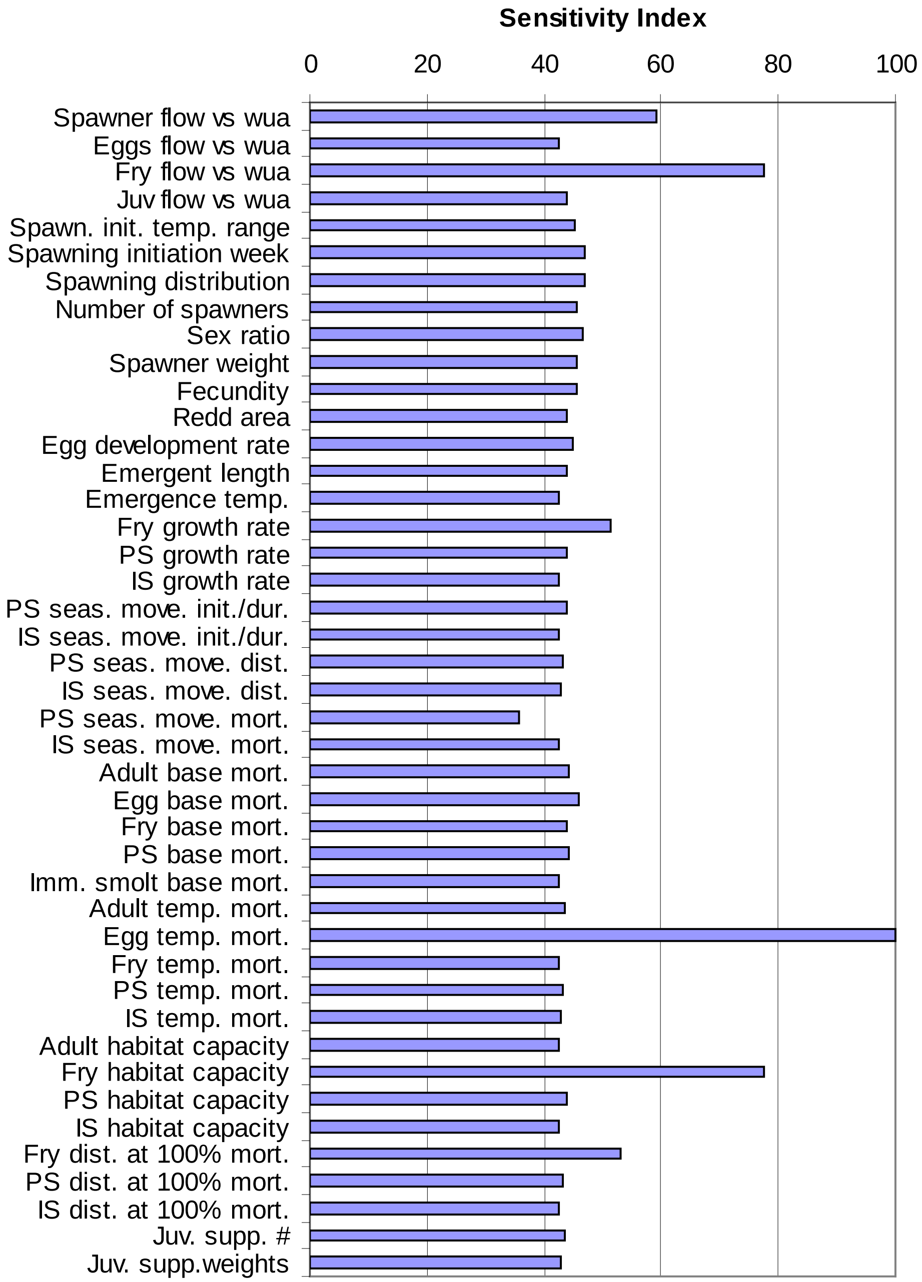
1. Arrayed according to total annual runoff and mean annual water temperature downstream from Keswick Dam.
2. Solid line is simple polynomial fit, and four labeled points are the water years selected for sensitivity study.

Figure 5-10. Individual Water Years Analyzed on the Sacramento River at Keswick

To summarize, maximum parameter sensitivity was chosen across three different cases: base compared with high and low parameter estimates, and then across four year types, all for each Chinook salmon run.

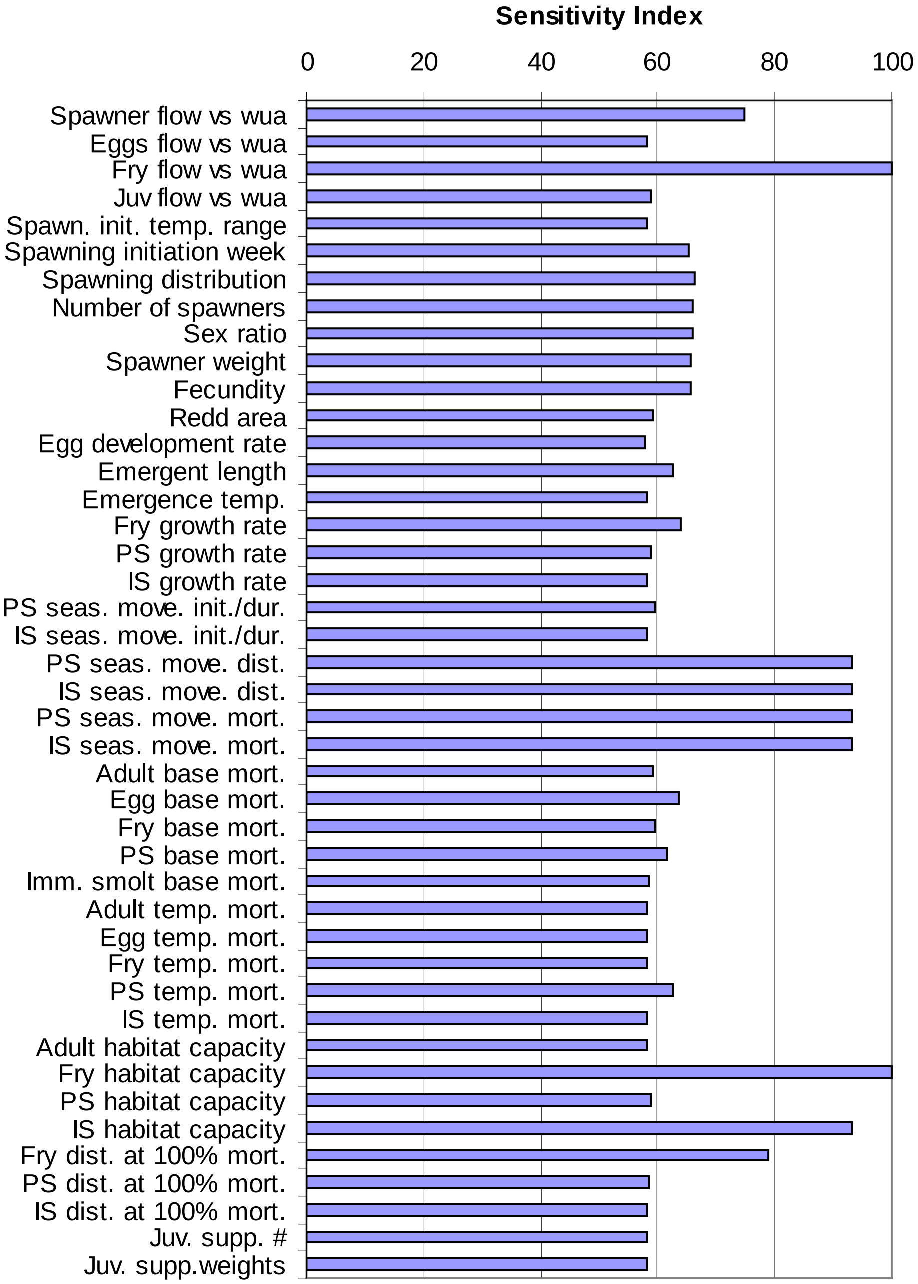
Sensitivity Analysis Findings

Figures 5-11 to 5-14 summarize the findings. Each parameter’s relative sensitivity is displayed by scaling all sensitivity values to a maximum value of 100, where 100 represents the largest change from baseline conditions for each run independently. Parameters rated as highly sensitive demand extra scrutiny. Parameters of lesser sensitivity are still important but are not likely to dominate SALMOD’s predictive ability. Parameters with low sensitivity warrant little scrutiny at this time.



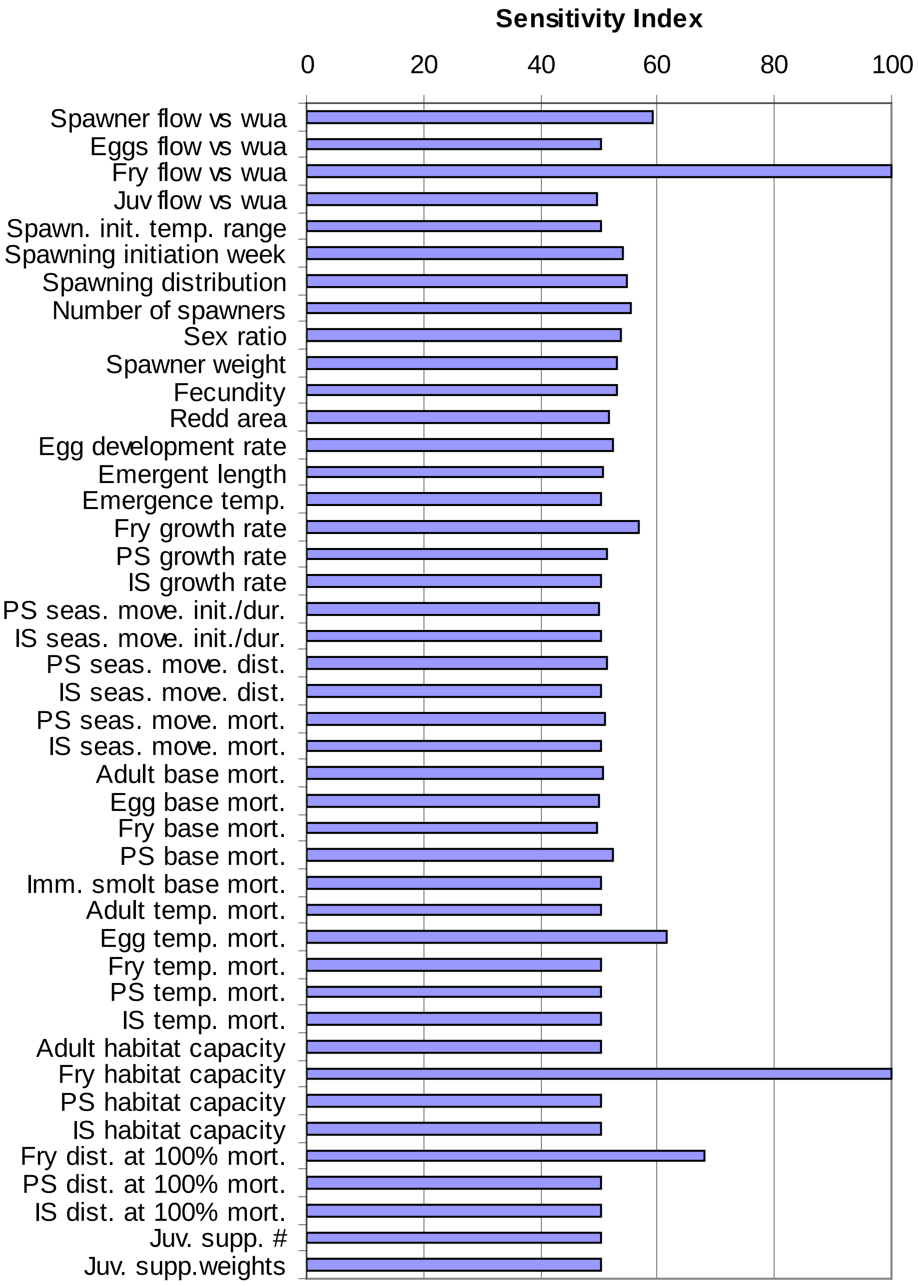
Note: Arranged from most sensitive at the top to least sensitive at the bottom

Figure 5-11. Sensitivity Analysis Results for Fall-Run Chinook Salmon



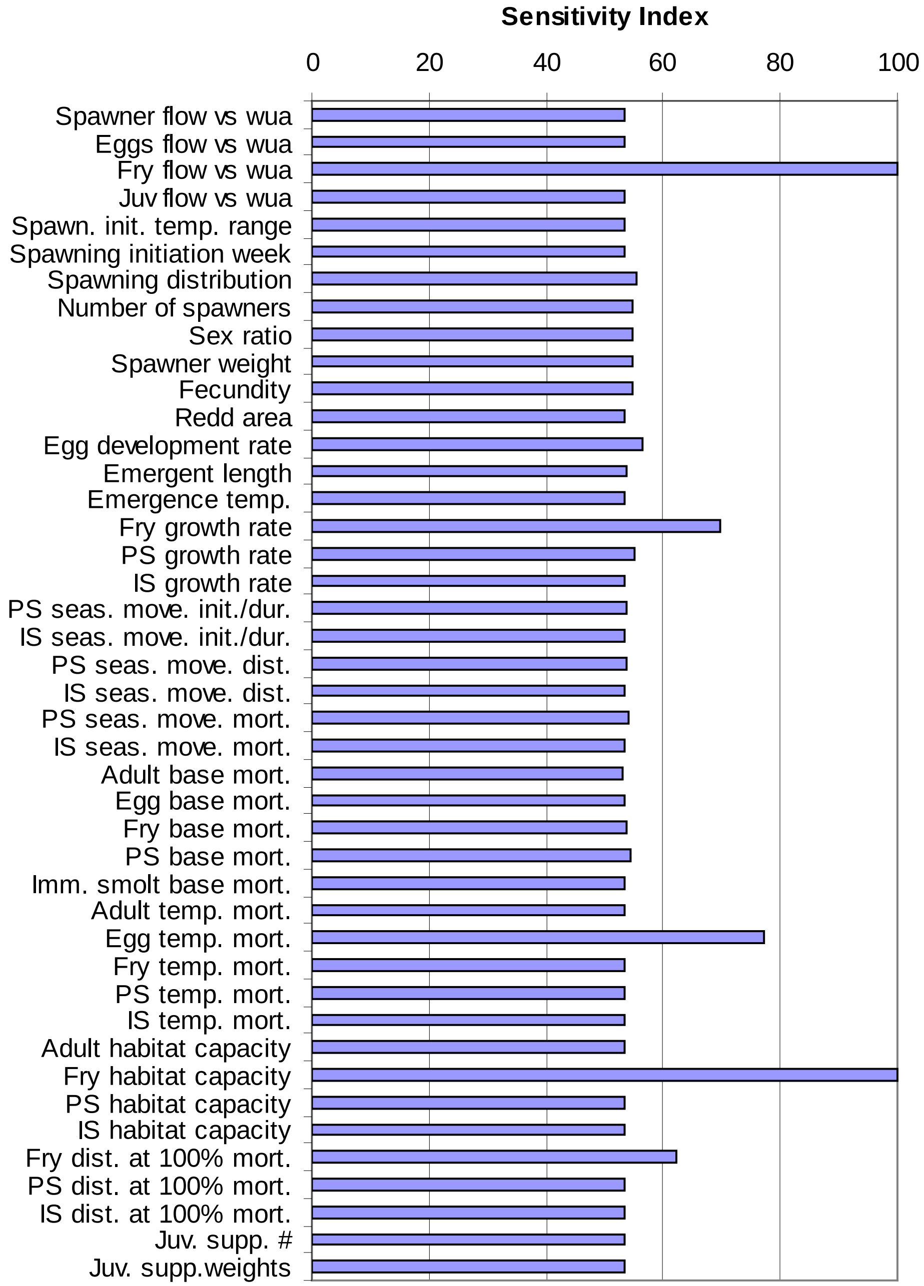
Note: Arranged from most sensitive at the top to least sensitive at the bottom.

Figure 5-12. Sensitivity Analysis Results for Late Fall-Run Chinook Salmon



Note: Arranged from most sensitive at the top to least sensitive at the bottom.

Figure 5-13. Sensitivity Analysis Results for Winter-Run Chinook Salmon



Note: Arranged from most sensitive at the top to least sensitive at the bottom.

Figure 5-14. Sensitivity Analysis Results for Spring-Run Chinook Salmon

Although a few distinct run-by-run differences were apparent from this analysis, it is also possible to develop some generalities. One factor that stands out across all runs is fry habitat (or capacity). This is not surprising given the inherent uncertainty with these parameters (Gard 2005) and because the results reflect the liberal 0.5 to 1.5X weighting, higher than for most other parameters. To a large degree, all stocks also showed some sensitivity to the maximum distance fry can move before suffering 100 percent mortality. This is a logical correlate. Fry growth rate also stands out across all runs, although far less important.

Beyond these few similarities, individual run differences are important. The fall-run showed sensitivity to spawning WUA and the parameter describing the distance that fry are forced to move to find available habitat before 100 percent mortality. The late fall-run showed sensitivity to more parameters than the other runs. Late fall fish were also sensitive to spawning WUA and fry movement distance, as well as presmolt and immature smolt seasonal movement parameters. Other parameters dealing with spawning (initiation week, spatial distribution, sex ratio, fecundity) were also of some importance. Winter-run and spring-run Chinook salmon had the aforementioned similarities but also showed some sensitivity to egg temperature mortality and fry growth rates.

Although the Sacramento River SA was performed somewhat differently than the SA on the Klamath River, several other factors that surprisingly relate directly to species life-history timing, emergence temperature, and spawning initiation week did not collectively emerge as important. Bartholow (2005) had shown that timing was a key determinant in predicting relative survival for the four runs of Chinook salmon in the Sacramento River. Instead, the results could be interpreted as indicating that most parameters fell into a moderate sensitivity range, neither outstanding nor zero.

SA does not address the issue of model realism. In other words, a parameter that has little influence on simulated model outcomes might be identified, but if the value is “wrong,” it will detract from the believability and trust in model results. In addition, in complicated, multiparameter models, errors in one parameter may be masked by errors in other parameters without significantly affecting model behavior. Should an apparently sensitive parameter be chosen as a management focus, it would be wise to test that sensitivity as a hypothesis before a full-scale effort. SA can also be used to address a model’s internal structure, which is not the principal objective here. However, SALMOD attempts solely to represent freshwater dynamics and is not a full life cycle model.

It is also important to remember that SA does not in any way identify parameters that are wrong. The model may well be, and should be, sensitive to parameter changes. A different form of SA that could be pursued is what might be called the ultimate SA, for which parameter variation could be examined that might lead to a change of decision in using the model. This would require much additional work, but the SA performed was of the variables, flow, and water temperature, and how variations may have had an effect on historical salmon production.

Interpreting Model Results

Because no true calibration has been completed for this SALMOD model application, note that simulated outmigration numbers and their attributes are best used not as absolute values, but rather as relative values (Prager and Mohr 1999). Even if the model were fully calibrated, measurements for outmigrating salmon are imprecise and subject to poorly understood biases. Further, because this is not a full life cycle model, including complex estuarine and ocean dynamics, nothing is known about what happens to salmon successfully migrating downstream from the RBPP, where other density-dependent phenomena may constrain the populations. As noted previously, simulated fish production values should be viewed as an index of production for each alternative, which can be used to make relative comparisons between alternatives, and should not be treated as an explicit prediction of absolute numbers of fish production under any alternative. Also, SALMOD is clearly not an ecosystem model (Link 2002) but instead a single species model in which “predictions” are limited to the target species.

Uncertainty Inherent in Model Results

Models can be misused (Radomski and Goeman 1996; Schnute and Richards 2001). The uncertainty and assumptions in this application have been discussed. Parameter values have come from a variety of sources representing studies in different locations and river settings, have been "extrapolated" across salmon runs, and in some cases, borrowed across species.

Model formulations are inexact approximations of the processes believed to be governing populations, not necessarily the "truth." Models act as metaphors of reality and also as filters to isolate a signal from background noise in the data. Three types of potential errors are inherent in fisheries models that frustrate this signal extraction (Schnute and Richards 2001). The first is process error, referring to the model’s inability to capture the full range of dynamism in birth, death, and growth rates. The second is measurement error, referring to the inability to precisely measure what is modeled. The third type of potential error is model uncertainty, referring to the occasional inability to know whether the model does in fact cover the full range of possible phenomena that may occur to a fish stock. Collectively, these three types of potential errors indicate that multiple, equally valid explanations to account for what was witnessed. As has been pointed out by modelers investigating the dynamics of fall-run Chinook salmon in the ocean, relationships can be spurious and fail with the addition of new data; relationships can be real, but environmental or recruitment stochasticity masks the relationship. Or relationships may not be stationary, but change over time for unclear reasons, making those relationships exceedingly difficult to determine (Prager and Mohr 1999).

Suggested remedies to these problems include vigilant skepticism, continued data collection to “disprove” the model, applying common sense, and implementing precautionary management strategies that are robust to fish stock failure (Schnute and Richards 2001).

Drawing Inferences from Model Results

Policy choices are needed, even when field experimentation is impossible or extremely difficult. Thus, choices will continue to be made based on inference. With inference, assumptions are made explicit. Assumptions, however carefully considered, may still be wrong (Schnute and Richards 2001). For this reason, there should always be an opportunity to rethink, revise, and expand the model.

With this in mind, the evolutionary progression of model development and application (Table 5 17) that shows that modeling, like any investigation, moves from general and suggestive to specific and credible (Holling and Allen 2002). Note in Table 5-17 that validity is always provisional rather than essential for model utility (Rykiel 1996). SALMOD for the Sacramento River is currently cycling between Stages 3 and 6, indicating that evaluation of management issues can begin as long as it is clear that the model remains a hypothesis and skepticism is promoted. SALMOD apparently rests on a sound theoretical footing and most, but not all, of its parameters are tied to sound empirical data. However, in light of the previously discussed uncertainties, any inferences drawn from the model results should keep in mind that the model is valid only for identifying general trends and the relative magnitude of impacts, and is not valid for making predictions about absolute changes in fish production. For any alternative plan assessed, the model results should only be viewed as an index of impacts on fish populations relative to other alternatives.

Table 5-17. Progression of Model Development and Application Stages

Model Development Stage	Attributes	Uses of Model Output at Each Development Stage
(9+) Repeated calibration/ verification loop	Confidence-driven	• Refine estimate of uncertainty • Evaluation is ongoing • Model becomes ever more trustworthy
(8) Verification	Understanding-driven	• “Confirm”/strengthen/predict/falsify • Continue to accumulate evidence • Uncertainty is poorly defined
(7) Calibration	Knowledge-driven	• “Suggest” (assuming model can be calibrated) • Gain precision
(6) Parameterized using best river-specific data	“Fact”-driven	• “Imply or infer” • Can begin to explore “solutions” to issues, but must be clear that model remains a hypothesis
(5) Testing	Plausibility?	• Question perceptions • Gain insight by identifying patterns • Revise data and implementation
(4) Parameterized from literature or general knowledge	Data-driven	• “Deduce” based on estimates and assumptions • Continue consensus-building on model structure and expected behavior • Gain realism
(3) Formalization and implementation	Box-and-arrow-driven	• Stimulate concrete thought-about variables, relationships, constraints, temporal and spatial scale, etc. • Speculation
(2) Conceptual formulation	Hypothesis-driven	• “Reason”
(1) Opinion	Experience- driven	• No real model

Discussion

It may not be possible to quantify the “confidence interval” for model predictions on the Sacramento River. The model has not been calibrated; therefore, there are no goodness-of-fit metrics except that the model has been called “in the ballpark” (Bartholow 2003). Bradford (1995) compiled representative egg-to-fry and egg-to-smolt survival ratios for several studied Chinook salmon streams; these averaged 3 to 4 percent. Comparable SALMOD egg-to-outmigrant survival rates down to Red Bluff average 7 to 14 percent depending on the run. It is recognized that SALMOD can display some apparent “noise” (e.g., small changes in any of the driving inputs such as discharge, temperature, number of adult spawners, can result in what seem to be small oscillations in simulated production). There are many reasons for this, but the model contains certain thresholds (e.g., temperature of emergence, discharge initiating redd scour) and properties of dealing only with integer numbers of fish (e.g., what if one spawning female dies?) that can induce nonlinear oscillations in the results. The original design criterion for SALMOD was to be able to detect production differences greater than 25 percent (Williamson 1993). Obviously, average predicted differences in this case are well within this design tolerance. Given these considerations, the conclusion is that any production differences, if true, probably would not be detectable in the field even through a long-term, rigorous statistical analysis (Korman and Higgins 1997).

It is important to remember that these scenarios are solely model characterizations of what alternative futures might be on the Sacramento River. These models, just like SALMOD, will have known and unknown biases and uncertainties. Even if these scenarios are good caricatures of possible alternative futures, actual day-to-day or week-to-week operation will certainly be different from any specific scenario. Ramping rates, TCD malfunctions, and a myriad of potential stochastic events will tend to influence actual production. Further, SALMOD has a distinct geographic boundary below which nothing is stated regarding survival rates of either adults or juveniles. Delta and ocean conditions are a “black box” in this regard. Finally, SALMOD is not an ecosystem model. Just because this model indicates some changes (both positive and negative) for Chinook salmon, it does not mean that one would not want altered flows during certain times of the year. As examples, channel-forming flows leading to gravel recruitment or substrate cleaning are an often-cited goal (see http://science.calwater.ca.gov/pdf/ eco_restor_sac_river.pdf), or salinity control in the Delta. A larger Shasta Reservoir would have a longer hydraulic retention time, likely processing nutrients differently with potential consequences for its food web dynamics (Saito et al. 2001). SALMOD only simulated four runs of a single species. Whatever changes may occur, they will likely benefit some organisms while being detrimental to others.

Following earlier modeling efforts (Bartholow 2003), the four run-specific models applied concentrated attention on presmolt and immature smolt outmigrants (greater than 60 mm) under the widely believed assumption that their subsequent downstream and ocean survival is better than that for fry (smaller than 60 mm). However, when simulating such a broad range of thermal and hydrologic conditions over 70 years, it was observed that under certain circumstances, some juveniles were still in the virtual river at the end of the 52-week biological year as if they were stream-type Chinook salmon. In part, this may be an unrealistic artifact of the way the models were constructed and perhaps could be cured in future applications. The 6°C (42°F) emergence temperature may be too high, the annual timing used may be incorrect, or there may be some combination of factors. The model used explicit steps to “flush” the larger fish (greater than 60 mm) down to Red Bluff but did not do so for fry. Assuming that some of these “residual” fry survive to subsequently outmigrate, either as young-of-year (YOY) or as yearlings, average production may have been underestimated (less than 1 percent difference). The conclusions of the study relative to production potential remain as described. However, there was a trend in a greater number of these “residual” fish as the simulated reservoir became larger and water temperatures became colder. These colder temperatures delayed the “normal” egg incubation period such that fry emerged slightly later or grew slightly slower, resulting in more fish less than 60 mm after 52 weeks. This may or may not be a concern in managing the river to promote stock recovery.

SALMOD predicts that cooler water temperatures will often reduce adult, egg, and juvenile thermal mortality, but at the cost of lengthening the egg incubation and juvenile growth periods for survivors. Lengthening this development window also lengthens the cumulative exposure to “base” and other potential mortality sources. Brannon et al. (2004) stated that most concerns about temperature in the ecological literature seem to be identified with increases in the lethal extremes. However, the far more profound impacts of temperature are related to the changes that occur well within the tolerance range of the species. A change in the mean incubation temperature of 1°C (1.8°F), for example, can alter the period of incubation and emergence by more than a month. At latitude 40.5°N, the upper Sacramento River would be expected to have “natural” mean April to September temperatures approaching 18°C (64.4°F), in contrast to the McCloud and Pit rivers, which tend to peak at about 15°C (59°F) with a mean closer to 13°C (55.4°F) (Brannon et al. 2004, Figures 16 and 17). With the TCD in place currently, the Sacramento River downstream from Keswick reaches a maximum average of about 12.5°C (54.5°F) and an average maximum of 17.5°C (61.7°F).

SALMOD can estimate a “globally optimum” water temperature regime across the four run models. This was done by constructing special software that repeatedly reran the simulation models, randomly varying the weekly thermal regime ±1°C (±1.8°F) around the median water temperature regime associated with the 18.5-foot dam extension. Median flows were used for all runs and retained the average longitudinal heat flux and discharge accretions. This simulation model ran more than 28,000 times and compiled 2 averages of the best 10 regimes, one representing the best overall percentage improvement from the median temperatures and one representing the best absolute improvement in numeric production. The results are shown in Figure 5-15, with these two average regimes having been smoothed to reduce their inherent jaggedness. Although there are obvious problems in the smoothing, the results are instructive. Most apparent is that both of the “ideal” thermal regimes generally lie within the ±1°C (±1.8°F) search tolerance, indicating that the starting water temperatures were, on average, very good for these fish. The exception is in midwinter when this envelope indicates that warmer temperatures would be “preferred.” Somewhat warmer spring water temperatures would also be beneficial, while late summer water temperatures could be cooler. Even very small changes extending over several weeks can add up to large differences in development and growth. However, some temperature alterations may be impossible for Shasta Lake. According to Reclamation, for about 4 months of the year (December to March), little can be done to provide warmer temperatures from the TCD such that Shasta Reservoir cannot deliver the "best" regime all of the time.

Figure 5-15 also indicates that maintaining seasonality remains important. The river is not like a hatchery, where it may be advisable to target relatively constant temperatures, at least for a specific run of fish. In the river, when trying to accommodate all four runs in this case, seasonality apparently needs to be maintained.

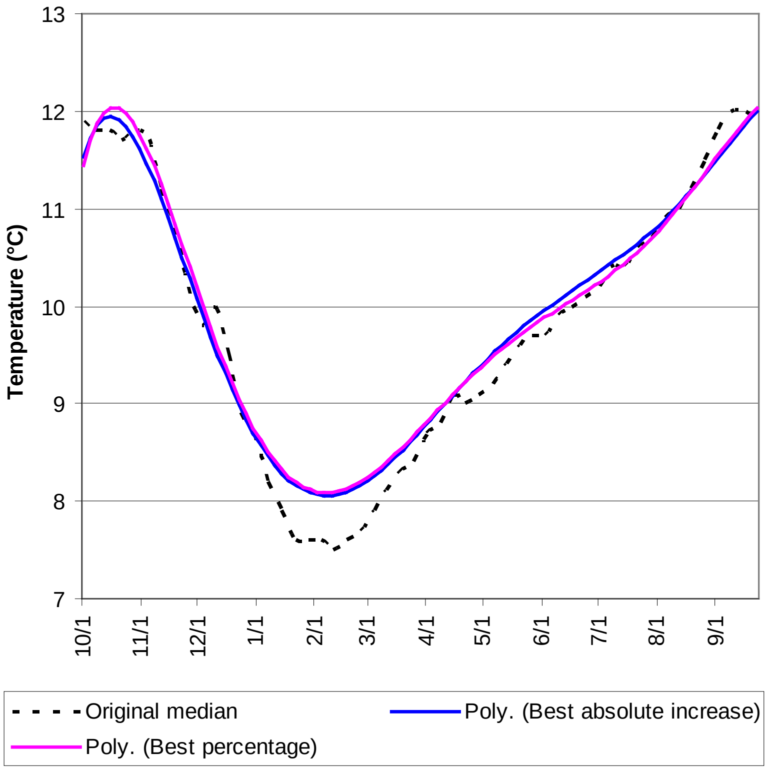


Figure 5-15. Idealized Annual (52-week) Thermal Regimes Compared to Median 18.5-foot Dam Water Temperatures

Chapter 6
Statewide Agricultural Production Model

Purpose and Need

The SWAP is used to assess the impacts on irrigated agriculture of implementing the CALFED surface storage projects. The model is linked to hydrologic impact analysis to show how water supply changes affect agricultural production and, in turn, how economic responses to these changes affect land use and the demand for and use of water supplies.

SWAP Model Background and Overview

The SWAP model is a regional agricultural production and economic optimization model that simulates the decisions of farmers across 93 percent of agricultural land in California. It is the most current in a series of production models of California agriculture developed by researchers at the UC Davis under the direction of Professor Richard Howitt in collaboration with DWR.

Model Background and Development History

SWAP is an improvement and extension of the Central Valley Production Model (CVPM). CVPM was developed in the early 1990s and was used to assess the impacts of the CVPIA (Reclamation and USFWS 1999). The SWAP model allows for greater flexibility in production technology and input substitution than CVPM, and has been extended to allow for a range of analyses, including interregional water transfers and climate change effects. Its first application was to estimate the economic scarcity costs of water for agriculture in the statewide hydro-economic optimization model for water management in California, (CALVIN) (Draper et al., 2003). More recently, the SWAP model has been used to estimate economic losses caused by salinity in the Central Valley (Howitt et al., 2009a), economic losses to agriculture in the Delta (Lund et al., 2007), economic losses for agriculture and confined animal operations in California’s southern Central Valley (Medellin-Azuara et al., 2008), and economic effects of water shortage to Central Valley agriculture (Howitt et al., 2009b). It is also being used in several ongoing studies of water projects and operations.

Model Overview

The SWAP model assumes that farmers select the crops, water supplies, and other inputs to maximize profit subject to resource constraints, technical production relationships, and market conditions. Farmers are assumed to face competitive markets in which no single farmer can influence crop prices, but an aggregate change in production can affect crop price. This competitive market is simulated by maximizing the sum of consumer and producer surplus subject to the following characteristics of production, market conditions, and available resources:

1. Constant Elasticity of Substitution (CES) production functions for every crop in every region. CES has four inputs: land, labor, water, and other supplies. CES production functions allow for limited substitution among inputs, which allows the model to select optimal levels of both total output and input use, and consequently input use intensity. Parameters are calculated using a combination of prior information (i.e., externally generated estimates) and the method of Positive Mathematical Programming (PMP) (Howitt 1995). Calibration using PMP is discussed in Attachment 15.

2. Marginal land cost functions are estimated using PMP. Additional land brought into production is assumed to be of lower productivity and thus requires a higher cost to cultivate. The PMP functions capture the increasing cost of bringing additional land into production, by using acreage response elasticities that relate changes in acreage to changes in expected returns and other information. PMP cost functions are described in the section called Exponential Land PMP Cost Function, and additional technical detail is provided in Attachment 15.

3. Groundwater pumping cost including depth to groundwater (see the section called Water Supply and Groundwater Pumping).

4. Crop demand functions (see the section called Crop Demand Functions and Attachment 15).

5. Crop demand shifts based on real income and population increases (see the section called Demand Shifts and Attachment 15).

6. Resource constraints on land, labor, water, and other input availability by region (see the sections called Water Supply and Groundwater Pumping and Economic and Agronomic Constraints).

7. Agronomic and economic constraints on perennial crop acreage changes, dairy herd and livestock silage requirements, stress irrigation, and other legal and physical constraints (see the section called Economic and Agronomic Constraints).

8. Technological change and climate-induced yield effects (see the section called Technological Change).

9. A water-transfer module that includes legal restrictions on water transfers in addition to physical infrastructure and flow capacities estimated by engineers in the Watershed Science Center at UC Davis.

The model chooses the optimal values of land, water, labor, and other input use subject to these constraints and characteristics. Profit is revenue minus costs where revenue is price multiplied by yield per acre times total acres, calculated for each crop in each region. Costs include both directly calculated input costs plus implicit costs described by the PMP function defined in the section called Exponential Land PMP Cost Function. Downward-sloping crop demand curves cause prices to decline as production increases (and vice versa), all other variables remaining constant. Over time, crop demands may shift out driven by real income growth and population increases. External data and elasticities are used to estimate these shifts. Factors 6 and 7 (described above) are physical production and feasibility constraints that must be satisfied, and may be expanded, depending on the study. For example, rotational constraints may be implemented. Factors 8 and 9 are features and innovations that may not be included in all projects; they are not used for SLWRI analysis described in this report.

The SWAP model incorporates project water supplies (SWP and CVP), other local surface water supplies, and groundwater. As conditions change within a SWAP region (e.g., the quantity of available project water supply increases or the cost of groundwater pumping increases), the model optimizes production by adjusting the crop mix, water sources and quantities used, and other inputs. It also fallows land when that appears to be the most cost-effective response to resource conditions.

The SWAP model is used to compare the long-run response of agriculture to potential changes in SWP and CVP irrigation water delivery, other surface or groundwater conditions, or other economic values or restrictions. Results from Reclamation’s and DWR’s operations planning model CalSim-II (Reclamation 2008a) are used as inputs into SWAP through a standardized data linkage tool (see Attachment 15 for a description of linking CalSim-II to SWAP). Groundwater analysis is used to develop assumptions, estimates, and, if appropriate, restrictions on pumping rates and pumping lifts for use in SWAP.

The model self-calibrates using PMP, which has been used in models since the 1980s and was formalized by Howitt (1995). PMP allows the modeler to infer the marginal decisions of farmers while only being able to observe limited average production data. PMP captures this information through a nonlinear cost or revenue function introduced to the model.

SWAP Regions and Crop Definitions

The SWAP model has 27 base regions in the Central Valley. The current model covers agriculture in the original 21 CVPM regions (Reclamation 1997) plus additional production regions in the Central Coast, South Coast, South

Lahontan, and Colorado River hydrologic regions. There are a total of 37 regions in the current model, but only 27 regions in the Central Valley are considered for SLWRI analysis. Figure 6-1 shows the California agricultural area covered in SWAP. Table 6-1 details the major water users in each of the regions.

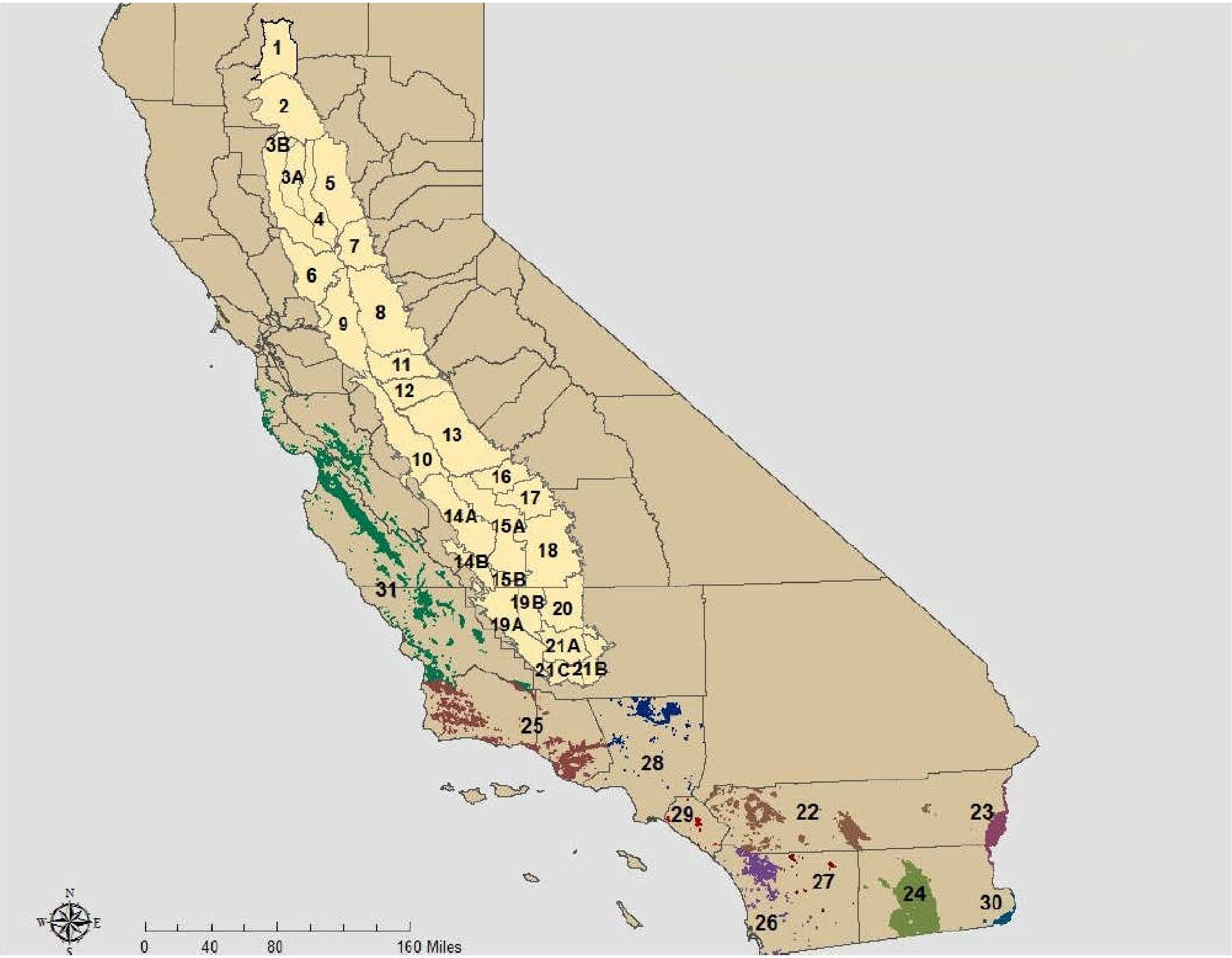


Figure 6-1. SWAP Coverage of Agriculture in California

Table 6-1. SWAP Region Summary SWAP Model Update and Application to Federal Feasibility Analysis

SWAP Region	Major Surface Water Users
1	CVP Users: Anderson Cottonwood ID, Clear Creek CSD, Bella Vista WD, and misc. Sacramento River water users
2	CVP Users: Corning Canal, Kirkwood WD, Tehama, and misc. Sacramento River water users
3a	CVP Users: Glenn Colusa ID, Provident ID, Princeton-Codora ID, Maxwell ID, and Colusa Basin Drain MWC
3b	Tehama Colusa Canal Service Area. CVP Users: Orland-Artois WD, most of Colusa County, Davis WD, Dunnigan WD, Glide WD, Kanawha WD, La Grande WD, and Westside WD
4	CVP Users: Princeton-Codora-Glenn ID, Colusa IC, Meridian Farm WC, Pelger Mutual WC, RD 1004, RD 108, Roberts Ditch IC, Sartain MWC, Sutter MWC, Swinford Tract IC, Tisdale Irrigation and Drainage Co., and misc. Sacramento River water users
5	Most Feather River Region riparian and appropriative users
6	Yolo and Solano counties. CVP Users: Conaway Ranch and misc. Sacramento River water users
7	Sacramento County north of American River. CVP Users: Natomas Central MWC, misc. Sacramento River water users, MWC, and Placer County WA
8	Sacramento County south of American River and northern San Joaquin County
9	Direct diverters within the Delta region. CVP Users: Banta Carbona ID, West Side WD, and Plainview
10	Delta Mendota service area. CVP Users: Panoche WD, Pacheco WD, Del Puerto WD, Hospital WD, Sunflower WD, West Stanislaus WD, Mustang WD, Orestimba WD, Patterson WD, Foothill WD, San Luis WD, Broadview, Eagle Field WD, Mercy Springs WD, San Joaquin River Exchange Contractors
11	Stanislaus River water rights: Modesto ID, Oakdale ID, and South San Joaquin ID
12	Turlock ID
13	Merced ID CVP Users: Madera ID, Chowchilla WD, and Gravely Ford
14a	CVP Users: Westlands WD
14b	Southwest corner of Kings County
15a	Tulare Lake Bed. CVP Users: Fresno Slough WD, James ID, Tranquility ID, Traction Ranch, Laguna WD, and RD 1606
15b	Dudley Ridge WD and Devils Den (Castaic Lake)
16	Eastern Fresno County. CVP Users: Friant-Kern Canal, Fresno ID, Garfield WD, and International WD
17	CVP Users: Friant-Kern Canal, Hills Valley ID, Tri-Valley WD, and Orange Cove
18	CVP Users: Friant-Kern Canal, County of Fresno, Lower Tule River ID, Pixley ID, portion of Rag Gulch WD, Ducor, County of Tulare, most of Delano-Earlimart ID, Exeter ID, Ivanhoe ID, Lewis Creek WD, Lindmore ID, Lindsay-Strathmore ID, Porterville ID, Sausalito ID, Stone Corral ID, Tea Pot Dome WD, Terra Bella ID, and Tulare ID
19a	SWP Service Area, including Belridge WSD, Berrenda Mesa WD
19b	SWP Service Area, including Semitropic WSD
20	CVP Users: Friant-Kern Canal. Shafter-Wasco, and South San Joaquin ID

Table 6-1. SWAP Region Summary SWAP Model Update and Application to Federal Feasibility Analysis (contd.)

SWAP Region	Major Surface Water Users
21a	SWP users and CVP users served by Cross Valley Canal and Friant-Kern Canal
21b	Arvin Edison WD and portions of Wheeler Ridge–Maricopa WSA
21c	SWP service area: Wheeler Ridge–Maricopa WSD
23-30	Production areas in the Central Coast, South Coast, South Lahontan, and Colorado River hydrologic regions

Note: The table does not include all water users. It is intended only to indicate the major users or categories of users. All regions in the Central Valley also include private groundwater pumpers.

Key:
CSD = Cross Section Development
CVP = Central Valley Project
Delta = Sacramento-San Joaquin Delta
IC = Irrigation Company
ID = Irrigation District
MWC = Mutual Water Company
RD = Reclamation District
SWAP=Statewide Agricultural Production Model
SWP = State Water Project
WA = Water Agency
WC = Water Code
WD = Water District
WSA = Wilderness Study Area
WSD = Water Service District

Crops are aggregated into 20 crop groups that are the same across all regions. Each crop group represents a number of individual crops, but many are dominated by a single crop. Irrigated acres represent acreage of all crops within the group, and production costs and returns are represented by a single proxy crop for each group. The current 20 crop groups were defined in collaboration with DWR and updated in March 2011. For each group, the representative (proxy) crop is chosen based on four criteria:

1. A detailed production budget is available from University of California Cooperative Extension (UCCE).
2. It is the largest or one of the largest acreages within a group.
3. Its water use (applied water) is representative of water use of all crops in the group.
4. Its gross and net returns per acre are representative of the crops in the group.

The relative importance of these criteria varies by crop. Crop group definitions and the corresponding proxy crop are shown in Table 6-2.

Table 6-2. SWAP Crop Groups SWAP Model Update and Application to Federal Feasibility Analysis

SWAP Definition	Proxy Crop	Other Crops
Almonds and Pistachios	Almonds	Pistachios
Alfalfa	Alfalfa Hay	
Corn	Grain Corn	Corn Silage
Cotton	Pima Cotton	Upland Cotton
Cucurbits	Summer Squash	Melons, Cucumbers, Pumpkins
Dry Beans	Dry Beans	Lima Beans
Fresh Tomatoes	Fresh Tomatoes	
Grain	Wheat	Oats, Sorghum, Barley
Onions and Garlic	Dry Onions	Fresh Onions, Garlic
Other Deciduous	Walnuts	Peaches, Plums, Apples
Other Field	Sudan Grass Hay	Other Silage
Other Truck	Broccoli	Carrots, Peppers, Lettuce, Other Vegetables
Pasture	Irrigated Pasture	
Potatoes	White Potatoes	
Processing Tomatoes	Processing Tomatoes	
Rice	Rice	
Safflower	Safflower	
Sugar Beet	Sugar Beets	
Subtropical	Oranges	Lemons, Misc. Citrus, Olives
Vine	Wine Grapes	Table Grapes, Raisins

SWAP Model Detail

This section is a nontechnical overview of the SWAP model. Technical detail is provided in Attachment 15. It is important to note that SWAP, like any model, is a representation of a complex system and requires assumptions and simplifications to be made. Significant effort has been expended to provide explicit assumptions and provide sensitivity analysis where appropriate.

Calibration Using PMP

The SWAP model self-calibrates using a three-step procedure based on PMP (Howitt 1995) and the assumption that farmers behave as profit-maximizing agents. In a traditional optimization model, profit-maximizing farmers would simply allocate all land, up until resource constraints become binding, to the most valuable crop(s). In other words, a traditional model would have a tendency for overspecialization in production activities relative to what is observed empirically. PMP incorporates information on the marginal production conditions that farmers face, allowing the model to exactly replicate a base year of observed input use and output. Marginal conditions may include inter-temporal effects of crop rotation, proximity to processing facilities, management skills, farm-level effects, such as risk and input smoothing, and heterogeneity in soil and other physical capital. In the SWAP model, PMP is used to translate these unobservable marginal conditions, in addition to observed average conditions, into a cost function. This cost function, referred to as a PMP cost function and derived in Attachment 15, allows the model to exactly replicate a base year of observed input use and output.

PMP is fundamentally a three-step procedure for model calibration:

1. In the first step a linear profit-maximization program is solved. In addition to basic resource availability and non-negativity constraints, a set of calibration constraints is added to restrict land use to observed values.

2. In the second step, the dual (shadow) values from the calibration and resource constraints are used to derive the parameters for an exponential PMP cost function and CES production function.

3. In the third step, the calibrated CES and PMP cost function are combined into a full profit maximization program. The exponential PMP cost function captures the marginal decisions of farmers through the increasing cost of bringing additional land into production (e.g., as a result of increasing development costs or decreasing quality).

Other input costs (other supplies, land, and labor) enter the objective function in both the first and third step.

Calibrating production models using PMP has been reviewed extensively in the recent literature. Heckelei and Wolff (2003) argue that shadow values from calibration and/or resource constraints are an arbitrary source of information for model calibration. Subsequent research suggests using exogenous information such as land rents instead of shadow values (Kanellopoulos et al., 2010). In the SWAP model, only limited observations are available, and the model is calibrated using traditional PMP with exogenous supply (acreage response) elasticity information. The SWAP model, and calibration by PMP, is a complicated process; thus, sequential testing is very useful for model validation, diagnosing problems, and debugging the model. Each stage in the SWAP model includes a corresponding model check. In other words, the calibration procedure follows a sequential process and includes a parallel set of diagnostic tests to check model performance. Diagnostic tests are discussed in Attachment 15.

Exponential Land PMP Cost Function

The SWAP model assumes additional land brought into production faces an increasing marginal cost of production. The most fertile land is cultivated first, and additional land brought into production is of lower “quality” because of poorer soil quality, drainage or other water quality issues, or other factors that cause it to be more costly to farm. This is captured through an exponential land cost function (PMP cost function) for each crop and region. The exponential function is advantageous because it is always positive and strictly increasing, consistent with the hypothesis of increasing land costs. The PMP cost function is specific to region and crop, reflecting differences in production across crops and heterogeneity across regions. Functions are calibrated using information from acreage response elasticities and shadow values of calibration and resource constraints. The information is incorporated in such a way that the average cost data (known data) are unaffected.

The exponential cost function is an improvement over previous PMP-based models, such as CVPM, which use a quadratic total cost (and therefore a linear marginal cost) function. The corresponding marginal cost functions are shown in Figure 6-2. Using a quadratic total cost function can result in negative marginal costs over a range of low acres, for a specific crop and region. This is difficult to justify if the PMP function represents land cost, and it can result in very high net returns per acre for very low acreage. The exponential cost function is always bounded above zero, by definition, which is consistent with observed costs of production. As additional acres are brought into production, the marginal costs of production increase. A potential disadvantage of the exponential function is that the cost can rise rapidly as acreage increases above the calibrated level. These effects on National Economic Development (NED) results are minimized because land costs are removed from the benefits calculation (see Section Other Supply Costs).

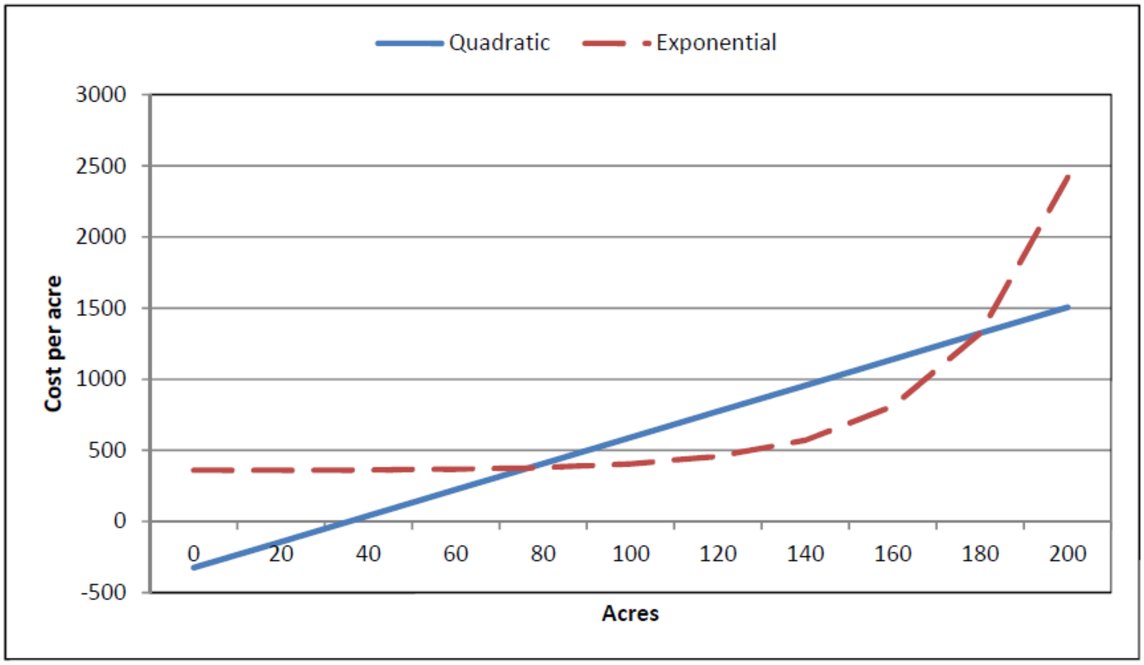


Figure 6-2. Comparison of Exponential and Linear Marginal PMP Cost Functions

Acreage Response Elasticities

The PMP cost functions are automatically calibrated by the model. Each function has an intercept and slope, so at least two data points are necessary. The shadow value on resource and calibration constraints (discussed in Attachment 15) provides information on the level of cost at the observed calibration, and the acreage response elasticity provides information on the slope.

Acreage response is one component of supply response. The acreage response elasticity is defined as the percentage change in crop acreage due to a 1 percent change in the crop's own price (or, more generally, revenue). This information is used to calibrate the slope of the PMP marginal cost function at the calibrated (base) level of acres for each region and crop. The section called Elasticities documents the acreage response elasticities used in SWAP.

Constant Elasticity of Substitution Production

Production is modeled with a CES production function for each region and crop with positive acres. In general, a production function captures the relationship between inputs and output. For example, land, labor, water, and other inputs are combined to produce output of any crop. CES production functions in the SWAP model are specific to each region, thus regional input use is combined to determine regional production for each crop. The calibration routine in SWAP guarantees that both input use and output exactly match a base year of observed data.

The SWAP model considers four aggregate inputs to production for each crop and region: land, labor, water, and other supplies. All units are converted into monetary terms (e.g., dollars of labor per acre instead of worker hours). Input use and cost per acre are documented in the section called SWAP Model Inputs and Supporting Data. Land is simply the number of acres of a crop in any region. Land costs represent basic land investment, cash overhead, and (when applicable) land rent. Labor costs represent machinery labor and manual labor. Other supplies is a broad category that captures a range of inputs, including fertilizer, pesticides, chemicals, custom, capital recovery, and interest on operating capital. Water costs and use per acre are discussed in the sections called Surface Water Costs through Applied Water per Acre.

The generalized CES production function allows for limited substitution among inputs (Reclamation 2012). This is consistent with observed farmer production practices (farmers are able to substitute among inputs to achieve the same level of production). For example, farmers may substitute labor for chemicals by reducing herbicide application and increasing manual weed control. Or, farmers can substitute labor for water by managing an existing irrigation system more intensively to reduce water use. The CES function in the version of SWAP used for the SLWRI feasibility analysis is non-nested, thus the elasticity of substitution is the same between all inputs.

Figure 6-3 shows an example of a CES production surface. In SWAP there are four inputs, to show the CES function as a 3-dimensional surface two inputs (other supplies and land) are held constant. The vertical axis shows total production of alfalfa in Region 15 given any combination of water and labor which are shown on the horizontal axes. Figure 6-2 illustrates two important aspects of the CES production function. First, substitution between inputs is seen by holding production constant (the vertical axis) and sliding around the production surface. There is substitution between water and labor, as shown by the curves on the production surface. Second, Figure 6-2 demonstrates the ability of SWAP to model deficit (stress) irrigation by farmers. Faced with water shortage, farmers may select to deficit irrigate some acres of crops. Holding labor constant and sliding along the production surface, as water is decreased production (yield) decreases as well. The nature of this relationship is determined endogenously by the calibration routine in SWAP. Additional restrictions can be imposed to incorporate exogenous agronomic data. To reproduce the observed input use and output, the CES function parameters must be estimated internally (endogenously) during the calibration process or they must use a combination of internal calculations and external data. This latter approach is used for SWAP. See Attachment 15 for more details.

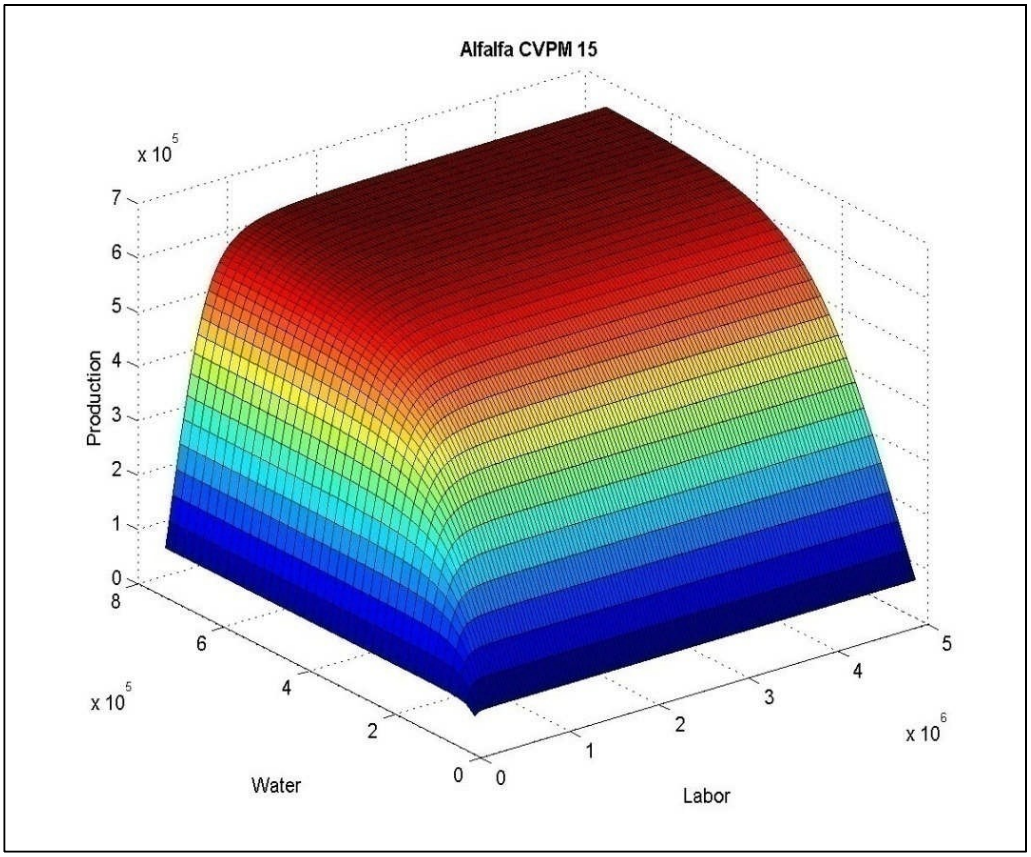


Figure 6-3. Example CES Production Function for Alfalfa in Region 15 (Land and Other Supplies Held Constant)

Crop Demand Functions

The SWAP model is specified with downward-sloping, California-specific crop demand functions. The demand curve represents consumer's willingness to pay for a given level of crop production. All other factors remaining constant, as production of a crop increases, the price of that crop is expected to fall. The extent of the price decrease depends on the elasticity of demand or, equivalently, the price flexibility. The latter refers to the percentage change in crop price due to a percent change in production. The SWAP model is specified with linear demand functions.

Demand functions are for the State of California with region-specific adjustments. In the current version of SWAP, the base market price of each crop is averaged across three regions in the Central Valley: North San Joaquin Valley, South San Joaquin Valley, and Sacramento Valley. Within each of the three regions, prices can adjust according to the underlying elasticity. The details of this procedure are provided in Attachment 15.

Demand Shifts

The nature of the demand function for specific commodities can change over time because of tastes and preferences, population growth, changes in income, and other factors. The SWAP model incorporates linear shifts in the demand functions over time resulting from growth in population and changes in real income per capita. Changes in the demand elasticity itself, resulting from changing tastes and preferences, are not considered in the model.

If population increases and all other determinants of demand (including per capita income, tastes, and preferences) remain constant, crop demand will increase proportionally. Population increases were modeled by assuming a population elasticity of 1 (quantity demanded increases by 1 percent for each 1 percent increase in population). For purposes of the SLWRI analysis, projected percent increases in California population were used to represent percent increases in the market demand for each crop.

Similarly, if real income increases, but all else remains constant, consumers' crop demands will shift according to the respective crop income elasticity of demand. The income elasticity is the percent change in demand caused by a 1 percent increase in real income. Projected increases in real income were drawn from existing studies. The income elasticity of demand for each crop group was estimated separately. The data are detailed in the section called Elasticities.

The future demand for crops produced in California will depend on future imports and exports. The proportion of California crops exported is assumed to remain constant through 2060. This is a key simplifying assumption and warrants further investigation and sensitivity analysis. The results of the sensitivity analysis are discussed in the Crop Demand Shifts, section.

Income- and population-induced demand shifts apply to only California-dominated crops (crops whose market price would be affected by changes in California production). Crops whose market price is largely independent of California production include grain, rice, and corn. The demand for California grain, rice, and corn is assumed perfectly elastic because the market share of California is small compared to overall domestic or world production. California is therefore modeled as a price taker, implying shifts in demand can be directly related to changes in world prices. In other words, rather than estimate the price response internally based on price responsiveness and demand curve shifts, SWAP simply uses the projected real change in world price.

Technological Change

Technological change refers to the innovations that have led to increasing crop yields over recent years. For policies with a long time horizon, it is likely that additional technological innovations will occur that will increase crop yields. The SWAP model includes an endogenous routine to estimate the percent change in future California crop yields resulting from technological innovations. The calculation is based on a 2004 analysis by the Agricultural Issues Center (AIC) at UC Davis (Brunke et al., 2004). The details of the procedure are provided in Attachment 15.

Note that the SWAP model does allow for some (limited) endogenous yield changes caused by a change in input mix. The nature of this effect is governed by the CES production functions and does not represent a technological shift in the production function.

Water Supply and Groundwater Pumping

Total available water for agriculture is specified on a regional basis in the SWAP model. Each region has six sources of supply, although not all sources are available in every region:

1. CVP (including Friant-Kern Class I).
2. CVP Settlement and Exchange.
3. Friant Kern Class 2.
4. SWP.
5. Local surface water.
6. Groundwater.

State and Federal project deliveries are estimated by DWR and Reclamation. Local surface water supplies are based on DWR estimates, reports of individual water suppliers, and, where necessary, drawn from earlier studies. The section called Surface Water Costs summarizes the surface water data in the SWAP model.

Costs for surface water supplies are compiled from information published by individual water supply agencies. There is no central data source for water prices in California. Agencies that prepared CVP water conservation plans or agricultural water management plans in most cases included water prices and related fees charged to growers. Other agencies publish and/or announce rates annually. Water prices used in SWAP are intended to be representative for each region, but vary in their level of detail. At least one large supplier in each region is used as the representative. In many regions, more than one supplier's price data are available. Where prices vary significantly within a region, depending on the water source (e.g., CVP contractors versus local water rights diverters), these distinctions are represented in the data. See the section called Surface Water Costs for further discussion.

Groundwater availability is specified by region-specific maximum pumping estimates. These are determined by consulting records from individual districts and information compiled by DWR. DWR analysts provided estimates of the actual pumping in the base year and the existing pumping capacity by region. The model determines the optimal level of groundwater pumping for each region up to the capacity limit specified. In some studies using SWAP or CVPM, the model has been used interactively with a groundwater model to evaluate short-term and long-term effects on aquifer conditions and pumping lifts. This was not part of the process used in the SLWRI analysis.

Pumping costs vary by region, depending on depth to groundwater and power rates. The SWAP model includes a routine to calculate the total costs of groundwater. The total cost of groundwater is the sum of fixed, operations and maintenance (O&M), and energy costs. Energy costs are based on a blend of agricultural power rates provided by Pacific Gas & Electric Company (PG&E).

The cost of electricity is expected to increase into the future, so the SWAP model includes estimates of future power cost increases based on DWR projections. As power costs increase, groundwater pumping becomes more expensive.

Economic and Agronomic Constraints

Agricultural production is subject to various economic and agronomic constraints that are likely to vary by crop and region. The SWAP model includes basic resource constraints on land and water supply, plus other constraints that can be used or modified to suit the specific analysis. These include: a constraint on how fast perennial crop acreage can change, minimum acreage requirements to provide dairy herd silage, and bounds on deficit irrigation allowed in the CES functions. The technical details of these constraints are discussed in Attachment 15.

Resource constraints in SWAP can potentially include maximum regional usage of all four inputs. However, typically only land and water are limiting factors to production. Regional water constraints are specified by the water supply input data discussed in the section called Water Supply and Groundwater Pumping. Land is not a constraint in the SWAP model; if it is profitable to do so, farmers can expand irrigated acreage. However, for some policy analyses, restricting new land coming into production may be necessary and appropriate. Similarly, other supplies and labor may be constrained if appropriate.

Deficit irrigation is allowed within the SWAP model, as detailed in the section called Constant Elasticity of Substitution Production Function. Stress irrigation is constrained so that applied water per acre drops by no more than 15 percent for any crop in any region. The corresponding yield reduction is determined by the shape of the region and crop-specific CES production function. The shape of this function and the relative profitability of crops determine the level of stress irrigation.

A regional silage constraint for dairy herd feed can be included in the model. The silage constraint forces production to meet the feeding needs of the California dairy herd, for each region. For example, each cow consumes 45 pounds of silage per day or about 8.2 tons annually, and corn grain yields are 30 tons per acre; therefore, each cow requires about 0.27 silage acres per year. Multiplying the silage acres per cow per year by the number of cows in each region yields the minimum silage requirement. Currently, the model assumes a constant herd size into the future, though additional information about future of herd sizes could be used.

Perennial crops in the SWAP model have a bearing life of between 25 and 30 years (with the exception of alfalfa). A portion of these acres will naturally be due for retirement any given season. Given the large establishment cost it is rare that farmers pull young fields out of production when facing water or other resource shortages. The SWAP model has a routine that calculates the maximum natural perennial retirement based on the time horizon of the analysis. For an analysis less than 30 years in the future, only some portion of perennials will be up for natural retirement. As the time horizon of the analysis approaches the maximum bearing life of the perennial, any proportion can be removed from production.

SWAP Model Inputs and Supporting Data

This section reviews the current data in the SWAP model that were updated for the SLWRI project. Land-use data are from 2005 and were prepared by DWR for a SWAP analysis in 2009 (Howitt et al., 2009a). DWR is now developing more detailed annual time series data on agricultural land use, but the current version of the SWAP model calibrates to year 2005 as a relatively normal base year. 2005 was neither abnormally dry nor wet, and crop markets had been relatively stable. Since 2005, California has experienced drought and unusually high commodity prices; therefore, more recent base years are not used. All prices and costs in SWAP are in constant 2005 dollars for consistency with the land-use data.

SWAP model data include land use; crop prices; yields; input costs; water costs, use, and availability; and relevant elasticity estimates. For brevity, this section includes data summarized by three regions: Sacramento, North San Joaquin, and South San Joaquin. Attachment 15 contains the tables of the full model data for the individual SWAP regions.

Crop yields and production costs are from current UCCE Crop Budgets, and crop prices are from county crop reports prepared by agricultural commissioners in each county, which are compiled annually by the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) California Field Office. The UCCE Crop Budgets are designed based on best, or at least above-average, management practices for a representative field. This is reflected in the descriptive text accompanying the published budgets, and was verified by personal communication with UCCE specialists. For example, yields used in the crop budgets' net return analysis are determined based on the UCCE specialist's knowledge and judgment, and represent good growing conditions and best management practices (BMP). In contrast, crop prices and yields reported by agricultural commissioners represent average conditions and practices; therefore, yields are average for the county, and are generally lower than those used in the UCCE Crop Budgets.

Using production costs from UCCE Crop Budgets (which are above average) together with average prices and yields reported in the county agricultural commissioner reports will generally lead to lower net returns than would be representative of California growers and, in some cases, results in negative net returns. Therefore, project benefits under this approach would be underestimated. More importantly, the SWAP model is designed to replicate actual growing conditions. To accurately estimate expected project benefits, UCCE Crop Budgets are used for both costs and yields, with prices still drawn from county averages reported in the agricultural commissioner crop reports. Under this approach, project benefits reflect the net farm income that can be attained if UCCE specialists' recommendations were followed. This can result in both revenues and costs that are somewhat higher than average for a region.

Land-Use Data

The SWAP model calibrates to a base year of observed land use, 2005. The SWAP model includes 37 individual SWAP regions. Regions 1 through 21C represent the Central Valley, and 2005 land-use data were prepared by analysts at DWR. DWR develops land-use estimates for small regions it calls Detailed Analysis Units (DAU). These are aggregated within a geographical information system (GIS) to create land use for the individual SWAP regions, and further aggregated to the larger hydrologic regions that DWR reported in the 2009

California Water Plan Update (DWR 2009). Table 6-3 summarizes land use in 2005 by three Central Valley regions within SWAP: Sacramento Valley, North San Joaquin Valley, and South San Joaquin Valley.

Table 6-3. Crop Acreage in 2005 SWAP Model Update and Application to Federal Feasibility Analysis

Crop Group	Sacramento Valley	North San Joaquin Valley	South San Joaquin Valley
Alfalfa	180,140	167,350	351,900
Almonds/Pistachios	150,050	328,340	325,600
Corn	165,800	176,890	326,400
Cotton	6,090	115,100	542,800
Cucurbits	34,470	23,610	33,500
Dry Bean	32,730	15,920	13,700
Fresh Tomatoes	12,070	16,530	9,900
Grain	152,910	30,030	181,700
Onions/Garlic	2,200	4,920	38,100
Other Deciduous	305,530	86,340	209,500
Other Field	67,030	138,940	228,000
Other Truck	32,990	52,950	123,600
Pasture	162,920	123,860	20,600
Potato	1,860	100	23,300
Processing Tomatoes	130,020	52,890	119,500
Rice	552,110	12,710	0
Safflower	41,740	2,200	5,100
Sugar Beet	0	7,900	13,100
Subtropical	28,350	6,760	212,400
Grapes	138,370	114,470	339,400

Source: DWR 2009

Crop Prices

The SWAP model is designed to represent actual conditions faced by growers in 2005. Growers make current planting decisions based on expectations of prices. The SWAP model does not attempt to model how growers form their price expectations; as an approximation, SWAP uses a 3-year simple average of county-level crop prices. The 3-year 2005–2007 averages of crop prices are calculated using the counties in each of the three Central Valley regions within SWAP: Sacramento Valley, North San Joaquin Valley, and South San Joaquin Valley. Crop prices for each SWAP region in the Central Valley correspond to one of these three areas.

Data for county-level crop prices are obtained from the respective county agricultural commissioners’ annual crop reports, which are compiled and released by the USDA annually (USDA 2011). A proxy crop, as defined in the section called SWAP Regions and Crop Definitions, is used for the representative price of each crop group. Data are summarized by crop and Central Valley region in Table 6-4.

Table 6-4. Crop Price per Ton (2005 dollars) SWAP Model Update and Application to Federal Feasibility Analysis

Crop Group	Sacramento Valley	North San Joaquin Valley	South San Joaquin Valley
Alfalfa	132.19	157.28	152.28
Almonds/Pistachios	4234.96	4226.68	4258.90
Corn	121.04	156.06	156.06
Cotton	2016.50	2016.50	2016.50
Cucurbits	464.10	464.10	464.10
Dry Bean	796.73	778.92	758.19
Fresh Tomatoes	463.65	463.65	560.60
Grain	142.68	162.69	163.00
Onions/Garlic	600.90	600.90	600.90
Other Deciduous	1502.47	1601.28	1674.88
Other Field	141.84	141.84	141.84
Other Truck	582.00	582.00	582.00
Pasture	220.00	220.00	220.00
Potato	224.60	224.60	224.60
Processing Tomatoes	51.10	52.25	53.80
Rice	245.66	220.87	222.40
Safflower	299.41	315.56	315.56
Sugar Beet	41.50	41.50	41.50
Subtropical	452.10	452.10	452.10
Grapes	610.00	610.00	610.00

Source: USDA 2011

Crop Yields

Crop yields for each crop group in the SWAP model correspond to the proxy crops and are based on BMPs. The corresponding costs of production, discussed in sections Interest Rates through Groundwater Costs, are based on cost studies that also reflect BMPs. Thus, crop yields in SWAP are slightly higher than those estimated by calculating county averages, but are more consistent with the production costs.

Crop yield data are compiled from the UCCE Production Cost Budgets (UCCE 2011). Yields for each region are based on the most recent proxy crop cost study available in the closest region. For example, if a cost study is not available for a particular crop in the Sacramento Valley, the North San Joaquin Valley study may be used. All of the studies are cited in Attachment 15. Crop yield data are summarized by crop and Central Valley region in Table 6-5.

Table 6-5. Crop Yield in Tons per Acre SWAP Model Update and Application to Federal Feasibility Analysis

Crop Group	Sacramento Valley	North San Joaquin Valley	South San Joaquin Valley
Alfalfa	7.00	8.00	8.00
Almonds/Pistachios	1.10	1.00	1.40
Corn	6.50	6.57	6.55
Cotton	0.63	0.58	0.58
Cucurbits	16.80	16.80	16.80
Dry Bean	1.25	1.25	1.25
Fresh Tomatoes	13.00	13.00	13.00
Grain	3.00	3.25	3.28
Onions/Garlic	13.00	13.00	13.00
Other Deciduous	2.70	2.70	2.70
Other Field	6.50	6.50	6.50
Other Truck	6.53	6.53	6.53
Pasture	2.50	2.50	2.50
Potato	25.00	25.00	25.00
Processing Tomatoes	35.00	40.00	40.00
Rice	5.00	5.00	5.00
Safflower	1.30	1.30	1.55
Sugar Beet	42.00	42.00	42.00
Sub-tropical	12.20	*12.20*	13.13
Grapes	7.00	6.50	6.50

Source: UCCE 2011

Interest Rates

Each UCCE Crop budget uses interest rates for capital recovery and interest on operating capital specific to the year of the study. These range from 4 percent to over 8 percent; therefore, they require adjustment to a common base year interest rate. Because the SWAP model is designed to replicate base 2005 conditions, interest rates are adjusted to reflect conditions in 2005.

Capital costs are currently included in the SWAP input data as annual capital recovery values in "other supply costs." Capital recovery costs are the annual costs of interest and depreciation on capital investments. For each capital investment, the budget estimates the purchase price, useful life of the equipment, and salvage value. A scaling of 60 percent is used to reflect a mix of new and used equipment. The sum across all capital investments represents the total capital recovery costs. The interest portion of the capital recovery is adjusted to a rate of 6.25 percent, based on interest rates used in UCCE Crop Budgets prepared in 2005. No adjustments are made to the other components of the capital recovery cost calculation.

Interest on operating capital is the interest paid on money used for annual operating costs, such as purchase of seed, fertilizer, and fuel. It is included as part of the other supply costs within SWAP input data. The UCCE Crop Budgets use a nominal interest rate that reflects the typical market rate for the year the budget represents. For use in SWAP, the interest on operating capital is adjusted to a rate of 6.25 percent, based on rates used in UCCE Crop Budgets prepared in 2005.

Land Costs

Land costs are derived from the respective UCCE Crop Budget and include land- related cash overhead plus rent and land capital recovery costs. Where appropriate, interest rates are adjusted, as described in the Interest Rates, section. Table 6-6 summarizes the land costs in SWAP, in 2005 dollars, by Central Valley region.

Land-related cash overhead includes office expenses, taxes, insurance, management salaries, and other land-specific cash expenses. For some budgets, this includes a portion of the farm that is rented. For these budgets, this expense is included in the cash overhead category, so no interest rate adjustment is necessary. Therefore, it is grouped into the land-related cash overhead component of land costs.

Land capital recovery cost corresponds to the rent value of the land as calculated by the capital recovery cost of the land. This category is adjusted to reflect a consistent interest rate of 6 percent.

The land input costs are based on the UCCE Crop Budgets, so they reflect the assumptions contained in these budgets. For example, grain (wheat as the proxy budget) in the Sacramento Valley is based on a hypothetical 2,900-acre farm that cultivates field and row crops. On the farm, wheat was part of a crop rotation that also included tomato, alfalfa, safflower, and corn. The assumptions for the hypothetical farm differ by crop and region. Different assumptions may alter the costs of production; however, the UCCE Crop Budgets represent the common BMPs in the region.

Table 6-6. Land Costs per Acre (2005 dollars) SWAP Model Update and Application to Federal Feasibility Analysis

Crop Group	Sacramento Valley	North San Joaquin Valley	South San Joaquin Valley
Alfalfa	249	317	317
Almonds/Pistachios	453	812	515
Corn	181	168	168
Cotton	196	217	217
Cucurbits	204	204	204
Dry Bean	154	209	209
Fresh Tomatoes	308	308	308
Grain	95	194	194
Onions/Garlic	336	336	336
Other Deciduous	526	526	526
Other Field	180	180	180
Other Truck	220	220	220
Pasture	92	92	92
Potato	680	680	680
Processing Tomatoes	344	298	298
Rice	269	269	269
Safflower	102	102	102
Sugar Beet	149	149	149
Sub-tropical	612	612	612
Grapes	1,024	1,352	1,352

Source: UCCE 2011

Other Supply Costs

Other supply costs are production inputs into the SWAP model. This category includes all inputs not explicitly included in the other three input categories (land, labor, and water), including fertilizers, herbicides, insecticide, fungicide, rodenticide, seed, fuel, and custom costs. Additionally, machinery, establishment costs, buildings, and irrigation system capital recovery costs are included. Where appropriate, interest rates are adjusted as described in the Interest Rates, sections.

Each subcategory of supply costs is broken down in detail in the respective crop budget. For example, safflower in the Sacramento Valley requires pre-plant nitrogen as aqua ammonia at 100 pounds per acre in fertilizer costs. Application of Roundup in February and Treflan in March account for herbicide costs. The sum of these individual components, on a per-acre basis, is used as base supply input cost data in the SWAP model. Attachment 15 provides the full dataset for each region.

The supply input costs are based on the UCCE Cost of Production Budgets, so they reflect the assumptions contained in these budgets. Different assumptions may alter the costs of production; however, the UCCE Cost Budgets represent common BMPs in the region.

Table 6-7 summarizes supply costs per acre in 2005 dollars by Central Valley region.

Table 6-7. Other Supply Costs per Acre (2005 dollars) SWAP Model Update and Application to Federal Feasibility Analysis

Crop Group	Sacramento Valley	North San Joaquin Valley	South San Joaquin Valley
Alfalfa	414	544	544
Almonds/Pistachios	1,900	1,678	1,607
Corn	329	531	531
Cotton	697	538	538
Cucurbits	2,919	2,919	2,919
Dry Bean	397	423	423
Fresh Tomatoes	4,480	4,480	4,480
Grain	227	278	278
Onions/Garlic	2,625	2,625	2,625
Other Deciduous	1,427	1,427	1,427
Other Field	465	465	465
Other Truck	3,215	3,215	3,215
Pasture	138	138	138
Potato	1,568	1,568	1,568
Processing Tomatoes	840	1,200	1,200
Rice	556	556	556
Safflower	121	121	121
Sugar Beet	779	779	779
Subtropical	4,333	4,333	4,333
Grapes	1,627	1,479	1,479

Source: UCCE 2011

Labor Costs

Labor is a production input into the SWAP model. This category includes both machine and nonmachine labor.

Labor wages per hour differ for machine and nonmachine labor, so they are reported separately in the UCCE Crop Budgets. Machine and nonmachine labor costs both include overhead to the farmer of federal and state payroll taxes, workers' compensation, and a small percentage for other benefits, which varies by budget. Additionally, a percentage premium (typically around 20 percent) is added to machine labor costs to account for equipment setup, moving, maintenance, breaks, and field repair. The sum of these components, reported on a per-acre basis, is used as input data into the SWAP model.

The labor input costs are based on the UCCE Cost of Production budgets, so they reflect the assumptions contained in these budgets. Different assumptions may alter the costs of production; however, the UCCE Crop Budgets represent common BMPs in the region. Table 6-8 summarizes labor costs in the SWAP model by Central Valley region.

Table 6-8. Labor Costs per Acre (2005 dollars) SWAP Model Update and Application to Federal Feasibility Analysis

Crop Group	Sacramento Valley	North San Joaquin Valley	South San Joaquin Valley
Alfalfa	18	21	21
Almonds/Pistachios	274	318	107
Corn	101	50	50
Cotton	130	199	199
Cucurbits	4,339	4,339	4,339
Dry Bean	106	55	55
Fresh Tomatoes	143	143	143
Grain	33	14	14
Onions/Garlic	682	682	682
Other Deciduous	223	223	223
Other Field	14	14	14
Other Truck	207	207	207
Pasture	24	24	24
Potato	410	410	410
Processing Tomatoes	373	276	276
Rice	81	81	81
Safflower	35	35	35
Sugar Beet	65	65	65
Sub-tropical	239	239	239
Grapes	828	756	756

Source: UCCE 2011

Surface Water Costs

SWAP includes five types of surface water: SWP delivery, three categories of CVP delivery, and local surface water delivery or direct diversion local surface water (LOC). The three categories of CVP deliveries are water service contract, including Friant Class 1 (CVP1); Friant Class 2 (CL2); and water rights settlement and exchange delivery (CVPS).[1]

CVP and SWP water costs have two components: a project charge and a district charge. The sum of these components is the region-specific cost of the individual water source.

The project charge is the price per acre-foot paid by the contractor (the local district or other entity holding the contract for water delivery) to the CVP or SWP. This charge does not apply to local surface water. CVP charges can be obtained from Reclamation's CVP water rate manuals. DWR charges are calculated for each of its contractors, who are obligated to repay costs regardless of water delivered (DWR 2008).

The district charge is the additional amount (above any CVP or SWP charge) that individual districts use to recover their costs of delivering the water to farms. This charge is also applied to local surface water costs. The district charge is composed of a water charge (assessed per acre-foot delivered) and a land assessment (charged per acre receiving water). Districts' rate structures vary substantially, but the SWAP model is defined over larger regions and uses average or typical values within each SWAP region.

Over time, the goal is to identify these components of costs for all applicable regions within the SWAP data. The current version of SWAP is capable of handling the water cost components; however, the data, especially district charges, are not available. The surface water cost data gathered for the current version of SWAP represent total costs to growers, but are not broken into the two components.

Table 6-9 summarizes surface water costs by source, averaged across SWAP regions in the three Central Valley regions. Water costs for each SWAP region can be found in Attachment 15.

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[1] CVP Settlement water is delivered to districts and individuals in the Sacramento Valley based on their pre- CVP water rights on the Sacramento River. San Joaquin River Exchange water is pumped from the Delta and delivered to four districts in the San Joaquin Valley in exchange for water rights diversion eliminated when Friant Dam was constructed. These two delivery categories are geographically distinct but for convenience are combined into one water supply category in SWAP.

Table 6-9. Surface Water Costs in SWAP (dollar per acre-foot) SWAP Model Update and Application to Federal Feasibility Analysis

Source	CVP1	CVPS	CL2	SWP	LOC
Sacramento Valley	23.53	13.45	14.75	23.25	14.15
Northern San Joaquin Valley	31.63	15.00	28.00	45.38	16.56
Southern San Joaquin Valley	60.46	15.00	28.00	67.00	43.92

Source: Reclamation, DWR, and Individual Districts

Key:
CL2 = Friant Class 2
CVP1 = Friant Class 1
CVPS = Water rights settlement and exchange delivery
LOC = local
SWP = State Water Project

Groundwater Costs

A key source of irrigation water, and often the most costly, is groundwater pumping. Groundwater pumping costs are broken out into fixed, energy, and O&M components in the SWAP model. Energy and O&M components are variable. Pumping costs are calculated as two components: the fixed cost per acre-foot based on typical well designs and costs within the region, plus the variable cost per acre-foot. The variable cost per acre-foot is O&M plus energy costs based on average total dynamic lift (TDL) within the region.

Energy costs depend on the price of electricity. Power costs can be varied by region and according to the time horizon of the relevant analysis depending on the projected cost of power. The current version of SWAP uses the same unit cost of electricity per kilowatt-hour (kWh) across all regions. Base electricity costs are derived from PG&E published rates. Energy cost is 18.9 cents per kWh, which is an average of PG&E’s AG-1B and AG-4B rates. Overall well efficiency is assumed to be 70 percent.

The TDL for each region is in feet, and includes both static lift and additional dynamic drawdown when pumps are operating. TDL varies by region and water-year type on SWAP. Thus, in dry years groundwater pumping costs per acre-foot increase because of increased depth to groundwater, plus additional drawdown caused by greater regional pumping rates. Base groundwater depth (static pumping lift) estimates are from the CVPM model, which in turn were provided by the Central Valley Groundwater-Surface Water Model (CVGSM). For scenario and projections analysis, changes in groundwater depths must be provided by external analysis such as a groundwater model; SWAP does not project changes in groundwater storage and depth.

Table 6-10 summarizes components of groundwater pumping costs by Central Valley regions, and Attachment 15 provides a breakdown by SWAP region.

Table 6-10. Groundwater Cost Components in SWAP Model Update and Application to Federal Feasibility Analysis

Source	Fixed Cost($/AF)	TDL (feet)	Efficiency (%)	$/kWh
Sacramento Valley	19.80	80.87	0.7	0.189
Northern San Joaquin Valley	27.00	88.92	0.7	0.189
Southern San Joaquin Valley	34.85	222.72	0.7	0.189

Source: Individual Districts and PG&E
Key:
AF = acre-foot
kWh = kilowatt-hour
TDL = total dynamic lift

Applied Water per Acre

Applied water is the amount of water applied by the irrigation system to an acre of a given crop for production in a typical year. Variation in rainfall and other climate effects will alter this requirement. Additionally, farmers may stress irrigate crops or substitute other inputs to reduce applied water. The latter effect is handled endogenously by the SWAP model through the respective CES production functions.

Applied water per acre (base) requirements for crops in the SWAP model are derived from DWR estimates (DWR 2009). DWR estimates are based on DAUs. An average of DAUs within a SWAP region is used to generate a SWAP region specific estimate of applied water per acre for SWAP crops. Table 6-11 summarizes applied water per acre by crop and Central Valley region. Attachment 15 details SWAP-region specific applied water requirements.

Table 6-11. Applied Water (acre-feet per acre) SWAP Model Update and Application to Federal Feasibility Analysis

Crop Group	Sacramento Valley	North San Joaquin Valley	South San Joaquin Valley
Alfalfa	4.55	4.38	4.38
Almonds/Pistachios	3.11	3.43	3.54
Corn	2.83	2.53	2.89
Cotton	3.00	3.33	2.70
Cucurbits	1.50	1.97	1.43
Dry Beam	2.27	2.55	2.40
Fresh Tomatoes	2.36	1.81	1.42
Grain	0.60	0.75	1.10
Onions/Garlic	2.77	3.32	2.35

Table 6-11. Applied Water (acre-feet per acre) SWAP Model Update and Application to Federal Feasibility Analysis (contd.)

Crop Group	Sacramento Valley	North San Joaquin Valley	South San Joaquin Valley
Other Deciduous	3.24	3.43	3.41
Other Field	2.49	2.60	2.54
Other Truck	2.85	0.96	0.88
Pasture	4.67	4.47	4.34
Potato	3.48	1.41	1.29
Processing Tomatoes	2.80	2.55	2.01
Rice	4.95	6.66	n/a
Safflower	0.82	1.83	1.99
Sugar Beet	n/a	1.42	2.18
Sub-tropical	2.32	2.60	2.71
Grapes	1.05	2.28	2.36

Source: DWR, 2009

Note:
These values are acreage-weighted averages. SWAP uses DWR estimates by subregion, shown in Attachment 15.

Available Water by Region and Source

Base water availability, by region, is discussed here. For analysis of a prospective project or operation, water availability would often vary by scenario. Data for scenario analysis generally is provided by external modeling or other analysis, and is read from a separate input file.

CVP water deliveries were derived from Reclamation operations data. Contract deliveries were obtained from Reclamation, and the difference between total and contract deliveries indicates deliveries for water rights settlements.

SWP water deliveries were obtained from DWR Bulletin 132 (DWR 2008). Kern County Water Agency (KCWA) provides additional details on SWP deliveries to member agencies by region.

Local surface water deliveries were obtained from individual district records and reports, DWR water balance estimates prepared for the California Water Plan Update (DWR 2009), and, where needed, data from the CVPM model. CVPM data were, in turn, provided by CVGSM.

Groundwater pumping capacity estimates are from a 2009 analysis by DWR in consultation with individual districts. Groundwater pumping capacity is intended to represent the maximum that a region can pump in a year given the aquifer characteristics and existing well capacities. For long-run analysis, additional pumping capacity could be installed, but careful groundwater analysis should be made to determine hydraulic feasibility. If groundwater analysis is not available, existing capacity constraints are assumed to hold.

Table 6-12 summarizes available base water supply by source and aggregated across SWAP regions in the three Central Valley regions.

Table 6-12. Available Water by Source (thousand acre-feet) SWAP Model Update and Application to Federal Feasibility Analysis

Source	CVP1	CVPS	CL2	SWP	LOC	GW
Sacramento Valley	409.47	1,323.23	0.00	0.00	3,320.30	2,537.90
Northern San Joaquin Valley	370.09	768.20	78.61	3.90	2,312.70	1,245.00
Southern San Joaquin Valley	1,959.81	0.00	197.85	1,372.90	2,844.20	3,116.30

Sources: DWR 2008; DWR 2009; individual district records and reports; and CVPM

Key:
CL2 = Friant Class 2
CVP1 = Friant Class 1
CVPS = Water rights settlement and exchange delivery
GW = Groundwater
LOC = local
SWP = State Water Project

Elasticities

SWAP uses a number of economic response parameters, called elasticities, to estimate rates of change in variables. An elasticity is the percent change in a variable, per unit of percent change in another variable or parameter. Acreage response elasticity is one component of supply response. It is the percentage change in acreage of a crop from a 1 percent change in that crop’s price. The SWAP model contains long-run and short-run estimates, and the analyst decides which of the elasticities to use. Long-run acreage response elasticities are used for the SLWRI feasibility study. Acreage response elasticities were estimated for the original CVPM model, and are used in SWAP (Reclamation 1997).

Income and population elasticities govern the shift of the crop-specific demand functions over time. Population elasticities are assumed equal to one. Income elasticity estimates are from Green et al. (2008). The literature on income elasticity estimates is sparse and many experts, including authors of some studies used in the SLWRI analysis, caution that these estimates often capture other unintended effects. Therefore, when reliable income elasticity estimates are unavailable, 0.2 is assumed for field and forage crops and 0.5 is assumed for fruit crops. Under specific conditions (not satisfied here), the price flexibility is the reciprocal of the absolute lower-bound own-price elasticity (Houck 1965). The price flexibilities, observed prices, and production are used to construct the individual crop demand functions. Price flexibilities were estimated for the CVPM model (Reclamation 1997), and some were updated based on estimates in Green et al. (2008). Table 6-13 summarizes the elasticities used in the SWAP model.

Table 6-13. Various Elasticities by Crop Group SWAP Model Update and Application to Federal Feasibility Analysis

Crop Group	Flexibility	Income	Population	Acreage Response	
				Long Run	Short Run
Alfalfa	-0.50	0.20	1.00	0.51	0.24
Almonds/Pistachios	-0.70	0.51	1.00	0.11	0.03
Corn	0.00	0.00	1.00	0.45	0.21
Cotton	-0.05	0.05	1.00	0.64	0.36
Cucurbits	-0.20	0.99	1.00	0.05	0.05
Dry Bean	-0.20	0.20	1.00	0.17	0.13
Fresh Tomatoes	-0.62	0.89	1.00	0.31	0.16
Grain	0.00	0.00	1.00	0.38	0.36
Onions/Garlic	-0.21	0.99	1.00	0.19	0.11
Other Deciduous	-0.25	0.50	1.00	0.11	0.03
Other Field	-0.20	0.20	1.00	1.89	0.63
Other Truck	-0.20	0.99	1.00	0.19	0.11
Pasture	-0.50	0.00	1.00	0.51	0.24
Potato	-0.10	0.20	1.00	0.19	0.11
Processing Tomatoes	-0.17	0.89	1.00	0.28	0.15
Rice	-0.05	0.00	1.00	0.96	0.96
Safflower	-0.20	0.20	1.00	0.34	0.34
Sugar Beet	-0.10	0.00	1.00	0.19	0.11
Subtropical	-0.80	0.50	1.00	0.50	0.30
Grapes	-0.80	0.51	1.00	0.11	0.03

Key:
SWAP = Statewide Agricultural Production Model

SWAP Adjustments and Post-Processing for SLWRI

To adhere to the Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation (P&G) and determine SLWRI contribution to NED, a series of adjustments to the SWAP model and data are necessary. Adjustments fall into two categories: pre- and post-processing.

Pre-processing adjustments are made before optimization with the SWAP model and include adjustments to SWAP input data and exogenous projections of future costs and demands. They can be viewed as assumptions specific to the project and scenario being analyzed that would change the costs and returns, and therefore the decisions made by farmers. For the SLWRI project, pre-processing adjustments include crop demand shifts, technological change, and power costs.

Post-processing adjustments are applied to SWAP output and include adjustments to prices and costs. They are adjustments needed in order for the results to comply with P&G and Reclamation guidelines for NED analysis. In particular, guidelines require that certain prices be used for valuing changes in physical inputs and outputs. They do not explicitly affect farmers' decisions, so they are applied after the SWAP optimization. For the SLWRI project, post-processing adjustments include interest rates, other supply costs, fallow land costs, normalized crop prices, consumer surplus, water costs, and management charges.

Pre-processing Adjustments

This section summarizes the pre-processing adjustments that are made before optimization with the SWAP model:

- Crop demand shifts
- Technological change
- Groundwater pumping power costs

Crop Demand Shifts

Crop demands are expected to shift in the future as a consequence of increased population, higher real incomes, changes in tastes and preferences, and related factors. The key changes included in the SLWRI analysis are population and real income. An increase in real income is expected to increase demand for agricultural products. Similarly, population increase is expected to increase crop demand. Changes in consumer tastes and preferences will have an indeterminate effect on demand and are not included in the SLWRI analysis.

The SLWRI analysis is concerned with California agriculture; it is necessary to consider the entire market for California crops, which includes international exports. Increases in demand for crops produced in California may be partially offset by other production regions depending on changing export market conditions. For example, today California is the dominant producer of almonds, but this may change if other regions in the United States or the world increase production; an increase in almond demand could be partially met by other regions. However, additional demand growth from markets like China may offset this effect. The net effect is indeterminate. In the absence of data or studies demonstrating which effect would dominate, California export share is assumed to remain constant for all crops in the future. This is a key assumption and is consistent with publications for the California Energy Commission

(Howitt et al., 2009b), the academic journal Climatic Change (Medellin-Azuara et al., 2008), and the 2009 DWR Water Plan (DWR 2009).

Crop demands are linear in the SWAP model, and population and real income changes induce a parallel shift in demand. Demand shifts are included for all of the alternative scenarios evaluated for the SLWRI project, including the No-Action Alternative. Consequently, benefits estimates that compare No Action to one of the Action Alternatives compare identical future market conditions.

For purposes of the demand shift analysis, a distinction is made between two types of crops grown in California: California-specific crops and global commodities. Global commodity crops include grain, rice, and corn;[2] all other crop groups are classified as California crops. Global commodity crops are those for which there is no separate demand for California's production. For these crops, California faces a perfectly elastic demand, and is therefore a price taker. The SLWRI analysis does not consider the international trade market for these crops; it is assumed that California's export share will continue to remain small in the future. For California-specific crops, California faces a downward sloping demand for a market that is driven by conditions in the United States and international export markets. California's export share and international market conditions are assumed to remain constant, so demand shifts are based solely on United States conditions. The SLWRI analysis does not model changes in tastes and preferences, only the shift in demand for these crops that will result from increasing population and real income. A routine in the SWAP model calculates the demand shift depending on the year of the analysis (2005 or 2030 for SLWRI).

Since California is a small proportion of global production for commodity crops, the only necessary information to estimate the shift in future demand is the long-run trend in real prices. Formally, the SLWRI analysis assumes that California will retain its small share of the global market for these crops. A recent report by the World Bank (2009) projects price increases (in real terms) until 2015 for rice, corn, and grains. Many experts in the field believe this is an overestimate because long-run real prices have been historically declining for these crops. To address this contradiction, at Year 2015 the analysis allows the historical downward trend in real prices to resume. The projected near-term annual increases are combined out to 2015, with the long-run trend resuming in 2015 to estimate the total percentage demand shift (change in real price).

Demand for California specialty crops is expected to increase with increasing population and income in the United States. Changes in U.S. income and population are estimated and combined with income and population elasticities of demand to determine the shift in demand for these crops. Income and population increases can be directly related to shifts in demand. Shifts from

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[2] Rice demand is very elastic but not perfectly elastic. For purposes of the demand shifting analysis, it is assumed to be perfectly elastic.

income changes and population are combined to determine the overall shift in demand. Elasticity estimates and data were summarized in Table 6-13.

According to the Bureau of Labor Statistics average incomes in the United States have increased 6.9 percent annually between 1982 and 1992, 5.6 percent annually between 1992 and 2002, and are projected to increase 5.4 percent annually until 2012, nominally (Bureau of Labor Statistics, 2007). With 3.4 percent average historical inflation, this is approximately 2 percent real annual income growth in the United States. According to the 2000 Census, the population in the United States is projected to increase by 5 percent every 5 years. These trends are extrapolated to determine income and population demand shifts in the SLWRI analysis.

Technological Change

Since World War II, crop yields have been increasing for most crops because of technological innovations such as hybrid seeds, better chemicals and fertilizer, improved pest management, and irrigation and mechanical harvesting advances. The expected future rate of growth in crop yields is a contentious topic among researchers. One argument is that yield increases have already started to level off and, at the same time, spending on agricultural research and development (R&D) has started to decrease. Therefore, yield increases are expected to level off in the future as R&D spending continues to decline. Alternatively, some researchers argue that yields are continuing to trend upward and there are many opportunities for further increases, even with limited spending on R&D. There is no general consensus on the expected rate of yield growth in the future within California and globally.

For the SLWRI analysis, the P&G allows for yield increases with several caveats. The most important requirement is that if yields increase, the cost of R&D needs to be incorporated. Furthermore, higher production costs need to be incorporated. No reliable and consistent data are available on the costs of R&D or expected production costs with higher yields, so this is omitted from the analysis.

It is important to note that the SWAP model does allow for some yield response to changing market conditions. This effect is referred to as endogenous yield changes. The SWAP model includes full CES production functions for each crop and region. As such, there is some endogenous yield change in response to changing market conditions. For example, the SWAP model allows for more inputs (e.g., labor, other supplies, and water) to be applied to existing land to increase yields. The relationship between inputs and yield varies by crop and region. Each relationship is determined in the PMP routine and based on empirical data. (See Attachment 15 for technical details.) The ability to adjust input use and generate marginally higher yields is consistent with observed practices. In general, this is plus or minus a few percentage points from the mean yield. Note that this is separate from technological (exogenous) yield change. There is no exogenous technological change included in the SLWRI analysis.

Technological change is omitted from the SLWRI analysis, but demand shifts are incorporated. This means that all of the increase in demand will be met with some combination of additional inputs applied to existing land (endogenous yield increases), additional land into production, and shifting crop mix. Supply response to higher prices is typically composed of several components, the largest of which include acreage and yield response. Exogenous technological change is not incorporated in the analysis, so endogenous yield effects and acreage responses may be overstated.

Groundwater Pumping Power Costs

Groundwater pumping is typically the most expensive water supply. Real power costs are expected to increase in the future, and groundwater pumping relies heavily on the cost of electricity. SWAP model input data were updated under the SLWRI project to break down groundwater pumping costs into fixed capital, energy, and O&M components. Energy pumping costs are escalated according to future marginal power cost estimates.

For the SLWRI analysis, a single future scenario is considered for each of the alternatives: 2030. A marginal power cost escalator is determined for each year and applied to the energy cost component of groundwater costs. The cost escalator is the ratio of the expected future power cost in 2030 to the base power cost in 2005, in 2005 dollars per megawatt-hour.

Expected future power costs are calculated using DWR’s forward price projections analysis using wholesale power costs. This calculates an average power cost for each month as the average of the peak (upper bound) and off-peak (lower bound) rates. An average of the monthly costs generates an average yearly cost. This cost is used to generate the power cost escalator by taking the ratio of the future year average to the current year average.

The power cost escalator for 2030 is 1.54. Power costs are expected to increase by 54 percent in real terms by 2030.

Post-processing Adjustments

This section summarizes the post-processing adjustments that are made after optimization with the SWAP model.

Interest Rates

Capital costs are currently included in the SWAP input data as annual capital recovery values in “other supply costs.” UCCE Crop Budgets prepared in different years use different interest rates to represent market conditions in the respective year of the budget. SWAP input data are based on budgets prepared between 2002 and 2010. Interest rates varied between 4 and 10 percent, depending on the budget. A consistent interest rate of 6.25 percent was used for all SWAP input data, as detailed in the Interest Rates, section.

For SLWRI analysis, the P&G requires that the federal discount rate be used for all interest and capital recovery calculations. The federal discount rate for Fiscal Year 2014 was 3.50 percent. A post-processing adjustment was applied to cost data components to adjust the interest rate from 6.25 percent to 3.50 percent. For interest on operating capital, a simple ratio adjustment of 3.50/6.25, or 0.56, is used. However, capital recovery costs include both a principal and interest component. Capital recovery factors were computed for a range of useful lives using both the SWAP rate of 6.125 percent and the federal discount rate of 3.50 percent, and it was determined that a ratio of 0.72 was an acceptable approximation for adjusting SWAP capital recovery charges for a P&G analysis. This ratio corresponds to an average useful life of between 15 and 20 years for farm investments.

Other Supply Costs

The SWAP model uses CES production functions with four aggregate inputs: land, labor, other supplies, and water. Other supplies include the cost of seed, fertilizers, chemicals, custom harvest, irrigation system, and other capital recovery costs. For the SLWRI analysis, it was necessary to identify individual components of the other supplies category to make P&G-required adjustments.

Two methods were discussed for disaggregating other supply costs in the SWAP model. The first method would use a nested CES production function to separate fixed capital and variable inputs. This is likely the preferred methodology, but would require substantial structural and coding changes to SWAP, and therefore was beyond the scope and time frame of the project. Instead, a second approach was adopted where other supply costs remain an aggregate input in the CES production functions, but are proportionally allocated to the various components. For each crop and region, the total other supply costs are the sum of the individual components. This is done within the SWAP data file, and any further adjustments, such as for interest rates, are made post-optimization. This procedure implicitly assumes that all components of other supply costs adjust proportionally to any change in the aggregate input use.

Other supply costs were divided into 12 categories, the most detailed level of disaggregation allowed by the UCCE Crop Budgets. For NED post-processing adjustments, other supply costs were divided into variable costs and capital costs. Specifically, eight areas were identified and broken out for NED post-processing:

1. All other variable supply costs and labor.

2. Interest on operating capital.

3. Machinery capital recovery costs.
4. Crop establishment costs.
5. Buildings capital recovery costs.
6. Irrigation system costs.
7. Land rent and cash overhead.
8. Land capital recovery costs.

Capital recovery costs for machinery and buildings were discussed to decide whether changes should be included in a long-run NED analysis. These capital items are “lumpy” in the sense that, for example, the same machines and buildings are required for farming 205 acres or 200 acres. The project team and Reclamation concurred that machinery and building investments, even in the long term, were unlikely to change for projects providing only small increases in water supply and irrigated acreage. Growers would likely have existing machinery and farm buildings that could be used on small increments of new land, especially if that land had been developed and farmed in the recent past.[3] This was the case for the initial application of SWAP to the SLWRI feasibility analysis, so capital recovery costs were removed from the NED analysis under all scenarios. Note that this did not mean they were assumed to be zero for any alternative, but only that they would not change when comparing an alternative to the No Action condition to compute benefits. Operational costs of machinery (labor, fuel, and repairs) remained as a cost.

During the review process, an argument was made that, since this is a long-run analysis, all inputs should be truly variable and consequently included in the NED benefits calculation. The size of this effect was assessed in an internal report that found benefits rise by less than 1 percent when capital recovery costs on machinery and buildings are excluded. It was determined that the decision to include or exclude these costs can be made according to the details of a particular project.

Land rent and cash overhead and land capital recovery costs were removed from the NED analysis under all scenarios. The NED analysis was adjusted to remove land costs that are included within the SWAP data file because lands being brought into irrigated production are already considered a sunk investment, especially if they were previously developed for irrigation. Sunk investments are irrelevant to determining the economic feasibility of new project investments. In addition, land values largely reflect capitalized net returns, which are not appropriate for inclusion in a budget-based benefit analysis (the purpose of the budget is to compute those net returns). Finally, some crop budgets included land rent paid to an owner rather than capital

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[3] This assumption would not be appropriate for all projects and can easily be modified.

recovery on owned land. From an NED perspective, rent is just a transfer of income between owner and tenant. Therefore, rents are removed from the NED analysis. The avoided variable cost of additional land brought into production is accounted for in a separate calculation based on fallow land costs, as described in the next section.

Interest on operating capital and capital recovery charges for permanent crop establishment and for irrigation systems was adjusted using interest factors as previously noted. No adjustments to the other SWAP supply costs (seed, fertilizer, chemicals, custom charges, and labor) were required to make them consistent with a P&G NED analysis.

Fallow Land Costs

If additional acres are brought into irrigated production, many of those acres are likely to represent land that was fallow in the past. As currently configured, SWAP does not account for the variable costs of production for these lands in the No Action Alternative. In most or all of the analyses planned for California, fallow land has already been developed for irrigated production and it is either in rotational fallow or has been set aside for some reason such as lack of water. Fallow land has a low annual maintenance cost (such as weed control, fence repair, and similar needs) that would be avoided if brought back into production.

An annual maintenance cost of $34.60 per acre (in 2005 dollars) was used for the application of NED analysis to the SLWRI feasibility study. This cost estimate is from a recent San Luis Unit Drainage study (Reclamation, 2002). To determine the number of fallow acres brought into production under any SLWRI alternative, each alternative scenario was compared to the No Action Alternative and the change in irrigated acres was calculated. Any additional acreage brought into production would avoid the annual fallow maintenance costs. Regions affected by the SLWRI water supply changes include land that is developed and dry-farmed and land that is developed for irrigated production but fallow. For the SLWRI feasibility study, the amount of fallow land in excess of rotational fallow was more than sufficient to account for acreage potentially brought into production.

Normalized Crop Prices

The base price per ton for each crop in the SWAP model is an average of 2005 through 2007 prices for each region (converted to the 2005 price level). These years are selected as a representation of farmer price expectation when planting decisions were made in 2005, the base year of data in SWAP. The calibration routine is designed to replicate the conditions farmers faced in 2005. Crop prices are discussed in greater detail in the section called Crop Prices of this report.

Prices under the various alternatives are estimated to represent conditions farmers would face in the future (e.g., 2030 for the SLWRI analysis). For the

SLWRI analysis, future prices vary according to (endogenous) market effects and (exogenous) demand shifts. The SWAP model requires that the market for each crop in each region clears such that supply equals demand. Supply is governed by the production and cost functions, and demand is governed by downward-sloping California-specific demand curves. Thus the market-clearing price is determined endogenously by the model. Exogenous demand shifts were discussed in the section called Crop Demand Shifts and capture demand shifts due to income and population increases. The net effect varies by crop and region but is taken to represent the expected future prices under any of the alternative scenarios.

As an exception to general guidance, the P&G allow for real price changes over time. Changes in prices due to changes in production are endogenously determined within the SWAP model, and this is consistent with market-based analysis allowed by the P&G.

The P&G state that USDA Current Normalized Prices (CNP) be used for benefits calculations when available. USDA has adjusted these prices to remove any federal subsidies, because such subsidies represent an NED cost that must be accounted for in comparing project benefits and costs. CNPs were used to adjust future prices after SWAP optimization as follows:

- • For crop groups covered by USDA’s CNP estimates, SWAP prices were converted to scaled CNP.
- • For crop groups without available CNP, the SWAP-predicted prices were used.

CNPs were identified for six crop groups in the SWAP model: corn, cotton, dry beans, grain, rice, and sugar beets. CNPs were not available at projected future conditions, whereas the SWAP model provided predictions of future crop prices. Therefore, CNPs for these six crops were scaled by the predicted real price increase by SWAP. The resulting procedure used CNPs, as required by P&G, and combined the additional information on expected real price increase from SWAP. Table 6-14 summarizes the results of this procedure. The scenario used in the example is the No-Action Alternative in 2025; different scenarios result in different adjustment ratios and, consequently, different scaled CNPs.

Table 6-14. Comparison of Crop Prices ($2005) SWAP Model Update and Application to Federal Feasibility Analysis

Crop	CNP	SWAP 2005	SWAP 2025	Ratio	Scaled CNP
Corn	107.81	144.39	203.00	1.41	151.57
Cotton	1,086.59	2,016.50	2,638.63	1.05	1,137.03
Dry Bean	852.74	774.88	841.08	1.09	925.60
Grain	137.94	155.43	212.01	1.19	164.69
Rice	280.19	230.79	389.87	1.42	397.81
Sugar Beet	37.55	41.50	41.88	1.01	37.89

Key:
CNP = current normalized price
SWAP = Statewide Agricultural Production Model

The CNP scaling ratio varies from 1.01 to 1.41. The largest increase in real price is expected for corn. This is largely due to an anticipated increase in demand. All scaled CNPs are above reported CNPs. However, only rice and dry beans scaled CNPs are above the SWAP estimate for 2025 under the No-Action Alternative scenario.

Consumer Surplus

Consumer surplus is the benefit (welfare gain) that consumers realize from being able to purchase crops at less than their maximum willingness to pay. Intuitively, the market price is determined where supply equals demand; however, many consumers would be willing to pay more than the market price (represented as a downward-sloping demand curve). In other words, what consumers actually pay is below the maximum willingness-to-pay for all units up to the market-clearing quantity. Mathematically, this is the area under the demand curve and above the market-clearing price. The area is called consumer surplus and is calculated in the SWAP model.

A change in the price of a crop will change the resulting consumer surplus and should therefore be included in a NED benefits analysis. Although this topic is not explicitly mentioned in the P&G for determination of irrigation benefits, it is consistent with the P&G overall conceptual basis that all benefits should be based on willingness to pay. For the SLWRI analysis, SWAP calculated the change in aggregate consumer surplus for each of the alternatives relative to the No-Action Alternative.

This procedure attributes all change in consumer surplus to the NED benefits calculation. However, some California production is exported internationally, so benefits to consumers would be outside the United States and should not be included in the NED analysis. A study conducted by the AIC at UC Davis reports that about 24 percent (in value terms) of California production is exported overseas (AIC 2011). As a rough test of the effect of non- domestic surplus on the analysis, this fraction was applied to the results of the irrigation benefits for the SLWRI feasibility analysis. The change in consumer surplus was reduced by 24 percent to approximate the portion attributable to the United

States, and NED benefits were reduced by just over 5 percent. On the other hand, this approach omits consumer and producer surplus in forward-linked markets (for example, processing markets that rely on California production as inputs). The project team decided that the net effect on benefits is indeterminate. The decision to include consumer surplus benefits but omit forward-linked benefits is a pragmatic one and warrants more investigation in the future.

Water Costs

In an NED benefit-cost analysis of a proposed project, the incremental investment and annual costs of the new water supply are accounted for on the cost side of the ledger, so including them as water costs within the benefits analysis would effectively be double-counting.

Current Reclamation water management plans were reviewed to provide a breakdown of total water charges into district charges versus CVP water costs. Then the CVP portion of water costs in SWAP related to the new project water supply were added back into net returns (benefits) in the post-processing stage to avoid double-counting in the NED calculation.

Finally, the changes in the amount and cost of groundwater pumping were explicitly accounted for in SWAP, so these were part of the benefits calculated. The SWAP post-processing spreadsheets calculated and itemized the change in groundwater pumping cost so that they were explicit and not masked by other components of the benefits.

Management Charge

Reclamation guidelines for preparing NED analysis under the P&G recommend including management costs at no less than 6 percent of variable costs. The post-processing step calculated the total variable costs reported by the SWAP model and added 6 percent of this number as a management charge. This item is broken out separately in the post-processing spreadsheets used to calculate benefits.

Adjustment to 2014 Dollars

As previously mentioned, SWAP returns were expressed in 2005 dollars. All P&G returns, after adjustment, were indexed to January 2014 dollars by means of the Federal Reserve Bank’s Gross National Product Implicit Price Deflator to enable a consistent comparison to SLWRI project costs.

Treatment of "Other Crops" as Defined in the P&G

The P&G describe a procedure for using a set of so-called basic crops for estimating the benefits of irrigation water supply. These include grains, hay, cotton, and similar commodities whose price would be unaffected by the project’s increased production. The rationale for this procedure is to avoid claiming benefits for specialty crops that have higher average net returns but for which market demand is limiting. In other words, the P&G basic crop procedure is intended to avoid claiming benefits for crops that cannot be supported by existing markets or whose increased production would drive down prices to all producers of those crops (including producers outside the project study area).

SWAP analysis explicitly accounts for the market demand for all crops and therefore incorporates any price effects caused by production changes. It also accounts for any shifts of production from existing regions in California to the project area. In general, SWAP's predictions of crop acreage changes resulting from new water project supply fall predominantly, but not completely, within the set of basic crops. This occurs because the model accounts for relatively inelastic demand for specialty crops and relatively steep marginal costs for bringing new specialty crop land into production. When specialty crop acreage does increase, it is accompanied by a model-wide price effect. It is acknowledged that the model does not include effects on other production regions outside of California. Foreign suppliers, in particular those in Mexico and other Central and South American countries, could be affected by price effects or even displacement of market share.

However, shifting net returns from production from foreign countries to the United States is considered an NED benefit.

Because SWAP explicitly accounts for price and cost effects associated with production of nonbasic crops, NED analysis using SWAP does not restrict irrigation benefits to only the basic crops. More detail on the structure of demand and cost functions in SWAP is provided in Section SWAP Model Detail and Attachment 15 of this report.

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Chapter 7
Delta Hydrodynamic Model

Methodology

Water quality in the Delta is a function of many factors, including tidal exchange, agricultural diversions and return flows, operation of flow control structures (Delta Cross Channel, temporary barriers in the south Delta, and Suisun Marsh Salinity Control Gate), Delta inflows (Sacramento River, Yolo Bypass, San Joaquin River, and eastside streams), and export pumping at CVP and SWP facilities. Delta outflow is the key determinant of salinity.

Successful and reliable Delta tidal hydraulic and salinity modeling depends on a number of important components. Preliminary components for successful tidal hydraulic and salinity modeling are as follows (Reclamation and DWR 2005):

- Accurate hydrology data to specify river inflows, agricultural diversions and drainage flows, export pumping diversions, and resulting Delta outflow.

- Accurate channel geometry, including surface area, channel depths, and intertidal volumes.

- Accurate tidal stage and flow records for specifying downstream tidal boundary conditions and for calibrating tidal stage variations and tidal flows that move into and out of the Delta channels in response to downstream tidal variations.

- Accurate tidal salinity (electrical conductivity (EC)) measurements for specifying downstream tidal salinity conditions and for calibrating tidal salinity variations and (indirectly) tidal flows that move salinity gradients in and out of the western Delta.

- Reasonable approximations of equations that describe the movement of water and salt as a function of the geometry, water surface slope, bottom friction forces, and velocity (i.e., momentum) gradients in the channel network that can be solved numerically, on a computer, and displayed as informative graphics (i.e., a “model”).

- Creative and innovative users who understand the basic issues and questions being addressed with the application of these Delta tidal hydraulic and salinity models, and who are able to illustrate and describe the results of the models.

The history of efforts by Reclamation and DWR to improve and innovate in each of these areas to support more accurate and reliable Delta tidal hydraulic and salinity modeling is briefly outlined below.

DWR developed the DAYFLOW data program to organize and standardize the daily hydrology data required to understand and evaluate historical Delta conditions. DAYFLOW files are now available from water year 1955 to present at the CDEC Web site at http://www.cdec.water.ca.gov. Less accurate estimates (because of fewer flow records) are available beginning with water year 1929.

Reclamation, DWR, USGS, and USACE have collected many channel cross sections and channel sounding surveys throughout the Delta channels. The most accurate channel geometry data are now updated and available through the Cross Section Development Program (CSDP) database of the DSM2 system. DSM2 and the CSDP both use the common datum of sea level (National Geodetic Vertical Datum 1929).

Tidal stage measurements have been collected by Reclamation, DWR, and USGS for many years. Instrumentation improvements have allowed many of the measurement stations to electronically record 15-minute stage elevations. Several of these stations are now available on a real-time basis through CDEC. A joint investigation was started in 1978 by Reclamation, DWR, USGS, the State Water Board, and USACE to determine the most appropriate method for direct measurements of Delta outflow. According to Oltmann 1998, Delta outflow can now be indirectly measured as the sum of four ultrasonic velocity meter (UVM) stations (Rio Vista, Threemile Slough, Jersey Point, and Dutch Slough).

Reclamation and DWR measurements of tidal salinity had already begun using electronic instruments to measure Delta salinity (as EC) to support ongoing water management operations of the CVP Jones (formerly Tracy) and planned SWP Banks facilities in the Delta during the 1960s. The Interagency Ecological Program (IEP) was established in 1970 as a joint investigation program for Delta water and fish management agencies. Many of the Delta EC measurements were collected to support these IEP efforts. The IEP database is extensive and can be accessed at the IEP Web site at http://www.iep.water.ca.gov. Many of the Delta tidal stations are now included in the CDEC database, which allows near real-time access to these hydraulic and water quality measurements. The history of modeling efforts is described in the next section.

Modeling History

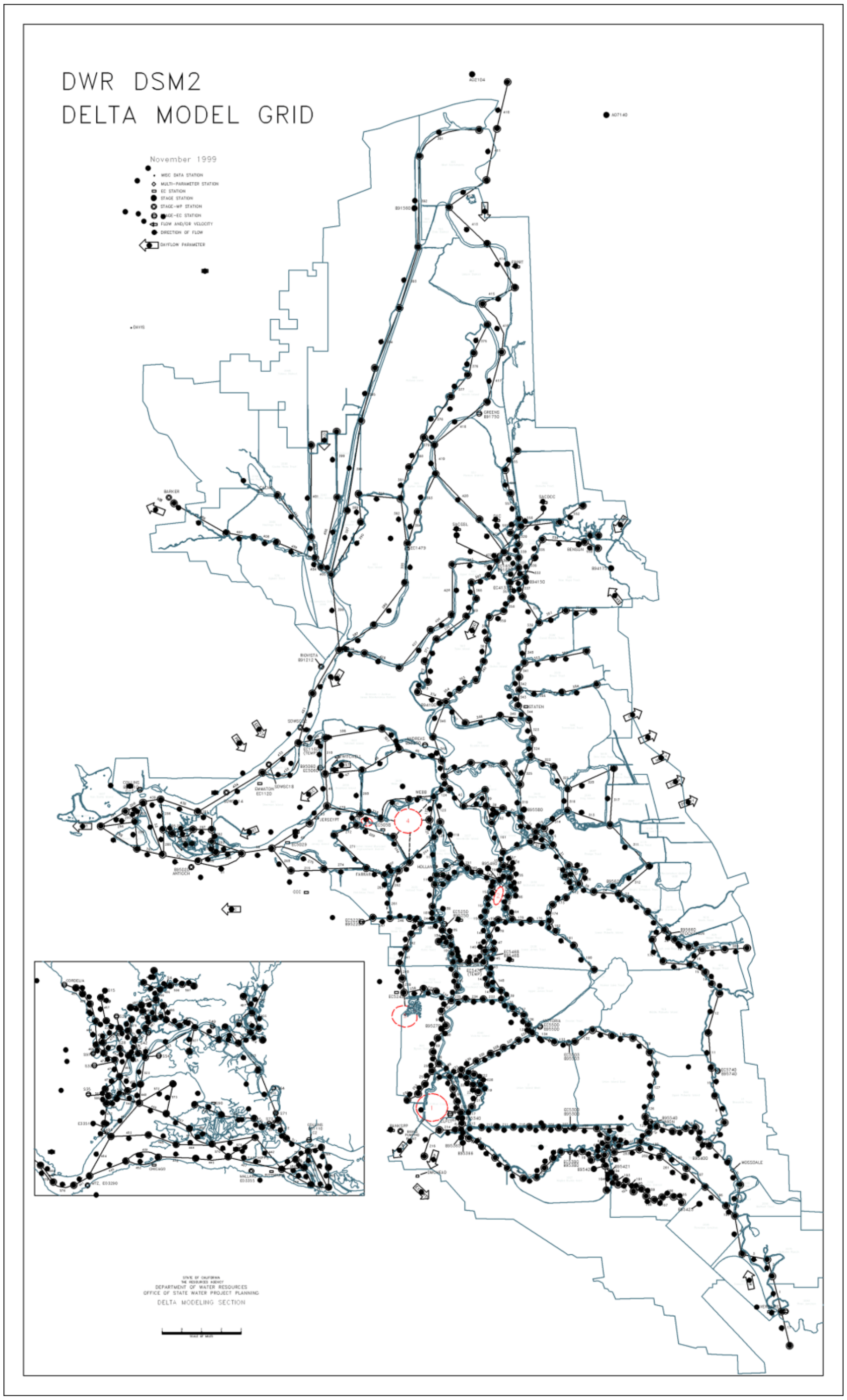
Various mathematical models have been developed to estimate hydrodynamic and water quality conditions in the Delta under different hydrologic conditions. A tidal hydraulic model of the Delta channels was first developed by DWR in 1969 (based on the Water Resources Engineers “Dynamic Estuary” link-node model) to calculate 15-minute stage and tidal flow (repeating tide) in a grid of Delta channels (DYNFLO). Salinity calculations were done in a second model (TVRK, time-varying Runga-Kutta solution technique) using the tidal flow and stage values calculated by DYNFLO for a month-long period. Consultants (i.e., HydroQual, which later became HydroScience) were contracted by DWR in 1981 to improve and verify these Delta flow and salinity models. A new Delta salinity model, called TVSALT, was developed based on the Federal EPA Water Quality Analysis Simulation Program model (also known as WASP), which had been developed in 1970 by the same consultants. FINEFLOW (a link-node model) was developed in 1984 to provide a more detailed simulation of south Delta channel tidal stages and flows. The FINEFLOW detailed grid was expanded to include the entire Delta in the improved DWR/RMA Delta hydrodynamic and water quality model developed in 1988.

Reclamation funded development of a Suisun Marsh tidal flow and salinity model by Dr. Hugo B. Fischer (UC Berkeley), beginning in 1976. DWR obtained a version of these models in 1981 to apply to Suisun Marsh facilities planning and required Environmental Impact Report (EIR) documentation of alternatives. The models (MFLOW and MQUAL) were soon modified by Dr. Fischer for DWR to simulate the entire Delta. This Delta model has been commonly called the Fischer Delta Model (FDM). In 1986, Flow Science developed an integrated and improved FDM model (Version 7) for DWR that included the Suisun Marsh channels.

DSM2

DSM2 is a branched 1-dimensional, physically based numerical model of the Delta developed by DWR in the late 1990s. DSM2-Hydro, the hydrodynamics module, is derived from the USGS Four Point model. DSM2-Qual, the water quality module, is derived from the USGS Branched Lagrangian Transport Model. Details of the model, including source codes and model performance, are available from the DWR, Bay-Delta Office, Modeling Support Branch Web site (http://modeling.water.ca.gov/delta/models/dsm2/index.html). Documentation of model development is discussed in annual reports to the State Water Board, Methodology for flow and salinity estimates in the Delta and Suisun Marsh, by the Delta Modeling Section of DWR.

The DSM2 schematic is shown in Figure 7-1. Key DSM2 inputs include tidal stage, boundary inflow and salinity concentration, and operation of flow control structures. Table 7-1 summarizes basic input requirements and assumptions.



Source: California Department of Water Resources, Bay-Delta Office, Delta Modeling Section, http://modeling.water.ca.gov/delta/models/dsm2/documentation.shtml.

Figure 7-1. Illustration of DSM2 Schematic

Table 7-1. DSM2 Input Requirements and Assumptions

Parameters	Assumptions
Period of simulation	October 1922 – September 1994
Boundary flows	CalSim-II output
Boundary stage	15-minute adjusted astronomical tide
Agricultural diversion & return flows	Delta Island Consumptive Use model, 2005/2020 LOD
Salinity	
Martinez EC	Computed from modified G-model, adjusted astronomical tide, and Net Delta Outflow from CalSim-II
Sacramento River	Constant value = 175 µS/cm
Yolo Bypass	Constant value = 175 µS/cm
Mokelumne River	Constant value = 150 µS/cm
Cosumnes River	Constant value = 150 µS/cm
Calaveras River	Constant value = 150 µS/cm
San Joaquin River	CalSim-II EC estimate using modified Kratzer equation
Agricultural drainage	Varying monthly values that are constant year to year
Facility operations	
Delta Cross Channel	CalSim-II output
South Delta barriers	Temporary barriers/SDIP operation of permanent barriers

Key:
µS/cm = microsiemens per centimeter
DSM2 = Delta Simulation Model 2
EC = electrical conductivity
LOD = level of development
SDIP = South Delta Improvements Program

In DSM2 model simulations, EC is typically used as a surrogate for salinity. Results from CalSim-II are used to define Delta boundary inflows. CalSim-II-derived boundary inflows include the Sacramento River flow at Hood, San Joaquin River flow at Vernalis, inflow from the Yolo Bypass, and inflow from the eastside streams. In addition, Net Delta Outflow from CalSim-II is used to calculate the DSM2 salinity boundary at Martinez.

Planning Tide at Martinez Boundary

Tidal forcing is imposed at the downstream boundary at Martinez as a time series (TS) of stage (for the hydrodynamic module) and salinity (for the water quality module). DWR has traditionally used a “19-year mean tide” (or “repeating tide”) in all DSM2 planning studies, in which the tide is represented by a single repeating 25-hour cycle. An “adjusted astronomical tide” was later developed by DWR that accounts for the spring-neap variation of the lunar tide cycle (DWR 2001a). However, before the CACMP effort, the adjusted astronomical tide had only been developed for a 16-year period, from 1976 to 1991; the 19-year mean repeating tide was used for simulating the 73-year period (1922 through 1994).

An updated version of DSM2 has been developed that simulates an 82-year (1922 through 2003) CalSim-II period of record using an adjusted astronomical tide.

Salinity Boundary Conditions

Martinez

Salinity at the Martinez downstream boundary reflects intrusion of saltwater into San Pablo Bay from the ocean. It is determined using an empirical model known as the modified G-model (DWR 2001b). The model calculates a 15-minute TS of salinity values based on the adjusted astronomical tide and Net Delta Outflow. Since these aggregate flows are available from CalSim-II, salinity at Martinez can be preprocessed and input to DSM2 as TS data. Each simulation has a different EC boundary condition at Martinez, reflecting the different inflows and exports from the Delta that occur in a particular scenario.

Sacramento River/Yolo Bypass/ Eastside Streams

The inflow salinities for the Sacramento River, Yolo Bypass, and eastside streams (Mokelumne River, Cosumnes River, and Calaveras River) were assumed to be constant at 175, 175, and 150 microsiemens per centimeter (µS/cm), respectively.

San Joaquin River at Vernalis

CalSim-II calculates EC for the San Joaquin River at Vernalis using a modified Kratzer equation. The resulting EC values were used to define the inflow salinity for DSM2. Potentially, each simulation has a different EC boundary condition at Vernalis, reflecting different upstream operations on the San Joaquin River and its tributaries. However, differences in salinity between scenarios were small.

Agricultural and Municipal and Industrial Return Flows

The salinity of agricultural return flows was based on an analysis of Municipal Water Quality Investigations data (DWR 1995). Monthly, regional representative EC values of drainage were determined for three regions in the Delta (north, west, and southeast regions). EC values vary by month, but are constant from year to year and are independent of the LOD. EC values were highest for the west region due to its proximity to the ocean. The monthly EC values follow a seasonal trend with the highest concentrations occurring in winter and spring during the rainfall-runoff season (approximately 820 µS/cm to 1,890 µS/cm). Lowest drainage concentrations occur in July and August (approximately 340 µS/cm to 920 µS/cm).

Delta Channel Flow

Sacramento River water flows into the central Delta via the Delta Cross Channel and Georgiana Slough. The Delta Cross Channel, constructed in 1951 as part of the CVP, connects the Sacramento River to the Mokelumne River via Snodgrass Slough. Its purpose is to increase flow in the lower San Joaquin River and to reduce salinity intrusion and the movement of saline water from Suisun Bay toward Contra Costa Water District's (CCWD) Rock Slough intake and the Jones Pumping Plant. Two radial gates regulate flow through the Delta Cross Channel. When the gates are open, flow through the Delta Cross Channel is determined by the upstream stage in the Sacramento River. Similarly, flow through Georgiana Slough is a function of the upstream Sacramento River stage. Sacramento River water is also transported southward through Threemile Slough, which connects the Sacramento River just downstream from Rio Vista to the San Joaquin River.

The mouth of the Old River, located upstream from the mouth of the Mokelumne River, is the major conduit for water flowing from the Sacramento River, through Georgiana Slough and the Delta Cross Channel, via the Mokelumne River, to the south Delta. Additional water for the CVP/SWP export pumps moves through the mouth of the Middle River, Columbia Cut, Turner Cut, False River, Fisherman's Cut, and Dutch Slough. Net flows at the mouth of the Old River and Middle River are influenced by CVP/SWP exports and south Delta irrigation diversions (approximately 40 percent of total net Delta diversions). Previous DSM2 simulations indicate that about 45 percent of south Delta exports flows through the mouth of the Old River or through the False River. About 40 percent of the south Delta exports flows through the mouth of the Middle River, and about 10 percent of the flow is through Turner Cut. This division of flow is insensitive to the magnitude of exports (Jones and Stokes 2004).

Flow Control Structures

A number of flow control structures are currently operated seasonally in the Delta. These structures can have a major impact on water quality by changing the pattern of flow through the Delta.

Clifton Court Forebay

In all DSM2 simulations, the Clifton Court Forebay gates were operated tidally using "Priority 3." Under Priority 3, the gates are closed 1 hour before and 2 hours after the lower low tide. They are also closed from 2 hours after the high low tide to 1 hour before the high tide. Discharge is proportional to the square root of the head difference across the gates. Maximum flow was capped at 15,000 cfs. The discharge coefficient was set equal to 2,400, which results in a flow of 15,000 cfs for a 1.0-foot head difference.

Delta Cross Channel

The Delta Cross Channel has a major impact on salinity in the central and south Delta. CalSim-II calculates the number of days the Delta Cross Channel is open in each month. The 1995 Water Quality Control Plan (State Water Board 1995) specifies that the gates be closed for 10 days in November, 15 days in December, and 20 days in January, from February 1 to May 20, and for 14 days between May 21 and June 15. In addition, the gates must be closed to avoid scouring whenever Sacramento River flow at the Delta Cross Channel is greater than 25,000 cfs. For DSM2 simulations, all partial month closings of the Delta Cross Channel were assumed to occur at the end of the month.

South Delta Barriers

DSM2 modeling of existing conditions includes the South Delta Temporary Barriers Project, which consists of four rock barriers that are temporarily installed across south Delta channels. The objectives of the project are as follows:

- Increase water levels, circulation patterns, and water quality in the south Delta area for local agricultural diversions.
- Improve operational flexibility of the SWP to help reduce fishery impacts and improve fishery conditions.

Details of the temporary barriers can be found on DWR's Web site (http://sdelta.water.ca.gov). Of the four temporary barriers, the Head of Old River barrier serves as a fish barrier and has been in place most years between September 15 and November 30 since 1963. The remaining three barriers serve as agricultural barriers and are installed between April 15 and September 30. Installation and removal dates of the barriers are based on the USACE Section 404 Permit, CDFW 1601 Permit, and various Temporary Entry Permits required from landowners and local reclamation districts. Table 7-2 gives the assumed temporary barrier operation for modeling existing conditions.

Table 7-2. Temporary Barrier Simulated Operation

Barriers	DSM2 Channel No.	Closure	Complete Removal
Head of Old River (spring)	54	April 15	May 15
Head of Old River (fall)	54	September 15	November 30
Middle River	134	April 15	November 30
Old River near Tracy	99	April 15	November 30
Grant Line Canal	206	May 15	November 30

Key:
DSM2 = Delta Simulation Model 2

DSM2 modeling of future conditions includes the four proposed South Delta Improvement Program permanent operable barriers, one each at the head of the Old River, Grant Line Canal, Old River at Tracy Road Bridge, and Middle River at Old River (Reclamation and DWR 2005). These gates are intended to replace the existing temporary barriers to minimize the number of in- and out-migrating salmon moving toward export pumps; maintain adequate water levels for south Delta farmers to prevent cavitation from occurring in their irrigation pumps; and improve water quality in south Delta channels by providing better circulation. The DWR Delta Modeling Section developed three sets of operations for the gates: Plans A, B, and C. Plan A focused on achieving higher water levels, but did not result in significant improvement in water quality. Plan B modified Plan A gate operations, resulting in slight improvement in circulation and water quality compared to Plan A. Plan C gate operations evolved to achieve the objective of improving water quality with better flow circulation in south Delta channels, in addition to maintaining adequate water levels. Plan C permanent barrier operations were assumed for Future Condition DSM2 simulations.

Suisun Marsh Salinity Control Gate

The Suisun Marsh Salinity Control Gate limits flow in Montezuma Slough from Suisun Marsh during flood tide, and allows drainage from the marsh during ebb tide. The gates are not operated in the summer months (June through September) and are not operated at all in some wet years. Actual gate operations are triggered by salinity levels in Suisun Marsh. However, in DSM2 months, gate operations are an input to the model. Suisun Marsh diversion and drainage flows have relatively little effect on salinity upstream from Chipps Island.

Delta Island Consumptive Use

DSM2 uses the Delta Island Consumptive Use (DICU) model to develop agricultural diversions and return flows to each of 142 Delta subareas on a monthly time step. An associated routine allocates the diversions and return flows to approximately 250 diversion nodes and 200 drainage nodes in DSM2. The DICU model considers precipitation, seepage, evapotranspiration, irrigation, soil moisture, leach water, runoff, crop type, and acreage. The net DICU is computed as diversions plus seepage less drainage. Positive values indicate a net depletion of water from the Delta channels; negative values indicate a net return flow from the Delta islands into the channels. DICU follows the seasonal pattern of irrigation diversions during the summer and drainage return flows from winter runoff.

DSM2 net channel accretions and depletions match the aggregated values used in CalSim-II so that the Net Delta Outflow is consistent between the two models.

Water Quality Conversions

DSM2 uses EC as a substitute for salinity. However, other water quality constituents were needed to assess potential impacts of the proposed alternatives.

DWR has derived relationships between EC, bromide, and chloride at Delta export locations for use in the In-Delta Storage Investigations (Suits 2001). Suits (2001) gives a regression equation for EC at the Old River at Rock Slough as a function of chloride at Contra Costa Canal Pumping Plant No. 1, and a regression equation relating EC to chloride at the Los Vaqueros intake. The relationship between EC and chloride in the vicinity of the Clifton Court Forebay and Delta-Mendota Canal (DMC) intake is more complex. In general, the relationship depends on whether the source water is derived from the San Joaquin River or the Sacramento River. The regression equation established by Suits is conservative, giving high values of chloride for a given EC. The relationship between chloride and bromide is fairly uniform with little site-specific variation (Suits 2001). Therefore, a single regression equation can be used for different export locations. Regression equations used to convert EC to chloride are given in Table 7-3.

Table 7-3. Relationship Between Salinity Parameters

Location	Slope	Intercept
Old River at Rock Slough to Contra Costa Canal (CCWD PP No.1)	0.268	-24.0
Clifton Court Forebay	0.273	-43.9
DMC Intake	0.273	-43.9

Source: Suits 2001
Key"
CCWD = Contra Costa Water District
PP = Pumping Plant

DSM2 output is included in Attachments 16 and 17 of the modeling appendix.

Chapter 8
Hydropower Modeling

SLWRI alternatives would affect the operations, energy use, and generation of existing hydropower facilities, and could also provide new opportunities for hydroelectric energy generation. The LTGen and SWPPower tools were used to simulate energy generation and consumption for CVP and SWP facilities, respectively. These two tools were originally BST April 2010 version, Power tools. This chapter provides an overview of modeling methodology used for LTGen and SWPPower.

Methods and Assumptions

For each SLWRI alternative, outputs from CalSim-II simulation were inputs to LTGen and SWPPower to simulate power generation and consumption throughout the CVP and SWP systems, respectively. These CalSim-II outputs include reservoir releases, conveyance flow rates, and end-of-month reservoir storages. Both LTGen and SWPPower are monthly models. Their simulation periods are from October 31, 1921, to September 30, 2003, the same simulation periods used in CalSim-II.

In LTGen and SWPPower, energy generation is a function of reservoir release, net head, and duration of generation. Net head is the actual head available for power generation; it is reservoir water surface elevation (a function of storage) minus tail race elevation (a function of release). Energy generation is also subjected to facility capacities.

Similarly, the calculation of energy required for pumping in both models is a function of pumping rate, pumping head (i.e., net head with hydraulic losses), and duration of pumping. It is also important to differentiate off-peak and on-peak pumping due to the difference in unit energy cost.

LongTermGen for CVP Energy Simulation

LTGen is a monthly model that simulates both power generation and consumption in the CVP system. The simulated powerplants include Trinity, Lewiston, Carr, Spring Creek, Shasta, Keswick, Folsom, Nimbus, and New Melones powerplants, and O'Neill and the CVP portion of Gianelli pumping-generating plants. Simulated pumping plants include C. W. “Bill” Jones, the CVP portion of Banks, Contra Costa, Pacheco, the CVP portion of Dos Amigos, Folsom, Corning, and Red Bluff pumping plants; San Luis, DMC, and Tehama-Colusa relift pumping plants; O'Neill and the CVP portion of Gianelli pumping-generating plants. Table 8-1 summarizes LTGen simulated CVP energy facilities and their corresponding CalSim-II inputs.

Functions and parameters assumed in LTGen were mostly provided by the Western Area Power Administration (Western) of the U.S. Department of the Interior, which is responsible for managing energy generated from the CVP system.

Table 8-1. CVP Facilities Simulated in LTGen and Corresponding CalSim-II Variables

CVP Facilities	CalSim-II Variables for Storage	CalSim-II Variables for Conveyance
Powerplants		
Trinity	S1	C1
Lewiston[1]	N/A	C100
Judge Francis Carr	S3	D100
Spring Creek	S3	D3
Shasta	S4 + S44	D4
Keswick	S5	C5
Folsom	S8	C8
Nimbus	S9	C9
New Melones	S10	C10
O'Neill	N/A	C702 minus C705
CVP portion of Gianelli	S11+S12+S13	D703
Pumping Plants		
C. W. “Bill” Jones	N/A	D418
CVP portion of Banks	N/A	D419_CVP
Contra Costa	N/A	D408
O'Neill	N/A	C702 minus C705
CVP portion of Gianelli	N/A	D703 minus C11
Pacheco	N/A	D11
CVP portion of Dos Amigos	N/A	C834 + D419_CVC
Folsom	N/A	D8
Corning	N/A	D419
Red Bluff	N/A	D419 + C171
Delta-Mendota Canal-California Aqueduct Intertie	N/A	C700A
San Luis Relift	N/A	C832
Delta-Mendota Canal Relift	N/A	C705
Tehama-Colusa Relift	N/A	C171

Note:
[1] It is assumed that no energy is generated at Lewiston Powerplant.
Key:
CVP = Central Valley Project
LTGen = LongTermGen
N/A = not applicable

Energy Generation

Using CalSim-II outputs as LTGen input, general modeling procedures and assumptions for monthly energy generation calculation in LTGen are as follows:

- Convert CalSim-II storage (unit in TAF) to reservoir water surface elevation (unit in feet) and CalSim-II release cfs to tail race elevation (unit in feet) using predefined correlation equations. Each reservoir has its own specific equations. The gross head of release available for power generation is equal to the elevation difference of reservoir water surface and tailrace. LTGen uses the average monthly storage for energy calculation.

- Calculate the energy factor (the amount of energy can be generated from each acre-foot of release kWh per acre-foot (kWh/acre-foot), as a function of the gross head. Each reservoir has its own specific energy factor equation.

- The total energy production at the powerplant (kWh) is the product of energy factor and releases through the turbine (acre-feet). In the model, the amount of releases that could go through the generator turbines is constrained by the assumed total turbine capacity. The difference between the CalSim-II release and the amount of release through the turbines is defined as spill. Energy foregone through spilling is the product of energy factor and spill.

- The amount of energy available at the load center is equal to the total generated energy from the powerplant minus assumed transmission losses.

Since power generated from the Lewiston Powerplant is not currently marketed through Western, LTGen assumed zero generation from the plant. For the Shasta Powerplant, since CalSim-II has a separate reservoir to represent the enlarged portion, the total of CalSim-II storage outputs for S4 and S44 were used in input for Shasta Reservoir total storage in LTGen.

Energy Consumption

The general modeling procedures and assumptions for the monthly calculation of CVP energy consumption in LTGen are as follows:

- Convert the CalSim-II pumping rate (unit in cfs) into a monthly volume (unit in TAF).

- Calculate the total required pumping energy at the pumping plant by multiplying the energy factor and the monthly volume of pumping. The energy factors, either defined by Western or calculated from a function of gross head, represent the amount of energy required to pump 1 acre-foot of water (kWh/acre-foot).

- Calculate the total required pumping energy at each pumping plant by adding estimated energy loss at the plant. Such losses are predefined in LTGen.

- Differentiate the pumping energy required during off-peak and on-peak hours. The goal is to maximize off-peak pumping first to minimize pumping costs. There are two sets of off-peak hour percentage assumptions. The first is a user-defined percentage. The second assumes that Sunday and holidays have zero on-peak hours while there are 16 on-peak hours and 8 off-peak hours for the remaining days.

San Luis Reservoir is a pump-storage reservoir that generates energy with releases and consumes energy during pumping. It is assumed that months with reservoir releases would have zero pumping. Since CalSim-II does not explicitly simulate the operations of O'Neill Forebay, the amount of O'Neill Pumping Plant is assumed to be the difference between CalSim-II arcs C702 and C705.

SWP Power California for SWP Energy Simulation

SWPPower is a monthly model used to simulate both power generation and consumption in the SWP system. Simulated SWP powerplants include Oroville, the Thermalito Complex, Alamo, Mojave, Devil Canyon, Warne, and Castaic powerplants, and the SWP portion of Gianelli Pumping-Generating Plant. Simulated SWP pumping plants are the SWP portion of Banks, SWP portion of Dos Amigos, Buena Vista, Teerink, Chrisman, Edmonston, Pearblossom, Oso, South Bay Aqueduct, Del Valle, Las Perillas, and Badger Hill pumping plants, and the SWP portion of Gianelli Pumping-Generating Plant. Table 8-2 summarizes SWPPower simulated SWP energy facilities and their corresponding CalSim-II inputs.

SWPPower uses a methodology to calculate SWP energy generation and consumption that is very similar to LTGen. Functions and parameters in SWPPower were provided by the State Operations Control Office (OCO).

LTGen and SWP Power Model output is included in Attachment 18 of the Modeling Appendix.

Table 8-2. SWP Facilities Simulated in LTGen and Corresponding CalSim-II Variables

SWP Facilities	CalSim-II Variables for Storage	CalSim-II Variables for Conveyance
Powerplants		
Oroville	S6	C6
Thermalito Complex	S7	C7 + C200A
SWP portion of Gianelli	S11+ S12 + S13	D805 minus C12
Alamo	N/A	C876
Mojave	N/A	C882
Devil Canyon	S25	C25
Warne	S28[1]	C892
Castaic	S28 and S29[1]	C893
Pumping Plants		
SWP portion of Banks	N/A	D419_SWP
SWP portion of Gianelli	N/A	D805 minus C12
SWP portion of Dos Amigos	N/A	C825
Buena Vista	N/A	C860
Teerink	N/A	C862
Chrisman	N/A	C864
Edmonston	N/A	C865
Pearblossom	N/A	C880
Oso	N/A	C890
South Bay	N/A	D801
Del Valle	N/A	D811
Las Perillas	N/A	D850
Badger Hill	N/A	C866

Note:

[1] CalSim-II storage numbers are used in the calculation of tailrace elevation.

Key:
N/A = Not applicable
SWP = State Water Project
LTGen = LongTermGen

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Chapter 9
Regional Economic Impact Modeling

SLWRI comprehensive plans may change the local economy due to project construction activities. An input-output (I-O) regional economics model was developed with IMPLAN software to estimate regional economic impacts specific to SLWRI comprehensive plan construction activities. A regional economic impact analysis has not been conducted for other potential direct effects, including changes in agricultural production, recreation, M&I water quality, flood control, or other areas potentially affected by the comprehensive plans. IMPLAN was used to estimate construction-related economic activity in the four-county region surrounding Shasta Lake. The four counties are Shasta, Tehama, Trinity, and Siskiyou. This chapter provides an overview of the modeling methodology used for the IMPLAN analysis.

Regional Economic Impact Analysis with Input-Output Modeling

Various approaches have historically been used to assess the effect a change in production or expenditure will have on a region's economy. The most common approach has arguably been the use of I-O models. The use of I-O models in economic impact analyses has increased dramatically with the advent of ready-made regional models. Ready-made models reduce both the time and cost of using I-O models for economic input assessment.

Concept

I-O analysis represents a means of measuring the flow of commodities and services among industries, institutions, and final consumers within an economy (or study area). An I-O model uses a matrix representation of a region's economy to predict the effect that changes in one industry will have on others as well as consumers, government, and foreign suppliers in the economy. I-O models capture all monetary market transactions in an economy, accounting for inter-industry linkages and availability of regionally produced goods and services. The resulting mathematical formulas allow I-O models to simulate or predict the economic impacts of a change in one or several economic activities on an entire economy. It is a static, linear model of all purchases and sales, or linkages, between sectors of an economy.

The measurement of linkages within a regional economy is based on the concept of a multiplier. A multiplier is a single number that quantifies the total economic effect resulting from initial spending, or output in a sector. For example, an output multiplier of 1.7 for the “widget” production sector indicates that every $100,000 of widgets produced (the initial spending, or output in this industry) supports a total of $170,000 in business sales throughout the economy (total output of all linked industries), including the initial $100,000 in widget output. Many types of multipliers can be produced by an I-O model, including specific multipliers for estimating impacts on industry output, employment, and value added–the main metrics of I-O analysis results. Each of these metrics is defined and described below.

- **Industry output** is the value of goods and services produced in a region, which includes the value of intermediate inputs (i.e., goods and services) used in the production process and value added. Intermediate inputs may or may not originate from a region. For example, direct industry output for construction refers to the value of construction, although some of the intermediate inputs used in the construction process may be imported into the region.

- **Value added** is the difference between industry output and the cost of intermediate inputs, and consists of four components (1) employee compensation, (2) proprietor income, (3) other property income, and (4) indirect business tax. Labor income represents the sum of employee compensation and proprietor income.

- **Employment** is measured by the number of annual full-time, part-time, and temporary positions. Estimated changes in employment are tied to economic relationships between industry output and labor productivity, regardless of availability and fluidity in the local labor force.

Components of industry output are displayed in Figure 9-1.

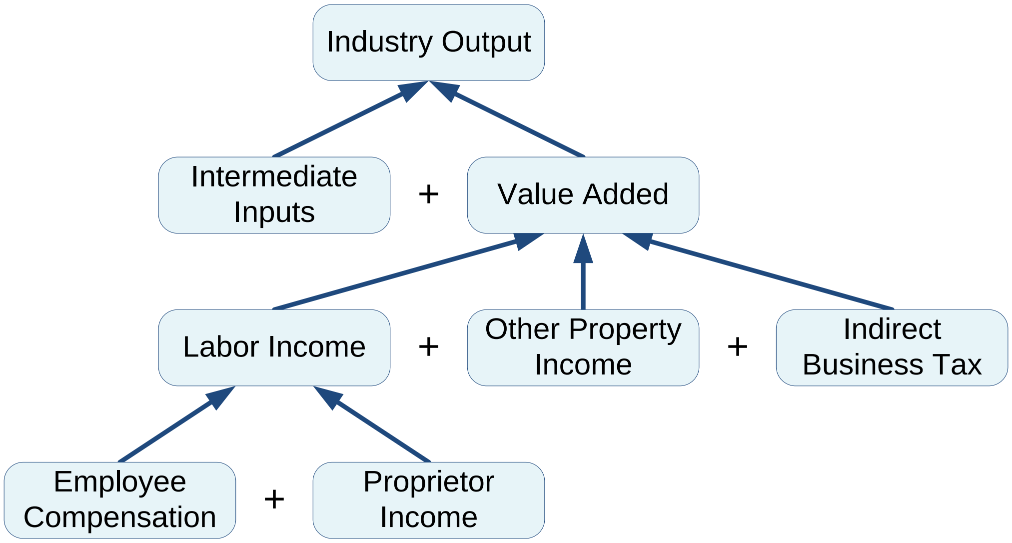

Figure 9-1. Components of Industry Output

I-O Modeling Limitations

While I-O models are useful in providing ballpark estimates of very short-run responses to changes in production/expenditures, their key limitations are linearity, absence of behavioral considerations, absence of markets and prices, and lack of formal constraints.

The limitations of I-O models are also the key advantages of Computable General Equilibrium (CGE) modeling. A CGE model is a nonlinear model of individual behavioral response to price signals, subject to labor, capital, and natural resources constraints (Charney and Vest, 2003). These advantages come with increased modeling complexity, much greater data needs, and time resources for operation. Therefore, while the use of CGE modeling is increasing, resource and data constraints make its use impractical at the multi-region level, and the use of I-O modeling is a practical choice for a large study area.

IMPLAN

IMPLAN (a computer-driven system of software and data commonly used to perform I-O based economic impact analysis) regional multipliers were used to assess the regional economic impacts associated with SLWRI comprehensive plan construction activities. The economic data needed to construct the central I-O table are extracted from various sources generated by the Department of Commerce, the Bureau of Labor Statistics, and other federal and State agencies.

Data are collected for 528 distinct industry sectors of the national economy, commonly known as North American Industry Classification (NAICS) (formerly Standard Industry Codes (SIC)). Industry sectors are classified on the basis of the primary commodity or service produced. National data are de-aggregated to produce data sets for each county in the United States, allowing analysis at the county level and for geographic aggregations such as clusters of contiguous counties, states, or groups of states.

IMPLAN predicts changes in industry output, value added, and employment as direct, indirect, and induced economic effects for affected industries within the study area, where:

Total Effects = Direct Effects + Indirect Effects + Induced Effects

- **Direct Economic Effects** refer to the response of a given industry (i.e., changes in output, income, and employment) based on final demand for that industry.
- **Indirect Effects** refer to changes in output, income, and employment resulting from the iterations of industries purchasing from other industries caused by the direct economic effects.

- **Induced Economic Effects** refer to changes in output, income, and employment caused by the expenditures associated with changes in household income generated by direct and indirect economic effects.

Applying the Four-County Regional Model

Regional economic impacts were modeled with IMPLAN software for construction-related economic activity in the four-county region surrounding Shasta Lake. The four counties are Shasta, Tehama, Trinity, and Siskiyou. The model is based on 2009 California County data and is expected that more current data will be obtained for the feasibility level report.

The construction activity associated with each of the comprehensive plans will take place over 4.5 to 5 years, depending upon the comprehensive plan. Because economic impacts are typically measured and reported in annual terms, the costs were converted to average annual expenditures. Therefore, the results should be interpreted as "dollars per year" or "jobs per year" for the duration of the construction period, and proper care must be taken when making direct comparisons among comprehensive plans.

The primary set of effects analyzed using the regional model is how project construction would affect output, personal income, and employment within the four-county area containing the dam and reservoir. The project costs were developed for each comprehensive plan by the engineering team, which also estimated the duration over which construction activity would take place. The costs were organized into categories to assess the required investment that would take place in certain primary sectors of the local economy, namely concrete- and steel-related manufacturing, rock and aggregate, and dam and non-residential construction. Table 9-1 provides a summary of project costs by category for the comprehensive plans.

Table 9-1. Project Construction Cost by Category

Category	Detail	CP1 ($ millions)	CP2 ($ millions)	CP3 ($ millions)	CP4 ($ millions)	CP4A ($ millions)	CP5 ($ millions)
Concrete	Manufacturing, testing, treatments, precast, structure erection, and pile driving	176	164	243	242	240	244
Metalwork	Manufacturing, testing, construction, preconstruction, mechanical, electrical, pipe, and temporary structures	376	334	334	334	330	336
Glass	Manufacturing, construction	1	1	1	1	0	1

Table 9-1. Project Construction Cost by Category (contd.)

Category	Detail	CP1 ($ millions)	CP2 ($ millions)	CP3 ($ millions)	CP4 ($ millions)	CP4A ($ millions)	CP5 ($ millions)
Interior	Carpet, tile, paint, appliance	1	1	1	1	1	1
Fill and Aggregate	Imported, onsite, reuse, manufacturing geofill/textiles, compaction, and construction	45	70	103	108	107	108
Asphalt and Roadway	Production, paving, roadway painting and signage	8	18	17	17	17	18
Timber	Construction and Timber Clearing	6	73	74	74	73	74
Plastics	PVC pipe, HDPE, rubber, and composites	2	2	2	3	3	3
Excavation and Demolition	Excavation, clearing and grubbing, structure demolition, salvaging, and relocating of equipment	97	111	106	108	106	108
Landscaping	Gardening, seeding, and planting	0	0	0	1	1	9
Planning, Engineering, Design, and Construction Mgmt.		160	174	198	200	200	203
Land Acquisition		30	47	69	70	70	70
Environmental Mitigation		71	77	88	88	88	88
Cultural Resources Mitigation		14	15	18	18	18	18
Water Use Efficiency Actions		2	3	3	2	3	4
Total Construction Cost		990	1,089	1,257	1,265	1,266	1,284
Duration (years)		4.5	5	5	5	5	5

Note:
Dollar values are expressed in millions, January 2014 price levels.
All numbers are rounded for display purposes; therefore, line items may not sum to total.
Key:
CP = comprehensive plan
HDPE = high-density polyethylene
PVC = polyvinyl chloride

The cost summary provides information as to the anticipated generalized expenditure pattern (production function) within IMPLAN associated with the dam construction activity. The IMPLAN production function is based upon an aggregation of national data distributed proportionally to states and counties, and may precisely match local conditions. However, adjustments for local conditions may be made within IMPLAN when additional data are available. The project cost summary was compared to the IMPLAN sector data detail for the region to confirm the local presence of businesses able to serve the project's need for materials and services. It was confirmed that local sources could be used for the primary construction service needs. The organized cost data were entered as inputs to appropriate sectors within the regional impacts model.

The engineering team considered the necessary and appropriate size of the construction crew on an average annual basis, considering the size and duration of the construction activity. It is estimated that a crew of approximately 350 would be sufficient for each of the comprehensive plans. The IMPLAN production function vector for construction was adjusted to ensure a direct employment ratio of 350 jobs per year, using CP4 and CP4A as the proxy. The average annual investment cost for the alternatives are shown in Table 9-2.

Table 9-2. Project Construction Cost, Average Annual Required Investment

Category	CP1	CP2	CP3	CP4	CP4A	CP5
Average Annual Construction Cost ($ millions)	220.0	217.8	251.4	252.8	253.0	256.6
Duration (years)	4.5	5	5	5	5	5

Note:
Dollar values are expressed in millions, January 2014 price levels.
Key:
CP = comprehensive plan

For each of the comprehensive plans, the procedure was the same for estimating regional economic impacts. Construction-related direct expenses were entered, and the model then calculated the indirect, induced, and total effects on the regional economy. The output of the model included total industry output, personal income, and jobs, all displayed on an average annual basis. Results of regional impact analysis conducted with IMPLAN software for the SLWRI are presented in Attachment 19 (Regional Economic Impacts) of the Modeling Appendix.

Chapter 10
Recreational Visitation

This chapter describes the process used to develop the potential change in recreational visitation at Shasta Lake expected with each SLWRI comprehensive plan for the EIS and Feasibility Report.

Background

Shasta Lake is the centerpiece of the Shasta Unit of the Shasta-Trinity National Forest. The combination of water surface and lands provides the opportunity for many types of outdoor recreation, with water oriented recreation as the main attraction. A study of recreational sites in Northern California performed by DWR estimated the number of annual visitors to Shasta Lake at 3 million per year (DWR, 2004).

Raising Shasta dam and related recreation facility relocations could change recreational participation at Shasta Lake through modernization of recreational facilities, increased average annual reservoir surface area and therefore boating capacity, and reduced reservoir drawdown during the peak recreation season (May to September) compared to without-project conditions.

Previous studies and Reclamation guidance indicate that reservoir recreation demand is sensitive to fluctuations in reservoir water elevations and surface area, changing in accord with rises and falls in lake water levels (English et al., 1995; Hanson et al., 2002; Platt, 2001; Platt and Munger, 1999).

A combination of two similar approaches is used to predict potential changes in annual visitation at Shasta Lake due to comprehensive plans for the EIS and Feasibility Report. Both methodologies are based upon water elevations during the year at Shasta Lake, with variations in treatment of drawdown and surface area during the recreation season. This is discussed in detail in the next section. Both methodologies predict similar increases in annual visitor days, but are based on slightly different predictive variables. For the purpose of the EIS and pertinent environmental impact assessments, the higher (upper bound) of the expected changes in annual visitation estimated from either method is used, to provide an upper limit on visits. However, for the purposes of the Feasibility Report and evaluation of NED benefit values, the lower expected changes in annual visitation predicted from either method is used to ensure a lower bound estimate of benefits.

Methodology

For the SLWRI Preliminary DEIS, an equation estimated by Bowker et al. (1994) was applied to predict the changes in recreational participation for each of the comprehensive plans documented in the Preliminary DEIS. This methodology was carried forward to estimate changes in annual visitation for the refined comprehensive plans portrayed here. In addition, an equation similar to that from Bowker et al. (1994) was developed, but with the modification of the May elevation variable to be May drawdown and the addition of surface area as a determinant of annual visitation. This was done following Reclamation guidance that indicates May drawdown (the difference between full pool and May water surface elevations) is potentially a better determinant of annual visitation than May elevation, and that surface area is a potential determinant of annual reservoir recreational visitation.

Bowker et al. (1994) completed a study of Shasta Lake recreation by performing a logarithmic regression that used 21 years of data (1971 to 1991). It was found that reservoir recreational visitation was positively related to the elevation of Shasta Lake in May (the beginning of the peak visitation season), inversely related to the change in reservoir water elevation between May and September (the end of the peak visitation season), and positively correlated to the year of the observation. The equation developed by Bowker et al. (1994) is Equation 1, below.

$$\ln(Visits) = -458.38 + 55.95 * \ln(Year) + 6.05 * \ln(May\ Elevation) - .17 * \ln(Drop) \tag{1}$$

Where:

ln is the natural logarithm function;

Visits is the number of recreation visitor days equivalent to one visitor onsite for 12 hours;

Year is the year of the observation;

May Elevation is the average May water level in Shasta Lake for the year in feet above sea level; and

Drop is the drawdown in feet of the water level from May to September.

This analysis applies the Bowker et al, (1994) method to compute recreational visitation days by using Shasta Lake water levels obtained from CalSim-II system operations model for each year from 1979 to 1994. Predicted visitation is then averaged over the time period for the without-project condition and each comprehensive plan.

In addition, a variation to the equation by Bowker et al. (1994) was developed and applied for 21 years of data (1971 to 1991). The time period 1971 to 1991 includes variation in water year types, from critically dry to wet conditions and includes a large range of potential changes in water operations and recreational visitation. In the new equation, the May Elevation variable was changed to May Drawdown (the difference between full pool and May water surface elevations) and average annual surface area (Surface Area) was added as a determinant of annual visitation. This follows Reclamation guidance (Platt, 2001; Platt and Munger, 1999) that indicates May drawdown is potentially a better determinant of annual visitation than May elevation, and that surface area is a potential determinant of annual reservoir recreational visitation. The new equation developed and applied to predict changes in recreational participation is Equation 2, below.

$$\ln(Visits) = -487.98 + 63.81 * \ln(Year) - .02 * \ln(May\ Drawdown) - .14 * \ln(Drop) + 1.18 * \ln(Surface\ Area) \tag{2}$$

It was found that May Drawdown was negatively correlated to annual visitation, and Surface Area positively correlated. The two methodologies described above were applied to estimate changes from the no project alternative in annual recreation visitation at Shasta Lake for each comprehensive plan. Results of the analyses are presented below.

Results

Existing and future condition predicted changes in annual visitation due to potential implementation of comprehensive plans are displayed for Equations 1 and 2 in Tables 10-1 and 10-2, respectively. For the purpose of the EIS and identifying the maximum potential impacts due to increased visitor days, the maximum existing and future condition expected changes in annual visitation estimated from either equation described above are displayed in Table 10-3, below. For the purposes of the Feasibility Report and evaluation of NED benefit values, the minimum existing and future condition expected changes in annual visitation estimated from either equation is displayed in Table 10-4, below.

Table 10-1. Equation 1 Predicted Change in Annual Visitation

Condition	Change in Visitor Days, Relative to Without-Project (1,000)					
	CP1	CP2	CP3	CP4	CP4A	CP5
Existing	78	164	216	363	308	198
Future	89	116	205	370	259	142

Key:
CP = comprehensive plan

Table 10-2. Equation 2 Predicted Change in Annual Visitation

Condition	Change in Visitor Days, Relative to Without-Project (1,000)					
	CP1	CP2	CP3	CP4	CP4A	CP5
Existing	78	147	209	301	260	199
Future	85	134	200	307	246	175

Key:
CP = comprehensive plan

Table 10-3. Upper Bound Predicted Change in Annual Visitation

Condition	Change in Visitor Days, Relative to Without-Project (1,000)					
	CP1	CP2	CP3	CP4	CP4A	CP5
Existing	78	164	216	363	308	199
Future	89	134	205	370	259	175

Key:
CP = comprehensive plan

Table 10-4. Lower Bound Predicted Change in Annual Visitation

Condition	Change in Visitor Days, Relative to Without-Project (1,000)					
	CP1	CP2	CP3	CP4	CP4A	CP5
Existing	78	147	209	301	260	198
Future	85	116	200	307	246	142

Key:
CP = comprehensive plan

Chapter 11
References

1.1 Chapter 1

Reclamation. *See* U.S. Department of the Interior, Bureau of Recreation.

U.S. Department of the Interior, Bureau of Reclamation. 2007. Shasta Lake Water Resources Investigation Plan Formulation Report. March.

1.2 Chapter 2

CALFED. *See* CALFED Bay-Delta Program

CALFED Bay-Delta Program. 2000. Programmatic Environmental Impact Statement/Environmental Impact Report, Record of Decision. 2000.

California Department of Water Resources. 1998. California Water Plan Update, DWR Bulletin 160-98. November.

___________. 2000. CALSIM Water Resources Simulation Model. Modeling Support Branch, Bay-Delta Office. Sacramento, California. http://modeling.water.ca.gov/hydro/model/index.html

———. 2005 (October). CalSim-II Model Sensitivity Analysis Study, Technical Memorandum Report. Bay-Delta Office. Sacramento, California.

Close, A., W.M. Haneman, J.W. Labadie, D.P. Loucks, J.R. Lund, D.C. McKinney, and J.R. Stedinger. 2003. A Strategic Review of CALSIM II and Its Use for Water Planning, Management and Operations in Central California. Prepared for the California Bay Delta Authority Science Program of Bay Governments. Oakland, California.

Draper, A.J., A. Munévar, S. Arora, E. Reyes, N. Parker, F. Chung, and L. Peterson. 2004. CALSIM: A generalized model for reservoir system analysis. Journal of Water Resources Planning and Management, ASCE, 130(6).

DWR. *See* California Department of Water Resources.

Ford, D., L. Grober, T. Harmon, J.R. Lund, and D. McKinney. 2006 (January). Review Panel Report; San Joaquin River Valley CalSim II Model Review.

National Marine Fisheries Service. 2004. Biological Opinion on the Long-Term Central Valley Project and State Water Project Operations Criteria and Plan. Southwest Region. Long Beach, California.

__________. 2009. (June 4). Biological Opinion and Conference Opinion on the Long-Term Central Valley Project and State Water Project. Southwest Region. Long Beach, California.

NMFS. *See* National Marine Fisheries Service.

Reclamation. *See* U.S. Department of the Interior, Bureau of Recreation.

Reclamation and DWR. *See* U.S. Department of the Interior, Bureau of Reclamation, and California Department of Water Resources.

State Water Board. *See* State Water Resources Control Board.

State Water Resources Control Board. 1978. Water Right Decision 1485 for the Sacramento-San Joaquin Delta and Suisun Marsh. August.

__________. 2000. Water Right Decision 1641. In the Matter of Implementation of Water Quality Objectives for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary. December.

__________. 2000. Revised Water Right Decision 1641. In the Matter of Implementation of Water Quality Objectives for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary. December.

U.S. Department of the Interior, Bureau of Reclamation. 2004. Shasta Lake Water Resources Investigation Initial Alternatives Information Report. June.

__________. 2007. Shasta Lake Water Resources Investigation Plan Formulation Report. March.

__________. 2011 (November). Draft Shasta Lake Water Resources Investigation Feasibility Report.

__________. 2011 (November). Preliminary Draft Environmental Impact Statement (EIS).

U.S. Department of the Interior, Bureau of Reclamation, and California Department of Water Resources. 2006 (January). CalSim-II San Joaquin River Peer Review Response.

USFWS. *See* U.S. Fish and Wildlife Service.

United States Fish and Wildlife Service, United States Department of the Interior, Bureau of Reclamation, Hoopa Valley Tribe, and Trinity County (USFWS, Reclamation, Hoopa Valley Tribe, and Trinity County). 1999. Trinity River Mainstem Fishery Restoration Draft EIS/EIR. October. <http://www.fws.gov/cno/arcata/fisheries/reports/treis/draft_document.html>. Last updated April 21, 2005.

1.3 Chapter 3

Reclamation. *See* U.S. Department of the Interior, Bureau of Recreation.

U.S. Department of the Interior, Bureau of Reclamation. 2003. Draft Upper Sacramento River Water Quality Modeling With HEC-5Q: Model Calibration and Validation. Prepared by Resource Management Associates, Inc. 105 pp.

1.4 Chapter 4

Reclamation. *See* U.S. Department of the Interior, Bureau of Reclamation.

USACE. *See* U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers. 1998. HEC-5Q Simulation of Flood Control and Conservation Systems, Appendix on Water Quality Analysis. Computer Program Manual. Kansas City District, Kansas City, Missouri. Prepared by Resource Management Associates, Inc.

U.S. Department of the Interior, Bureau of Reclamation. 1999. Shasta Temperature Control Device CFD Modeling Study. Water Resources Research Laboratory. Denver, Colorado.

__________. 2003. Draft Upper Sacramento River Water Quality Modeling With HEC-5Q: Model Calibration and Validation. Prepared by Resource Management Associates, Inc. 105 pp.

1.5 Chapter 5

Armour, C.L. 1991, Guidance for Evaluating and Recommending Temperature Regimes to Protect Fish. U.S. Fish and Wildlife Service. Biological Report, V. 90, No. 22. 13 pp.

Baker, P.F., T.P. Speed, and F.K. Ligon. 1995. Estimating the influence of temperature on the survival of Chinook salmon smolts *(Oncorhynchus* *tshawytscha)* migrating through the Sacramento-San Joaquin River delta of California. Canadian Journal of Fisheries and Aquatic Science, V. 52. pp 855–863.

Bartholow, J.M. 1996. Sensitivity of a salmon population model to alternative formulations and initial conditions. Ecological Modeling, V. 88, Nos. 1–3. pp. 215–226.

__________. 2003. Modeling Chinook Salmon with Salmod on the Sacramento River, California: Project Completion Report. Revised. 97 pp. plus appendix. (Available on request.)

__________. 2005. Modeling Chinook salmon with Salmod on the Sacramento River, California. Hydroecologie Appliquee, V. 14, No. 1. pp. 193–219.

Bartholow, J.M., and J.A. Henriksen. 2006. Assessment of Factors Limiting Klamath River Fall-Run Chinook Salmon Production Potential Using Historical Flows and Temperatures. USGS Open File Report.

Bartholow, J.M., J.Heasley, J. Sandelin, B.A.K. Coughlan, J. Laake, and A. Moos. 2001. Salmod: A Population Model for Salmonids. User's Manual. Version W3: USGS/FORT Internal Publication. 76 pp. http://www.fort.usgs.gov/products/Publications/4046/4046.asp.

Bartholow, J.M., J.L. Laake, C.B. Stalnaker, and S.C. Williamson. 1993. A salmonid population model with emphasis on habitat limitations. Rivers, V. 4, No. 4. pp. 265–279.

Bartholow, J.M., R.B. Hanna, L. Saito, D. Lieberman, and M. Horn. 2001. Simulated Limnological Effects of the Shasta Lake Temperature Control Device. Environmental Management, V. 27, No. 4. pp. 609–627.

Beechie, T., E. Beamer, and L. Wasserman. 1994, Estimating Coho salmon rearing habitat and smolt production losses in a large river basin, and implications for habitat restoration. North American Journal of Fisheries Management, V. 14. pp. 797–811.

Berggren, T.J., and M.J. Filardo. 1993. An analysis of variables influencing the migration of juvenile salmonids in the Columbia River Basin. North American Journal of Fisheries Management, V. 13. pp. 48–63.

Berman, C.H., and T.P. Quinn. 1991. Behavioral thermoregulation and homing by spring-run Chinook salmon, *Oncorhynchus tshawytscha* (Walbaum), in the Yakima River. Journal of Fish Biology, V. 39. pp. 301–312.

Bigelow, P.E. 1996. Evaluation of the Sacramento River Spawning Gravel Restoration and Winter-Run Chinook Salmon Redd Survey, 1987–1993, Final Report. U.S. Fish and Wildlife Service, North Central Valley Fish and Wildlife Office. Red Bluff, California. 110 pp.

Bjornn, T.C. 1971. Trout and salmon movements in two Idaho streams as related to temperature, food, stream flow, cover, and population density. Transaction of the American Fisheries Society, V. 100, No. 3. pp. 423–438.

Bohlin, T., C. Dellefors, U. Faremo, and A. Johlander. 1994. The energetic equivalence hypothesis and the relation between population density and body size in stream-living salmonids. American Naturalist, 143(3):478–493.

Boles, G. 1988. Water temperature effects on Chinook salmon (*Oncorhynchus tshawytscha*) with emphasis on the Sacramento River, a literature review. California Department of Water Resources, Northern District. 42 pp.

Bovee, K.D., T.J. Newcomb, and T.J. Coon. 1994. Relations Between Habitat Variability and Population Dynamics of Bass in the Huron River, Michigan. National Biological Survey Biological Report 22. 79 pp.

Bradford, M.J. 1995. Comparative review of Pacific salmon survival rates. Canadian Journal of Fisheries and Aquatic Science, V. 52. pp. 1,327–1,338.

Brannon, E.L., M.S. Powell, T.P. Quinn, and A. Talbot. 2004. Population structure of the Columbia River Basin Chinook salmon and steelhead trout. Reviews in Fisheries Science, V. 12. pp. 99–232.

Brett, J.R. 1956. Some principles in the thermal requirements of fishes. The Quarterly Review of Biology, V. 31. pp. 75–87.

Burns, J.W., 1971. The carrying capacity for juvenile salmonids in some northern California streams. California Fish and Game, V. 57, No. 1. pp. 44–57.

Busacker, G.P., I.R. Adelman, and E.M. Goolish. 1990. Chapter 11–Growth. In Methods for Fish Biology, C.B. Schreck and P.B. Moyle, eds. American Fisheries Society. Bethesda, Maryland.

California Department of Fish and Game. 2011 (February 1). GrandTab, California Central Valley Sacramento and San Joaquin River Systems Chinook Salmon Escapement Hatcheries and Natural Areas. Fisheries Branch, Anadromous Resources Assessment. Sacramento, California.

Capra, H., P.Breil, and Y. Souchon. 1995. A new tool to interpret magnitude and duration of fish habitat variations. Regulated Rivers: Research and Management, V. 10. pp. 281–289.

Chapman, D.W. 1962. Aggressive behavior in juvenile Coho salmon as a cause of emigration: Journal of the Fisheries Research Board Canada, V. 19, No. 6. pp. 1,047–1,080.

__________. 1966. Food and space as regulators of salmonid populations in streams. American Naturalist, V. 100, No. 913. pp. 345–357.

Combs, B.D., and R.E. Burrows. 1957. Threshold temperatures for the normal development of Chinook salmon eggs. The Progressive Fish-Culturist, V. 19. pp. 3–6.

Conder, A.L., and T.C. Annear. 1987. Test of weighted usable area estimates derived from a PHABSIM model for instream flow studies on trout streams. North American Journal of Fisheries Management, V. 7. pp. 339–350.

Crisp, D.T. 1981. A desk study of the relationship between temperature and hatching time for eggs of five species of salmonid fishes. Freshwater Biology, V. 11, No. 4. pp. 361–368.

__________. 1988. Prediction, from temperature, of eyeing, hatching and “swim-up” times for salmonid embryos. Freshwater Biology, V. 19. pp. 41–48.

Dill, L.M., R.C. Ydenberg, and A.G.H. Fraser. 1981. Food abundance and territory size in juvenile Coho Salmon *(Oncorhynchus kisutch)*. Canadian Journal of Zoology, V. 59. pp. 1,801–1,809.

Donaldson, E.M. 1990, Reproductive indices as measures of the effects of environmental stressors in fish. In Biological indicators of stress in fish, S.M. Adams, ed., American Fisheries Society Symposium 8. Bethesda, Maryland. pp. 109–122.

Dunning, J.B. Jr., and six others. 1995. Spatially explicit population models, current forms and future uses. Ecological Applications, V. 5, No. 1. pp. 3–11.

EPA. *See* U.S. Environmental Protection Agency

Flett, P.A., K.R. Munkittrick, G. Van Der Kraak, and J.F. Leatherland. 1996. Overripening as the cause of low survival to hatch in Lake Erie Coho salmon (*Oncorhynchus kisutch*) embryos. Canadian Journal of Zoology, V. 74. pp. 851–857.

Gard, M. 1995. Identification of the Instream Flow Requirements for Anadromous Fish in the Streams Within the Central Valley of California, Annual Progress Report, Fiscal Year 1995, Appendix D, Sacramento River Hydrology. U.S. Fish and Wildlife Service. Sacramento, California. Unnumbered pages.

__________. 2003. Identification of the Instream Flow Requirements for Steelhead and Fall, Late-Fall, and Winter-Run Chinook Salmon Spawning in the Sacramento River Between Keswick Dam and Battle Creek. U.S. Fish and Wildlife Service. Sacramento, California.

__________. 2005. Variability in flow-habitat relationships as a function of transect number for PHABSIM modeling. River Research and Applications, V. 21. pp. 1,013–1,019.

Geist, D.R., T.P. Hanrahan, E.V. Arntzen, G.A. McMichael, C.J. Murry, and Y. Chien. 2002. Physiochemical characteristics of the hyporheic zone affect redd site selection by chum salmon and fall-run Chinook salmon in the Columbia River. North American Journal of Fisheries Management, V. 22. pp. 1,077–1,085.

Gouraud, V., J.L. Bagliniere, P. Baran, C. Sabaton, P. Lim, and D. Ombredane. 2001. Factors regulating brown trout populations in two French rivers, application of a dynamic population model. Regulated Rivers: Research and Management, V. 17. pp. 557–569.

Grant, J.W.A., and D.L. Kramer. 1990. Territory size as a predictor of the upper limit to population density of juvenile salmonids in streams. Canadian Journal Fisheries Aquatic Science, V. 47, No. 9. pp. 1724–1737.

Grant, J.W.A., S.O. Steingrimsson, E.R. Keeley, and R.A. Cunjak. 1998. Implications of territory size for the prediction of salmonid abundance in streams. Canadian Journal of Fisheries and Aquatic Science, V. 55 (Suppl. 1). pp. 181–190.

Hanna, R.B. 2000. Shasta Lake water quality modeling investigations for Shasta enlargement, environmental impact statement data needs, year-end report 2000, initial findings, methods, and recommendations. U.S. Geological Survery, Fort Collins, Colorado, pp. 31.

Hannah, D.M., I.A. Malcom, C. Soulsby, and A.F. Youngson. 2004. Heat exchanges and temperatures within a salmon spawning stream in the cairngorms, Scotland, Seasonal and sub-seasonal dynamics. River Research and Applications, V. 20. pp. 635–652.

Healey, M.C. 1994. Variation in the life-history characteristics of Chinook salmon and its relevance to the conservation of the Sacramento winter-run of Chinook salmon. Conservation Biology, V. 8, No. 3. pp. 876–877.

Healey, T.P. 1977. The Effect of High Temperature on the Survival of Sacramento River Chinook (king) Salmon, *Oncorhynchus tshawytsch*a, Eggs and Fry. California Department of Fish and Game. Anadromous Fisheries Branch Administrative Report No. 79–10. 7 pp.

Heggenes, J., S.J. Saltveit, and O. Lingaas. 1996. Predicting fish habitat use to changes in water flow, Modeling critical minimum flows for Atlantic salmon, *Salmo salar*, and brown trout, *S. trutta*: Regulated Rivers: Research and Management, V. 12. pp. 331–344.

Heming, T.A., J.E. McInerney, and D.F. Alderdice. 1982. Effect of temperature on initial feeding in alevins of Chinook salmon (*Oncorhynchus tshawytscha*): Canadian Journal of Fisheries and Aquatic Science, V. 39. pp. 1,554–1,562.

Hettrick, Nick. U.S. Fish and Wildlife Service, Arcata, California. 2006—personal communication.

Hinze, J.A., Culver, A.N., and G.V. Rice. 1956. Annual Report, Nimbus Salmon and Steelhead Hatchery. Inland administrative report number 56–25.

Holling, C.S., and C.R. Allen. 2002. Adaptive inference for distinguishing credible from incredible patterns in nature. Ecosystems, V. 5. pp. 319–328.

Holtby, L.B., and J.C. Scrivener. 1989. Observed and simulated effects of climatic variability, clear-cut logging, and fishing on the numbers of chum salmon (*Oncorhynchus keta*) and Coho salmon (*O. kisutch*) returning to Carnation Creek, British Columbia. In Proceedings of the National Workshop on effects of habitat alteration on salmonid stocks, C.D. Levings, L.B. Holtby, and M.A. Henderson, eds. Canadian Special Publication Fisheries and Aquatic Sciences, V. 105. pp. 62–81.

Hume, J.M.B., and E.A. Parkinson. 1987. Effect of stocking density on the survival, growth, and dispersal of steelhead trout fry (*Salmo gairdneri*). Canadian Journal of Fisheries and Aquatic Science, V 44. pp. 271–281.

Irvine, J.R. 1986. Effects of varying discharge on the downstream movement of salmon fry, *Oncorhynchus tshawytscha* Walbaum. Journal of Fish Biology, V. 28. pp. 17–28.

Jensen, A.J., B.O. Johnsen, and T.G. Heggberget. 1991. Initial feeding time of Atlantic salmon, *Salmo* salar, alevins compared to river flow and water temperature in Norwegian streams. Environmental Biology of Fishes, V. 30. pp. 379–385.

Kent, J.J. 1999. Application and SA of a salmonid population model for the Sacramento River, California. Master's Thesis, Colorado State University. Fort Collins, Colorado. 79 pp.

Korman, J., and P.S. Higgins. 1997. Utility of escapement time series data for monitoring the response of salmon populations to habitat alteration. Canadian Journal Fisheries and Aquatic Sciences, V. 54. pp. 2,058–2,067.

Lapointe, M., B. Eaton, S. Driscoll, and C. Latulippe. 2000. Modeling the probability of salmonid egg pocket scour due to floods. Canadian Journal Fisheries and Aquatic Sciences, V. 57. pp. 1,120–1,130.

Leitritz, E., and R.C. Lewis. 1980, Trout and salmon culture (hatchery methods). California Fish Bulletin No. 164. University of California, Berkeley. 197 pp.

Ligon, F., A. Rich, G. Rynearson, D. Thornburgh, and W. Trush. 1999. Report of the scientific review panel on California Forest Practice Rules and salmonid habitat. Prepared for the Resources Agency of California and the National Marine Fisheries Service. Sacramento, California. 181 pp. http://www.krisweb.com/biblio/cal_nmfs_ligonetal_1999_srprept.pdf

Link, J.S. 2002. Ecological considerations in fisheries management, when does it matter? Fisheries, V. 27, No. 4. pp. 10–17.

Marine, K.R. 1992. A background investigation and review of the effects of elevated water temperature on reproductive performance of adult Chinook salmon (*Oncorhynchus tshawytscha*). Department of Wildlife and Fisheries Biology, University of California, Davis. 30 pp. plus appendix. October.

Marine, K.R., and J.J. Cech, Jr. 2004. Effects of high water temperature on growth, smoltification, and predator avoidance in juvenile Sacramento River Chinook salmon. North American Journal of Fisheries Management, V. 24. pp. 198–210.

McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. U.S. Environmental Protection Agency. Seattle, Washington. EPA 910-R-99-010, 1999. 279 pp. http://www.critfc.org/tech/EPAreport.htm

McDonald, J. 1960. The behavior of Pacific salmon fry during their downstream migration to freshwater and saltwater nursery area. Journal of the Fisheries Research Board Canada, V. 17, No. 5. pp. 655–676.

McNeil, W.J. 1967. Randomness in the distribution of pink salmon redds. Journal of the Fisheries Research Board Canada, V. 24, No. 7. pp. 1,629–1,634.

Mesick, C.F. 1988. Effects of food and cover on numbers of Apache and brown trout establishing residency in artificial stream channels: Transactions of the American Fisheries Society, V. 117, No. 5. pp. 421–431.

Mikulich, L.V., and Y.I. Gavrenkov. 1986. Some biological properties and feeding of downstream migrating juvenile chum salmon, *Oncorhynchus keta*, from the Southern Maritime Territory. Journal of Ichthyology, V. 26. pp. 38–46.

Milhous, R.T., M.A. Updike, and D.M. Schneider. 1989. Physical Habitat Simulation System Reference Manual - Version II: Instream Flow Information Paper No. 26. Washington, D.C. U.S. Fish and Wildlife Service. Biological Report 89(16). Variously paged.

Montgomery, D.R., E.M., Beamer, G.R. Pess, and T.P. Quinn. 1999. Channel type and salmonid spawning distribution and abundance. Canadian Journal of Fisheries and Aquatic Science, V. 56. pp. 377–387.

Moyle, P.B. 2002. Inland Fishes of California, Revised and Expanded. Berkeley, University of California Press. 502 pp.

Myrick, C.A., and J.J. Cech, Jr. 2001. Temperature Effects on Chinook Salmon and Steelhead, a Review Focusing on California's Central Valley Populations. Bay-Delta Modeling Forum Technical Publication 01–1. http://www.cwemf.org/Pubs/TempReview.pdf. 57 pp.

__________. 2004. Temperature effects on juvenile anadromous salmonids in California’s central valley. Reviews in Fish Biology and Fisheries, V. 14. pp. 113–123.

National Marine Fisheries Service. No date. Biological Opinion, Fishery Management Plan for Commercial and Recreational Salmon Fisheries off the Coasts of Washington, Oregon, and California of the Pacific Fishery Management Council Agency, National Marine Fisheries Service, Northwest and Southwest Regional Fishery Management Divisions. http://swr.nmfs.noaa.gov/evaluat3.htm. Viewed 11/2/05.

Neilson, J.D., and C.E. Banford. 1983. Chinook salmon (*Oncorhynchus tshawytscha*) characteristics in relation to redd physical features. Canadian Journal of Zoology, V. 61. pp. 1,524–1,531.

National Marine Fisheries Service. 2009. (June 4). Biological Opinion and Conference Opinion on the Long-Term Central Valley Project and State Water Project. Southwest Region. Long Beach, California.

NMFS. *See* National Marine Fisheries Service.

Orth, D.J. 1987. Ecological considerations in the development and application of instream flow-habitat models. Regulated Rivers: Research and Management, V. 1. pp. 171–181.

Poole, G., and 11 others. 2001. Technical synthesis, scientific issues relating to temperature criteria for salmon, trout, and char native to the Pacific Northwest. U.S. Environmental Protection Agency, Portland, Oregon. EPA 910-R-01-007. 21 pp. http://yosemite.epa.gov/R10/WATER.NSF/6cb1a1df2c49e4968825688200712cb7/bd029c92a81bf25f88256a020072a8c7/$FILE/Final_Synthesis.PDF.

Prager, M.H., and M.S. Mohr. 1999, Population dynamics of Klamath River fall-run Chinook salmon, stock-recruitment model and simulation of yield under management. National Marine Fisheries Service, National Oceanographic and Atmospheric Administration, Southwest Fisheries Science Center. Tiburon, California. 36 pp.

Quinn, T.P., and N.P. Peterson. 1996. The influence of habitat complexity and fish size on over-winter survival and growth of individually marked juvenile Coho salmon (*Oncorhynchus kisutch*) in Big Beef Creek, Washington. Canadian Journal of Fisheries and Aquatic Science, V. 53. pp. 1,555–1,564.

Radomski, P.J., and T.J. Goeman. 1996. Decision making and modeling in freshwater sport-fisheries management. Fisheries, V. 21, No. 12. pp. 14–21.

Reclamation. *See* U.S. Department of the Interior, Bureau of Recreation.

Resource Management Associates, Inc. 2003. Draft, Upper Sacramento River Water Quality Modeling with HEC-5Q, Model Calibration and Validation. Variously paged.

Richardson, T.H., and P. Harrison. 1990. An Analysis of Fish and Wildlife Impacts of Shasta Dam Water Temperature Control Alternatives. 63 pp. U.S. Fish and Wildlife Service. Sacramento, California. December.

Richter, A., and S.A. Kolmes. 2005. Maximum temperature limits for Chinook, Coho, and chum salmon, and steelhead trout in the Pacific Northwest. Reviews in Fisheries Science, V. 13. pp. 23–49.

RMA. *See* Resource Management Associates, Inc.

Rykiel, Jr., E.J. 1996. Testing ecological models: the meaning of validation. Ecological Modeling, V. 90. pp. 229–244.

Sabaton, C., L. Siegler, V. Gouraud, J.L. Bagliniere, and S. Manne. 1997. Presentation and first applications of a dynamic population model for brown trout, *Salmo trutta* L., aid to river management. Fisheries Management and Ecology, V. 4. pp.425–438.

Saito, L., B.M. Johnson, J. Bartholow, and R.B. Hanna. 2001. Assessing ecosystem effects of reservoir operations using food web-energy transfer and water quality models. Ecosystems, V. 4, No. 2. pp. 105–125.

Saito, L., and J Bartholow. 1997. Summary of water temperature calibration for a CE-QUAL-W2 model of Shasta Lake, California. http://smig.usgs.gov/SMIG/features_0997/shasta_w2.html.

Saltveit, S.J., T. Bremnes, and O.R. Lindas. 1995. Effect of sudden increase in discharge in a large river on newly emerged Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) fry. Ecology of Freshwater Fish, V. 4, No. 4. pp. 168–174.

Schnute, J.T., and L.J. Richards. 2001. Use and abuse of fishery models. Canadian Journal of Fisheries and Aquatic Science, V. 58. pp. 10–17.

Shelbourne, J.E ., J.R. Brett, and S. Shirahata. 1973. Effect of temperature and feeding regime on specific growth rate of sockeye salmon fry (*Oncorhynchus nerka*), with a consideration of size effect. Journal of the Fisheries Research Board Canada, V. 30, No. 8. pp. 1,191–1,194.

Shepherd, B.G., G.F. Hartman, and W.J. Wilson. 1986. Relationships between stream and intragravel temperatures in coastal drainages, and some implications for fisheries workers. Canadian Journal of Fisheries and Aquatic Science, V. 43. pp. 1,818–1,822.

Smith, C.E., W.P. Dwyer, and R.G. Piper. 1983. Effect of water temperature on egg quality of cutthroat trout. Progressive Fish-Culturist, V. 45, No. 3. pp. 176–178.

Stalnaker, C., B.L. Lamb, J. Henriksen, K. Bovee, and J. Bartholow. 1995. The Instream Flow Incremental Methodology, a Primer for IFIM. National Biological Service Biological Science Report 29. 44 pp.

Sullivan, K., D.J. Martin, R.D. Cardwell, J.E. Toll, and S. Duke. 2000. An analysis of the effects of temperature on salmonids of the Pacific Northwest with implications for selecting temperature criteria. Sustainable Ecosystems Institute. http://www.sei.org/pub.html#reports.

Thompson, L., and C. Mosser. 2011. Use of SALMOD in a Decision-Making Framework for Adaptation of Water Operations: Answers to Questions Regarding OCAP RPA Actions for the Salmonid Integrated Life-Cycle Models Workshop. 5 pp. University of California, Davis. April.

Titus, R.G., and H. Mosegaard. 1991. Selection for growth potential among migratory brown trout (*Salmo trutta*) fry competing for territories, evidence from otoliths. Canadian Journal of Fisheries and Aquatic Science, V. 48. pp. 19–27.

U.S. Department of the Interior, Bureau of Reclamation. 2008. Biological Assessment on the Continued Long-term Operations of the Central Valley Project and the State Water Project. Mid-Pacific Region. Sacramento, California.

U.S. Environmental Protection Agency. 2003. EPA Region 10 guidance for Pacific Northwest state and tribal temperature water quality standards: EPA 910-B-03-002. Region 10 Office of Water, Portland, Oregon, April 2003, 49 pp. http://www.epa.gov/r10earth/temperature.htm

U.S. Fish and Wildlife Service. 1995. Working Paper on Restoration Needs, Habitat Restoration Actions to Double Natural Production of Anadromous Fish in the Central Valley of California. Volume 3, Table 3-xa-1. http://www.delta.dfg.ca.gov/afrp/documents/WorkingPaper_v3.pdf.

___________. 1999. Effect of Temperature on Early-Life Survival of Sacramento River Fall- and Winter-Run Chinook Salmon. USFWS Report, North Central Valley Fish and Wildlife Office. Red Bluff, California. 41 pp.

___________. 2005a. Flow-Habitat Relationships for Chinook Salmon Rearing in the Sacramento River Between Keswick Dam and Battle Creek. Sacramento, California. 249 pp.

___________. 2005b. Flow-Habitat Relationships for Fall-Run Chinook Salmon Spawning in the Sacramento River Between Battle Creek and Deer Creek. Sacramento, California. 99 pp.

U.S. Fish and Wildlife Service and Hoopa Valley Tribe. 1999. Trinity River Flow Evaluation, Final Report. 307 pp. plus appendix.

USFWS. *See* U.S. Fish and Wildlife Service

USFWS and Hoopa Valley Tribe. *See* U.S. Fish and Wildlife Service and Hoopa Valley Tribe

Vogel, D.A., and K.R. Marine. 1991, Guide to Upper Sacramento River Chinook Salmon Life-History. CH2M HILL, Redding, California. Produced for the U.S. Department of the Interior, Bureau of Reclamation, Central Valley Project. 55 pp. plus appendix.

Williamson, S.C., J.M. Bartholow, and C.B. Stalnaker. 1993. Conceptual model for quantifying presmolt production from flow-dependent physical habitat and water temperature. Regulated River: Research and Management. V. 8, Nos. 1&2. pp. 15 to 28.

Randall, D., L. Cleland, C.S. Kuehne, G.W. Link, and D.P. Sheer. 1997. Water Supply Planning Simulation Model Using Mixed-Integer Linear Programming Engine. Journal of Water Resources Planning and Management. March/April.

State Water Board. *See* State Water Resources Control Board.

State Water Resources Control Board. 1987. Economic Value of Reliable Water Supplies. Bay-Delta Hearings, State Water Contractors Exhibit 51. June.

1.6 Chapter 6

AIC. *See* Agricultural Issues Center.

Agricultural Issues Center. 2011. California Agricultural Exports. http://aic.ucdavis.edu/pub/exports.html. Accessed December 2011. University of California, Davis.

Arrow, K.J., H.B. Chenery, B.S. Minhas, and R.M. Solow. 1961. "Capital-Labor Substitution and Economic Efficiency." *Review of Economics and Statistics.* 43 (3): 225–250.

Brunke, H., D. Sumner, and R.E. Howitt. 2004. “Future Food Production and Consumption in California Under Alternative Scenarios.” California Water Plan Update 2005, California DWR Bulletin 160-05. Sacramento, California.

Bureau of Labor Statistics. 2007. “The U.S. economy to 2016: slower growth as boomers begin to retire.” Betty W. Su. Monthly Labor Review Online. www.bls.gov/opub/mlr/2007/11/art2full.pdf. Accessed May 2011.

Draper, A. J., M. W. Jenkins, K. W. Kirby, J. R. Lund, and R. E. Howitt. 2003. “Economic-Engineering Optimization for California Water Management.” *Journal of Water Resources Planning and Management* 129: 3.

DWR. *See* California Department of Water Resources.

California Department of Water Resources. 2008. Management of the California State Water Project, Bulletin 132-07. Sacramento, California.

__________. 2009. California Water Plan Update, 2009. Bulletin 160-09. Sacramento, California.

Green, R., R. Howitt, and C. Russo. 2008. "Estimation of Supply and Demand Elasticities of California Commodities." Department of Agricultural and Resource Economics. University of California, Davis.

Heckelei, T., and H. Wolff. 2003. Estimation of Constrained Optimisation Models for Agricultural Supply Analysis based on Generalised Maximum Entropy. *European Review of Agricultural Economics* 30: 27-50.

Houck, J. 1965. The Relationship of Direct Price Flexibilities to Direct Price Elasticities. *Journal of Farm Economics* 47: 789–792.

Howitt, R. E. 1995. "Positive Mathematical-Programming." *American Journal of Agricultural Economics* 77(2), 329-342.

Howitt, R. E., D. MacEwan, and J. Medellin-Azuara. 2009a. Economic Impacts of Reductions in Delta Exports on Central Valley Agriculture. *Agricultural and Resources Economics Update* pp. 1-4. Giannini Foundation of Agricultural Economics. Davis, California.

Howitt, R. E., J. Medellin-Azuara, and D. MacEwan. 2009b. Estimating Economic Impacts of Agricultural Yield Related Changes. California Energy Commission, Public Interest Energy Research (PIER). Sacramento, California.

Howitt, R. E., J. Medellin-Azuara, D. MacEwan, J. R. Lund, R. Hoagland, F. Farnam, T. Hawkins, and S. Hatchett. 2010. Economic Modeling of Agriculture and Water in California. Prepared for California Department of Water Resources for inclusion in Water Plan Update 2013.

Kanellopoulos, A., P. Berentsen, T. Heckelei, M. van Ittersum, and Oude Lansink. 2010. Assessing the Forecasting Performance of a Generic Bio-Economic Farm Model Calibrated with two Different PMP Variants. *Journal of Agricultural Economics* 61: 274–294.

Lund, J., E. Hanak, W. Fleenor, R. Howitt, J. Mount, and P. Moyle. 2007. Envisioning Futures for the Sacramento-San Joaquin Delta. Public Policy Institute of California. San Francisco, California.

Medellin-Azuara, J., J.J. Harou, M.A. Olivares, K. Madani-Larijani, J.R. Lund, R.E. Howitt, S.K. Tanaka, M.W. Jenkins, and T. Zhu. 2008. "Adaptability and Adaptations of California's Water Supply System to

Dry Climate Warming." *Climatic Change* 87 (Suppl 1):S75–S90. DOI 10.1007/s10584-007-9355-z.

Reclamation. *See* U.S. Department of the Interior, Bureau of Reclamation.

Reclamation and USFWS. *See* U.S. Department of the Interior, Bureau of Reclamation and U.S. Fish and Wildlife Service.

Salhofer, K. 2000. Elasticities of Substitution and Factor Supply Elasticities in European Agriculture: A Review of Past Studies. Report to the Directorate for Food, Agriculture and Fisheries of the Organization for Economic Cooperation and Development. 1977.

UCCE. *See* University of California Cooperative Extension.

University of California Cooperative Extension. 2011. Cost of Production Studies. Various Crops and Dates. Department of Agricultural and Resource Economics. Davis, California. http://coststudies.ucdavis.edu. Accessed January.

USDA. *See* U.S. Department of Agriculture.

U.S. Department of Agriculture. 2011. California County Agricultural Commissioners' Data. Various crop years. Prepared by the National Agricultural Statistics Service California Field Office. http://www.nass.usda.gov/Statistics_by_State/California/Publications/AgComm/Detail/index.asp. Accessed January 2011.

U.S. Department of the Interior, Bureau of Reclamation and U.S. Fish and Wildlife Service. 1999. Central Valley Project Improvement Act Programmatic Environmental Impact Statement. Mid-Pacific Region. Sacramento, California.

U.S. Department of the Interior, Bureau of Reclamation. 1997. Central Valley Production Model, Central Valley Project Improvement Act Draft Programmatic EIS. Technical Appendix Volume 8. Mid-Pacific Region. Sacramento, California.

__________. 2002. San Luis Unit Drainage Feature Re-evaluation. Plan Formulation Report. Mid-Pacific Region. Sacramento, California.

__________. 2008a. Biological Assessment on the Continued Long-term Operations of the Central Valley Project and the State Water Project. Appendix D: CALSIM II Model. Mid-Pacific Region. Sacramento, California.

__________. 2008b. Upper San Joaquin River Basin Storage Investigation. Plan Formulation Report. Mid-Pacific Region. Sacramento, California.

__________. 2012. Statewide Agricultural Production Model Update and Application to Federal Feasibility Analysis. Mid-Pacific Region. Sacramento, California. May, 2012.

U.S. Water Resources Council. 1983. Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation." March.

Vincent, D. P. 1977. Factor Substitution in Australian Agriculture. *Australian Journal of Agricultural Economics* 21:2 119–129.

World Bank. 2009. "Double Jeopardy: Responding to High Fuel and Food Prices." Paper presented at G8 Hokkaido-Toyako Summit. July 2.

1.7 Chapter 7

DWR. *See* California Department of Water Resources

California Department of Water Resources. 1995. Representative Delta island return flow quality for use in DSM2. Department of Water Resources, Sacramento, California. May 1995.

__________. 2001a. Planning tide at the Martinez boundary. Chapter 10 in Methodology for flow and salinity estimates in the Sacramento-San Joaquin Delta and Suisun Marsh – Twenty-second annual progress report to the State Water Resources Control Board. Department of Water Resources, Sacramento, California. August 2001.

__________. 2001b. Improving salinity estimates at the Martinez boundary. , Chapter 11 in Methodology for flow and salinity estimates in the Sacramento-San Joaquin Delta and Suisun Marsh – Twenty-second annual progress report to the State Water Resources Control Board. Department of Water Resources, Sacramento, California. August 2001.

Jones & Stokes. 2004. "Delta-Mendota Canal/California Aqueduct Intertie," Proposed Finding of No Significant Impact/Negative Declaration and Draft Environmental Assessment, Initial Study. Jones & Stokes, Sacramento, California. September 2004.

Oltmann, R.N. 1998. Measurement of Delta outflow using ultrasonic velocity meters and comparison with mass-balance calculated outflow. Interagency Ecological Program for the Sacramento–San Joaquin Estuary Newsletter 11(1). Winter.

Reclamation and DWR. *See* U.S. Department of the Interior, Bureau of Recreation, and California Department of Water Resources.

Suits, B. 2001. Relationships between EC, chloride, and bromide at Delta export locations. Memorandum dated May 29, 2001, Bob Suits to Paul Hutton, Department of Water Resources, Sacramento, California.

State Water Board. *See* State Water Resources Control Board.

State Water Resources Control Board. 1995. Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary. State Water Resources Control Board, Sacramento, California, 95-1 WR May 1995.

U.S. Department of the Interior, Bureau of Recreation, and California Department of Water Resources. 2005. South Delta Improvements Program. Draft Environmental Impact Statement/Environmental Impact Report. October 2005.

1.8 Chapter 8

None

1.9 Chapter 9

Charney, A.H., and Vest, M.J. 2003. "Modeling Practices and Their Ability to Assess Tax/Expenditure Economic Impacts." Eller College of Business and Public Administration. University of Arizona, Tucson.

1.10 Chapter 10

Bowker, J.M., H.K. Cordell, L.J. Hawks, and D.B.K. English. 1994. An Economic Assessment of Alternative Water-Level Management forShasta and Trinity Lakes. Unpublished report. United States Department of Agriculture, Forest Service. Athens, Georgia.

California Department of Water Resources. 2004. Assessment of Regional Recreation Barriers to Recreation. R-14. Oroville Facilities Relicensing. FERC Project No. 2100.

DWR. *See* California Department of Water Resources.

English, D.B.K., J.M. Bowker, J.C. Bergstrom, and H.K. Cordell. 1995. Estimating the Economic Impacts of Recreation Response to Resource Management Alternatives. General Technical Report SE-91. United States Department of Agriculture, Forest Service, Southern Research Station. Asheville, North Carolina. 24 pp.

Hanson, T.R., L.U. Hatch, and H.C. Clonts. 2002. Reservoir Water Level Impacts on Recreation, Property, and Nonuse Values. Journal of the American Water Resources Association. 38 (4): 1007 1018.

Platt, J. 2001. Reservoir Recreation Use Estimation Modeling with Water Level Fluctuation. Technical Memorandum EC-2001-02. United States Department of the Interior, Bureau of Reclamation. 51 pp.

Platt, J., and D. Munger. 1999. Impact of Fluctuating Reservoir Elevation and Recreation Use and Value. Technical Memorandum EC 1991-1. United States Department of the Interior, Bureau of Reclamation. 50 pp.

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