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Modeling Appendix

Shasta Lake Water Resources Investigation, California

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Bureau of Reclamation
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U.S. Department of the Interior
Bureau of Reclamation **November 2011**

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Abbreviations and Acronyms

°F	degrees Fahrenheit
°C	degrees Celsius
AC	costs per acre
ACID	Anderson-Cottonwood Irrigation District
AW	applied water
Bay Area	San Francisco Bay Area
Bay-Delta	San Francisco Bay/Sacramento-San Joaquin Delta
BMP	Best Management Practices
BO	Biological Opinion
CA Power	SWP Power California
CAC	County Agricultural Commissioner
CACMP	Common Assumptions Common Modeling Package
CALFED	CALFED Bay-Delta Program
CalSim-II	California Water Resources Simulation Model II
CCC	Contra Costa Canal
CCWD	Contra Costa Water District
CDEC	California Date Exchange Center
CES	Constant Elasticity of Substitution
cfs	cubic feet per second
CIMIS	California Irrigation Management Information System
cm	centimeter
CONV	Conveyance
CP	comprehensive plan
CP	control point
CPED	constant price elasticity of demand
CPS	consumer profit and surplus
CSDP	Cross Section Development Program
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
CVPM	Central Valley Production Model
D-xxxx	State Water Resources Control Board Water Right Decision No. xxxx
DAU	detailed analysis unit
Delta	Sacramento-San Joaquin Delta

DFG	California Department of Fish and Game
DICU	Delta Island Consumptive Use
DMC	Delta-Mendota Canal
DSM2	Delta Simulation Model Version 2
DWR	California Department of Water Resources
EC	electrical conductivity
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
ETAW	evapotranspiration of applied water
FDM	Fischer Delta Model
g	grams
g/m^2	grams per cubic meter
GCC	Glenn-Colusa Canal
GCID	Glenn-Colusa Irrigation District
HEC	Hydrologic Engineering Center
HSI	habitat suitability index
IEP	Interagency Ecological Program
KCWA	Kern County Water Agency
kg	kilogram
km	kilometer
kWh	kilowatt hour
kWh/acre-foot	kilowatt hour/acre-foot
IAIR	Initial Alternatives Information Report
IFIM	Instream Flow Incremental Methodology
IWR-MAIN	Institute for Water Resources Municipal and Industrial Needs
LCPSIM	Least Cost Planning Simulation Model
LOD	level of development
LP	linear programming
LT	lethal temperature
LTG	LongTermGen
m	meter
M&I	municipal and industrial
mm	millimeter
MNR	marginal net revenue
MOU	Memorandum of Understanding
μS/cm	microsiemens per centimeter

MWDSC	Metropolitan Water District of Southern California
MWQI	Municipal Water Quality Investigations
NLP	Non-Linear Programming
NMFS	National Marine Fisheries Service
NODOS	North of Delta Offstream Storage
NR	net revenue
O&M	operations and maintenance
OCAP	Operations Criteria and Plan
OCO	Operations Control Office
PEIS	Programmatic Environmental Impact Statement
PFR	Plan Formulation Report
PHABSIM	Physical Habitat Simulation System
PMP	Positive Mathematical Programming
PP	Pumping Plant
PROSIM	Process Simulation
PVA	population viability analysis
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
ROD	Record of Decision
RBDD	Red Bluff Diversion Dam
RMA	Resource Management Associates
SA	sensitivity analysis
SDIP	South Delta Improvement Program
SLWRI	Shasta Lake Water Resources Investigation
SRWQM	Sacramento River Water Quality Model
SWP Power	State Water Project Power
SWRCB	State Water Resources Control Board
SWP	State Water Project
TAF	thousand acre feet
TCC	Tehama-Colusa Canal
TCCA	Tehama-Colusa Canal Authority
TCD	temperature control device
TMDL	total maximum daily load
TMS	Temperature Modeling System
TS	time series
UC Davis	University of California – Davis
USACE	United States Army Corps of Engineers
USBR	U.S. Department of the Interior, Bureau of Reclamation
USEPA	U.S. Environmental Protection Agency

USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
USWS	U.S. Weather Service
UVM	ultrasonic velocity meter
WASP	Water Quality Analysis Simulation Program
WES	U.S. Army Engineer Waterways Experiment Station
Western	Western Area Power Authority
WQCP	Water Quality Control Plan
WRESL	Water Resources Simulation Language
WRIMS	Water Resources Integrated Modeling System
WSD	Water Service District
WUA	weighted usable area
WWD	Westlands Water District
YOY	young-of-year

Chapter 1
Introduction

To support the Shasta Lake Water Resources Investigation (SLWRI), a suite of modeling tools was used to analyze the effects of the project on different resource areas. Many of these tools were developed or refined as part of the CALFED Bay-Delta Program (CALFED) Surface Storage Investigation Common Assumptions effort. Each of the CALFED Surface Storage Investigations is using the same tools for a consistent approach and methodology to evaluate the respective projects.

A previous version of the Common Assumptions Common Model Package (CACMP) was used for the Reclamation March 2007 SLWRI Plan Formulation Report (PFR). The current version of the CACMP uses seven different modeling tools, a statewide water resource planning tool (CalSim-II), a water temperature model (SRWQM), a salmon mortality model (SALMOD), an urban water supply economics model (LCPSIM), an agricultural production and economics model (CVPM), a delta hydrodynamic and water quality model (DSM2), and power generation models for the CVP (LTGen) and the SWP (SWPPower). Modeling output from each of these tools for various alternatives can be compared to a common baseline to determine the relative effect of the alternative on the resource area of interest.

- The California Water Resources Simulation Model II (CalSim-II) provides information about the Central Valley Project (CVP) and State Water Project (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.

- The Sacramento River Water Quality Model (SRWQM) 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 the Red Bluff Diversion Dam (RBDD).

- SALMOD uses CalSim-II Sacramento River flows and inflows, and SRWQM water temperatures to simulate Chinook salmon mortality and escapement.

- The Least Cost Planning Simulation Model (LCPSIM) uses CalSim-II water supply deliveries to municipal and industrial (M&I) contractors to assign an economic value at the Sacramento-San Joaquin Delta (Delta) for project contribution to urban water supply reliability.

- The Central Valley Production Model (CVPM) uses CalSim-II water supply deliveries to agricultural contractors to simulate the decisions of agricultural producers (farmers) in the Central Valley of California. The model selects crops, water supplies, and irrigation technology to maximize profit.

- The Delta Simulation Model, Version 2 (DSM2), uses CalSim-II Delta inflows, outflows, and exports to determine Delta water quality and water levels.

- LongTermGen (LTGen) and State Water Project (SWPPower) use CalSim-II reservoir storages, releases, and project pumping to determine the energy generation and usage of the CVP and SWP.

This modeling technical appendix documents the assumptions used in 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, is used in the SLWRI to evaluate the environmental and water supply benefits and impacts of each SLWRI alternative. A comparative analysis of benefits will also be used to support alternatives evaluation and contribute to the selection of an alternative.

This chapter describes CalSim-II and its application in reservoir operations studies for the SLWRI.

Background

WRIMS

CalSim-II is a particular application of the Water Resources Integrated Modeling System (WRIMS). WRIMS is generalized water resources software developed by the California Department of Water Resources (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 the U.S. Department of the Interior, Department of Reclamation (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 a 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. 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.

CalSim-II can be used in either a comparative or an absolute mode. The comparative mode consists of comparing two model runs: one containing 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. In the absolute mode, 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, CalSim-II modeling output is used in the comparative model rather than the absolute mode.

Common Assumptions

Reclamation, DWR, and their consultants are developing a set of "Common Assumptions" studies as part of CALFED. These studies, when completed, will provide a common baseline for analyzing the storage projects defined in the 2000 CALFED Record of Decision (ROD). CalSim-II is one of the tools being developed as part of the CACMP. Two CalSim-II studies have been developed: the first study represents the existing conditions, and the second study represents the future conditions. The SLWRI studies are based on the CACMP CalSim-II Version 8D for future conditions.

Model Assumptions

Table 2-1 summarizes CalSim-II assumptions for the CACMP Version 8D (unpublished) Existing Condition and Future Condition studies. The regulatory conditions simulated within CalSim-II for the SLWRI alternatives include Biological Opinions (BO) from the U.S. Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NMFS), published in 2005 and 2004, respectively. New BOs were released by USFWS and NMFS in 2008 and 2009, respectively. Several lawsuits were filed challenging the validity of the 2008 USFWS BO and 2009 NMFS BO and Reclamation's acceptance of the RPA included with each BO (*Consolidated Salmonid Cases, Delta Smelt Consolidated Cases*). On November 13, 2009, and March 5, 2010, the District Court concluded that Reclamation had violated NEPA by failing to perform a NEPA analysis before provisionally adopting the 2008 USFWS RPA and 2009 NMFS RPA. On December 14, 2010, the District Court found the 2008

USFWS BO to be unlawful and remanded the BO to USFWS. The District Court issued a similar ruling for the 2009 NMFS BO on September 20, 2011. On May 4, 2011, in the *Delta Smelt Consolidated Cases*, the District Court ordered USFWS to prepare a draft BO by October 1, 2011, which was subsequently extended to an unspecified date to be agreed upon by involved parties. Reclamation and USFWS must then prepare a final BO and final NEPA document by November 1, 2013, and December 1, 2013, respectively.

The legal challenges and changing environmental conditions result in uncertainty with regard to both current and future operations. These operational uncertainties are likely to continue, and current and future water operation conditions may be different because operational constraints governing water operations are likely to change with release of revised USFWS and NMFS BOs. The existing SLWRI modeling analysis is being used for comparison purposes, and reflects expected variation among the plans, including the type and relative magnitude of anticipated impacts and benefits. Because of the lingering uncertainty about future water operations, the Draft Feasibility Report and Preliminary Draft EIS are based on existing studies.

Modeling studies will be updated to reflect changes in water operations resulting from ongoing OCAP reconsultation and other relevant water resources projects and programs, including, potentially, BDCP/DHCCP efforts. The results of these updated studies will be incorporated into future SLWRI documents.

Table 2-1. CalSim-II Inputs for the Common Assumptions Common Modeling Package Version 8D

	Existing Condition	Future Condition
Planning Horizon	2004[1]	2030[1]
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]	Same
SWP (FRSA)	Land-use based, limited by contract amounts[5]	Same
Nonproject	Land-use based	Same
Federal refuges	Recent historical Level 2 deliveries[6]	Firm Level 2 water needs[6]
American River Basin		
Water rights	2004[7]	Sacramento Area Water Forum[7 8]
CVP	2004[7]	Sacramento Area Water Forum (PCWA modified) [7 8]
PCWA	No CVP contract water supply	35 TAF CVP contract supply diverted at the new American River PCWA Pump Station
San Joaquin River Basin[9]		
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	Land-use based, based on New Melones Interim Operations Plan[10]	Same
South of Delta		
CVP	Demand based on contract amounts[4]	Same
Federal refuges	Recent historical Level 2 deliveries[6]	Firm Level 2 water needs[6]
CCWD	124 TAF CVP contract supply and water rights[11]	195 TAF CVP contract supply and water rights[11]
SWP	Demand varies based on pattern used for 2004 OCAP Today studies; Table A transfers occurring in 2005 and 2006 are not included	Demand based on full Table A amounts[5 12]
Article 56	Based on 2002-2006 contractor requests	Same
Article 21	MWD demand up to 100 TAF/month from December to March, total of other demands up to 84 TAF/month in all months [5 12]	MWD demand unlimited but subject to capacity to convey and deliver; KCWA demand of up to 2,555 cfs; others same as existing

Table 2-1. CalSim-II Inputs for the Common Assumptions Common Modeling Package Version 8D (contd.)

	Existing Condition	Future Condition
FACILITIES		
System-Wide	Existing facilities[1]	Same
Sacramento Valley		
Shasta Lake	Existing, 4,552 TAF capacity	Same
Colusa Basin	Existing conveyance and storage facilities	Same
Upper American River	PCWA American River pump station not included	PCWA American River pump station included
Lower Sacramento River	Freeport Regional Water Project not included	Freeport Regional Water Project included
Delta Export Conveyance		
SWP Banks Pumping Plant	6,680 cfs capacity[1]	Same
CVP C.W. “Bill” Jones Pumping Plant (formerly Tracy PP)	4,200 cfs plus diversion upstream from DMC constriction	4,600 cfs capacity in all months (allowed for by the Delta-Mendota Canal-California Aqueduct Intertie)
Los Vaqueros Reservoir	Existing storage capacity, Alternative Intake Project not included	Existing storage capacity, 100 TAF; Alternate Intake Project included[14]
San Joaquin River		
Millerton Lake (Friant Dam)	Existing, 520 TAF capacity	Same
South of Delta (CVP/SWP project facilities)		
South Bay Aqueduct enlargement	None	430 cfs capacity from junction with California Aqueduct to Alameda County FC&WSD Zone 7 point
California Aqueduct East Branch enlargement	None	None
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
Clear Creek		
Minimum flow below Whiskeytown Dam	Downstream water rights, 1963 Reclamation proposal to USFWS and NPS, and USFWS discretionary use of CVPIA 3406(b)(2)	Same

Table 2-1. CalSim-II Inputs for the Common Assumptions Common Modeling Package Version 8D (contd.)

	Existing Condition	Future Condition
Upper Sacramento River		
Shasta Lake end-of-September minimum storage	SWRCB WR 1993 Winter-Run Biological Opinion (1,900 TAF)	Same
Minimum flow below Keswick Dam	Flows for SWRCB WR 90-5 and 1993 Winter-Run Biological Opinion temperature control, and USFWS discretionary use of CVPIA 3406(b)(2)	Same
Feather River		
Minimum flow below Thermalito Diversion Dam	1983 DWR, DFG agreement (600 cfs)	Same
Minimum flow below Thermalito Afterbay outlet	1983 DWR, DFG agreement (750 – 1,700 cfs)	Same
Yuba River		
Minimum flow below Daguerre Point Dam	SWRCB RD-1644 Interim Operations[15]	Same
American River		
Minimum flow below Nimbus Dam	SWRCB D-893[16] and USFWS discretionary use of CVPIA 3406(b)(2)	Same
Minimum flow at H Street Bridge	SWRCB D-893	Same
Lower Sacramento River		
Minimum flow near Rio Vista	SWRCB D-1641	Same
Mokelumne River		
Minimum flow below Camanche Dam	FERC 2916-029[13], 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, DFG agreement, and USFWS discretionary use of CVPIA 3406(b)(2)	Same
Minimum dissolved oxygen	SWRCB D-1422	Same
Merced River		
Minimum flow below Crocker-Huffman Diversion Dam	Davis-Grunsky (180 – 220 cfs, Nov – Mar), Cowell Agreement, and 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. CalSim-II Inputs for the Common Assumptions Common Modeling Package Version 8D (contd.)

	Existing Condition	Future Condition
San Joaquin River		
San Joaquin River below Friant Dam/Mendota Pool	None	None
Maximum salinity near Vernalis	SWRCB D-1641	Same
Minimum flow near Vernalis	SWRCB D-1641, and Vernalis Adaptive Management Plan per San Joaquin River Agreement	Same[17]
Sacramento-San Joaquin Delta		
Delta Outflow Index (flow and salinity)	SWRCB D-1641	Same
Delta Cross Channel gate operation	SWRCB D-1641	Same
Delta exports	SWRCB D-1641, USFWS discretionary use of CVPIA 3406(b)(2)	Same
OPERATIONS CRITERIA: RIVER-SPECIFIC		
Upper Sacramento River		
Flow objective for navigation (Wilkins Slough)	Discretionary 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
Flow below Nimbus Dam	Discretionary operations criteria corresponding to SWRCB D-893 required minimum flow	Same
Sacramento Area Water Forum mitigation water	None	Sacramento Water Forum (up to 47 TAF/yr in dry years)[5]
Feather River		
Flow at mouth of Feather River (above Verona)	Maintain DFG/DWR flow target of 2,800 cfs for April through September dependent on Oroville inflow and FRSA allocation	Same
Stanislaus River		
Flow below Goodwin Dam	1997 New Melones Interim Operations Plan	Same
San Joaquin River		
Salinity at Vernalis	D-1641	San Joaquin River Salinity Management Plan[18]

Table 2-1. CalSim-II Inputs for the Common Assumptions Common Modeling Package Version 8D (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 (SOD allocations are reduced because of D-1641 and 3406(b)(2) allocation related export restrictions)	Same
CVP municipal & industrial	100% - 50% based on supply (SOD allocations are reduced because of D-1641 and 3406(b)(2) allocation related export restrictions)	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	Same
CVP/SWP Coordinated Operations		
Sharing of responsibility for in-basin use	1986 Coordinated Operations Agreement (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)	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)
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 SWRCB D-1641; use of CVPIA 3406(b)(2) only restricts CVP exports	Same
Dedicated CVP conveyance at Banks	None	SWP to convey 50,000 AF/yr of Level 2 refuge water at Banks PP (July and August)
North of Delta accounting adjustments	None	CVP to provide the SWP a maximum of 37,500 AF/yr of water to meet in-basin requirements through adjustments in COA accounting (released from Shasta)
Sharing of export capacity for lesser priority and wheeling-related pumping	Cross Valley Canal wheeling (max of 128 TAF/yr), CALFED ROD defined Joint Point of Diversion	Same
San Luis Low Point	San Luis Reservoir is allowed to operate to a minimum storage of 100 TAF	Same

Table 2-1. CalSim-II Inputs for the Common Assumptions Common Modeling Package Version 8D (contd.)

	Existing Condition	Future Condition
CVPIA 3406(b)(2)		
Policy decision	Per 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	1995 WQCP, fish flow objectives (October to January), VAMP (April 15 to May 15) CVP export restriction, 3,000 cfs CVP export limit in May and June (D-1485 Striped Bass), post-(May 16 to 31) VAMP CVP export restriction, ramping of CVP export (June), upstream releases (February through September)	Same
Accounting adjustments	Per May 2003 Interior decision, no limit on responsibility for nondiscretionary D-1641 requirements with 500 TAF target, no reset with the storage metric, and no offset with the release and export metrics, 200 TAF target on costs from October to January	Same

Source: Common Assumptions Common Modeling Package V8D Assumptions Matrix, 2007

Notes:

[1] A detailed description of the assumptions selection criteria and policy basis used is included in the policy section of the Common Assumptions Common Modeling Package report.

[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 No-Action Alternative 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. Assumptions regarding CVP agricultural and M&I service contracts and Settlement Contract amounts are documented in the Common Assumptions Common Modeling Package Report, Tables 4 (north of Delta) and 6 (south of Delta) of Appendix B: CACMP Delivery Specifications.

[5] SWP contract amounts have been reviewed and updated, as appropriate. Assumptions regarding SWP agricultural and M&I contract amounts are documented in the Common Assumptions Common Modeling Package Report, Table 2 (north of Delta) and Table 3 (south of Delta) of Appendix B: CACMP Delivery Specifications.

[6] Water needs for Federal refuges have been reviewed and updated, as appropriate. Assumptions regarding firm Level 2 refuge water needs are documented in the Common Assumptions Common Modeling Package Report Table 4 (north of Delta) and 6 (south of Delta) of Appendix B: CACMP Delivery Specifications. As part of the water transfers technical memorandum (Appendix A: Characterization and Quantification), incremental Level 4 refuge water needs have been documented as part of the assumptions of future water transfers.

[7] Assumptions regarding American River water rights and CVP contracts are documented in the Common Assumptions Common Modeling Package Report, Table 5 of Appendix B: CACMP Delivery Specifications.

[8] Sacramento Area Water Forum 2025 assumptions are defined in Sacramento Water Forum's EIR. PCWA CVP contract supply is modified to be diverted at the PCWA pump station. Assumptions regarding American River water rights and CVP contracts are documented in the Common Assumptions Common Modeling Package Report, Table 4 of Appendix B: CACMP Delivery Specifications.

Table 2-1. CalSim-II Inputs for the Common Assumptions Common Modeling Package Version 8D (contd.)

Notes (continued):

[9] 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). Updates to the San Joaquin River have been included since the preliminary model release in August 2005. In addition, a dynamic groundwater simulation is currently being developed for the San Joaquin River Valley, but is not yet implemented. 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.

[10] The CACMP CalSim-II model representation for the Stanislaus River does not necessarily represent Reclamation's current or future operational policies.

[11] The existing CVP contract is 140 TAF. The actual amount diverted is reduced because of supplies from the Los Vaqueros project. The existing Los Vaqueros storage capacity is 100 TAF. Associated water rights for Delta excess flows are included.

[12] Table A and Article 21 deliveries into the San Francisco Bay Area Region–South and South Coast Region in the CACMP are a result of interaction between CalSim-II and LCPSIM. More information regarding LCPSIM is included in the Common Assumptions Common Modeling Package Report and the CALSIM-LCPSIM integration technical memorandum (see Appendix C: Analytical Framework).

[13] Mokelumne River flows reflect EBMUD supplies associated with the Freeport Regional Water Project.

[14] The CCWD Alternate Intake Project (AIP) is a new intake at Victoria Canal to operate as an alternate intake for Los Vaqueros Reservoir. This assumption is consistent with the future no-project condition defined by the Los Vaqueros Enlargement study team.

[15] Interim D-1644 is assumed to be implemented.

[16] Sacramento Area Water Forum Lower American River Flow Management Standard is not included in the CACMP. Reclamation has agreed in principle to the Flow Management Standard, but flow specifications are not yet available for modeling purposes.

[17] It is assumed that either VAMP, a functional equivalent, or D-1641 requirements would be in place in 2030.

[18] The CACMP CalSim-II model representation for the San Joaquin River does not explicitly implement the CALFED Salinity Management Plan.

Key:
AF = acre-feet
AF/yr = acre-feet per year
Ag = agricultural
AIP = Alternative Intake Project
CALFED = CALFED Bay-Delta Plan
CCWD = Contra Costa Water District
cfs = cubic feet per second
COA = Coordinated Operations Agreement
CVP = Central Valley Project
CVPIA = Central Valley Project Improvement Act
DFG = Department of Fish and Game
DMC = Delta-Mendota canal
DWR = California Department of Water Resources
D-xxxx = Water Right Decision
EBMUD = East Bay Municipal Utility District
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
KCWA = Kern County Water Agency
M&I = municipal and industrial
MWD = Metropolitan Water District
NPS = National Park Service
OCAP = Operating Criteria and Plan
PCWA = Placer County Water Agency
PP = Pumping Plant
RD = Revised Decision
Reclamation = United States Department of the Interior, Bureau of Reclamation
ROD = Record of Decision
SOD = south of Delta
SWP = State Water Project
SWRCB = State Water Resources Control Board
TAF = thousand acre-feet
TAF/yr = thousand acre-feet per year
USFWS = United States Fish and Wildlife Service
VAMP = Vernalis Adaptive Management Plan
WQCP = Water Quality Control Plan
WR = water right
yr = year

Four-Step Simulation

Modeling Central Valley Project Improvement Act (CVPIA) (b)(2) requires knowledge of project operations under different regulatory baseline conditions. Simulation of (b)(2) requires knowledge of operations under Water Right Decision 1485 (D-1485) (SWRCB 1978) and D-1641 (SWRCB 2000). An 82-year simulation of project operations under a single regulatory regime is referred to as a CalSim-II single-step study. Modeling the SLWRI requires simulating four steps, simulated in sequence. Each step represents a "layer" of constraints and operations. The four steps are listed below in the order they are performed:

1. D-1641 step, for State Water Resources Control Board (SWRCB) D-1641, includes a water right decision issued in December 1999 recognizing current Delta water quality standards (the 1995 SWRCB Water Quality Control Plan (WQCP) for the San Francisco Bay/Sacramento-San Joaquin Delta (Bay-Delta)).

2. D-1485 step, for SWRCB D-1485, includes the former Delta water quality standards, issued in August 1978.

3. B2 step, for CVPIA(3406(b)(2) legal actions (commonly known as B2 actions), annually dedicates 800 thousand acre-feet (TAF) or 600 TAF in Shasta critical years of CVP yield for targeted fish actions.

4. Conveyance (CONV) step, when the new CALFED facility (in this case, the Shasta Lake enlargement), is implemented and operations that include the modified facility are simulated.

The four-step simulation process is as follows: for each water year, CalSim-II models the first step, D-1641, for 12 months, then models the next step for the same 12 months, and then models the next step for the same 12 months, etc., through all four steps. The output of each step is transferred and used as input for the next step. For example, the B2 step requires cumulative results from the D-1641 and D-1485 steps to determine the required fishery release for a particular month. At the end of the last step, CONV, all operational constraints and objectives have been applied, and water allocations for a particular water year are finalized. However, the B2 results become initial conditions (input) for modeling the next water year, beginning with the first step, D-1641. This simplifies the process if the models need to be rerun for different enlargement scenarios; rather than rerunning all four steps, it is possible to only run the CONV step for the different enlargements.

Operating Rules for the SLWRI

Operations of Shasta Dam depend on conditions in Trinity Lake, Whiskeytown Lake, and Keswick Reservoir. This section describes selected assumptions of the CACMP CalSim-II Study V8 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.

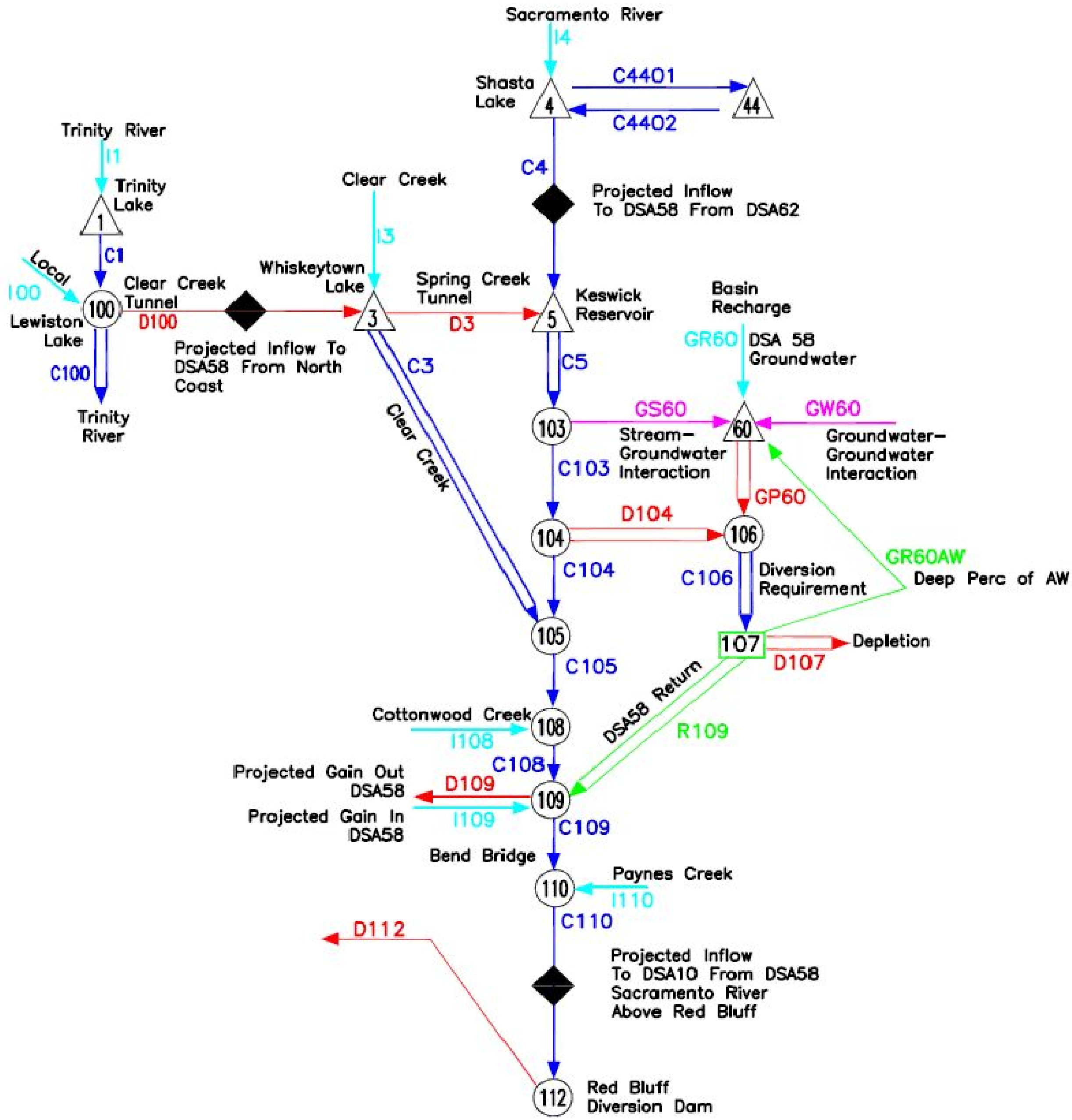


Figure 2-1. CACMP CalSim-II V8D Schematic for SLWRI Primary Study Area, Including Shasta Reservoir and Sacramento River to Red Bluff Diversion Dam

A 2004 winter-run Chinook salmon Biological Opinion (BO) was issued by the National Marine Fisheries Service (NMFS), of the National Oceanic and Atmospheric Administration, and adopted by the California Department of Fish and Game (DFG). The BO includes requirements for Sacramento River flows and temperature at various locations, CVP and SWP coordination and cooperation, Shasta Reservoir carryover storage, and operational restrictions at the RBDD. 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 CACMP CalSim-II V8 Study for the SLWRI include the following:

- **Shasta Reservoir operation –** Shasta Reservoir capacity is 4,552 TAF, with a maximum objective release capacity of 79,000 cubic feet per second (cfs). The end-of-September storage target for Shasta Reservoir is 1,900 TAF, except in the driest 10 percent of water years, to conserve sufficient cold water for meeting temperature criteria for the winter-run Chinook incubation period (summer to early fall). 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.

- **Keswick Dam hydropower generation –** The assumed total Keswick Dam hydropower capacity is 15,000 cfs.

- **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 and 4,200 cfs, respectively). After meeting the monthly minimum instream flow requirement below Lewiston Lake,[1] and the Trinity Lake end-of-September minimum storage target of 600 TAF, 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 3,000 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,[2] water is diverted through Spring Creek Tunnel to Keswick Reservoir.

[1] This minimum requirement, an annual amount of 369 to 815 TAF per the 1999 Trinity River Mainstem Fishery Restoration Record of Decision (ROD) (USFWS, Reclamation, Hoopa Valley Tribe, and Trinity County), is a lookup value that varies by month and the Trinity index; the Trinity index changes in April.

[2] This requirement is a lookup value that varies by month and the Shasta index.

- **Minimum flow requirement below Keswick Dam –** As defined in the 2004 NMFS Operations Criteria and Plan (OCAP) BO, the minimum flow requirement below Keswick Dam between October 1 and March 31 is 3,250 cfs.

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

- **Flow objective for navigation control point –** The monthly navigational flow objective at Wilkins Slough is 3,500, 4,000, or 5,000 cfs according to the beginning-of-month Shasta Reservoir storage. 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.

SLWRI Hydrologic Analysis

Primary planning objectives of the SLWRI are as follows:

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

- Increase water supplies and water supply reliability for agricultural, M&I, and environmental purposes to help meet future water demands, primarily through enlarging Shasta Dam and 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 with hydrologic impacts on the California water supply system (e.g., changes in channel flow rates or water allocation logic) were simulated in CalSim-II. 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 PFR (Reclamation 2007), and are being updated for the Preliminary Draft Environmental Impact Statement and Draft Feasibility Report.

[3] 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.

Common Assumptions and Definitions

Reclamation and DWR, in coordination with the California Bay-Delta Authority, have developed common model input assumptions, a common analytical framework and associated tools and methodologies for integrated hydrologic and economic analysis, and common reporting metrics for the CALFED surface water storage programs. Additional assumptions specific to 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 2-2. Water moves between the two reservoirs through two arcs, C4401 (from S4 to S44) and C4401 (S44 to S4), which have no capacity constraints. During a time step (month), water is not allowed to flow into or out of S44.

Table 2-2. S44 Storage Volume for SWLRI Alternatives

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

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

Key:
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; after the S4 storage level reaches S4_Level5, 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. Shasta Reservoir storage for levels 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.

- "Year-type" is the Sacramento Valley water year hydrologic classification, as defined by SWRCB in 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.

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 HEC-5Q 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 HEC-5Q, 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 - 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

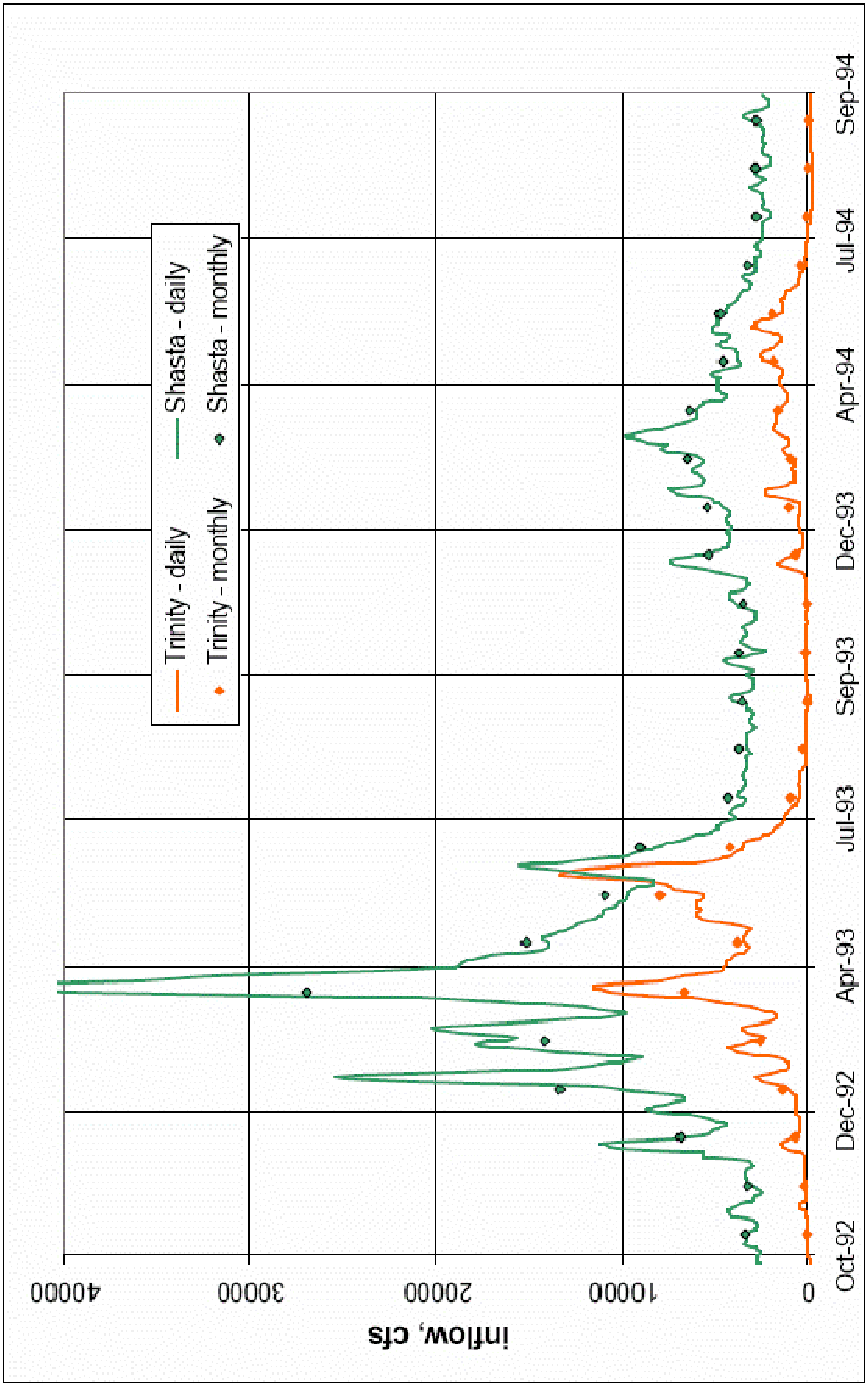
Since reservoir outflow and diversion rates are a function of CalSim-II operating assumptions, historical flow patterns are not meaningful. Consequently monthly flows were simply smoothed for a better transition at the end of the month. Initially, flows were defined without regard for reservoir volume 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 outflows maintaining monthly outflow volume.
3. Increase Shasta release if Steps 1 and 2 cannot meet minimum flow requirements (excess release volumes are made up in later months when Shasta 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 HEC-5Q. Miscellaneous project gains were combined and assumed as diffuse inflows or withdrawals in HEC-5Q.

Figure 3-1 shows the results of calibrating temporal downsizing of CalSim-II model output.



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

Figure 3-1. Trinity and Shasta CalSim-II Monthly Flows and Downscaled Daily Flows

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Chapter 4
Sacramento River Water Temperature Model

Introduction

A HEC-5Q model was developed and calibrated for the upper Sacramento River system, including Trinity Dam, Trinity River to Lewiston, Lewiston Dam, Clear Creek Tunnel, Whiskeytown Dam, Spring Creek Tunnel, Shasta Dam, Keswick Dam, Sacramento River from Keswick to Knights Landing, Clear Creek below Whiskeytown, RBDD, Black Butte Dam, and downstream Stony Creek. This model was then modified and extended to include the North-of-the-Delta Offstream Storage (NODOS) options for the purpose of evaluating the impacts of creating Sites Reservoir, and impacts of accompanying diversions on temperature and water quality. The NODOS model extends from Keswick Dam to Knights Landing, and includes the Sacramento River, RBDD, Black Butte Dam and downstream Stony Creek, Tehama-Colusa Canal, Glenn-Colusa Canal, Colusa Basin Drain, proposed Maxwell pipeline, enlarged Funks Reservoir, and proposed Sites Reservoir.

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 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.

HEC-5Q 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.

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 upper Sacramento River HEC-5Q 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 include 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 HEC-5Q upper Sacramento River model is shown in Figure 4-1.

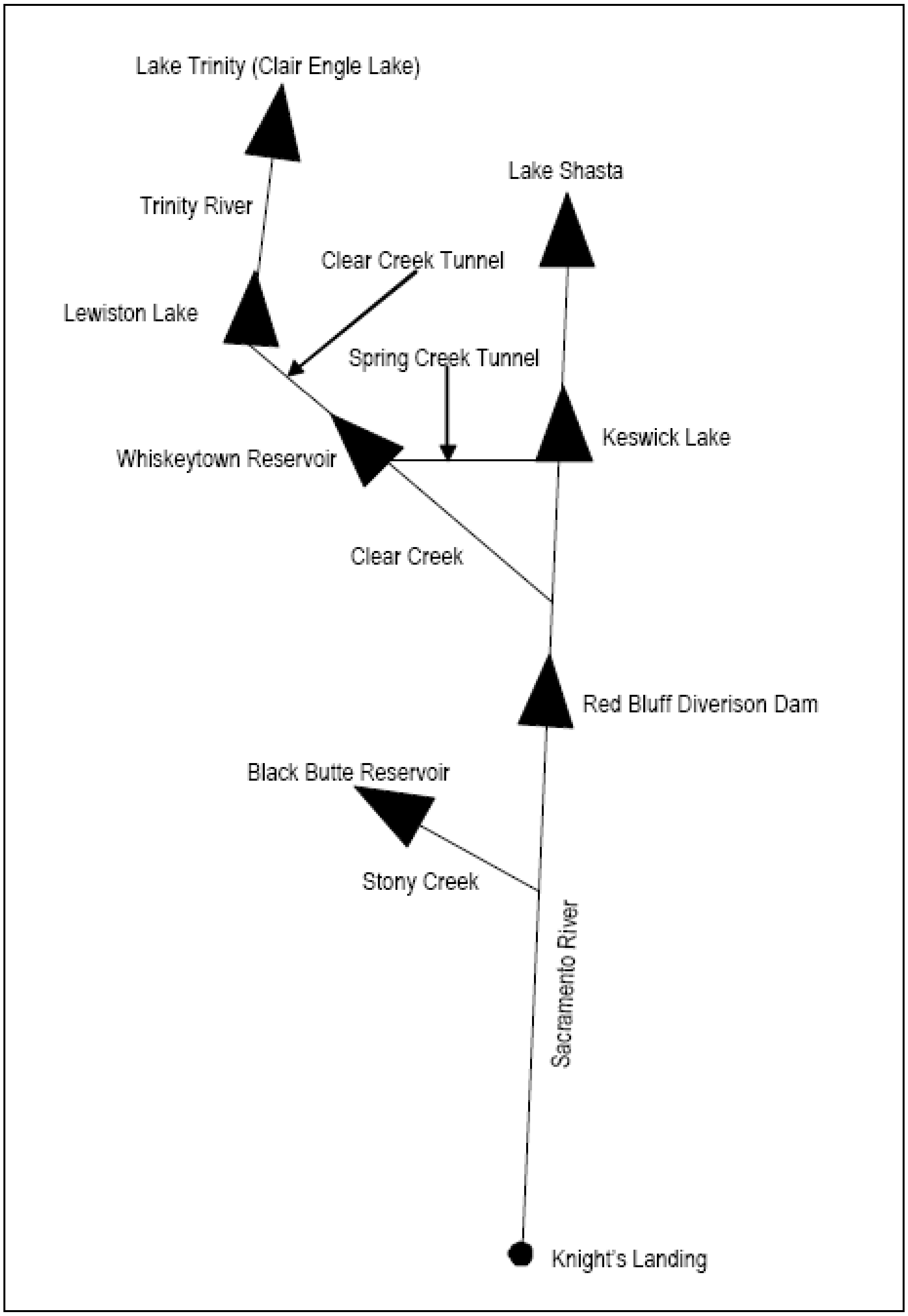


Figure 4-1. Schematic of the HEC-5Q Upper Sacramento River Model

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 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 5 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 reservoir 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 U.S. Army Engineer 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 Appendi**x** on Water Quality Analysis (USACE 1998).

Control point 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 gate to lowest 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.

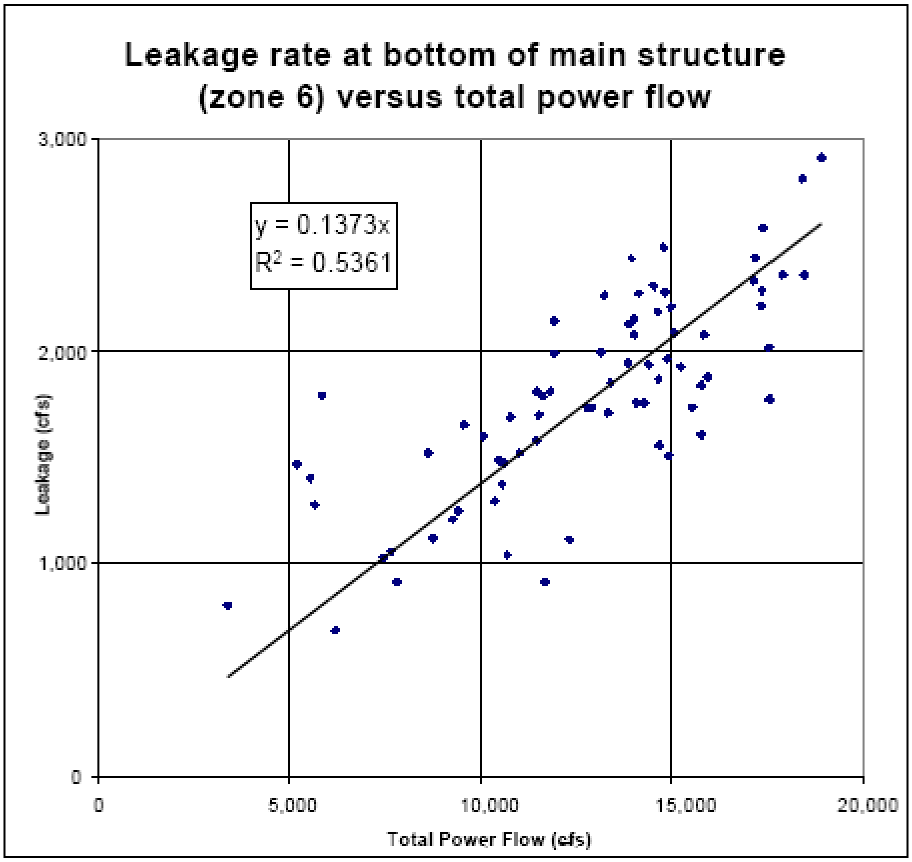
The Shasta Dam TCD algorithm is transparent under nonupper Sacramento River model applications. The TCD option is triggered by inserting a control record into the HEC-5Q data set. The record takes the form of "Shasta Dam TCD opp TCD_opp.log" where the latter part is an output file. The output file contains 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." Prior to 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, Comp. vs. Obs. 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
Kf = 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):

<u>Target is between middle and upper gate</u>:
Qg = Nt * 0.18 * Qm + Nm * Qm (R2 = 0.09)

<u>Target is between middle and penstock gate</u>:
Qg = Np *(467 + 0.476) * Qm + Nm * Qm (R2 = 0.87)

<u>Target is between lower and penstock gate</u>:
Qg = Np *(690 + 0.127) * Qb + Qb (R2 = 0.83)

where

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

Qm = flow through middle gate

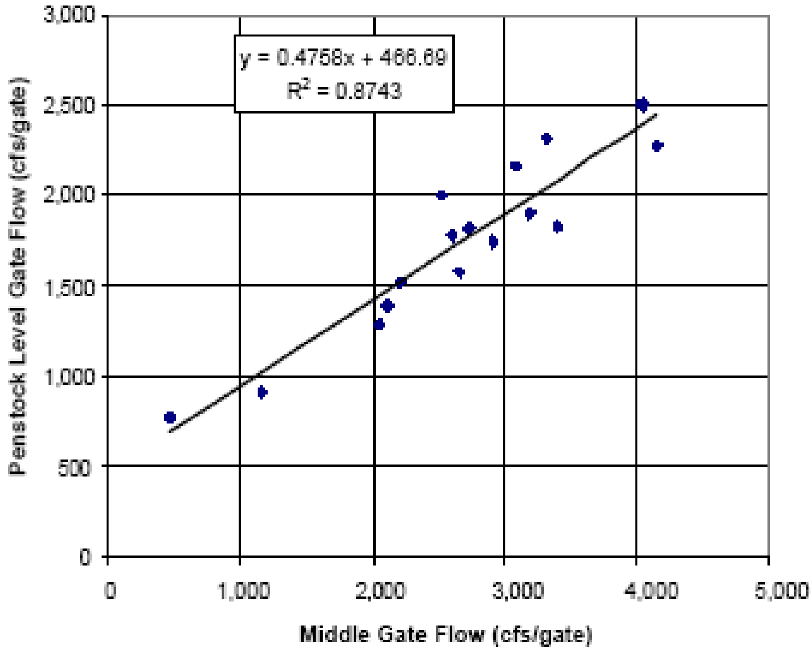
Qb = flow through the lower gate

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.

HEC-5Q 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 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 HEC-5Q cross section data. The accuracy of the HEC-5Q 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.

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.

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
Moultin Weir	35
Colusa Weir	40
Tisdale Weir	50
Knights Landing	62

Key:
GCID = Glenn-Colusa Irrigation District

Hydrologic Boundary Conditions

HEC-5Q upper Sacramento River hydrologic model 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 control point.

Water temperature was simulated by HEC-5Q 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 inflow** – flow-weighted temperatures of the three major tributaries
- **Trinity inflow** – Trinity River above Trinity Lake (provided by Mike Deas)

- **Whiskeytown 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

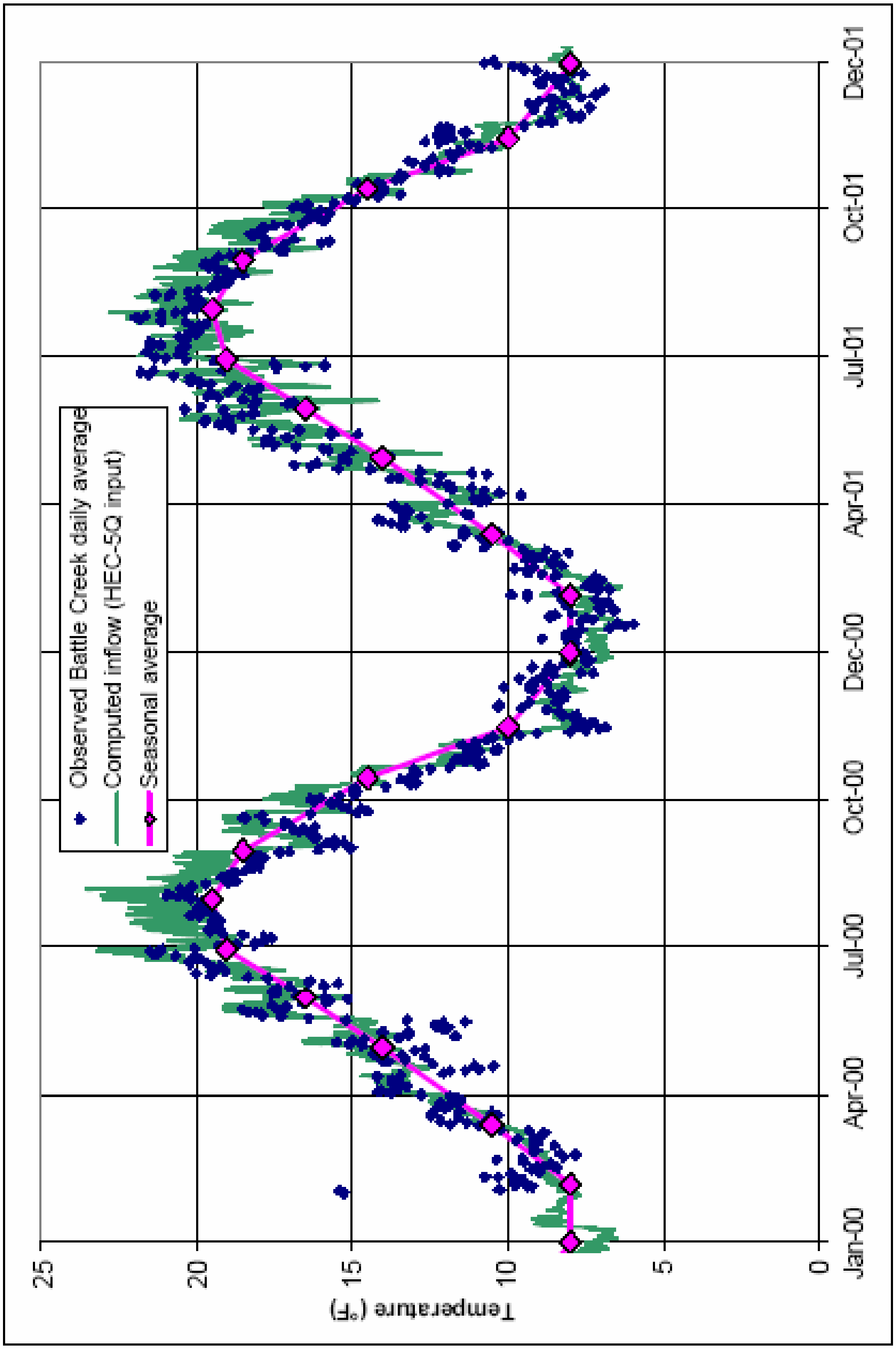
Tributary	Available Reservoir Inflow Data		
	Start	End	No. of Days
Sacramento River	Feb-90	Jun-01	3,418
McCloud River	May-90	Jun-01	3,481
Pitt River	Nov-89	Jun-01	3,913
Stuart's Fork Trinity River	Apr-00	Jun-02	586
East Fork Trinity River	Apr-00	Jun-02	714
Trinity River	Apr-00	Jun-02	711

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 in 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. Prior to 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 HEC-5Q. 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

HEC-5Q 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 Tehama-Colusa Canal; 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.

HEC-5Q Calibration Results

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

Reservoir Temperature Calibration Results

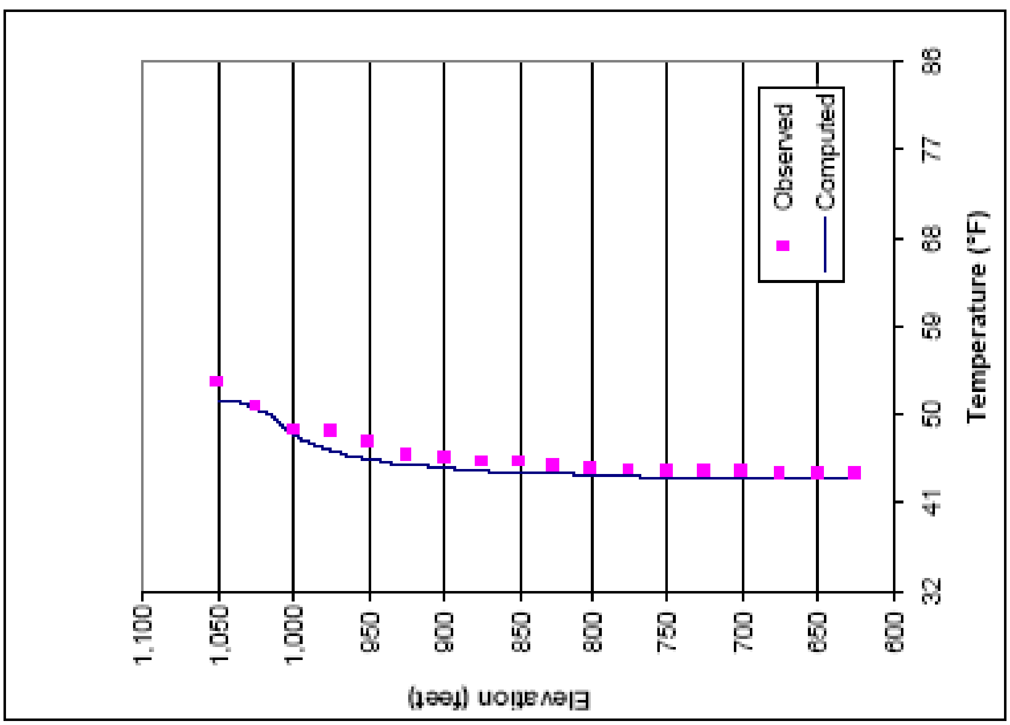
Computed and observed vertical reservoir temperature profiles are plotted for numerous dates during 1999 through 2002 in Figures 4-5 through 4-52.

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.

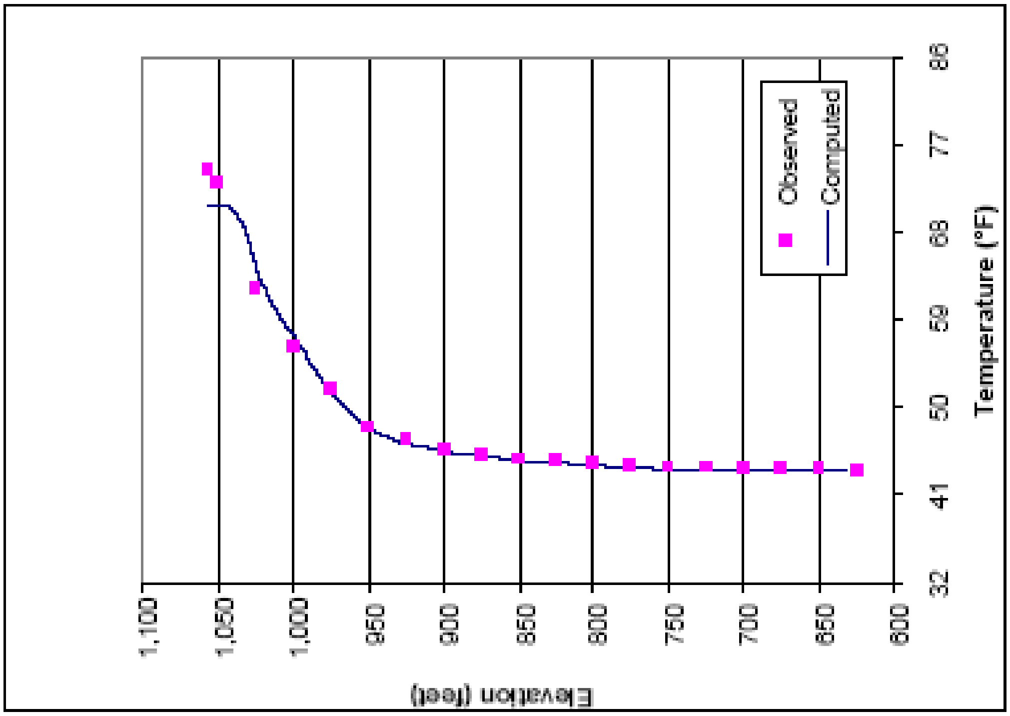
Trinity Reservoir temperature profiles are shown in Figures 4-37 through 4-44. Computed values are in excellent agreement with observed data for all of the profiles. The only notable deviations occur on September 20, 1999, when the computed surface temperature is approximately 2°F warmer than observed,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



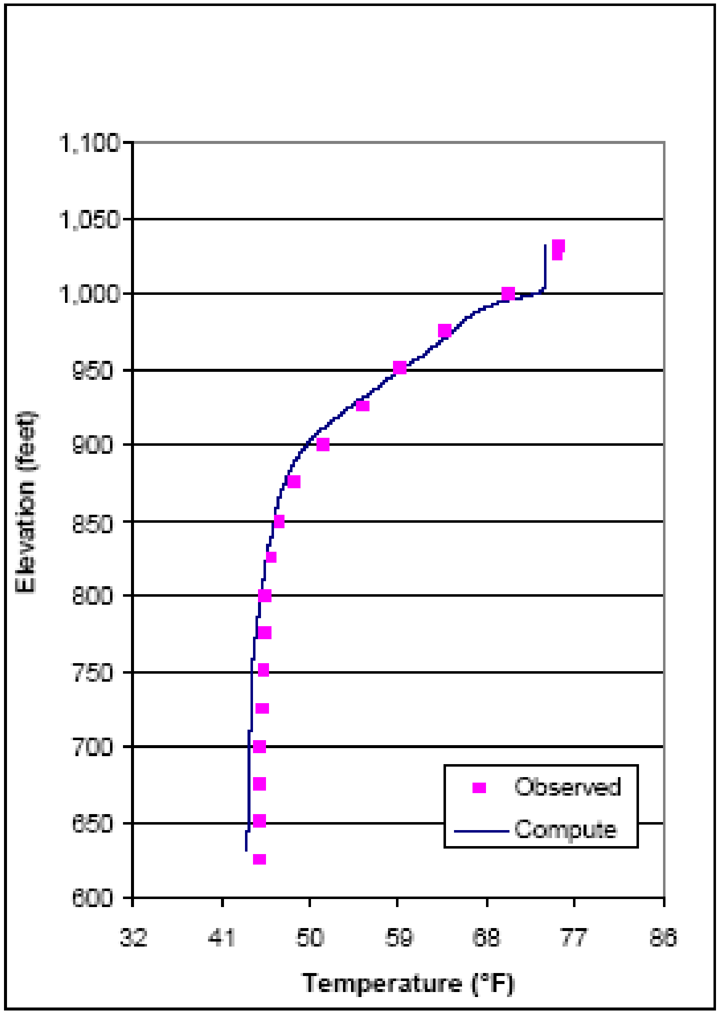
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



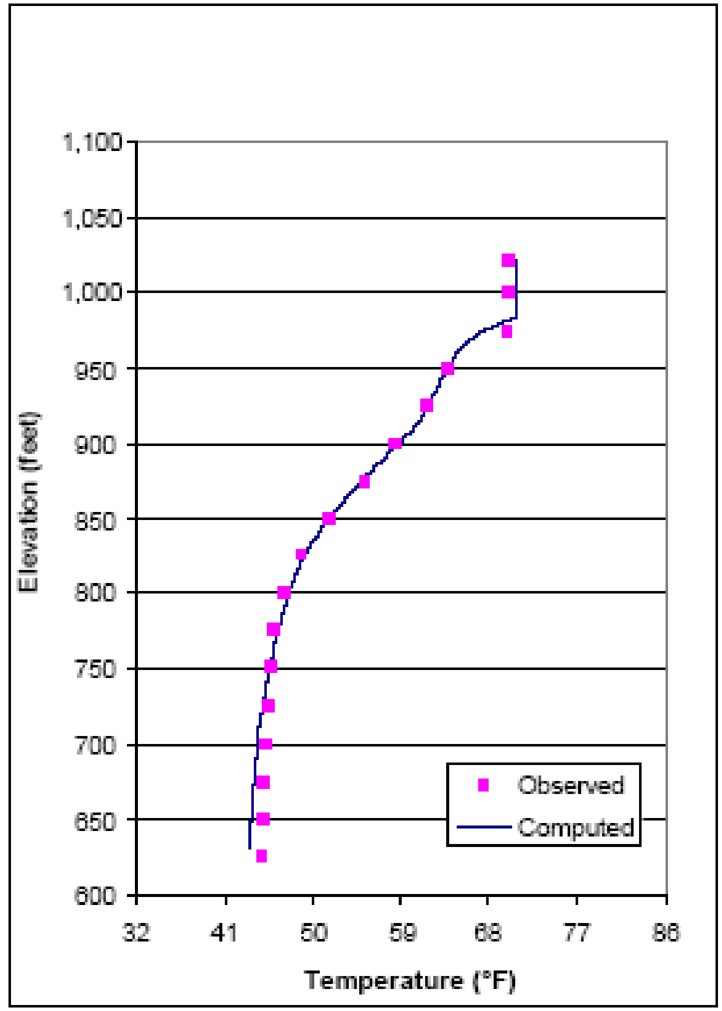
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



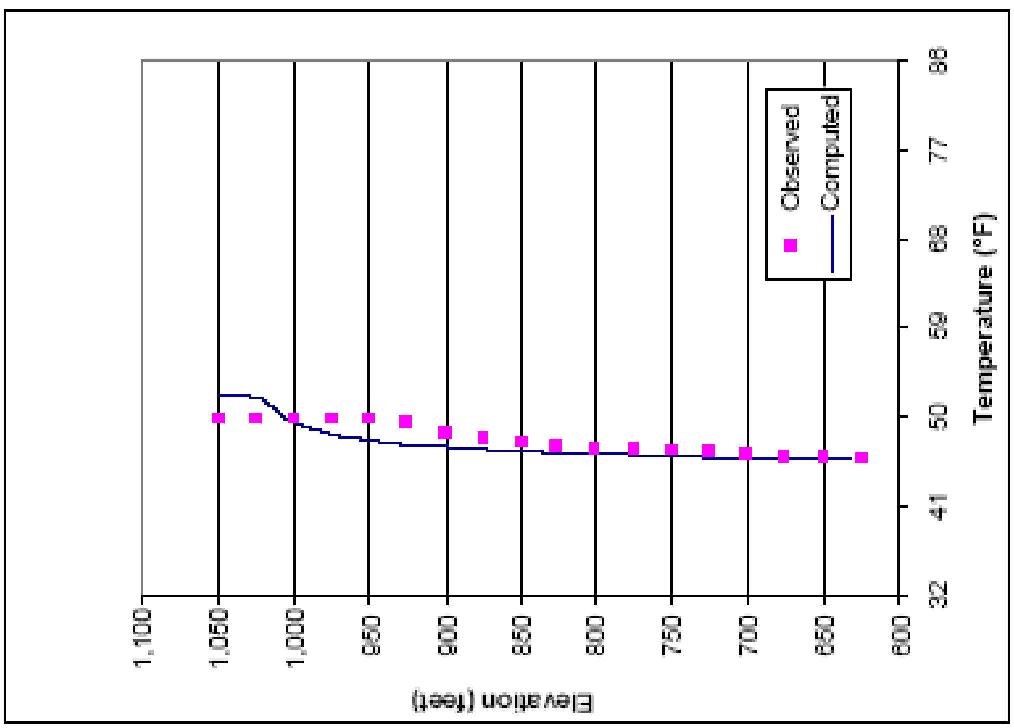
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



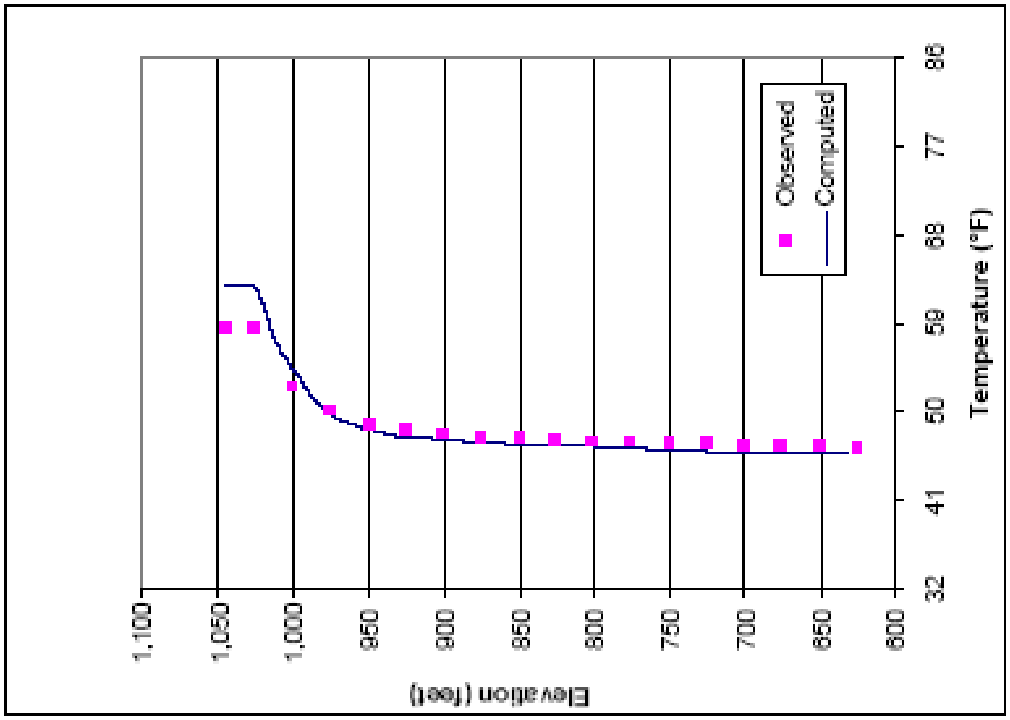
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



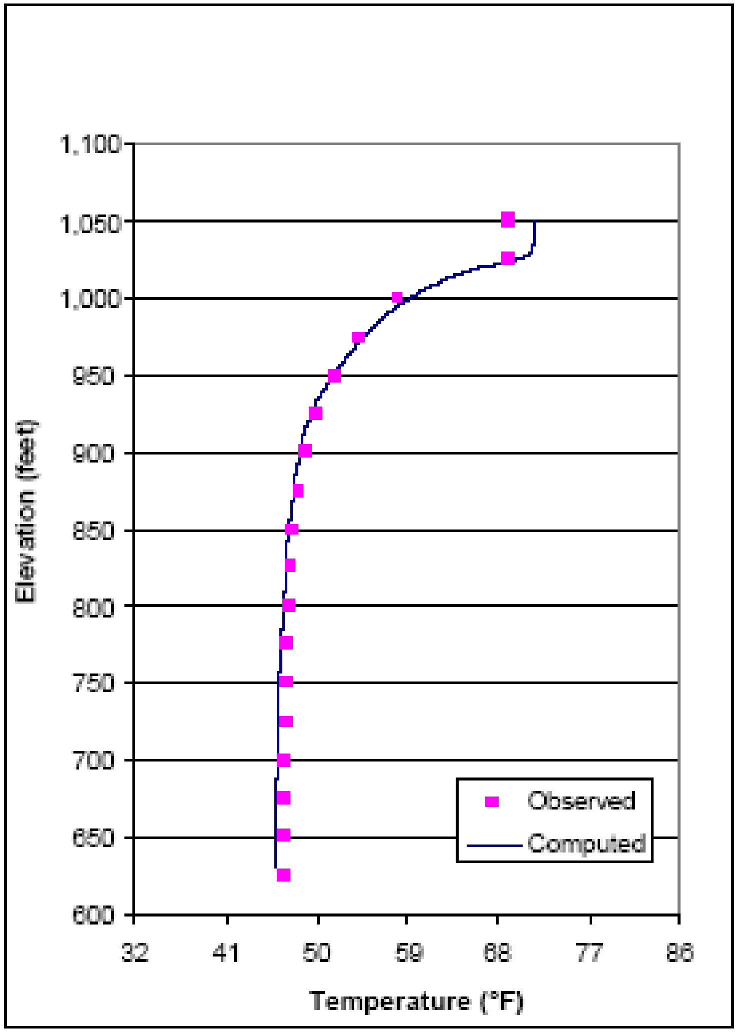
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



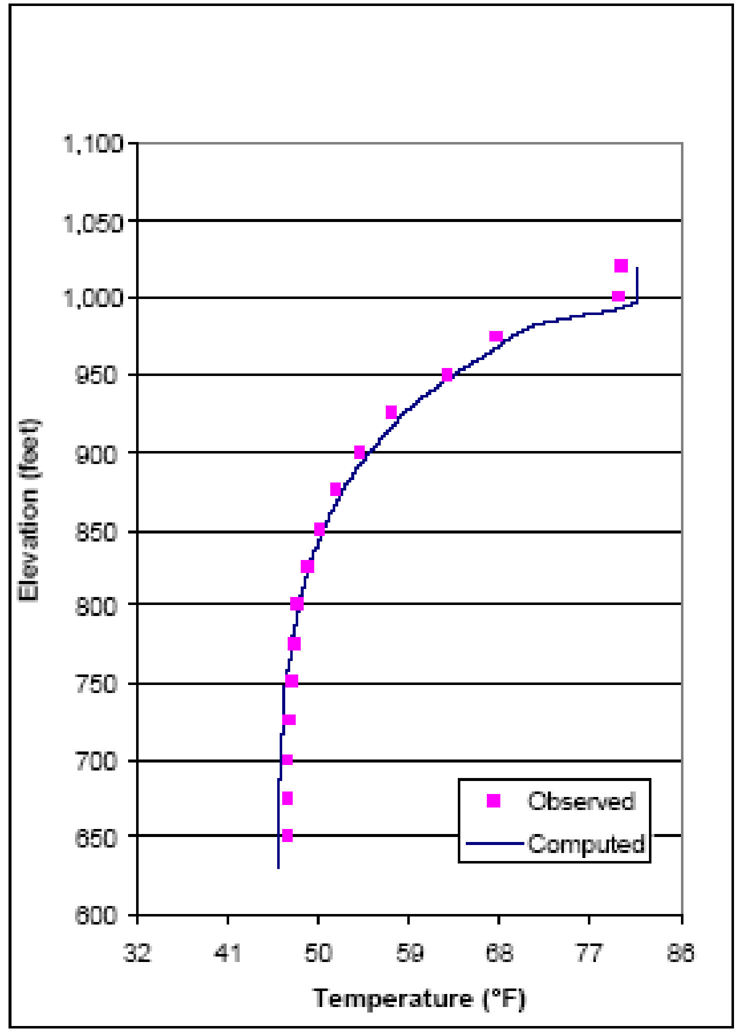
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



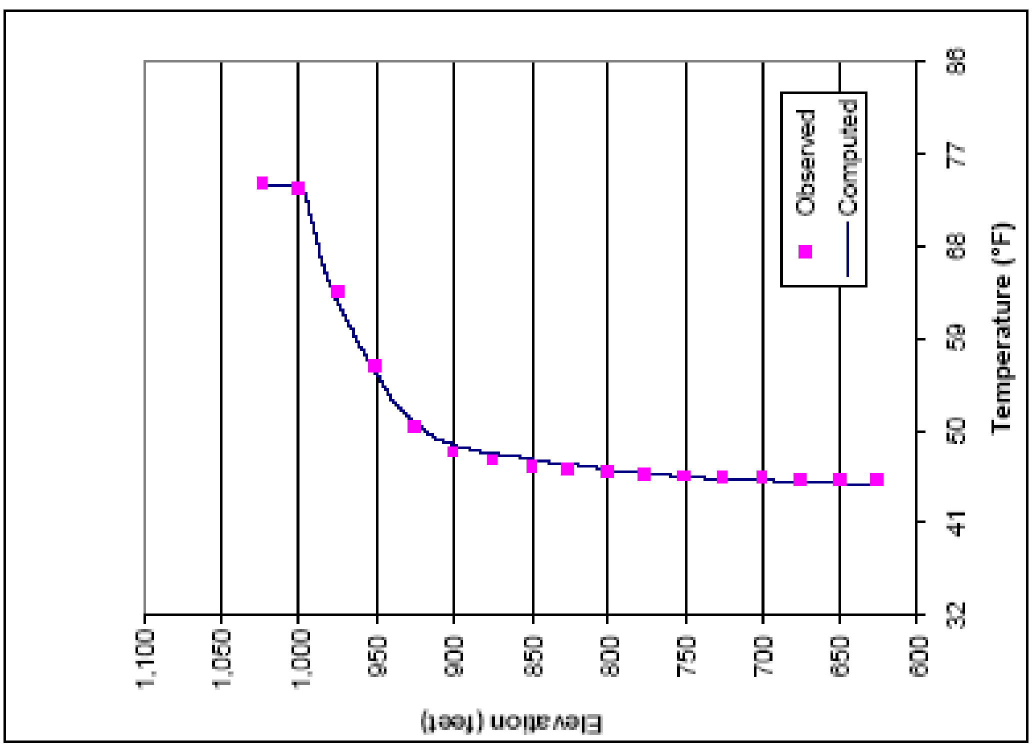
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



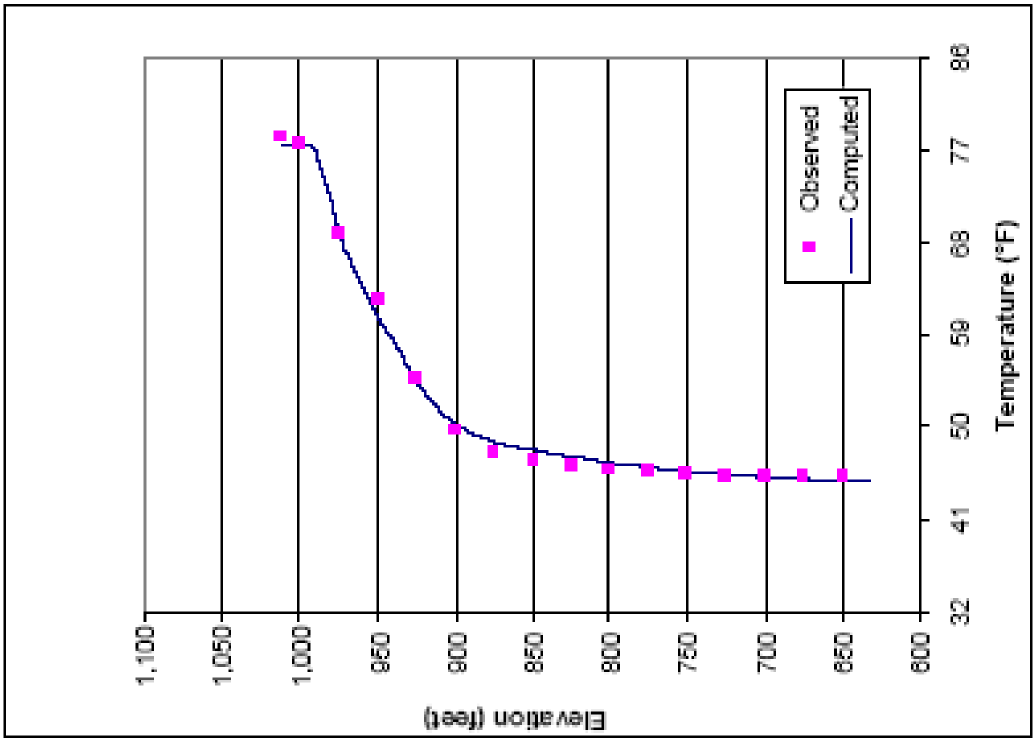
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



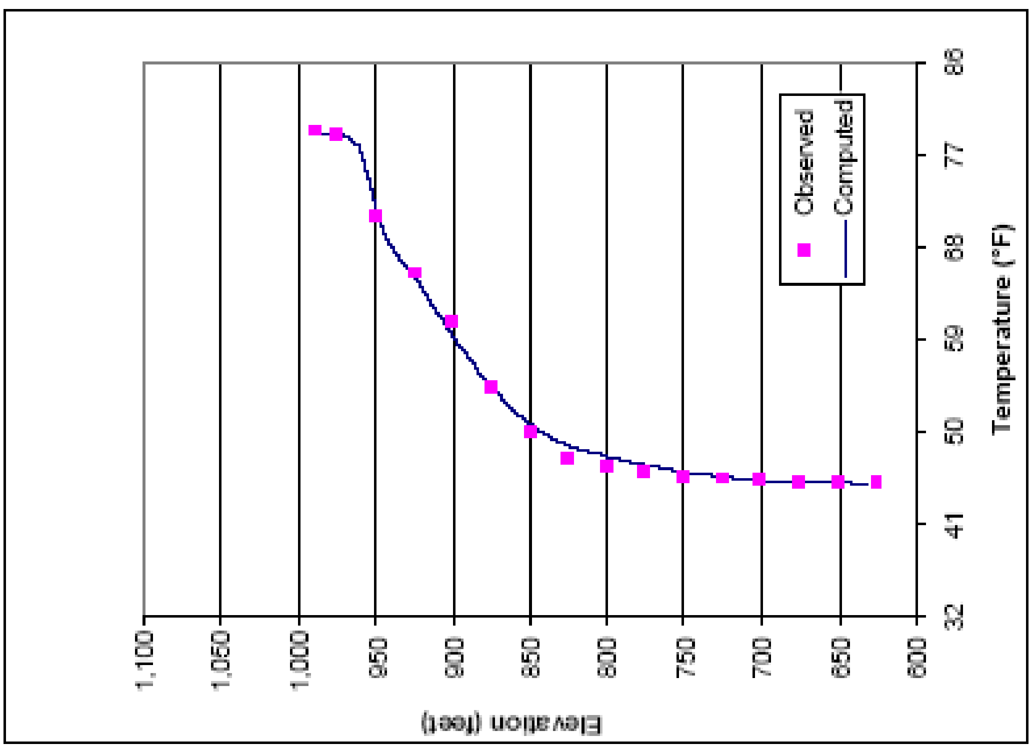
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



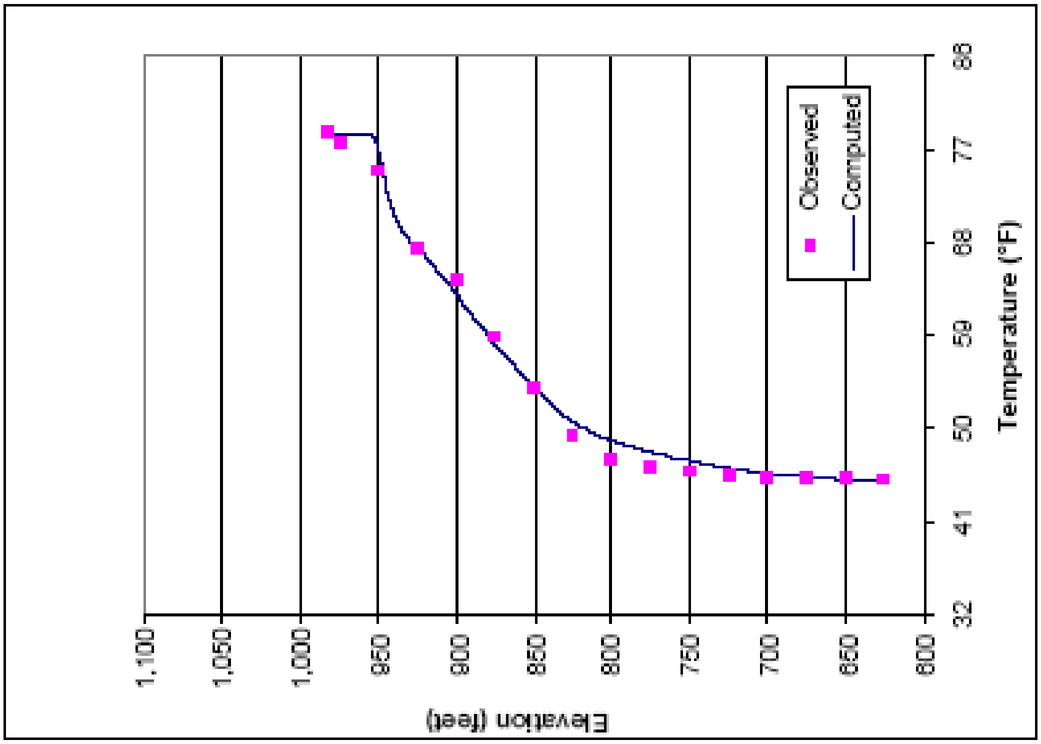
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



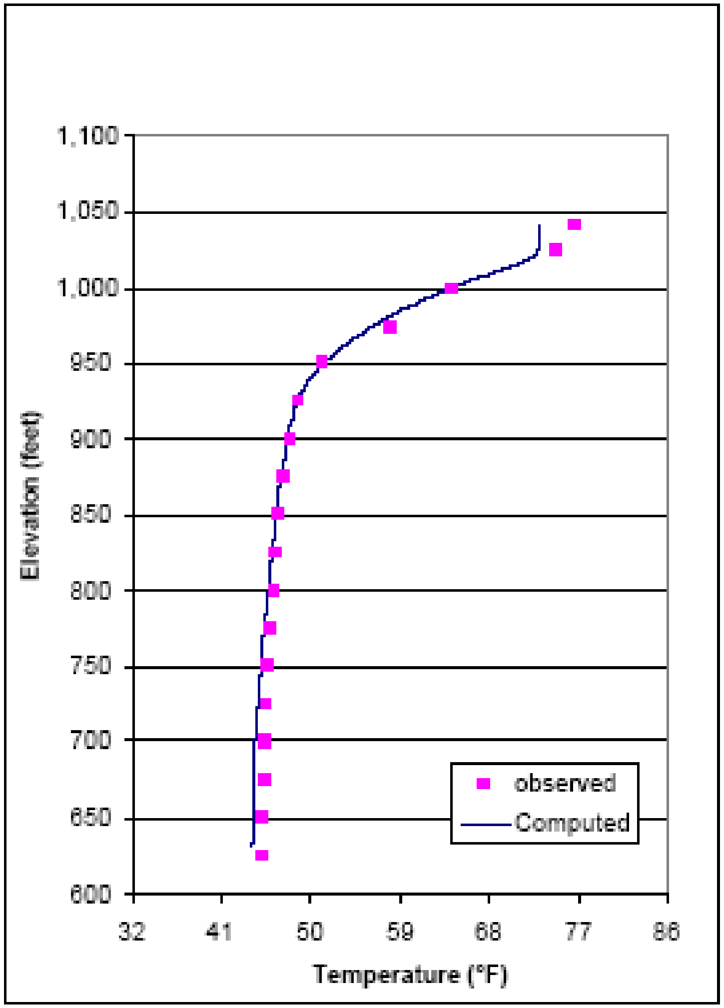
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



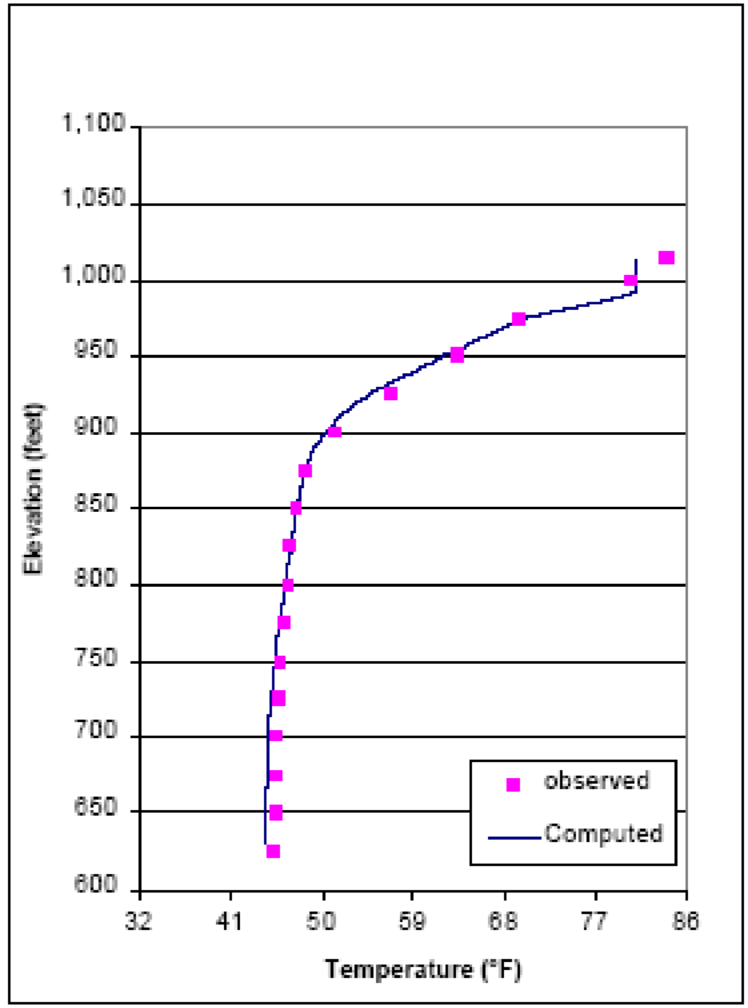
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



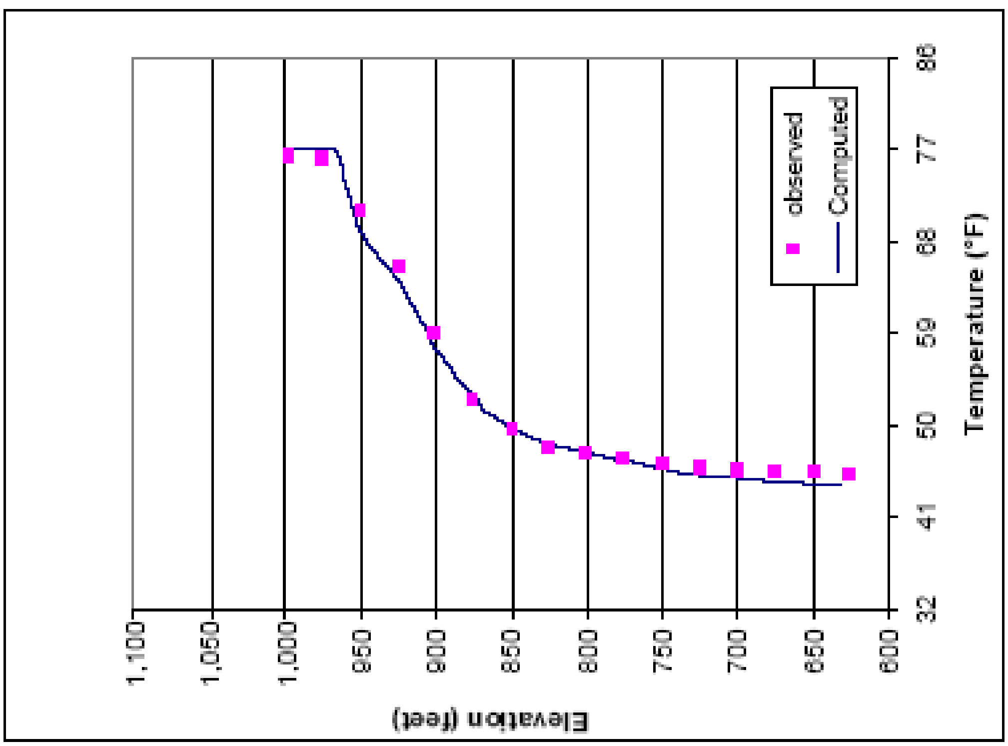
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



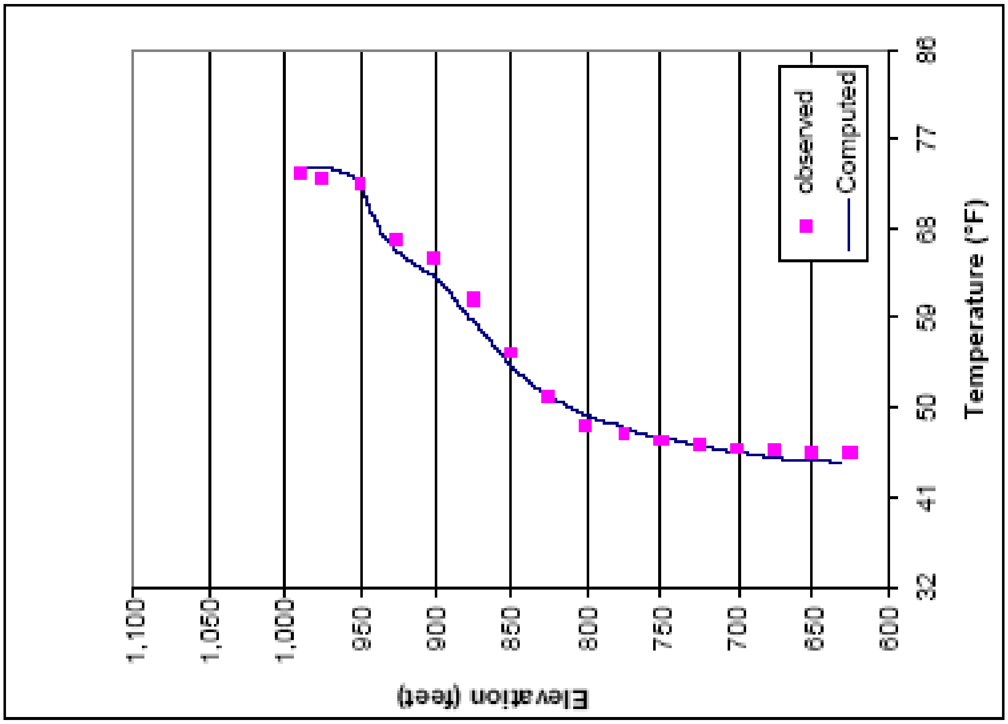
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



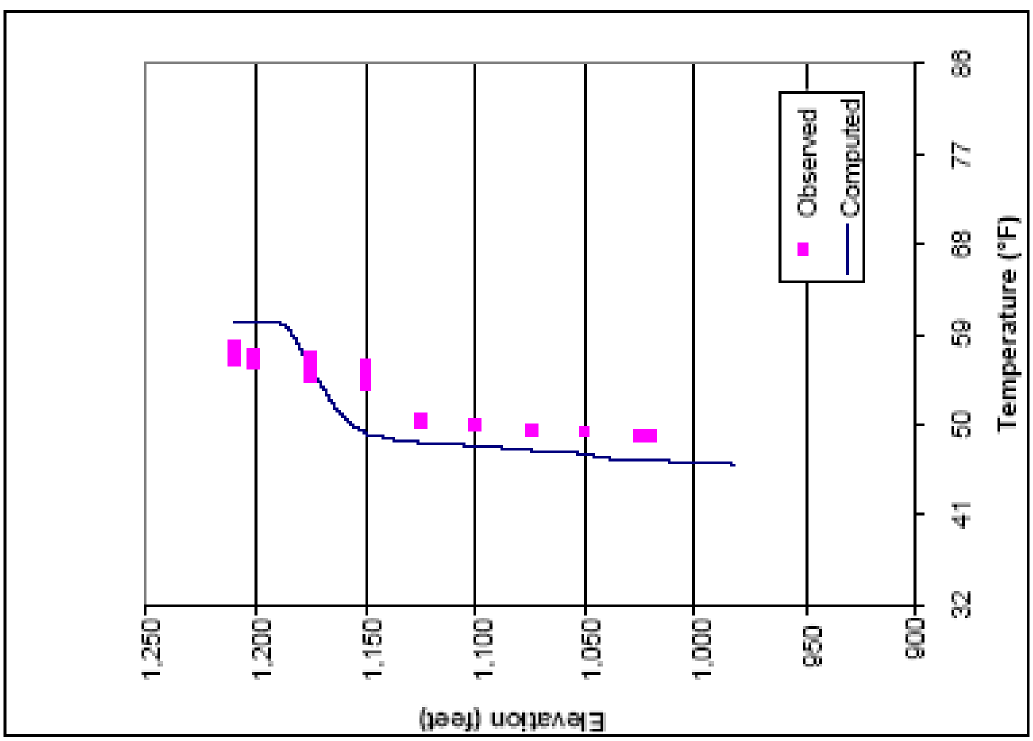
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



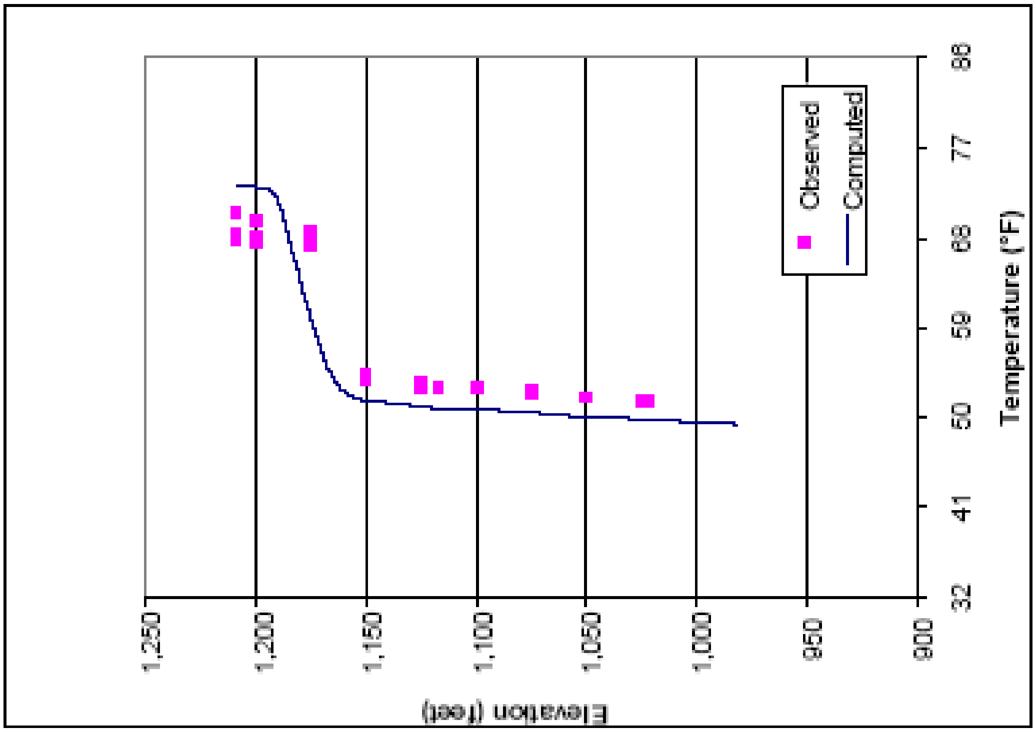
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



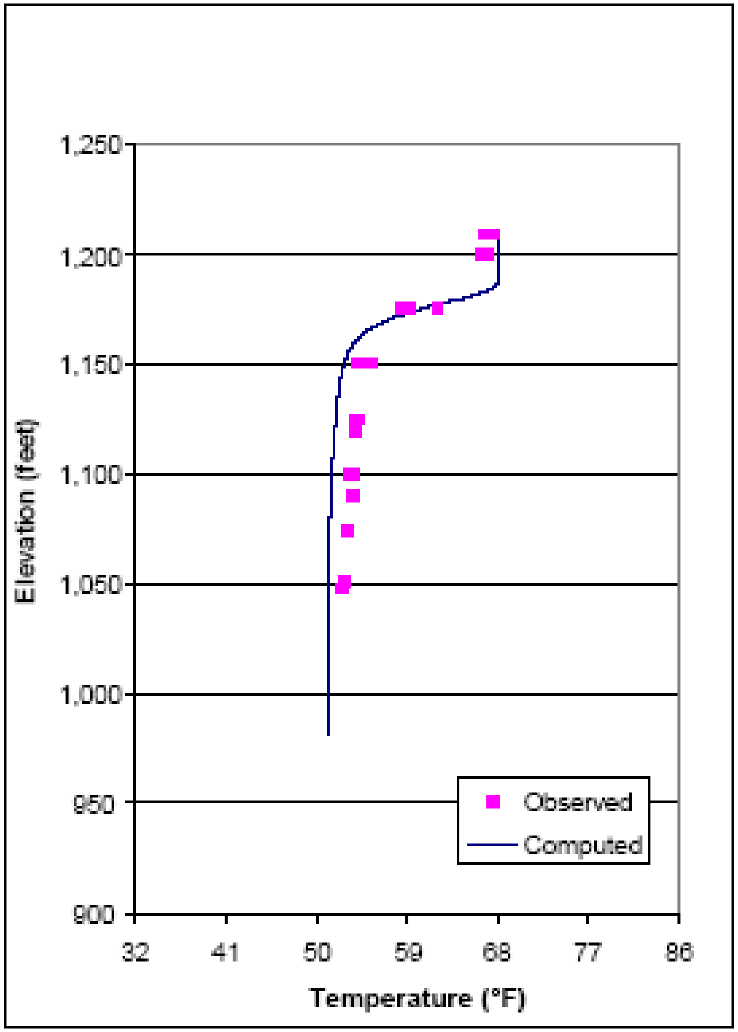
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



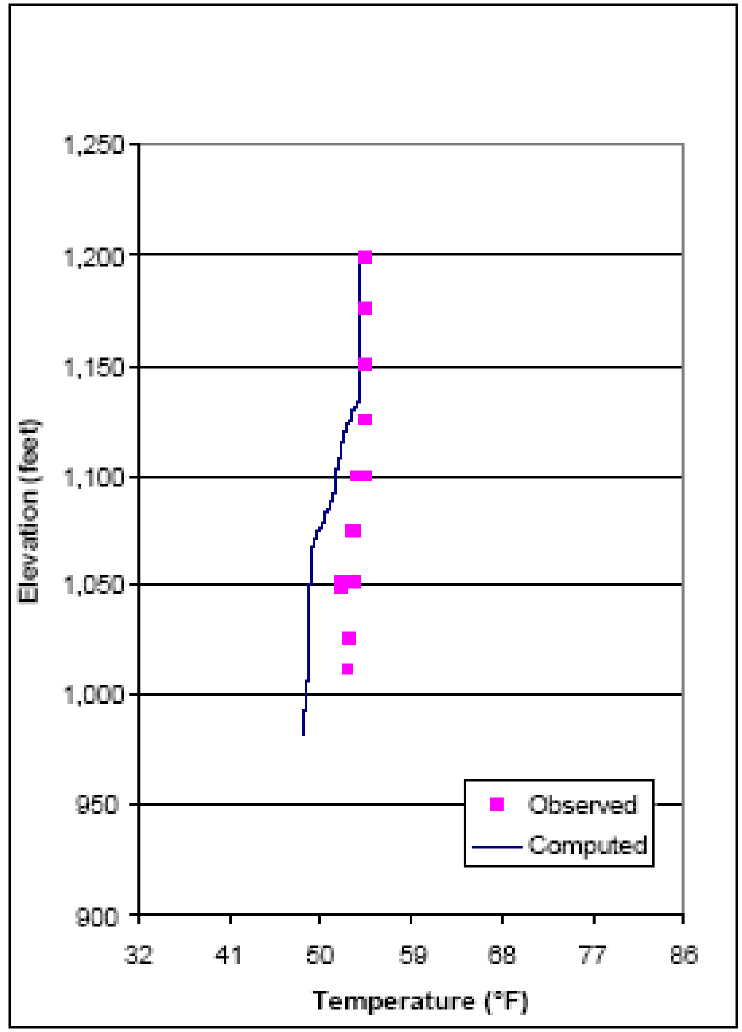
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



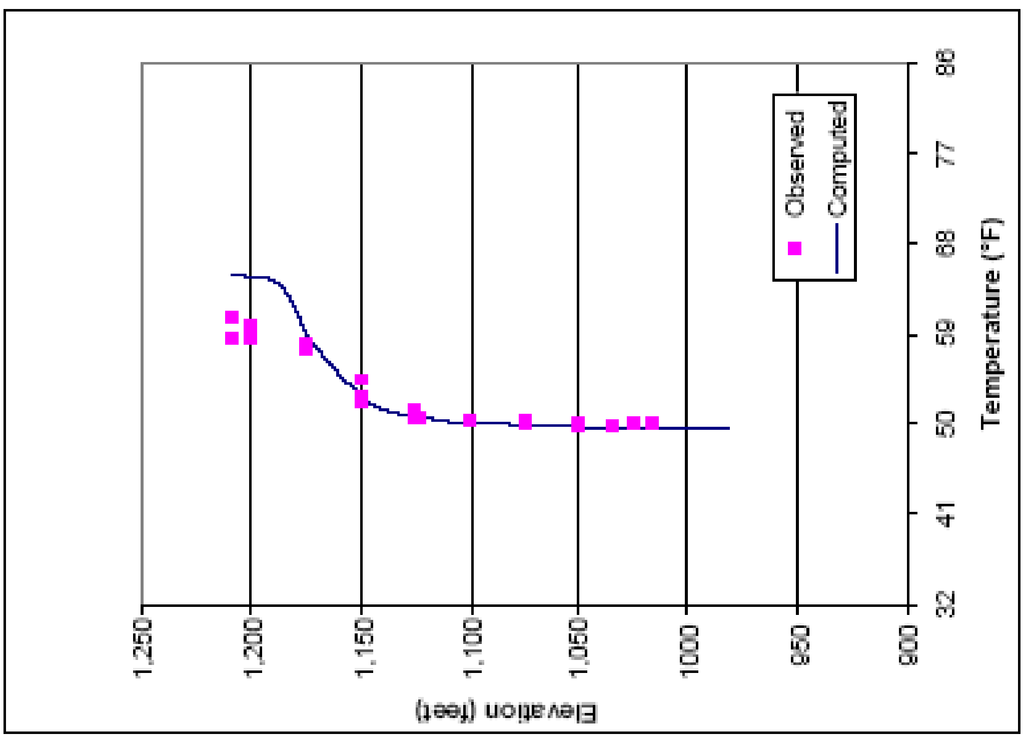
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



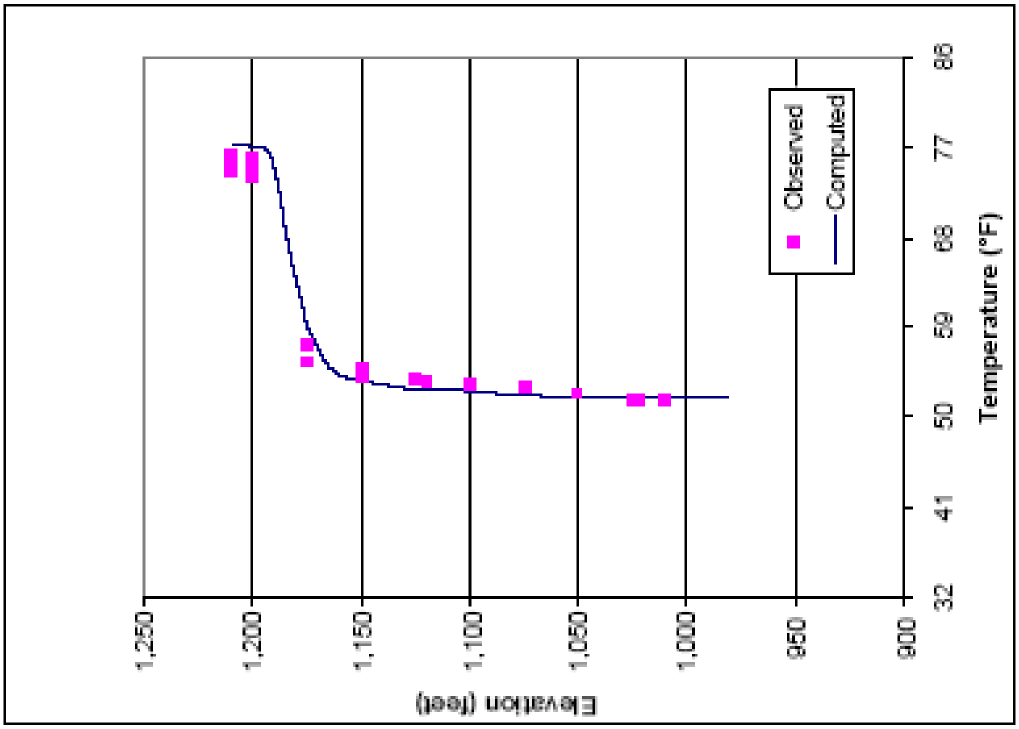
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



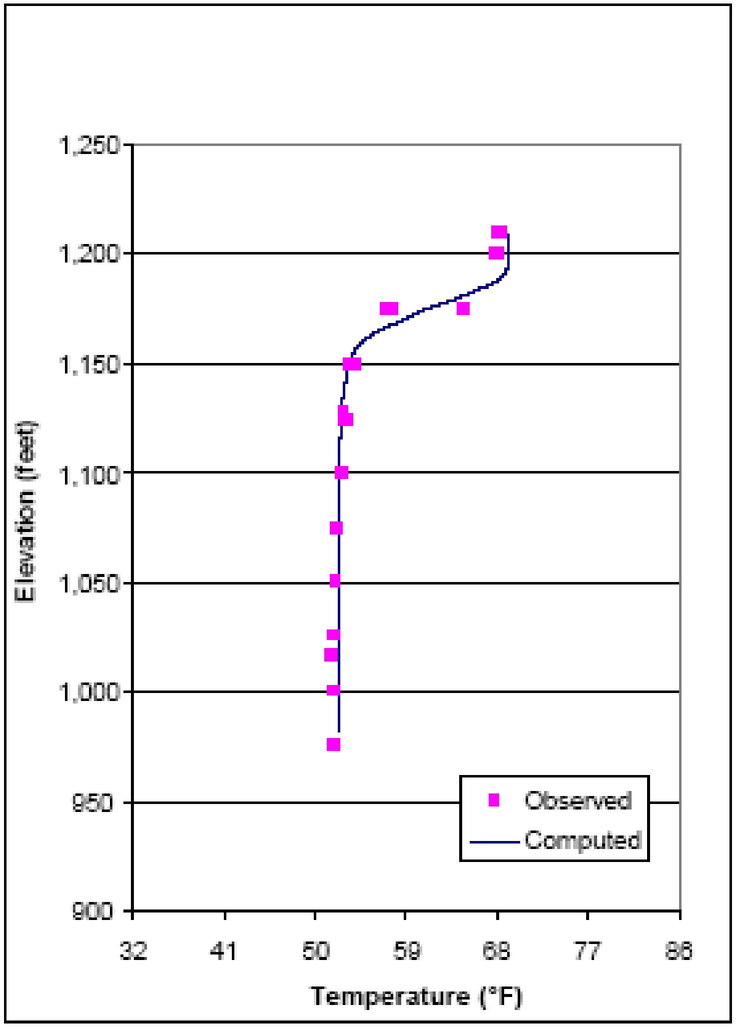
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



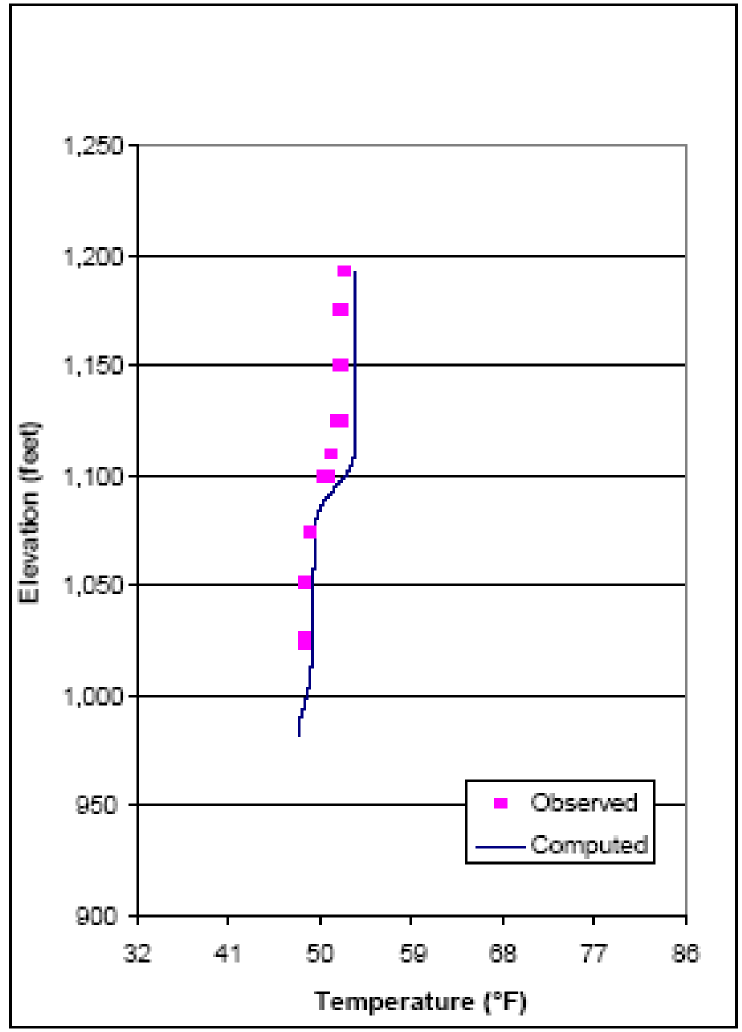
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



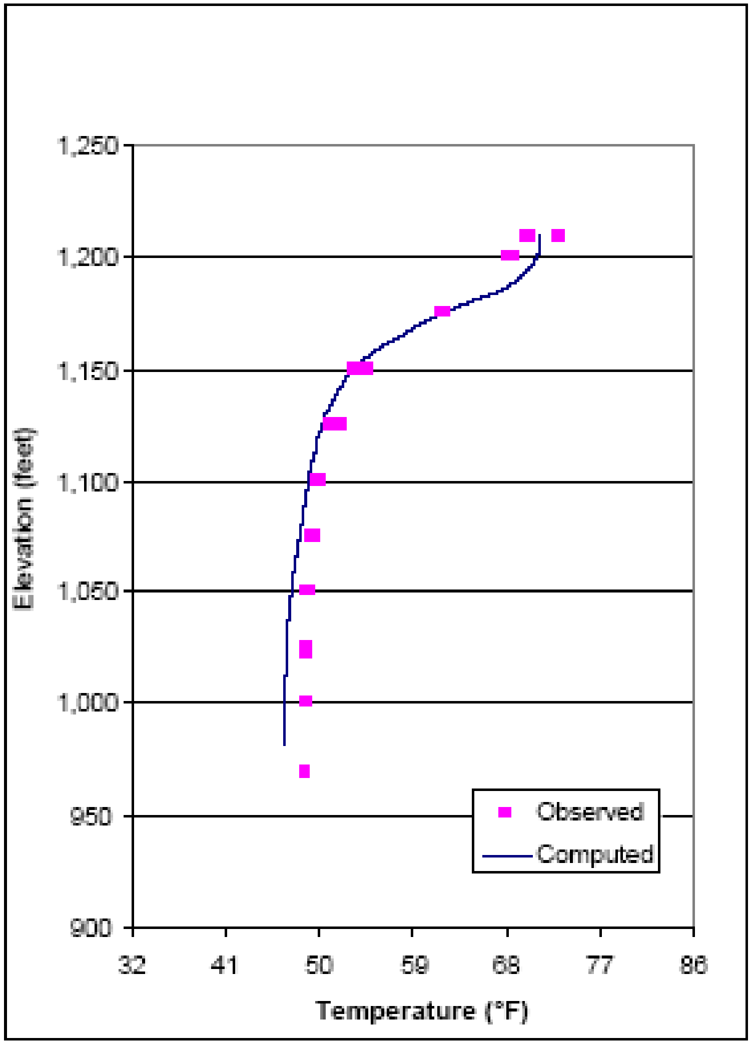
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



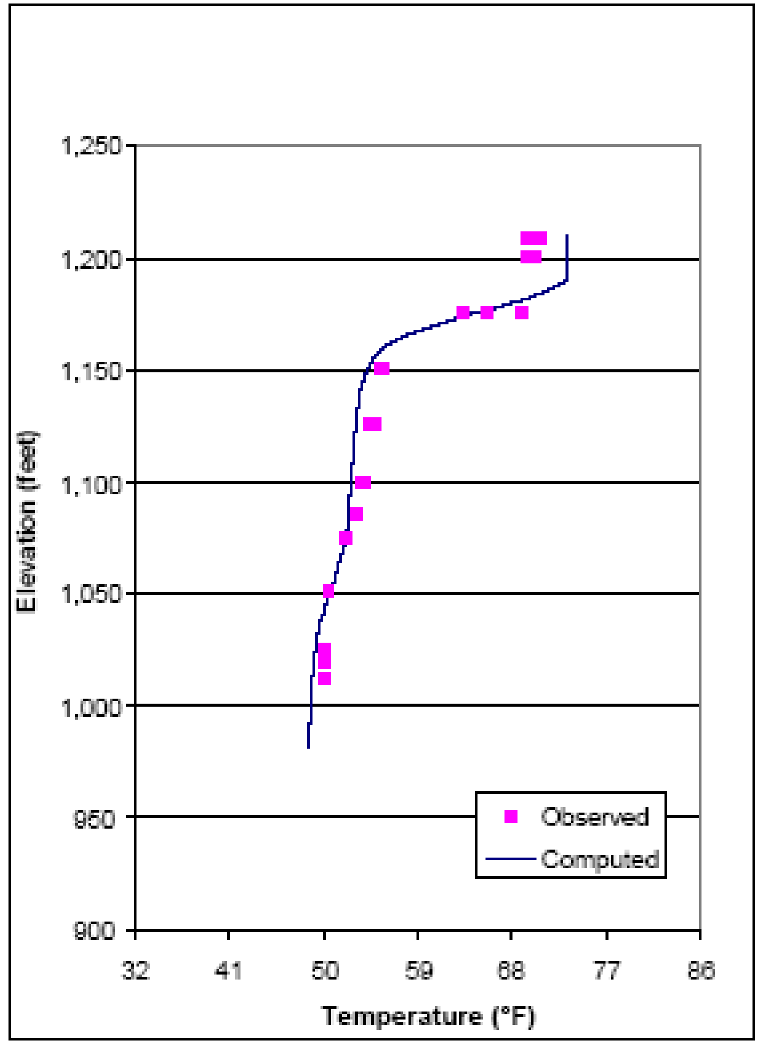
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



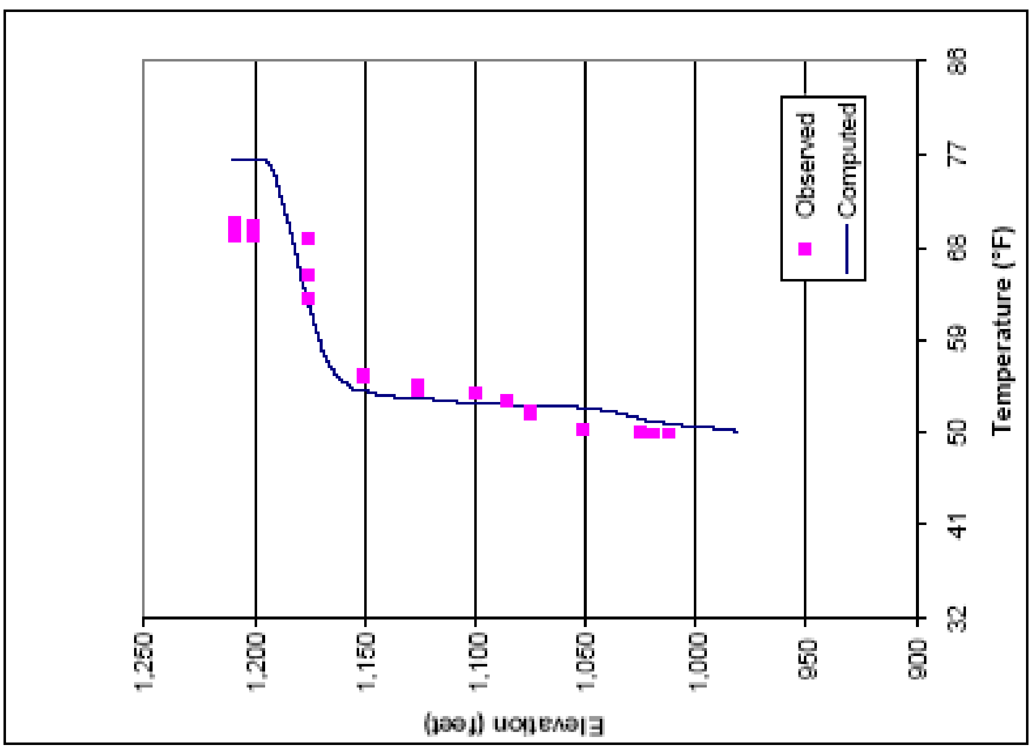
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



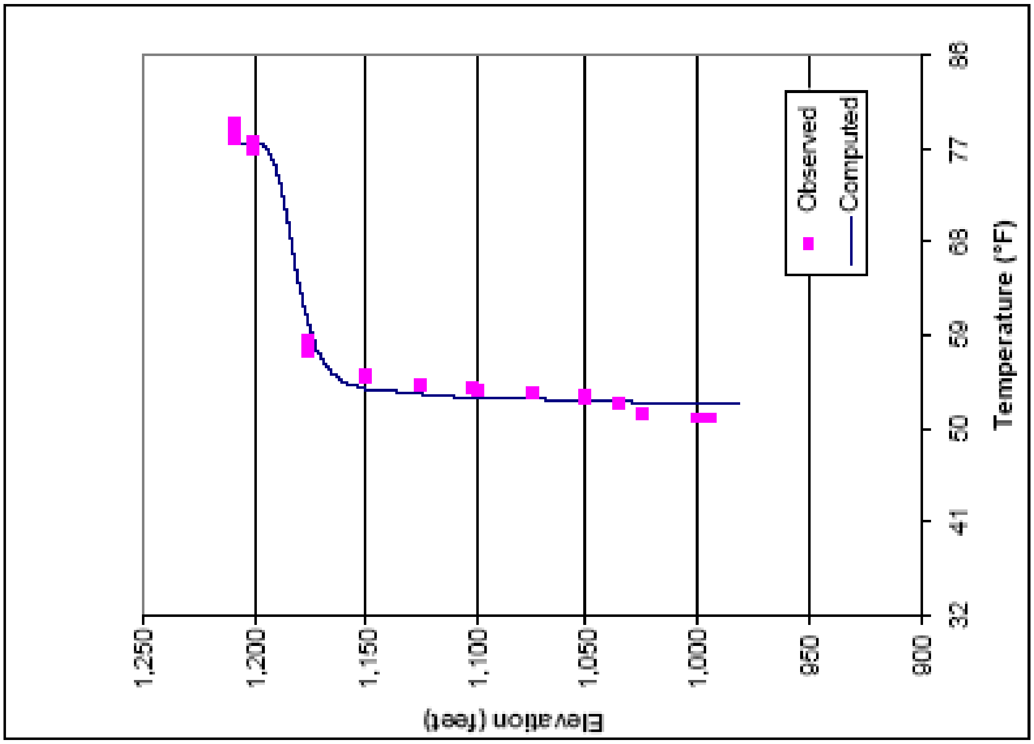
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



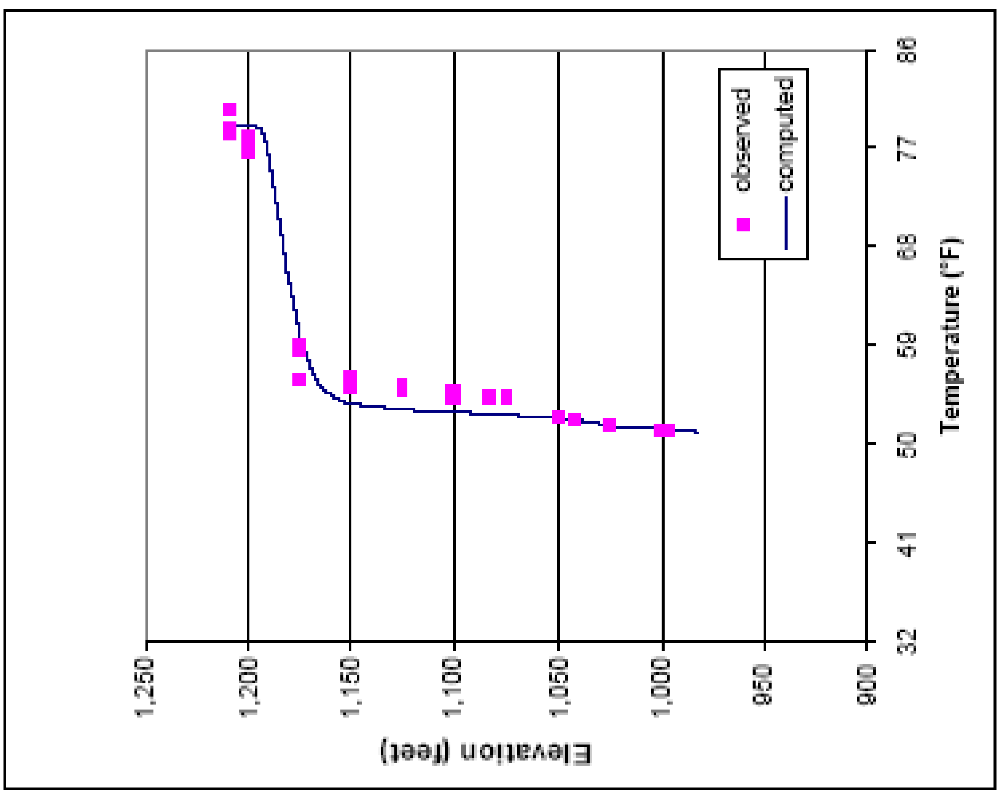
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



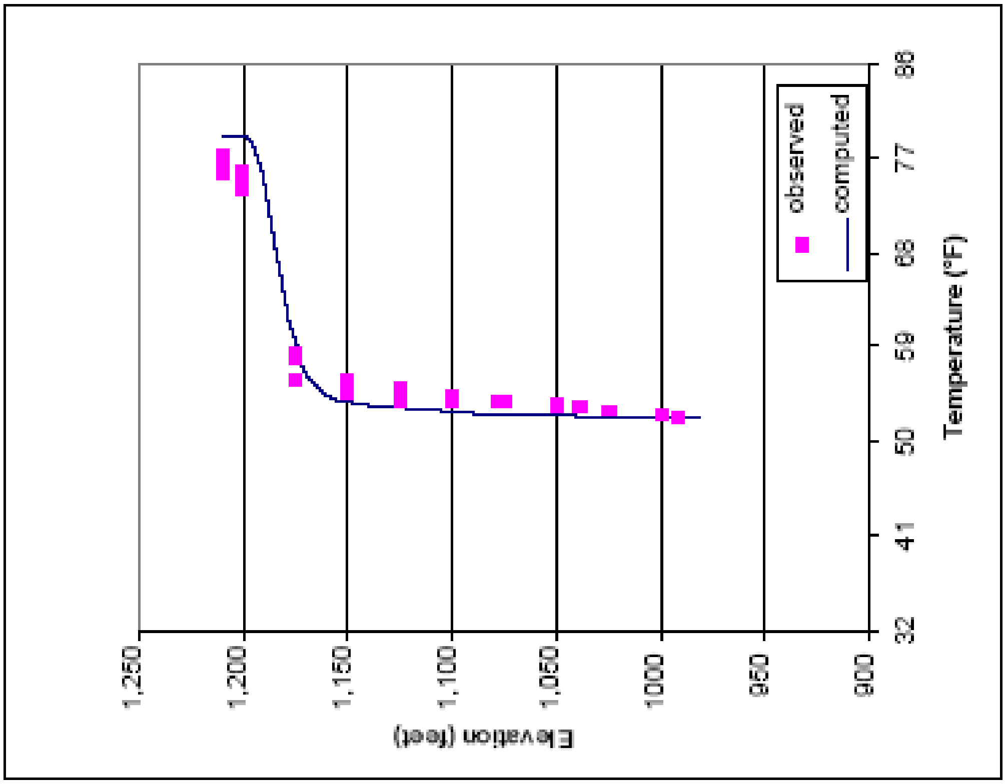
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



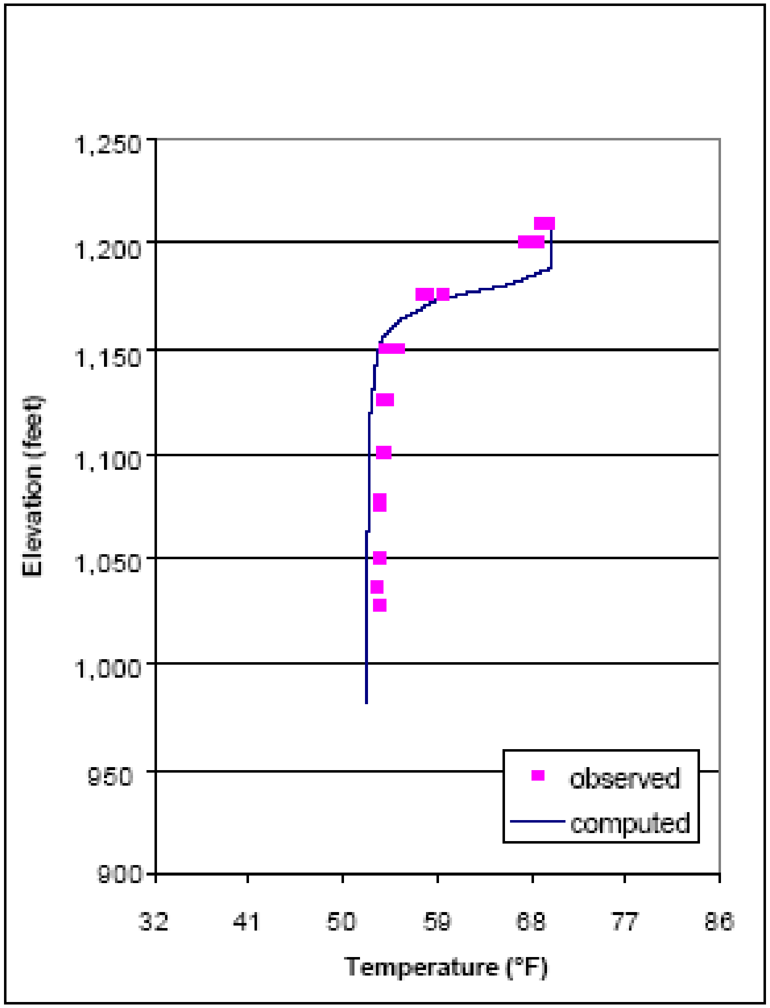
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



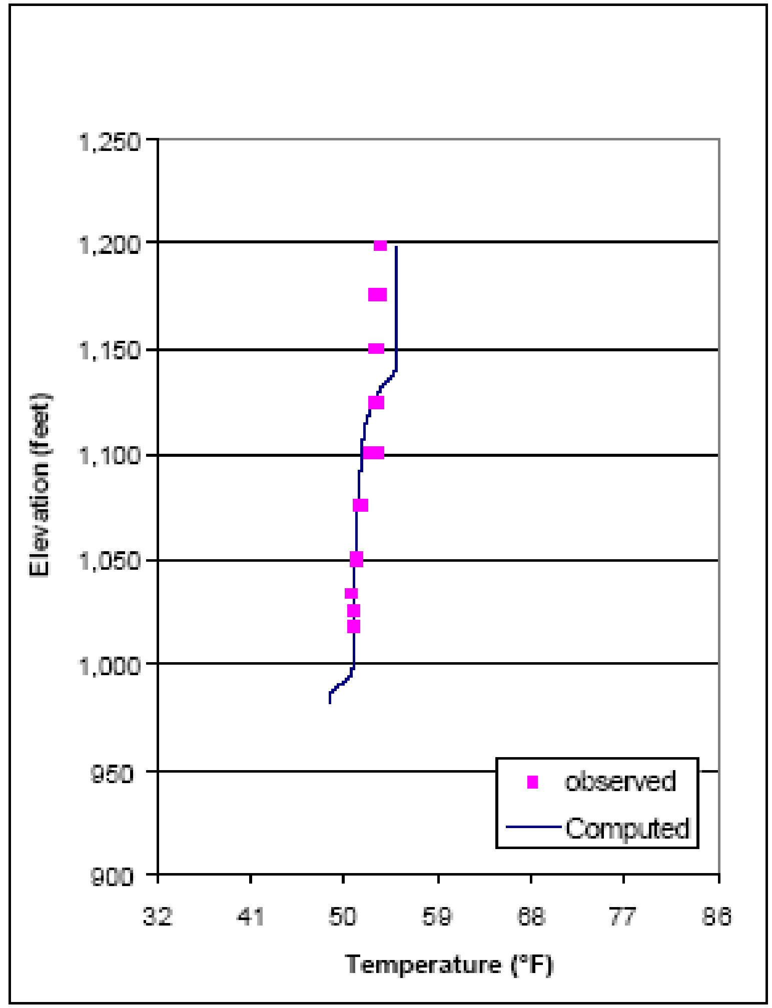
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



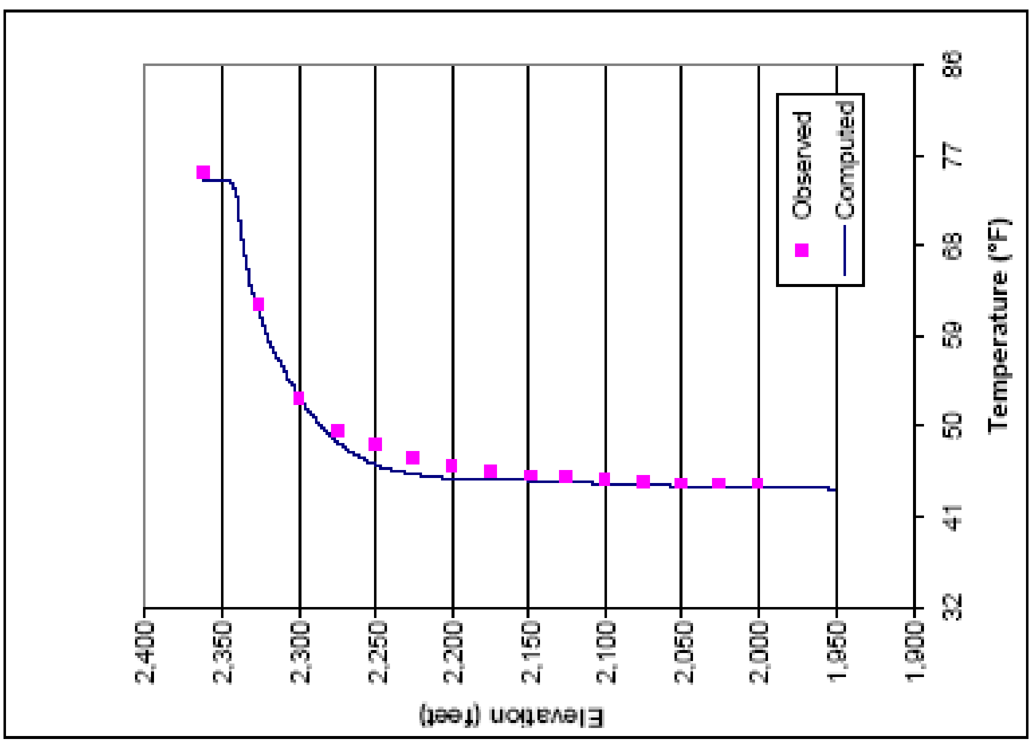
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



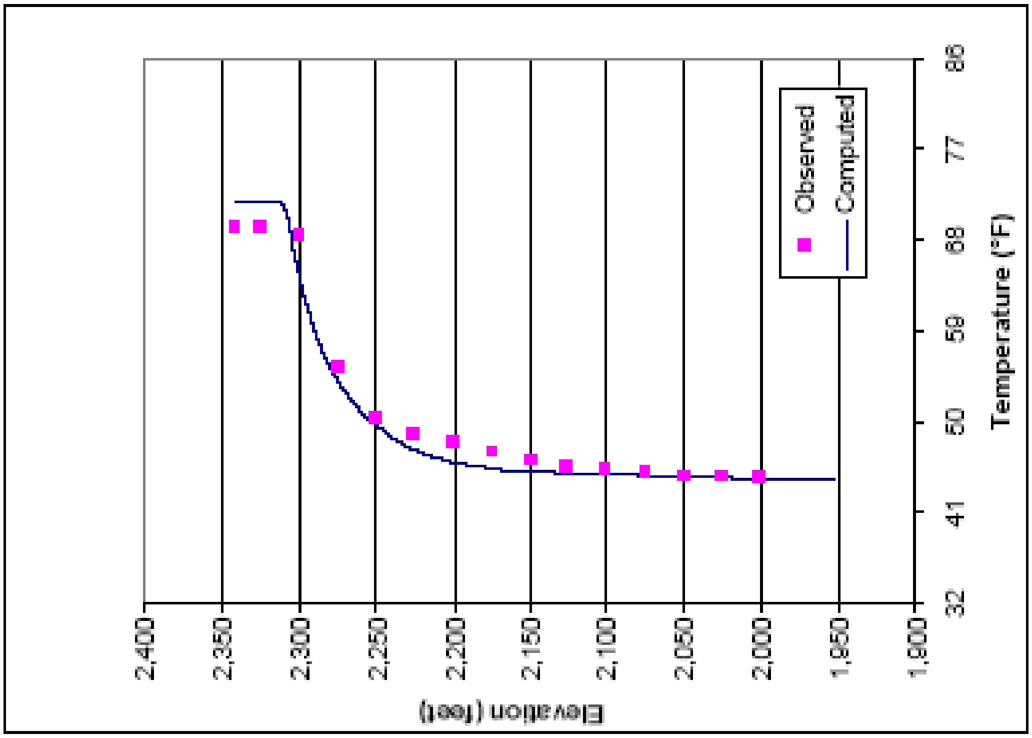
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



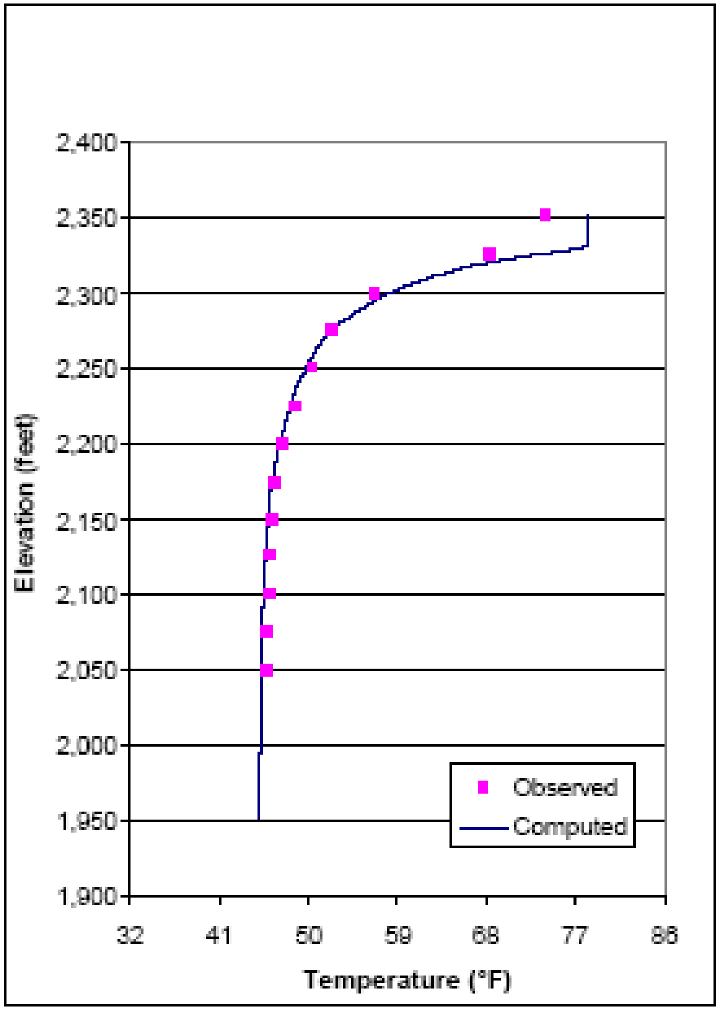
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



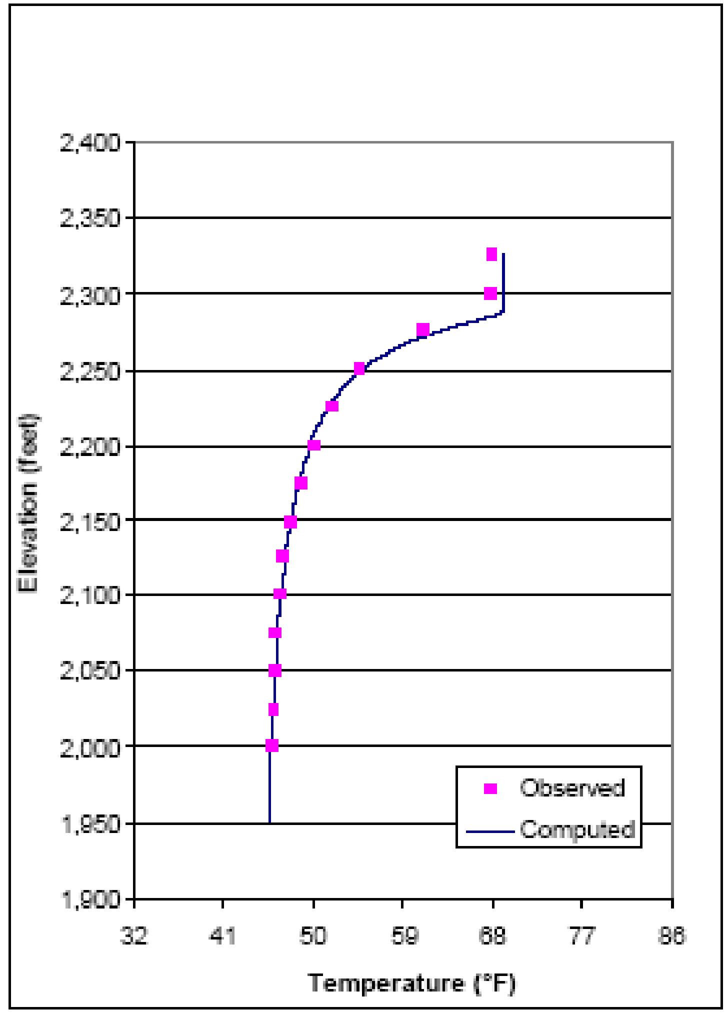
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



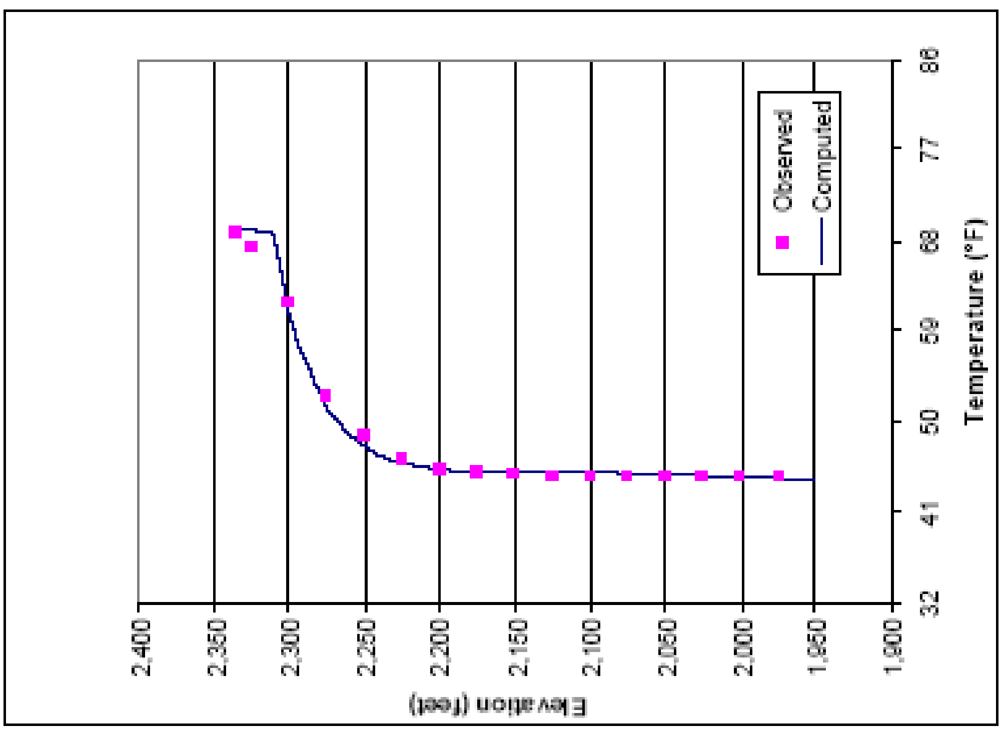
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



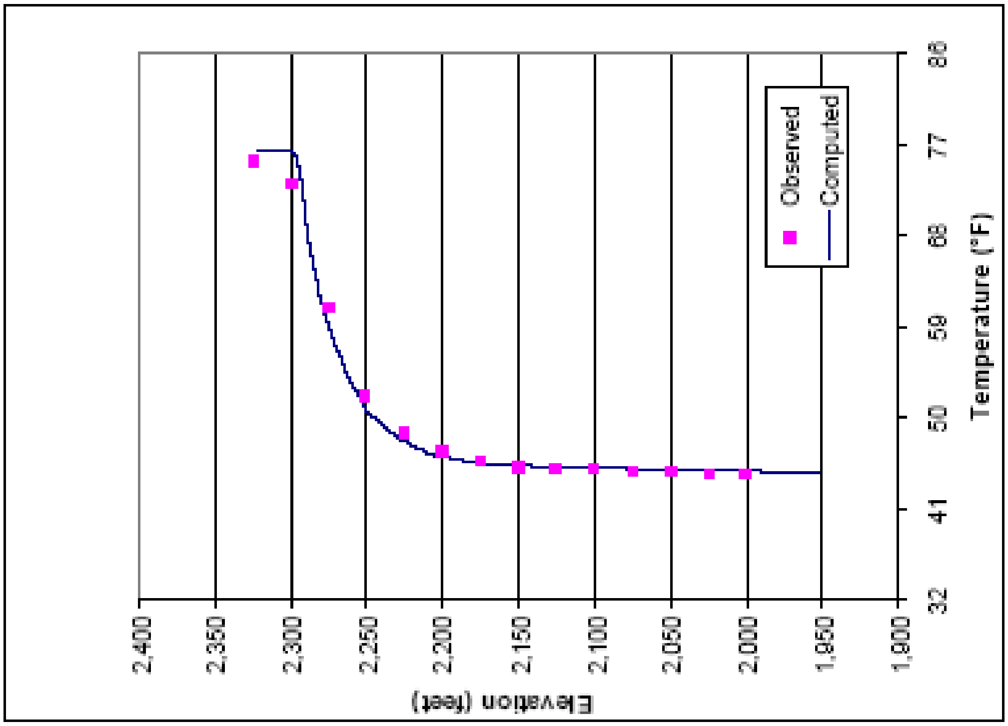
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



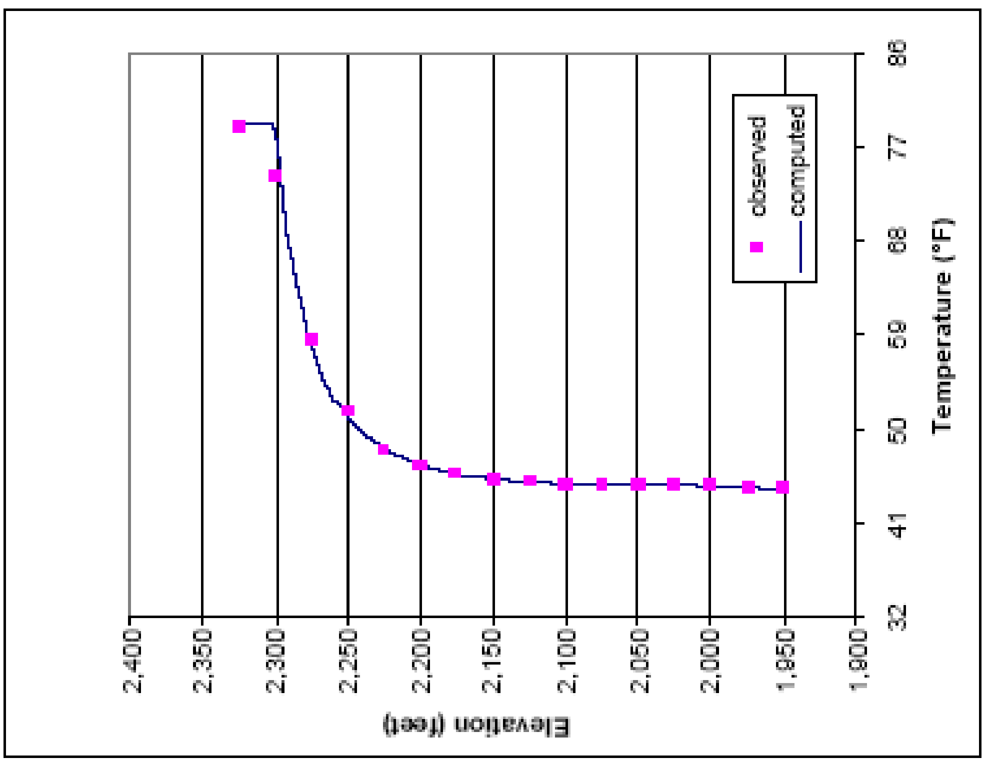
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



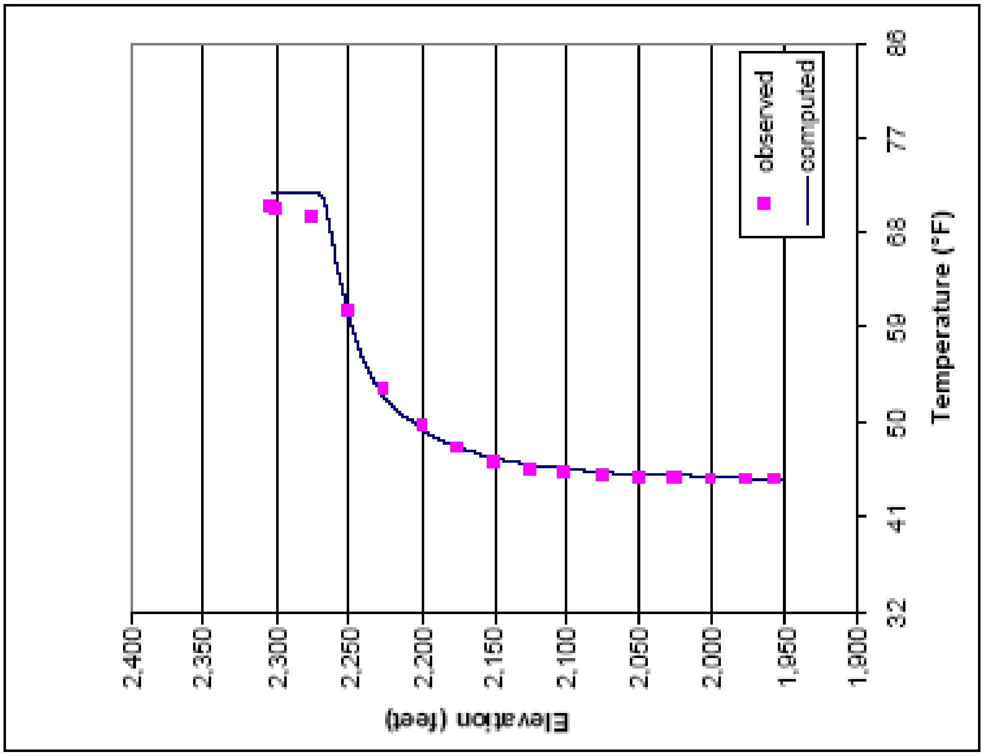
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



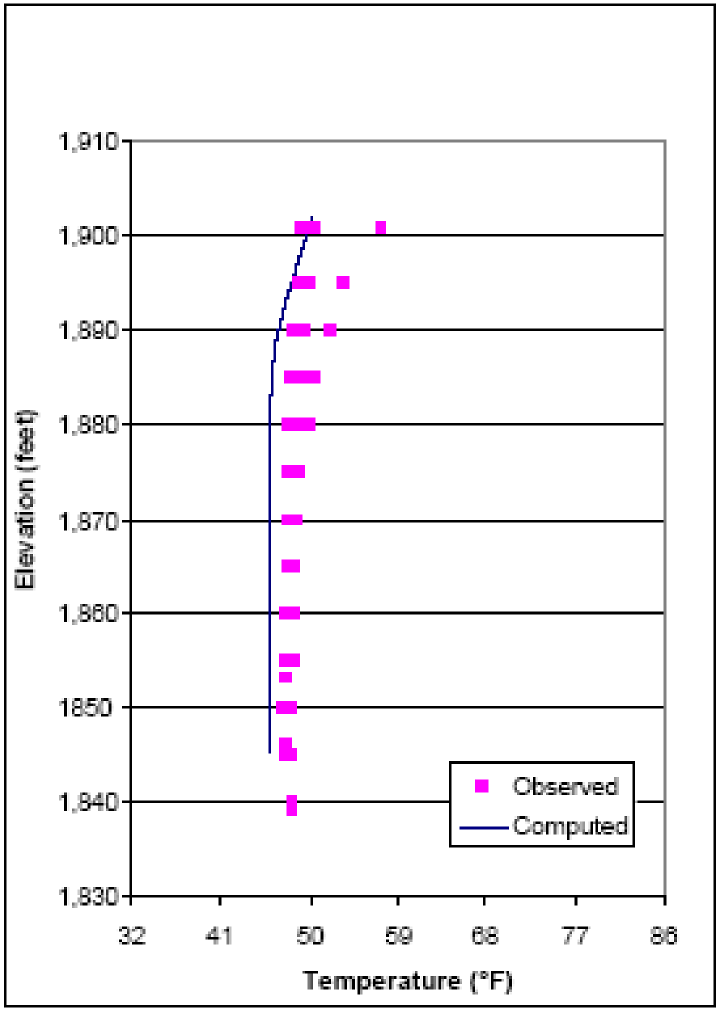
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



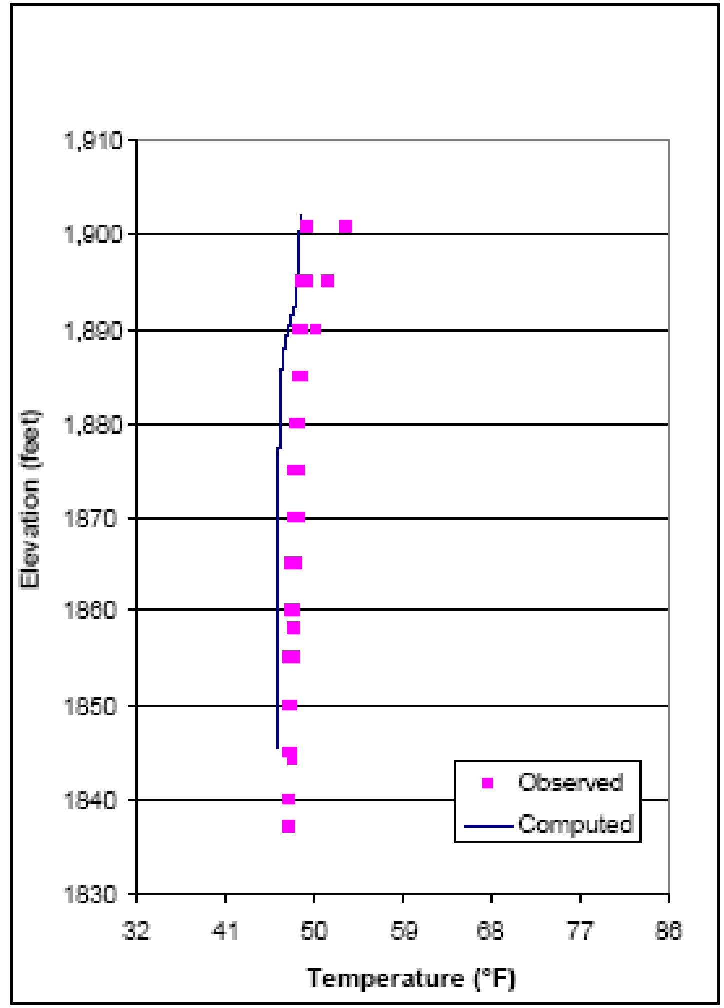
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



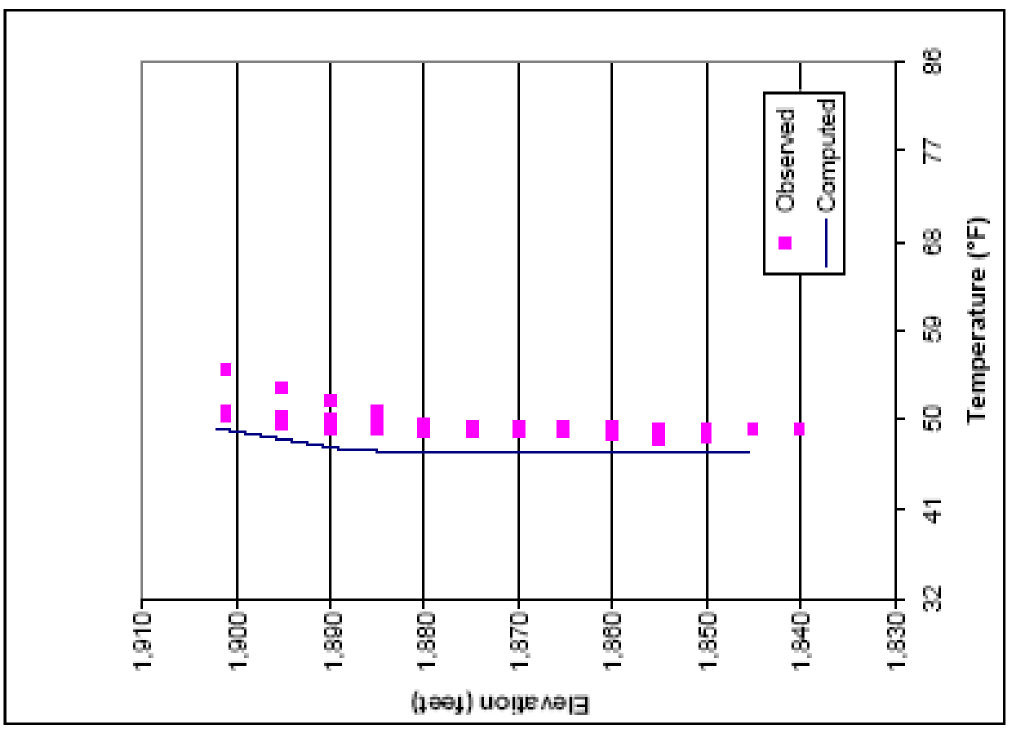
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



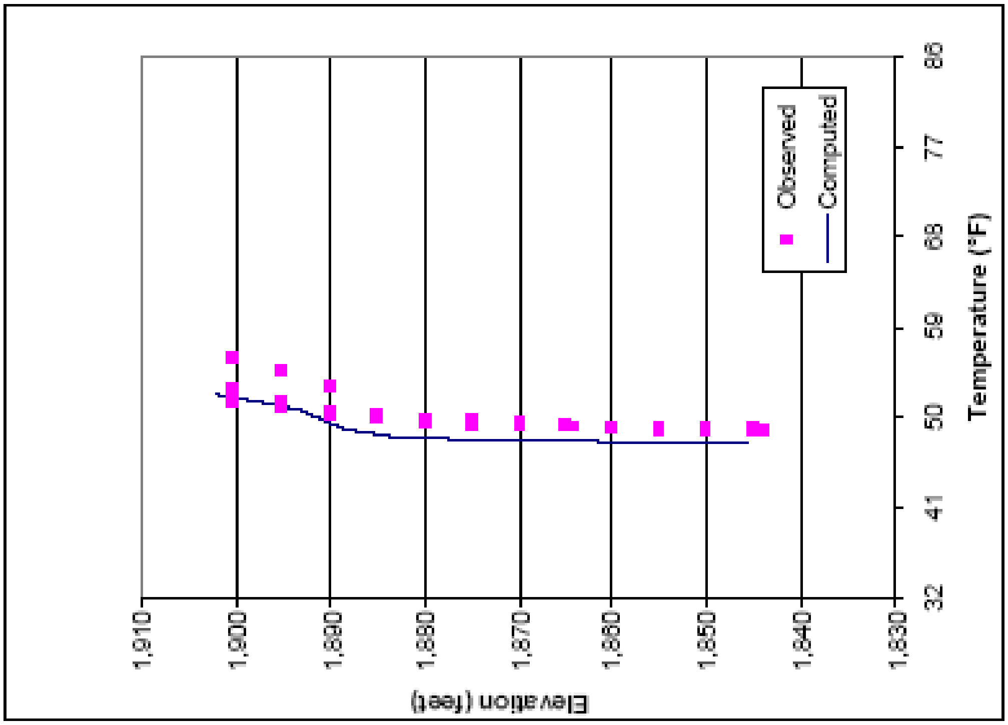
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



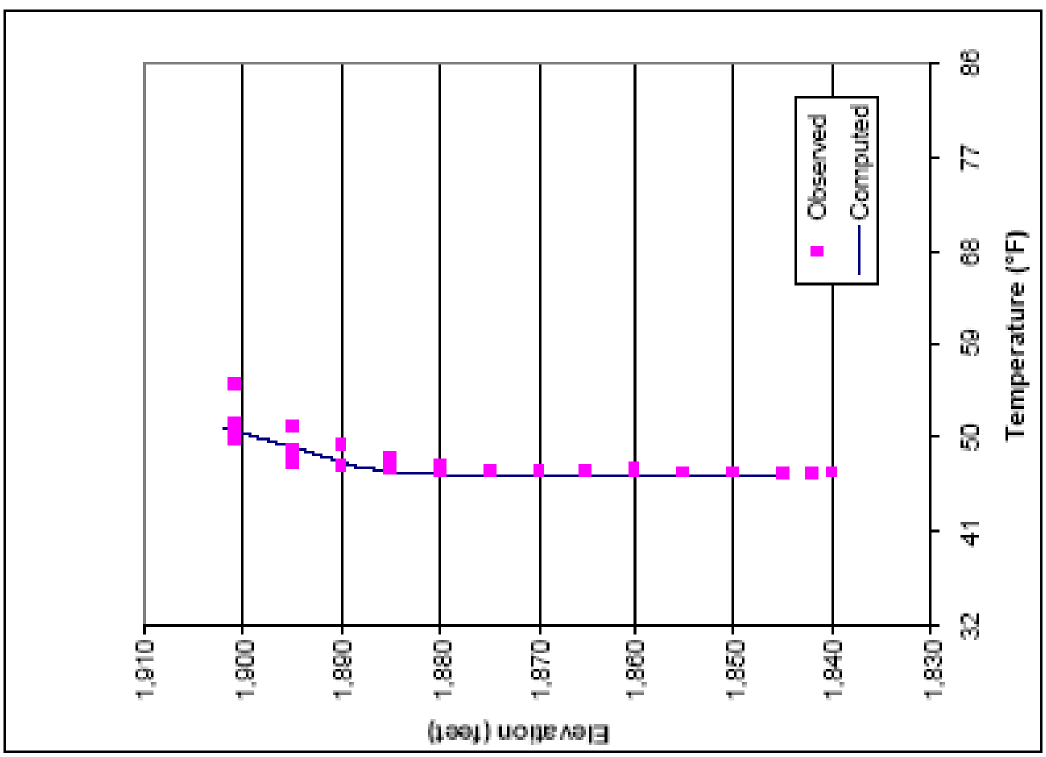
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



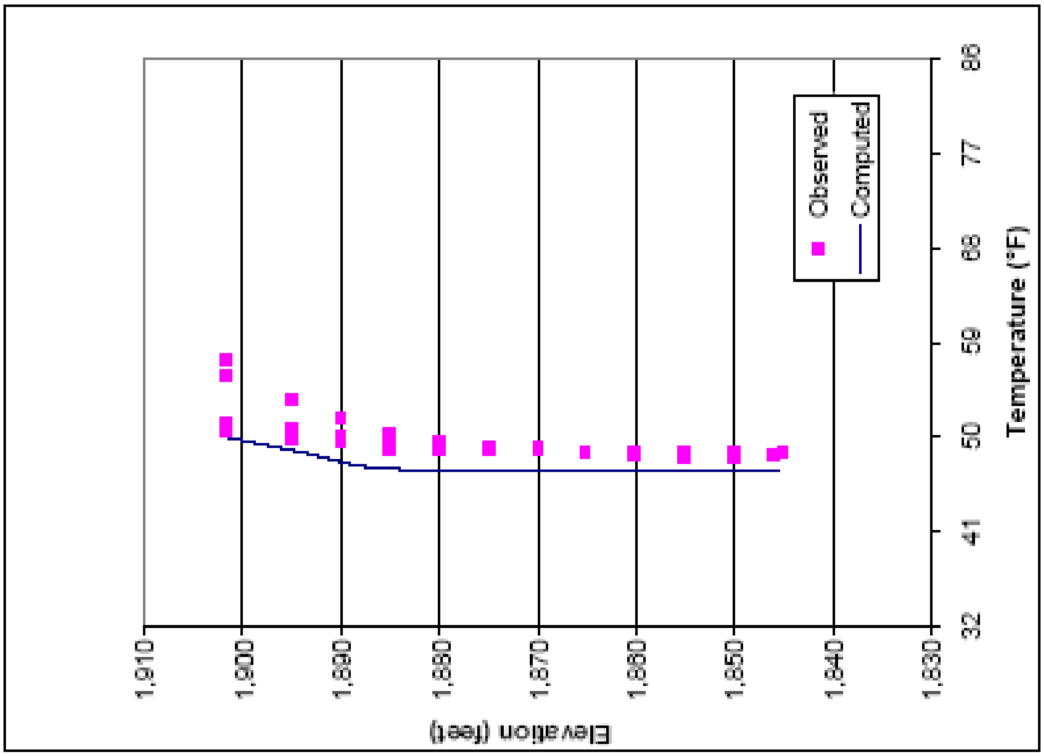
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



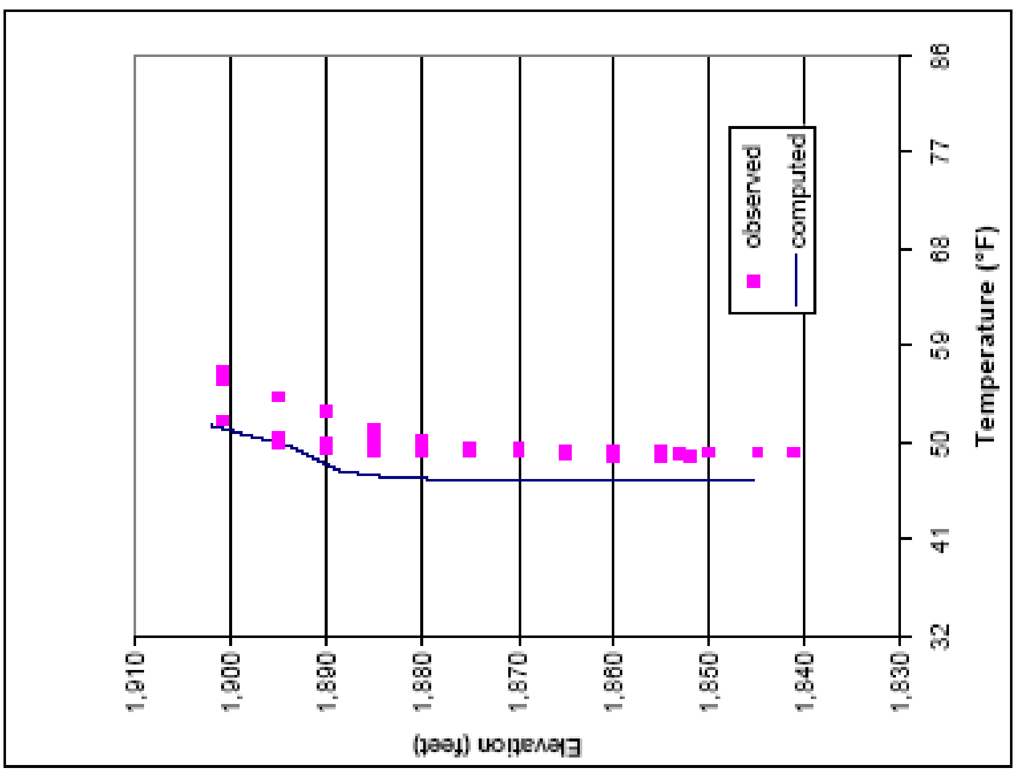
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



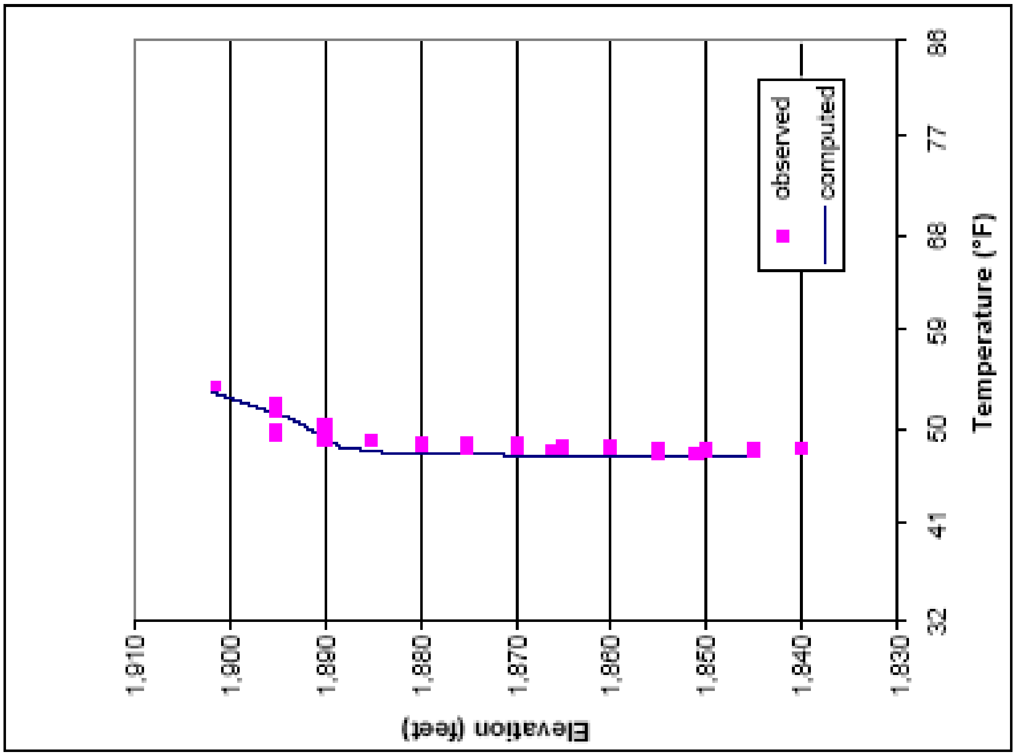
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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



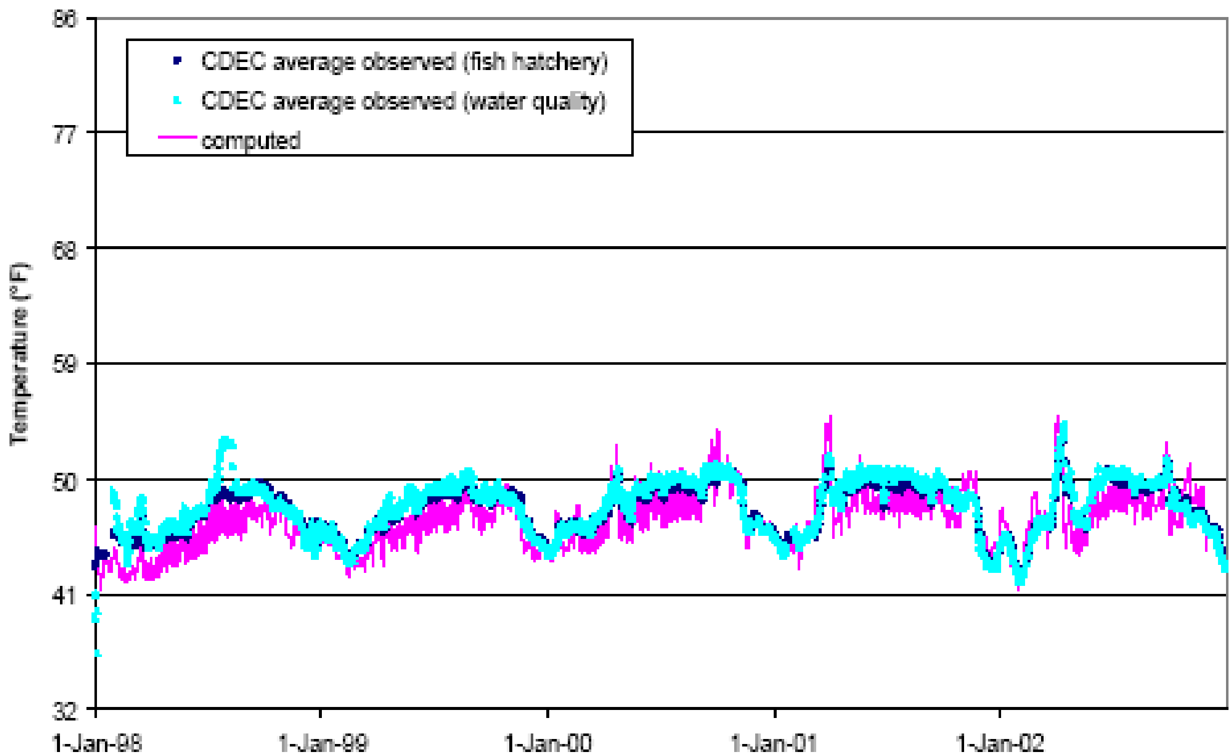
Source: U.S. Department of the Interior, Bureau of Reclamation 2003.

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

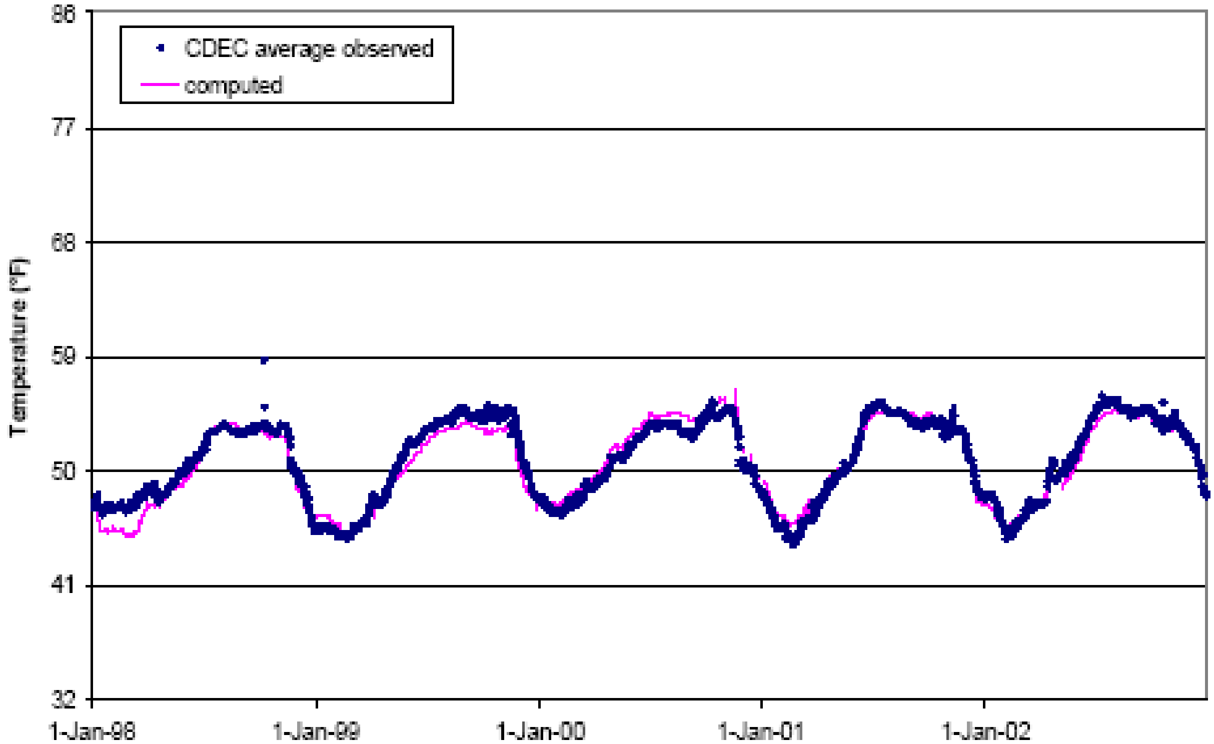


Figure 4-54. Computed and Observed Mean Daily Water Temperatures at Spring Creek Powerhouse

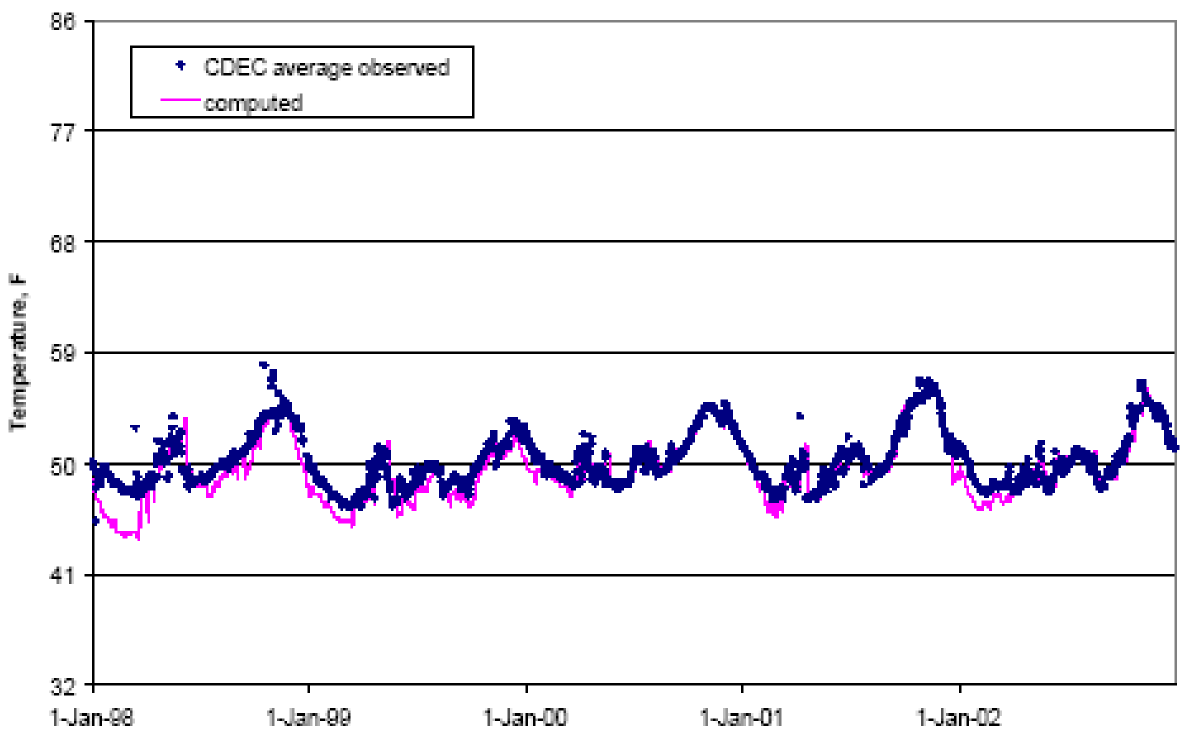


Figure 4-55. Computed and Observed Mean Daily Water Temperatures in Sacramento River Below Shasta Dam

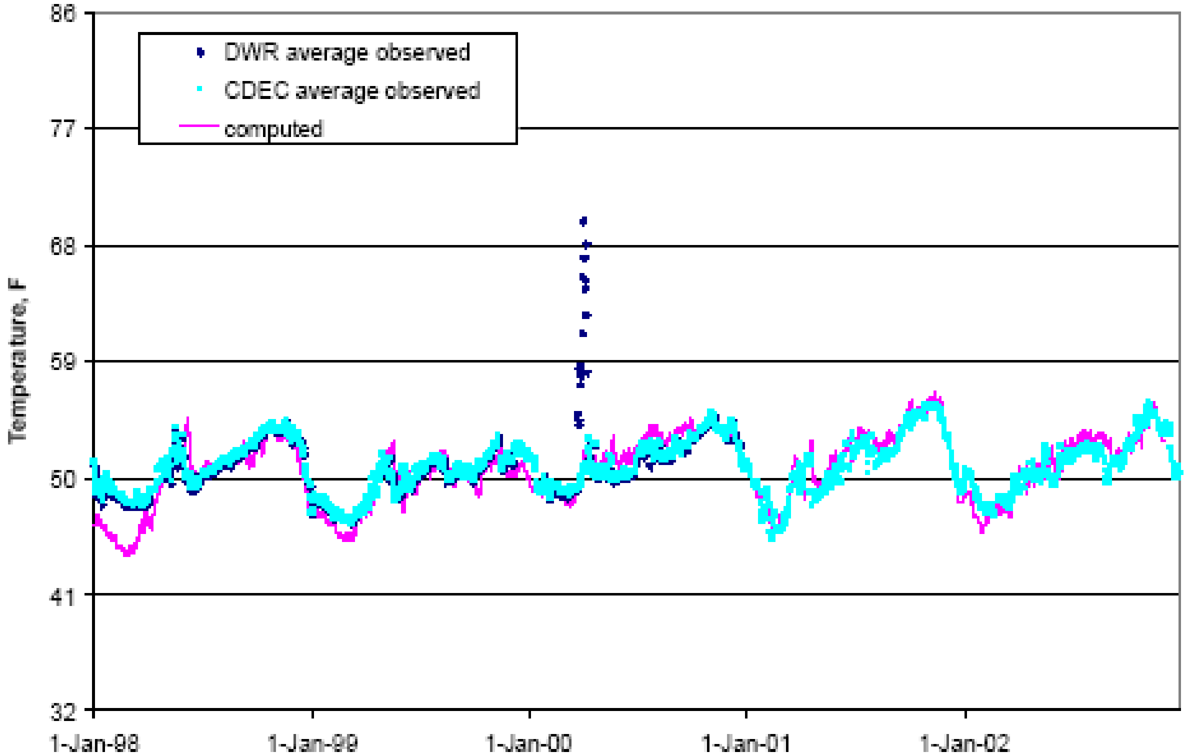


Figure 4-56. Computed and Observed Mean Daily Water Temperatures in Sacramento River Below Keswick Dam

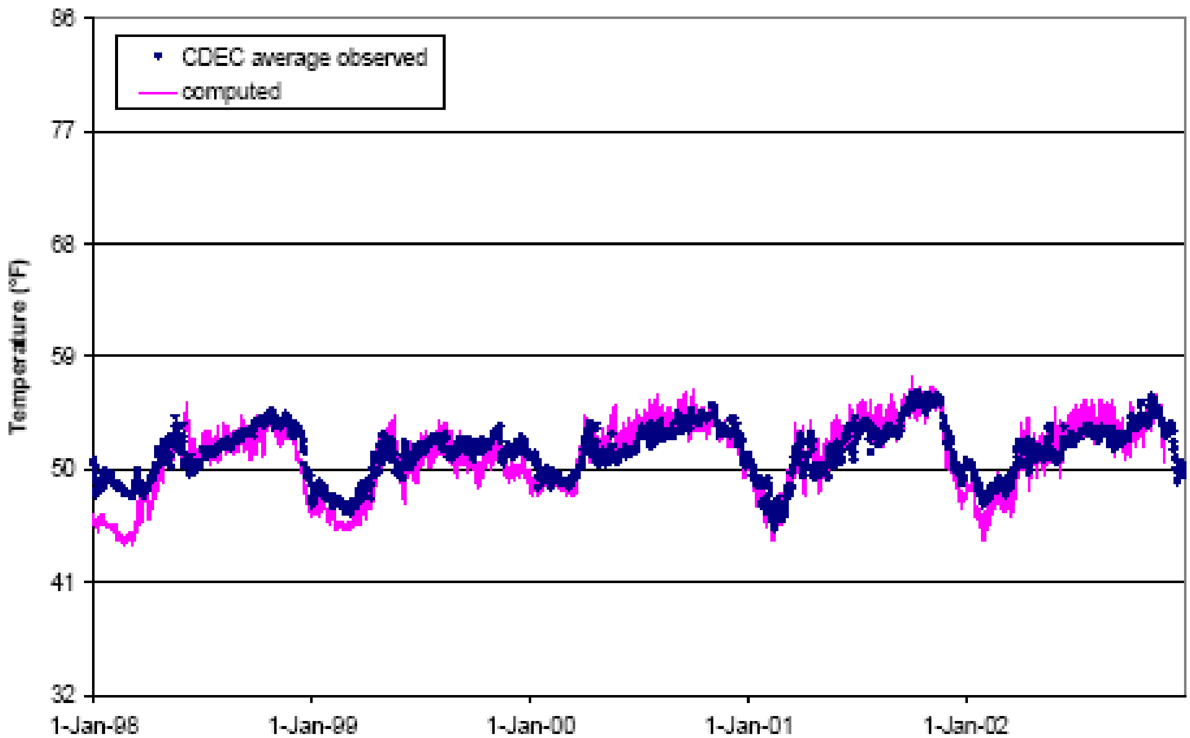


Figure 4-57. Computed and Observed Mean Daily Water Temperatures in Sacramento River Clear Creek (Bonneview)

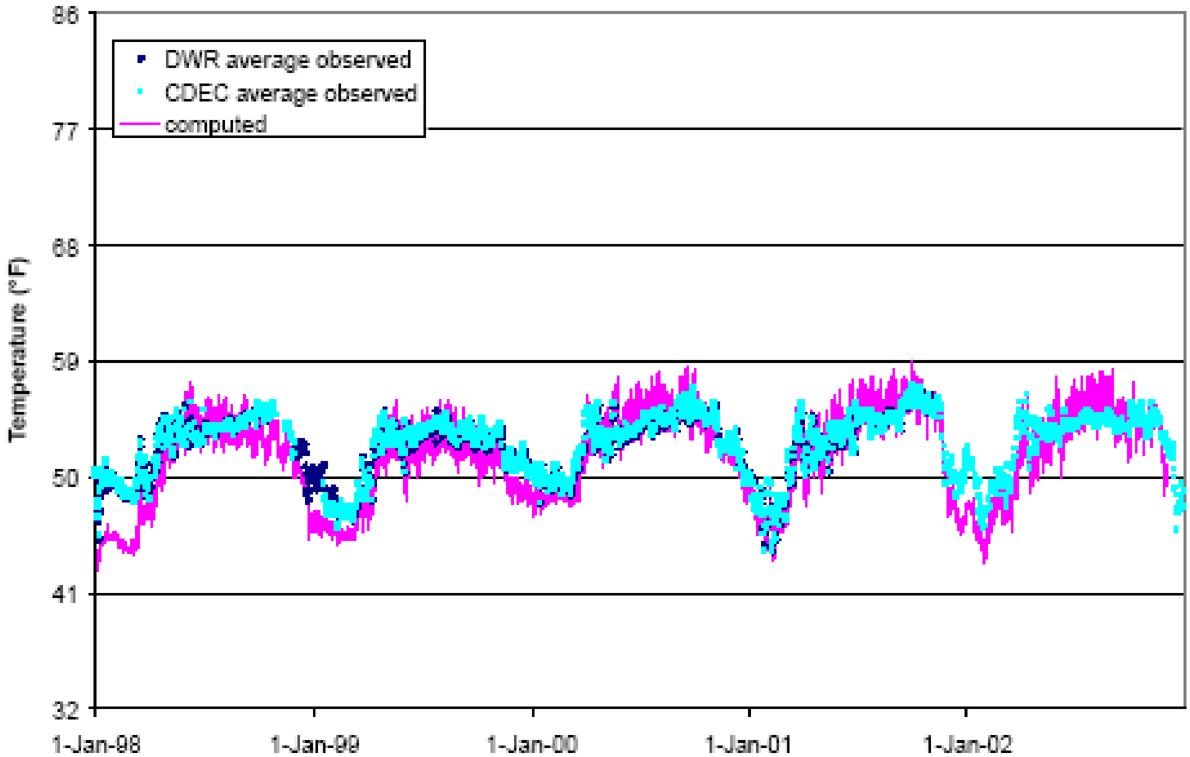


Figure 4-58. Computed and Observed Mean Daily Water Temperatures in Sacramento River at Balls Ferry

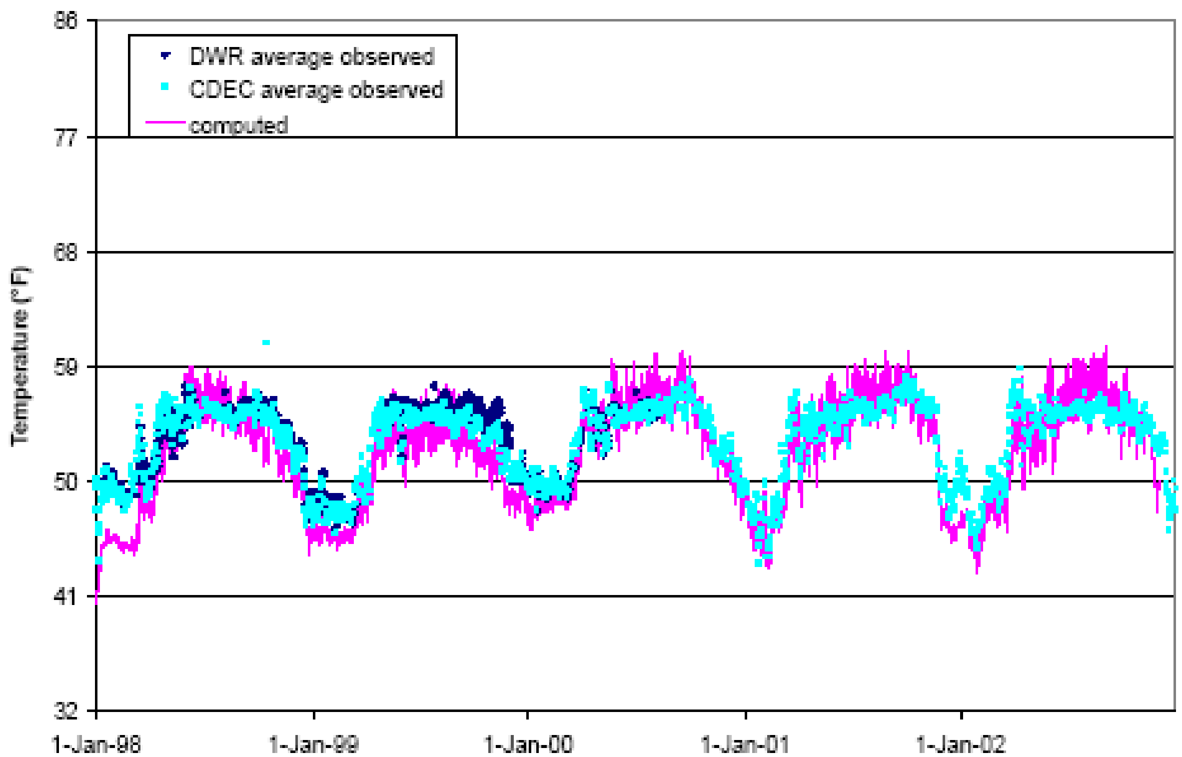


Figure 4-59. Computed and Observed Mean Daily Water Temperatures in Sacramento River at Jellys Ferry

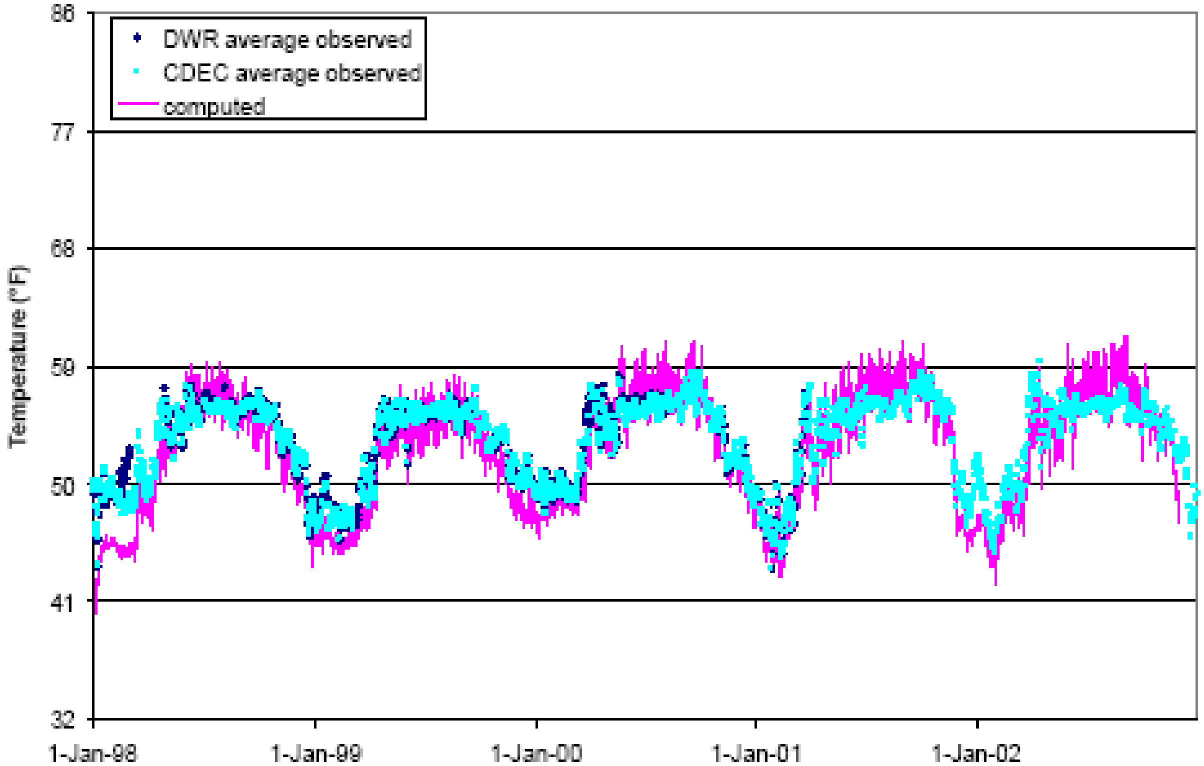


Figure 4-60. Computed and Observed Mean Daily Water Temperatures in Sacramento River at Bend Bridge

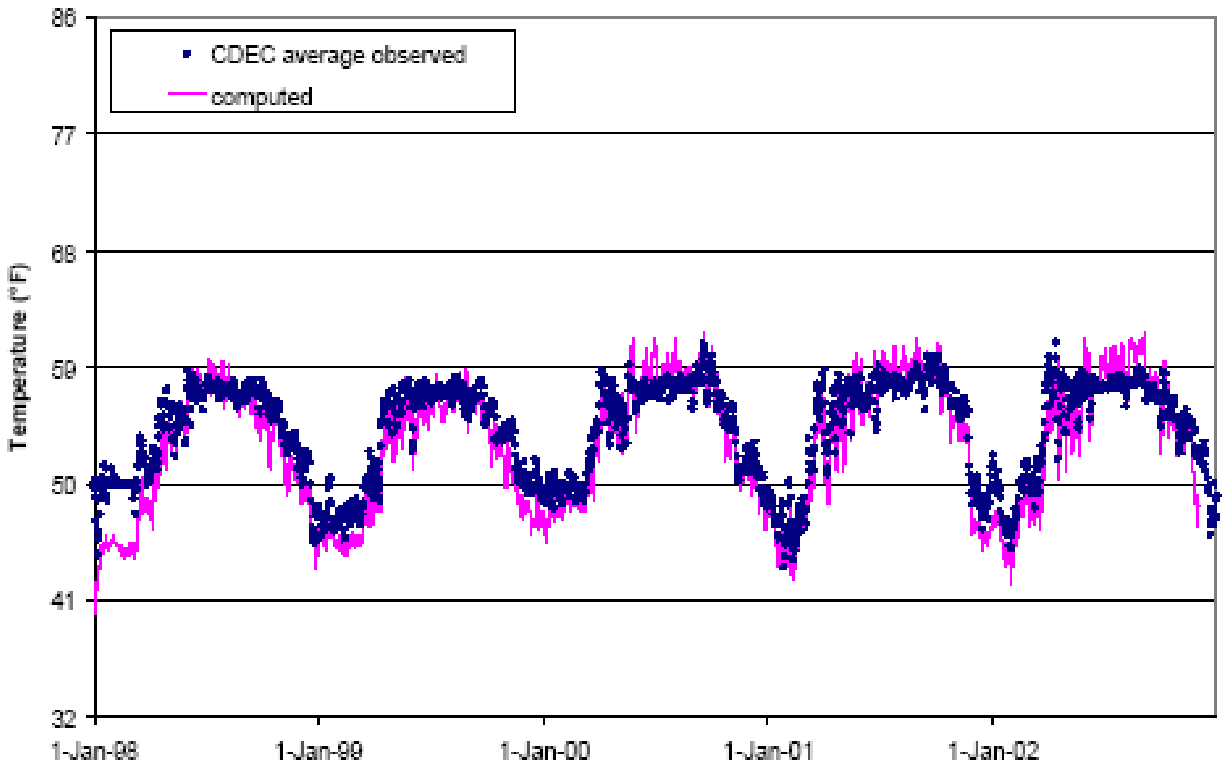


Figure 4-61. Computed and Observed Mean Daily Water Temperatures in Sacramento River at Red Bluff Diversion Dam

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 less than 1°F of average observed data throughout most of calibration period.
4-55	Sac. R. below Shasta Dam	Computed temperatures are within less than 1°F of average observed data throughout most of the calibration period.
4-56	Sac. R. below Keswick Dam	Computed temperatures are within less than 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 as much as 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 HEC-5Q 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 Reservoir, Lewiston, and Keswick dams; temperature time series at Spring Creek Powerhouse; and temperature profile observations in Shasta Lake. 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.

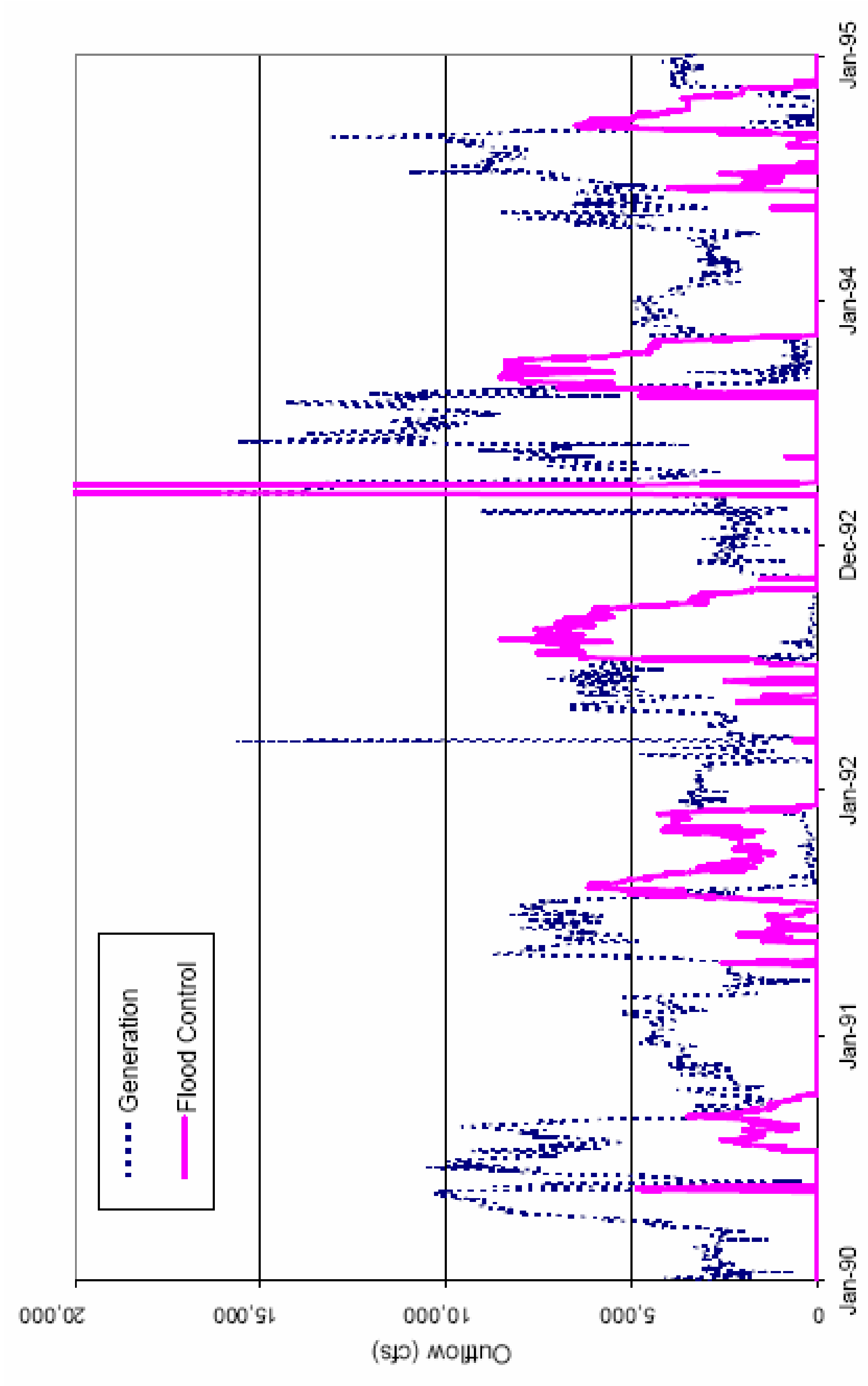


Figure 4-62. Shasta Dam Penstock and Flood Control Outlet Flows During 1990 to 1995 Sacramento River Temperature Control Operation

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.

HEC-5Q Validation Results

The following sections briefly discuss the validation results.

Shasta Reservoir Temperature Calibration Results

Computed and observed vertical reservoir temperature profiles for Shasta 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 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.

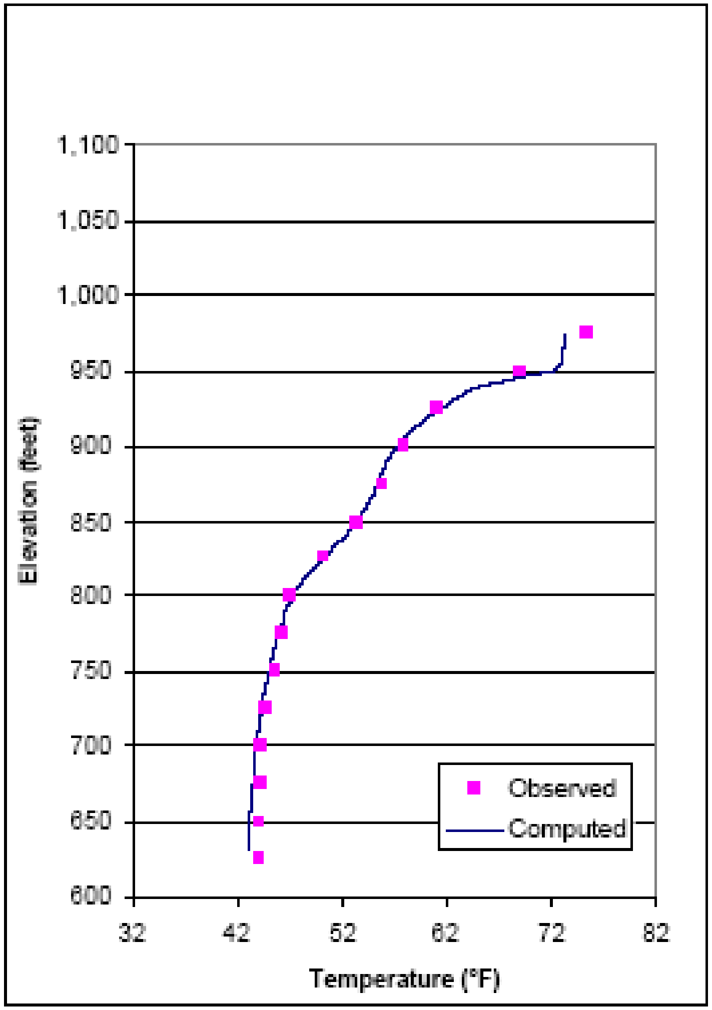


Figure 4-63. Computed and Observed Temperature Profiles in Shasta Reservoir on July 5, 1990

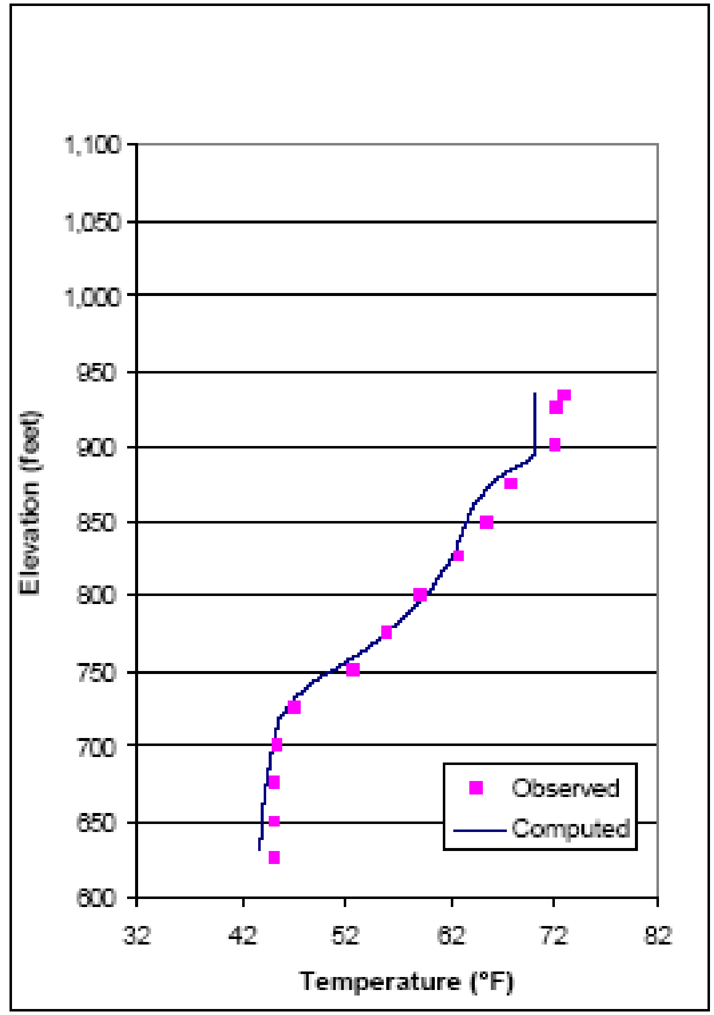


Figure 4-64. Computed and Observed Temperature Profiles in Shasta Reservoir on September 21, 1990

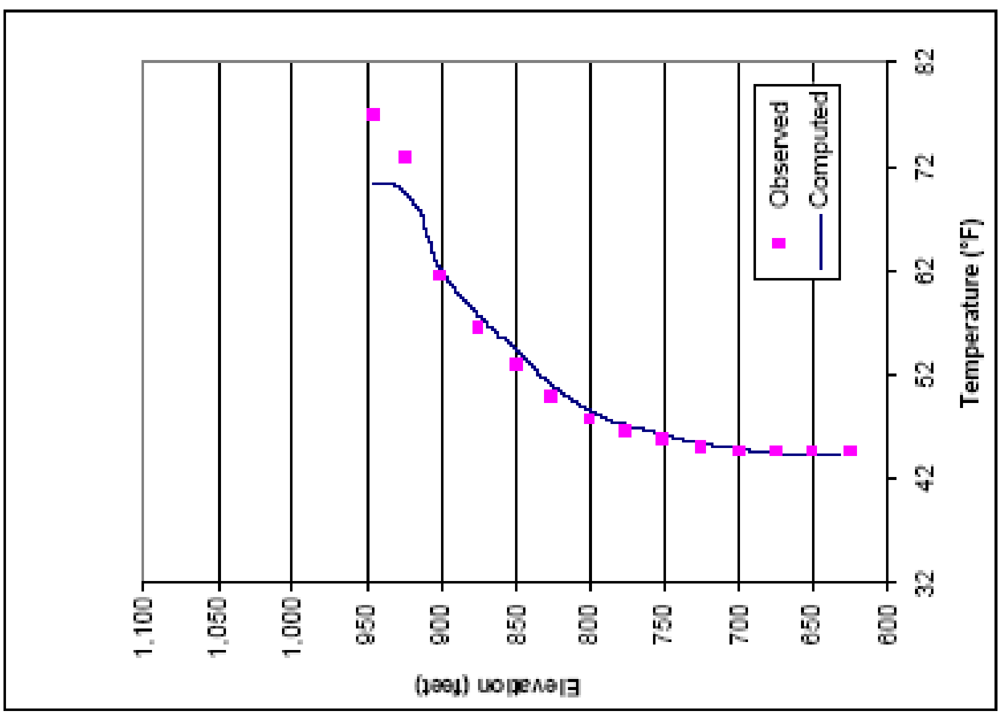


Figure 4-65. Computed and Observed Temperature Profiles in Shasta Reservoir on July 3, 1991

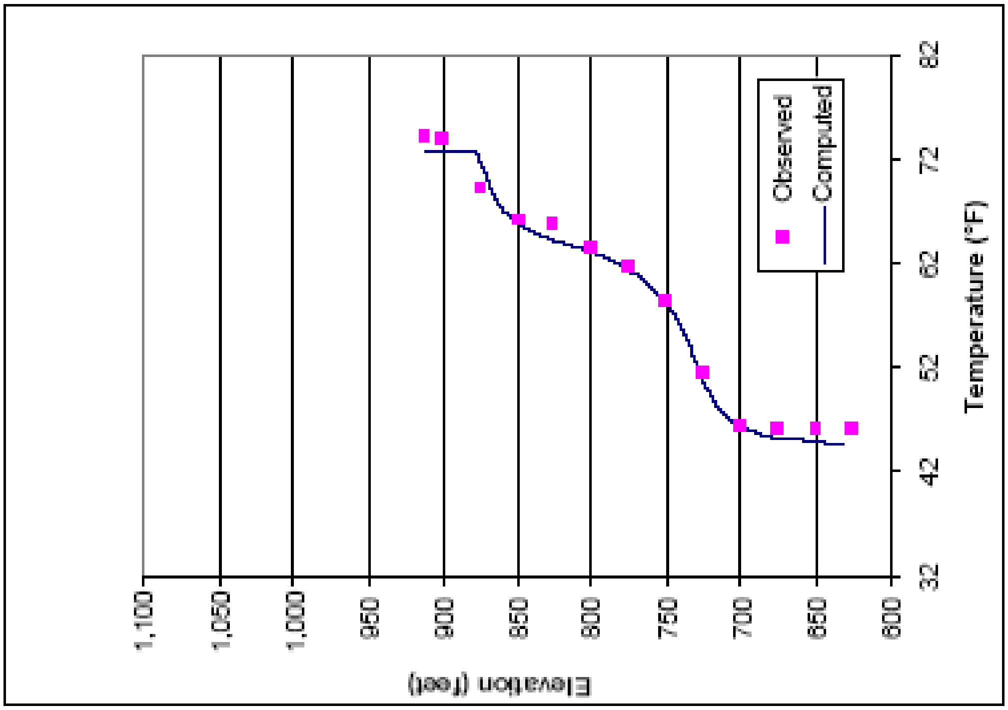


Figure 4-66. Computed and Observed Temperature Profiles in Shasta Reservoir on September 19, 1991

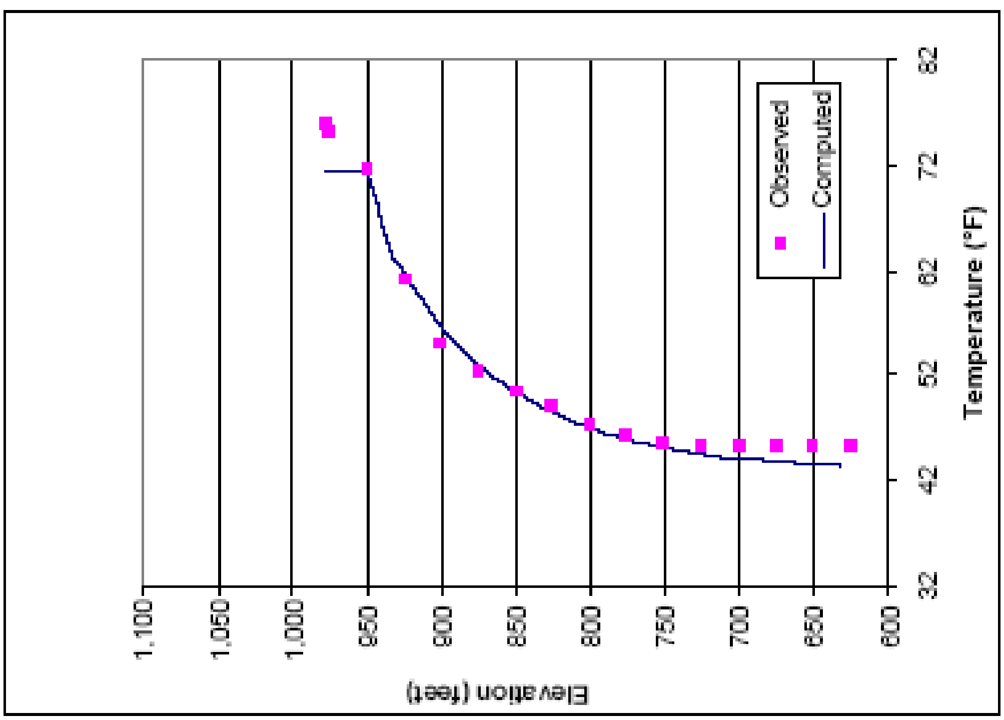


Figure 4-67. Computed and Observed Temperature Profiles in Shasta Reservoir on July 8, 1992

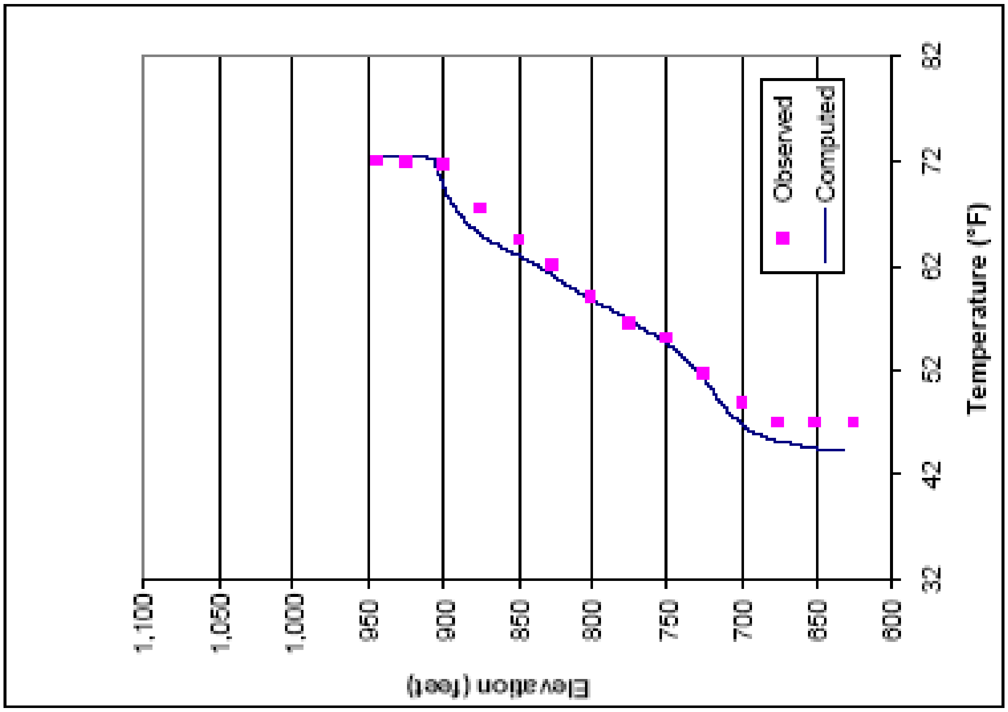


Figure 4-68. Computed and Observed Temperature Profiles in Shasta Reservoir on September 15, 1992

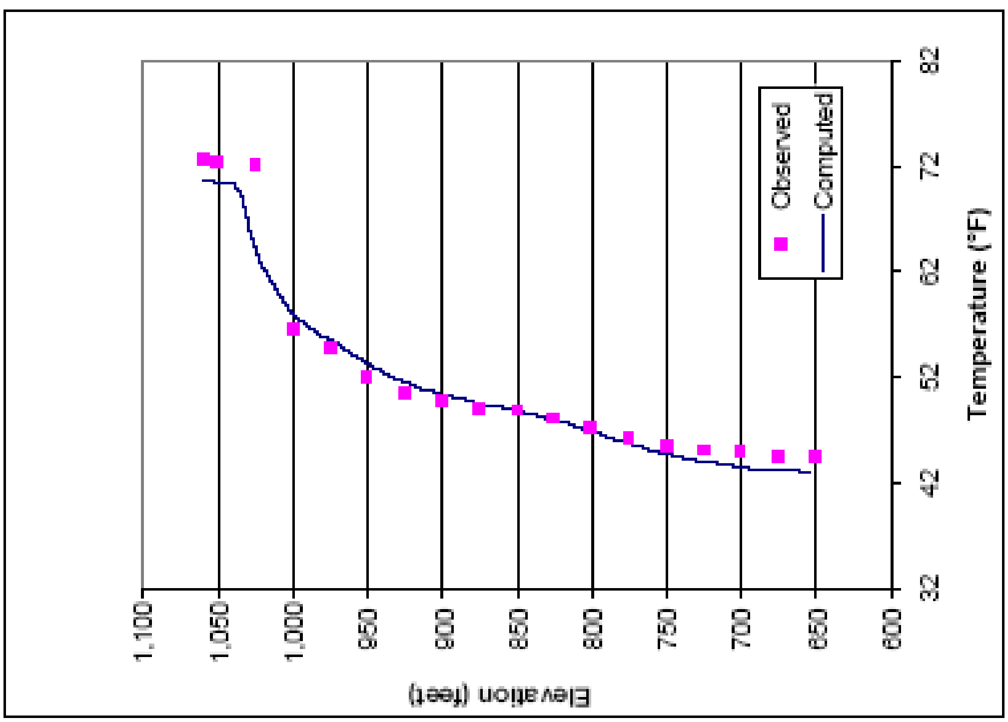


Figure 4-69. Computed and Observed Temperature Profiles in Shasta Reservoir on June 30, 1993

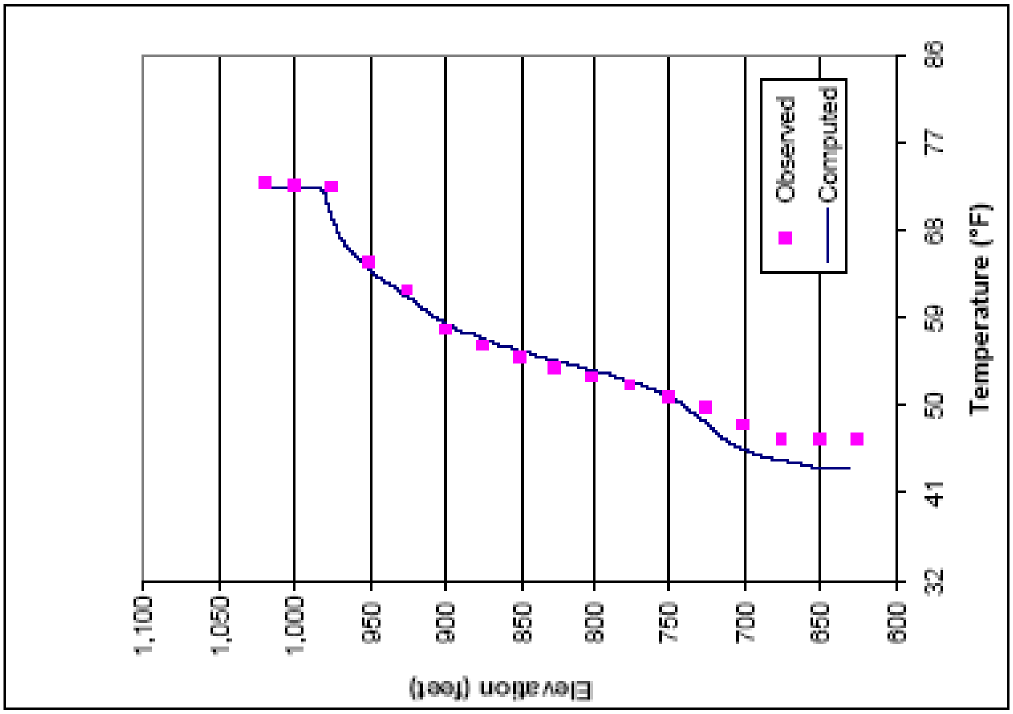


Figure 4-70. Computed and Observed Temperature Profiles in Shasta Reservoir on September 17, 1993

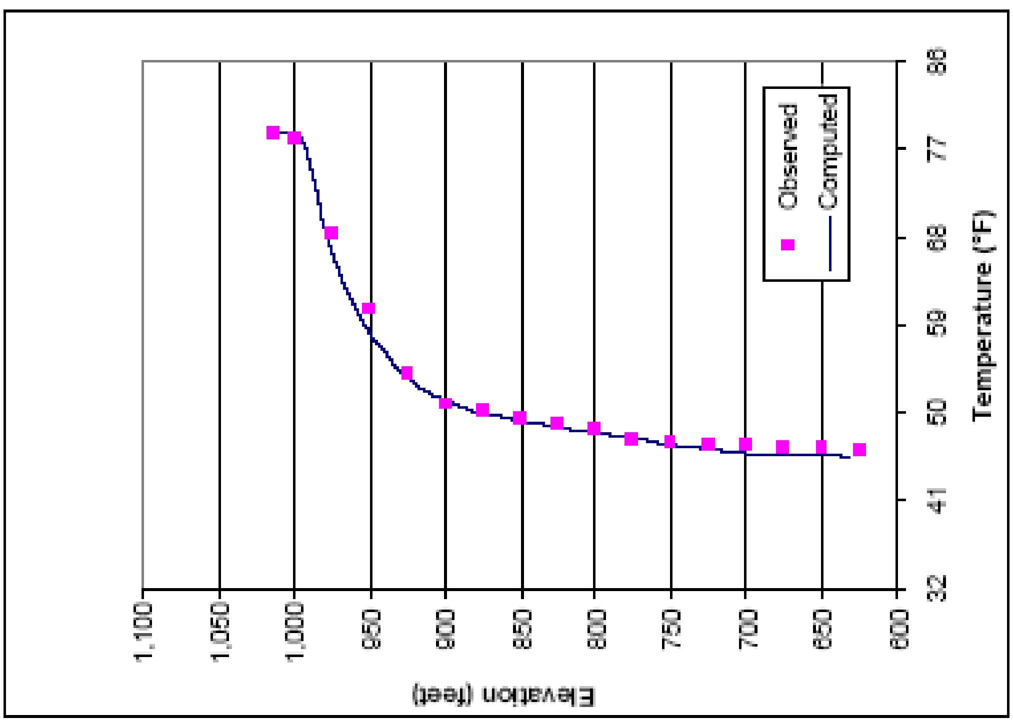


Figure 4-71. Computed and Observed Temperature Profiles in Shasta Reservoir on July 13, 1994

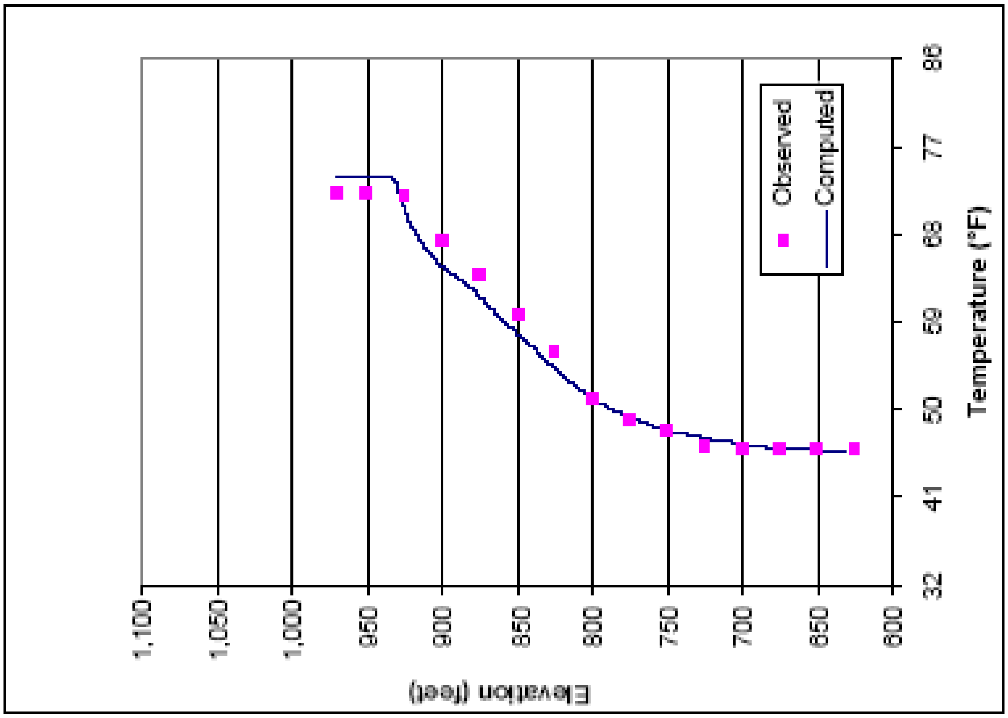


Figure 4-72. Computed and Observed Temperature Profiles in Shasta Reservoir on September 14, 1994

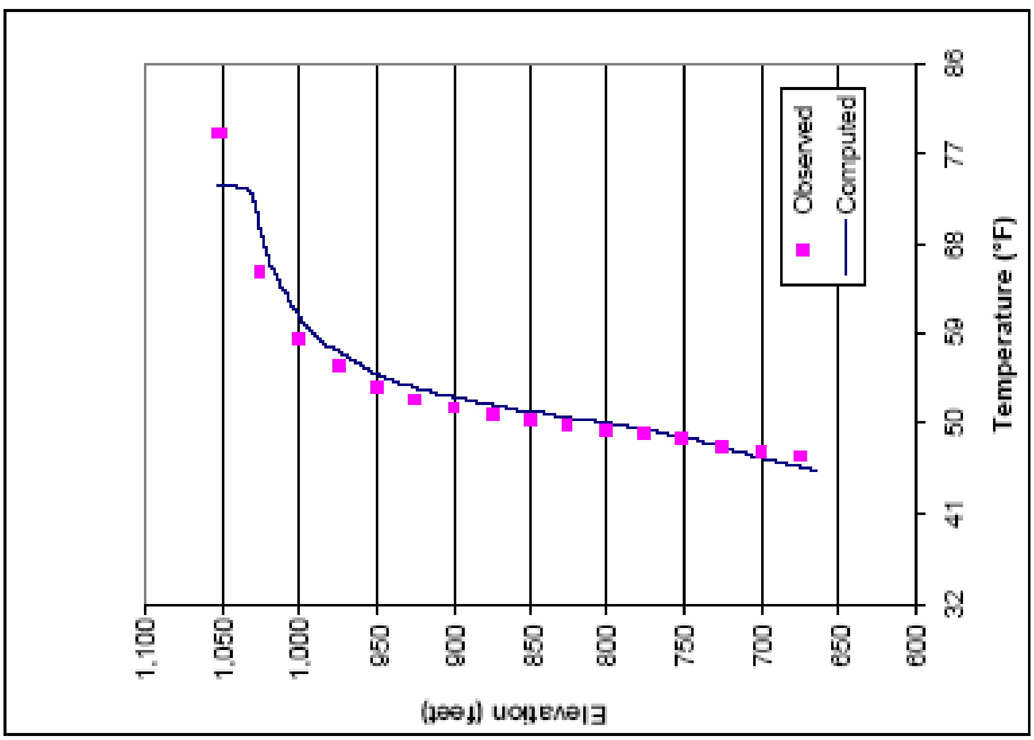


Figure 4-73. Computed and Observed Temperature Profiles in Shasta Reservoir on July 7, 1995

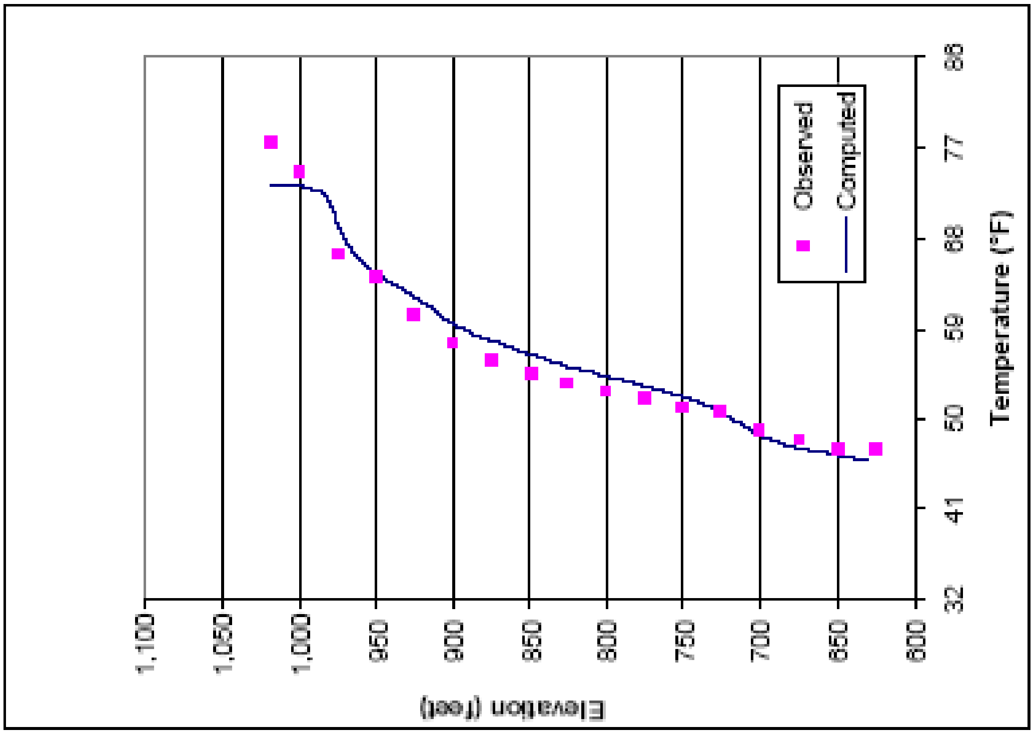


Figure 4-74. Computed and Observed Temperature Profiles in Shasta Reservoir on September 14, 1995

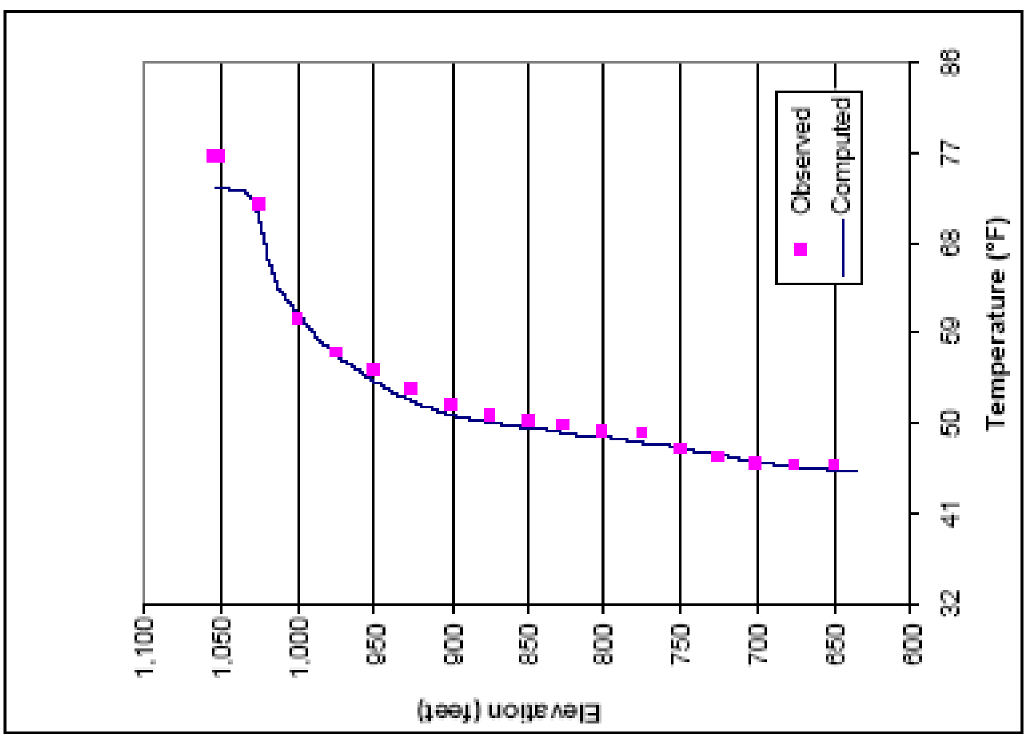


Figure 4-75. Computed and Observed Temperature Profiles in Shasta Reservoir on July 2, 1996

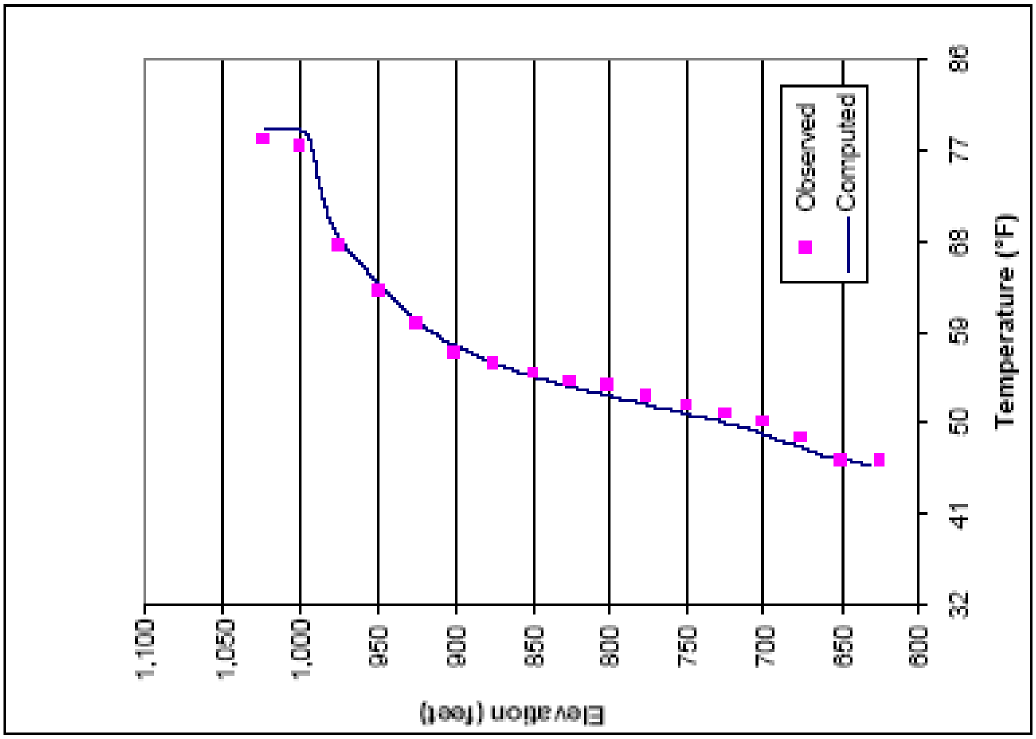


Figure 4-76. Computed and Observed Temperature Profiles in Shasta Reservoir on August 26, 1996

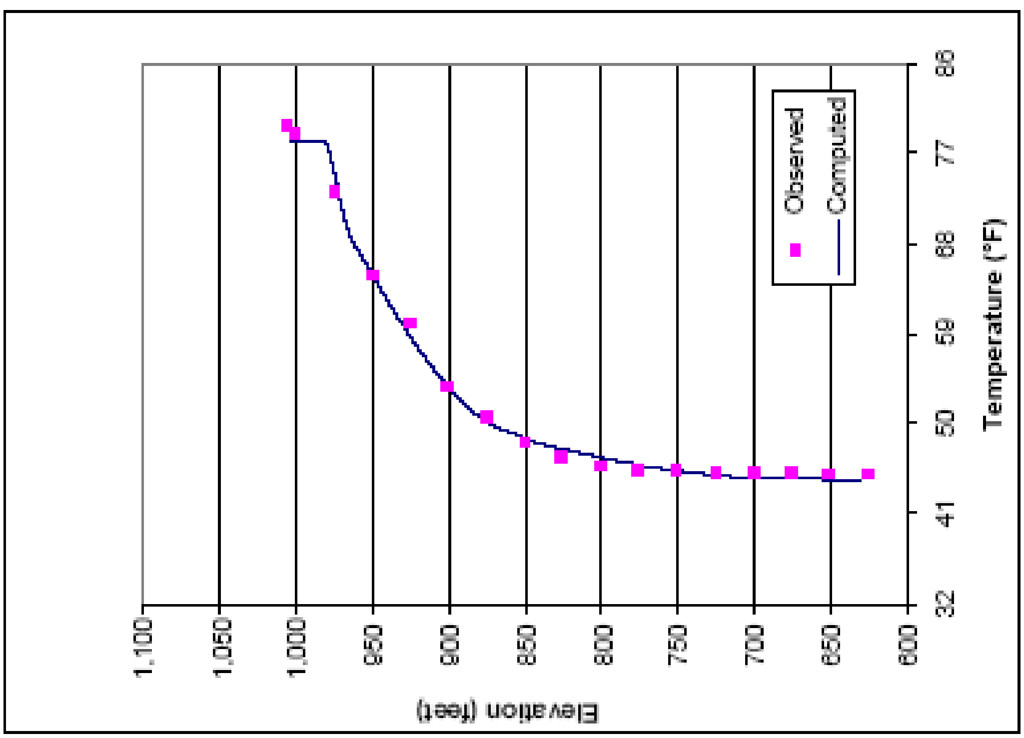


Figure 4-77. Computed and Observed Temperature Profiles in Shasta Reservoir on August 1, 1997

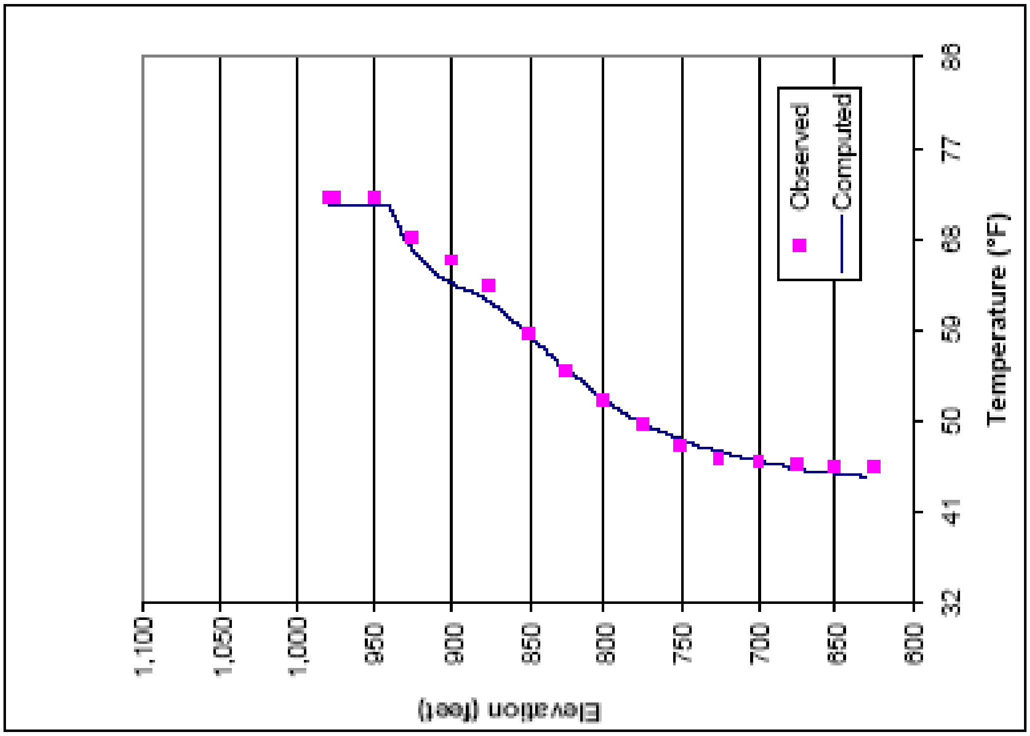


Figure 4-78. Computed and Observed Temperature Profiles in Shasta Reservoir on September 16, 1997

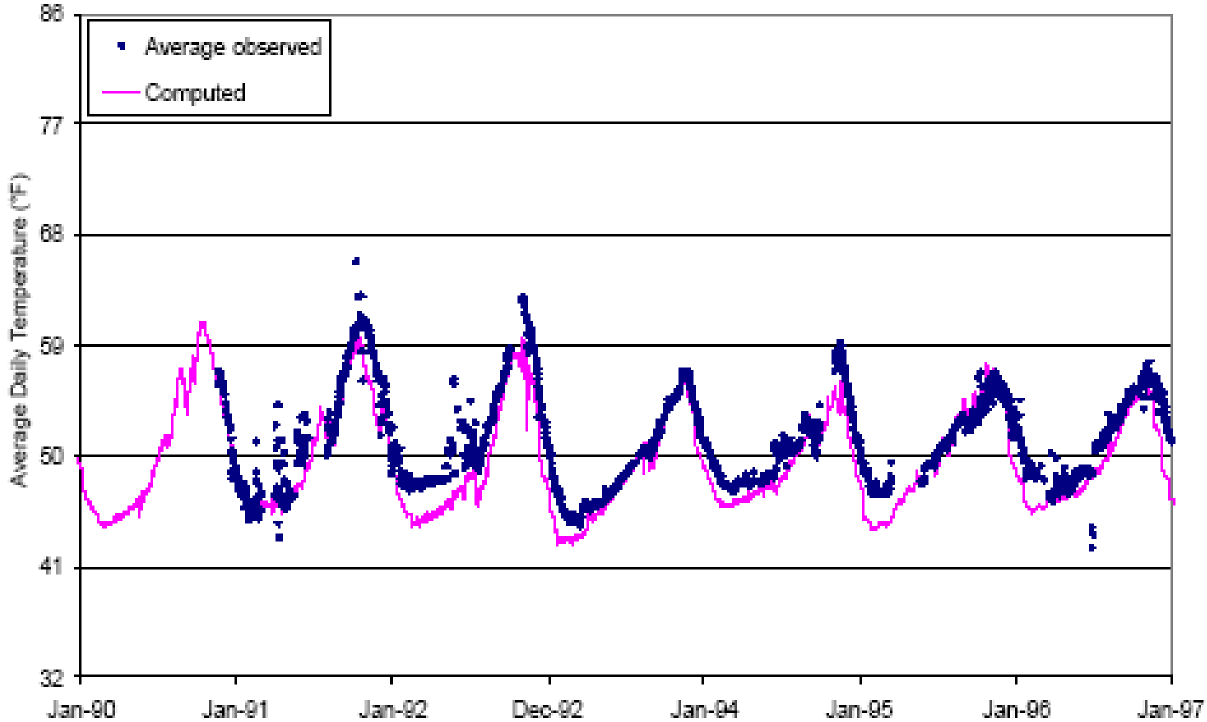


Figure 4-79. Computed and Observed Temperature Time Series in Sacramento River Below Shasta Dam (with observed low level/penstock flow rates and no TCD)

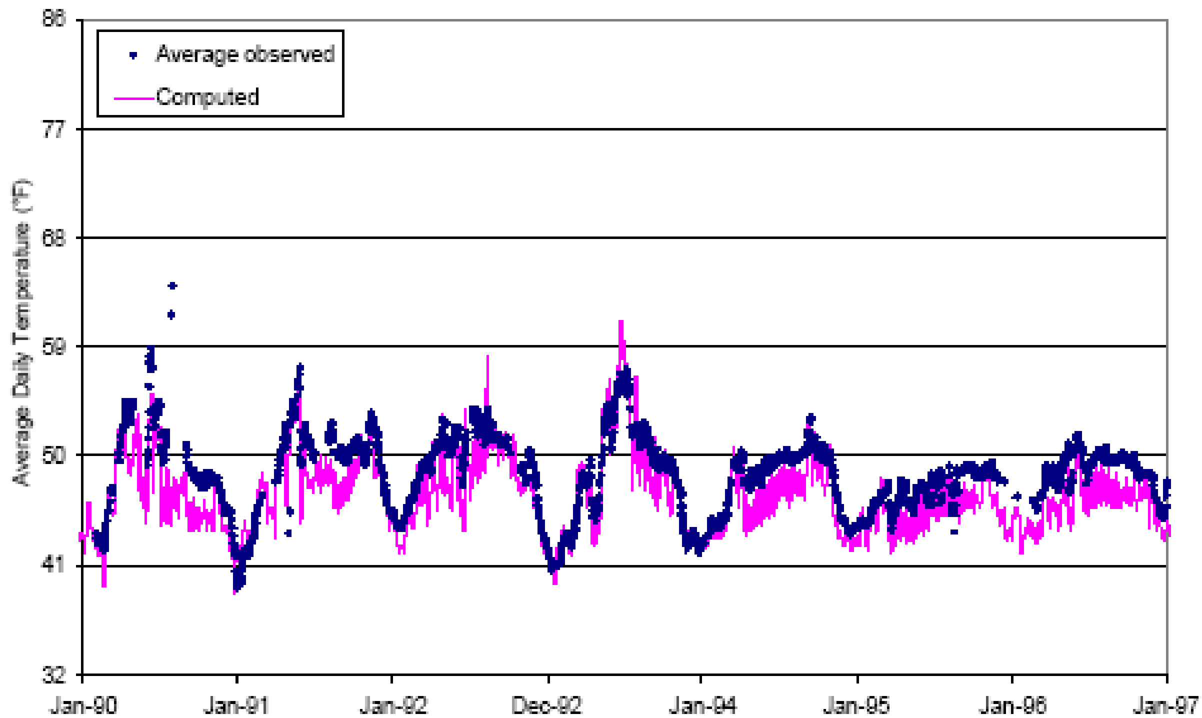


Figure 4-80. Computed and Observed Temperature Time Series in Trinity River at Lewiston

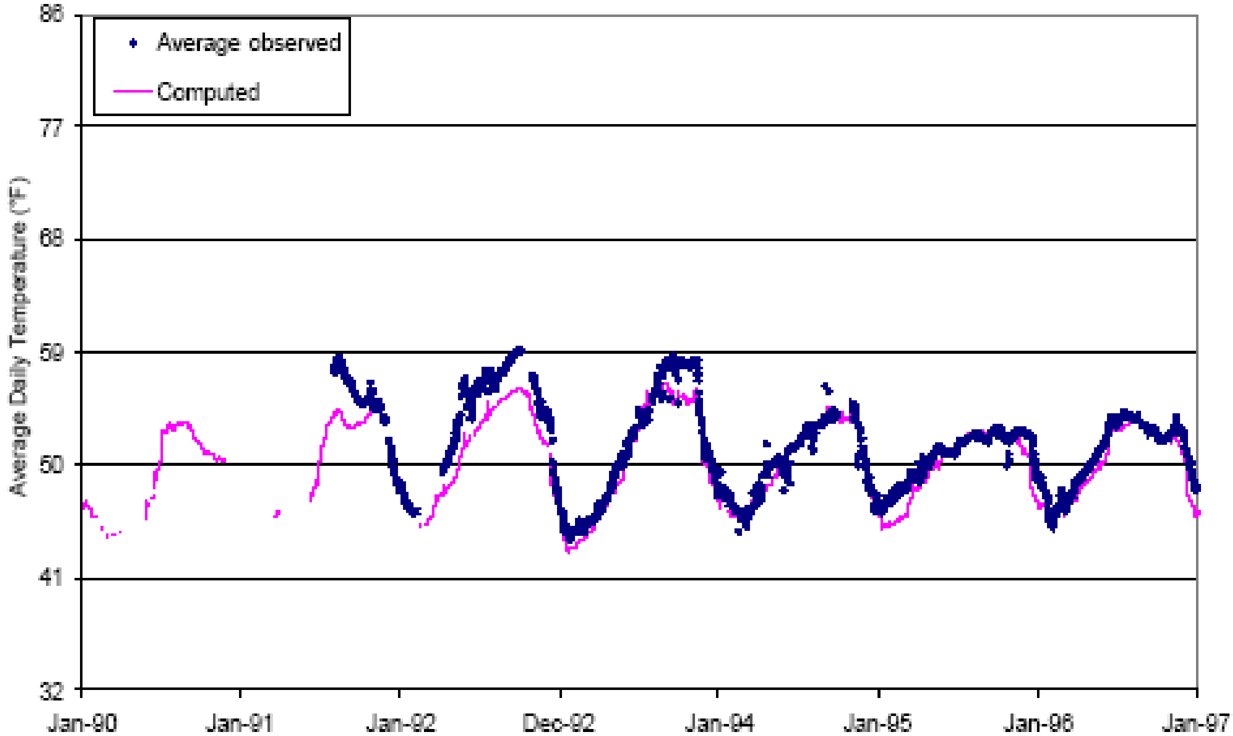


Figure 4-81. Computed and Observed Temperature Time Series in Spring Creek Powerhouse at Keswick

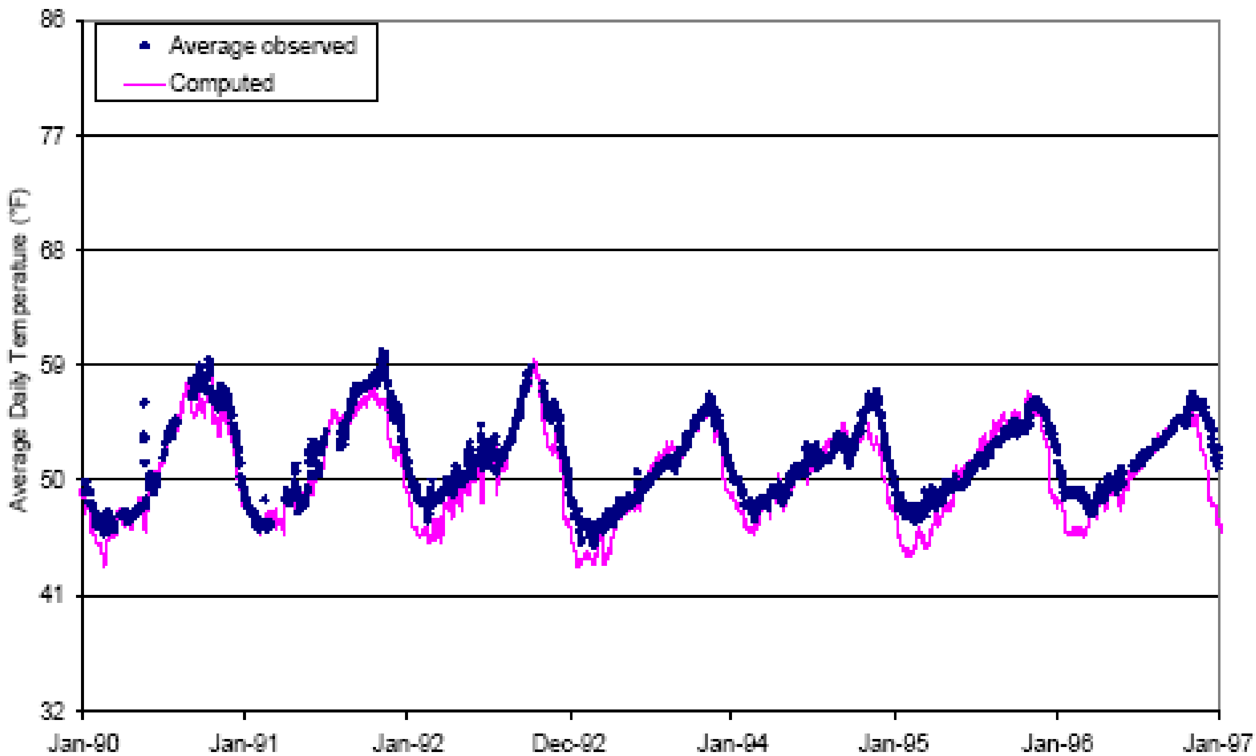


Figure 4-82. Computed and Observed Temperature Time Series in Sacramento River at Keswick

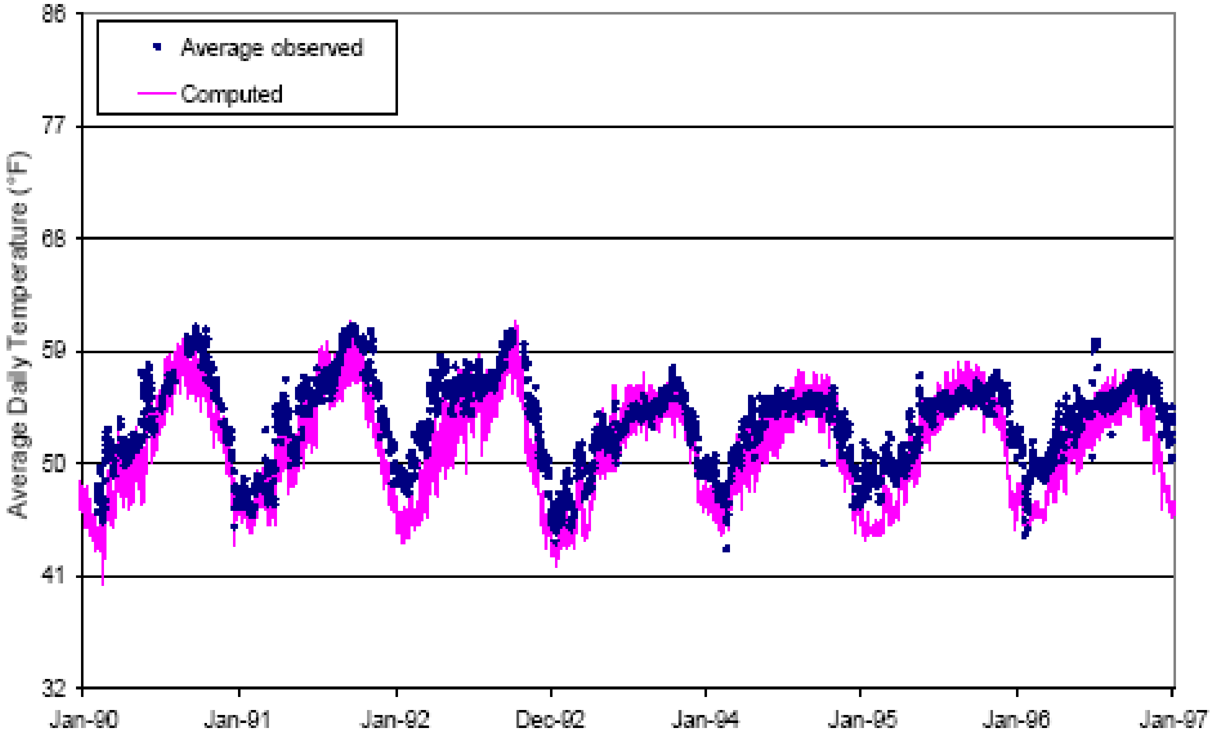


Figure 4-83. Computed and Observed Temperature Time Series in Sacramento River at Balls Ferry

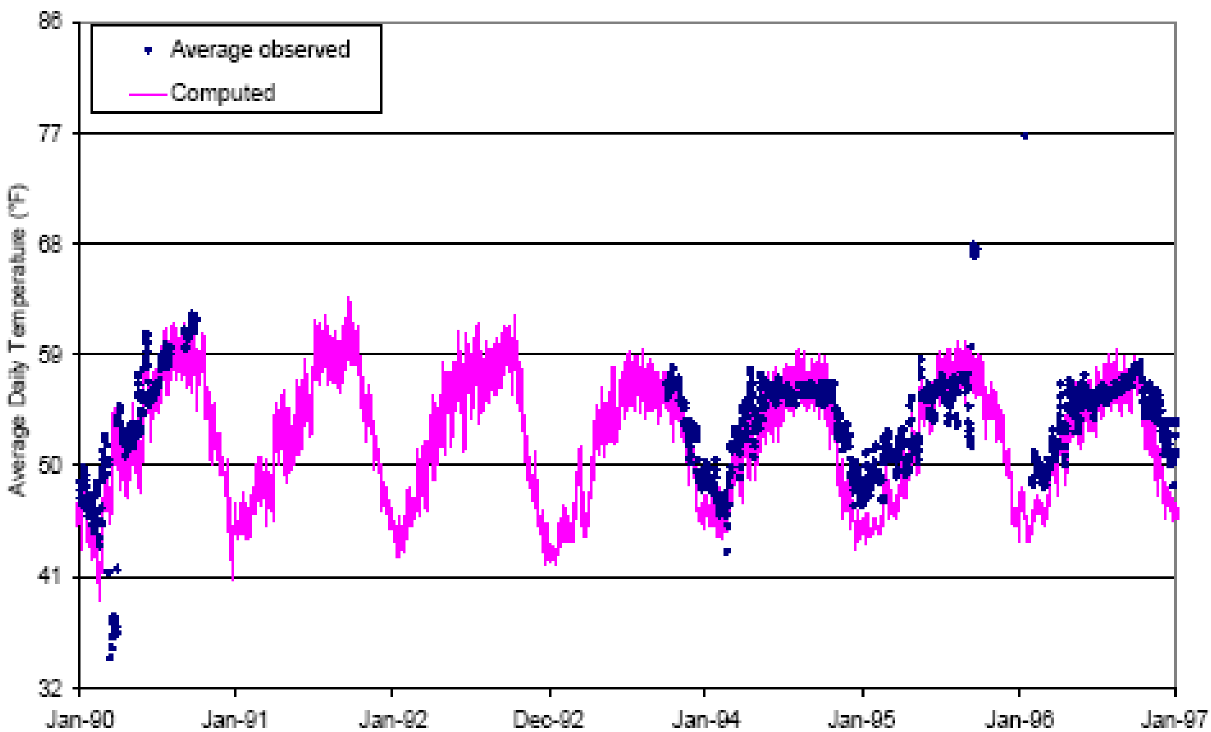


Figure 4-84. Computed and Observed Temperature Time Series in Sacramento River at Bend Bridge

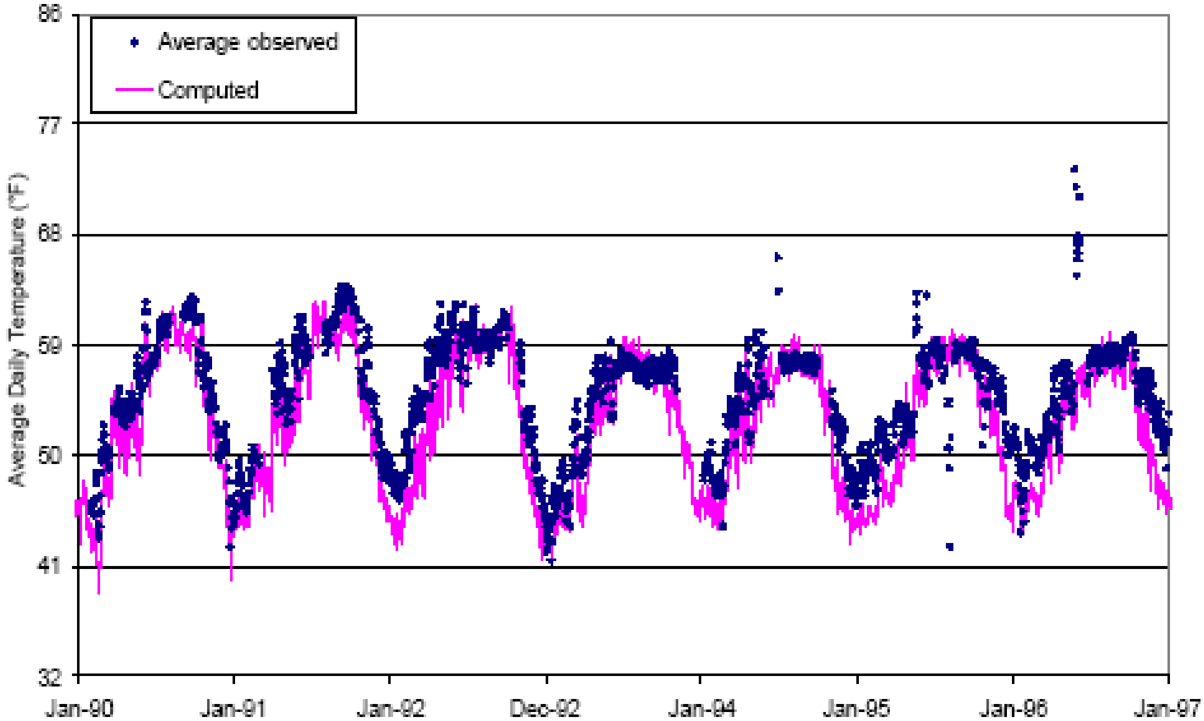


Figure 4-85. Computed and Observed Temperature Time Series in Sacramento River at Red Bluff Diversion Dam

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 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 (SALMOD) predicts the degree to which river flows and temperatures may reduce 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 production associated with hydrologic and meteorologic scenarios representing 80-plus years.

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.

The model predicts that effects on average numeric production of the various Chinook salmon runs would be quite small (less than 2 percent) and likely difficult to measure on the river with certainty. Predicted improvements in thermally induced mortality, especially in specific low-water years, tend to be offset by more frequent and disadvantageous reductions in spawning and juvenile rearing habitat.

Specific suggestions are made regarding future modeling activities and further reducing model parameter uncertainty.

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 raise Shasta Dam to various heights to determine which alternative best meets the goals. Raising the dam may affect the reservoir's ability to deliver cold water in some years, potentially improving 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.

Multiple alternatives to identify the least environmentally damaging practicable alternative were evaluated. Scenarios selected by Reclamation include the following:

- “Baseline” scenario, representing existing and reasonably foreseeable future facilities, constraints, and delivery obligations portrayed against a backdrop of historical water availability and meteorology (No-Action Alternative).
- 6.5-foot dam raise and accompanying enlarged Shasta Reservoir (Comprehensive Plan 1 (CP1)).
- 12.5-foot dam raise (CP2).
- 18.5-foot dam raise (CP3).

In addition, 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) 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 meteorologic 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 Shasta Dam scenarios 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 an existing salmon production model for the Sacramento River between Keswick Dam and Battle Creek. This model, 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).

Specific Objectives of the Present Study

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) These new parameter estimates have been incorporated for the Sacramento River. For this study, the previous study area, which terminated at Battle Creek, was extended downstream to the RBDD inundation zone, a reach where water temperatures may be more of an issue for spawning and rearing salmon.

Given the revised SALMOD model parameters, the specific objective of this effort has been to exercise the model to estimate the effects of alternative water temperature and flows for the various Shasta Dam scenarios. Effects have been measured by estimates of overall production for each of the four runs of Chinook salmon.

USGS performed this analysis solely to assist the resource and management agencies with a framework for making informed decisions. No specific water management recommendations or any specific scenario endorsement were made by USGS.

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

SALMOD (Version 3.74) is a component of the Instream Flow Incremental Methodology, or 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 Sacramento River for two reasons. First, SALMOD has been applied previously on the Sacramento (Kent 1999; Bartholow 2003). Second, USGS has recently completed a thorough review and update of model parameters and techniques on the Klamath River that enable a smooth transfer of relevant model parameters to the Sacramento River (Bartholow and Henriksen 2006).

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. 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 1 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[4] types (e.g., pools, riffles, runs) categorized primarily by channel structure and hydraulic geometry but

[4] 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).

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.

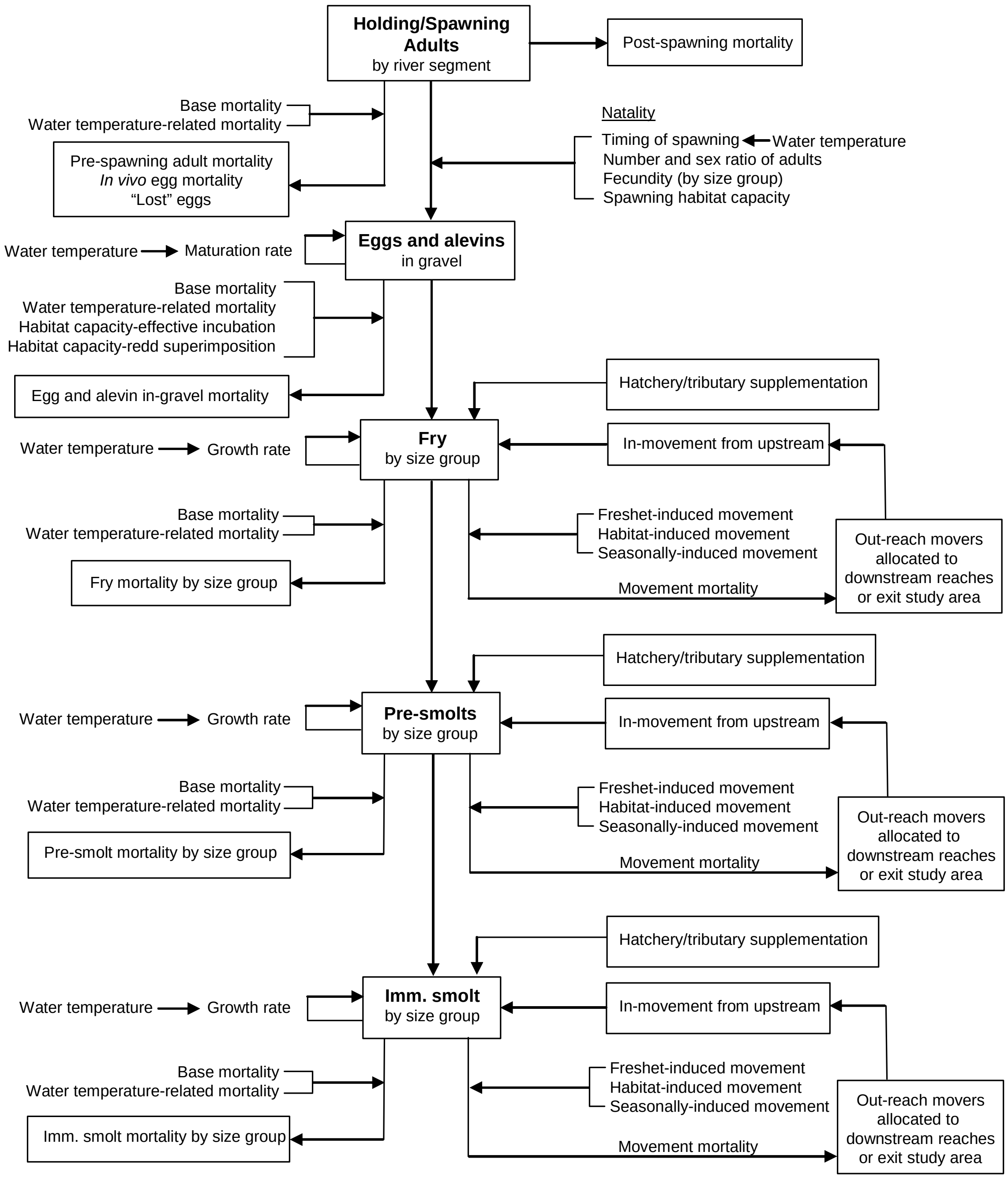


Figure 5-1. Conceptual Illustration of Factors Important in Controlling Salmon Production Throughout SALMOD Biological Year

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., $temperature_1$, $mortality\ rate_1$, $temperature_n$, $mortality\ rate_n$). 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

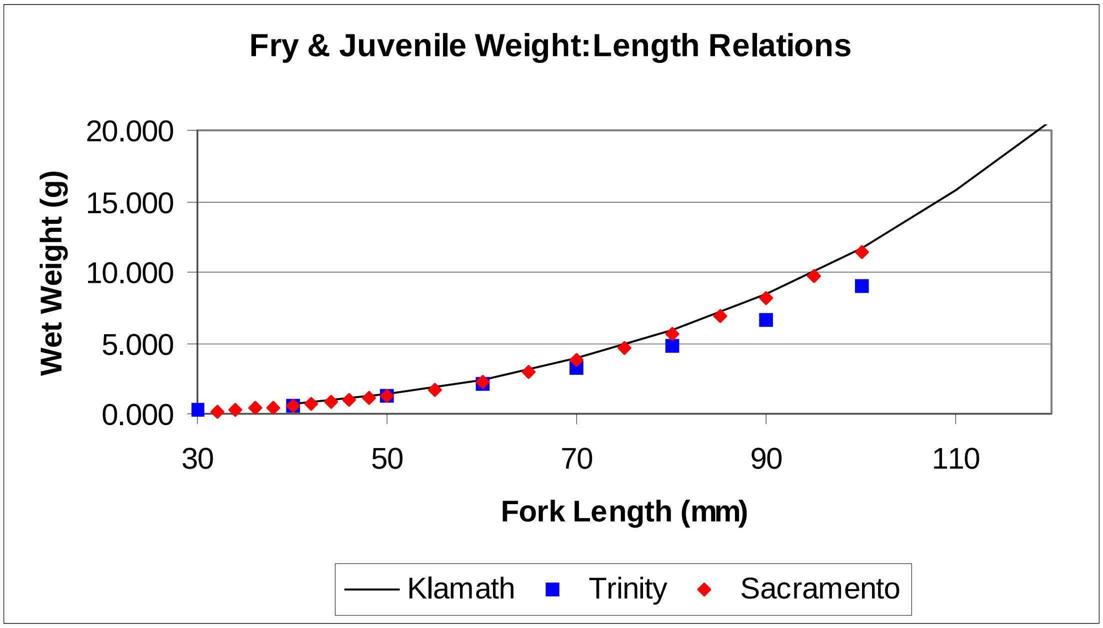
Kent (1999) used a formula based on a cubic regression of fork length and wet weight developed for naturally reared fall-run Chinook salmon with lengths between 30 and 100 mm. A cubic regression was used because the length and weight relationship for fish is approximately cubic (Busacker et al. 1990):

$$WW(g) =$$

$$-0.67 + 0.0282FL - 0.000491FL^2 + 0.0000141FL^3 \text{ (R unspecified)}$$

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

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, but it has also been noted that diseased juveniles (often found on the Klamath River) can appear to have higher condition factors (Nick Hettrick, USFWS Arcata, pers. com., 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

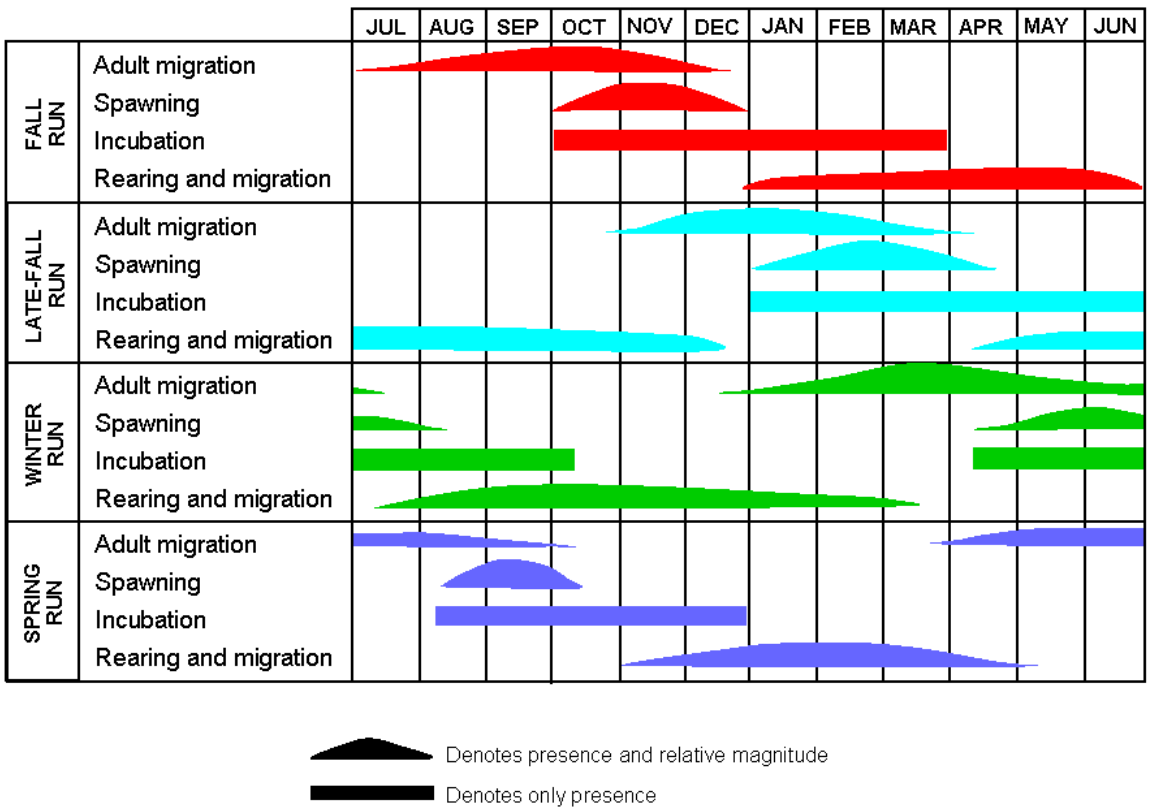
Weight (g)	Fork Length (mm)	Weight (g)	Fork Length (mm)
1.112	48	11.34	100
1.275	50	15.258	110
1.742	55	20.008	120
2.3	60	40.1	150
2.961	65	92	200
3.734	70	310.5	300
4.632	75	1,437.5	500
5.663	80	3,944.5	700
6.839	85	5,888	800
8.17	90	12,000	900

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 (DFG) 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 RBDD in small numbers (Poytress 2005).

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.



Source: Vogel and Marine 1991.

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

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

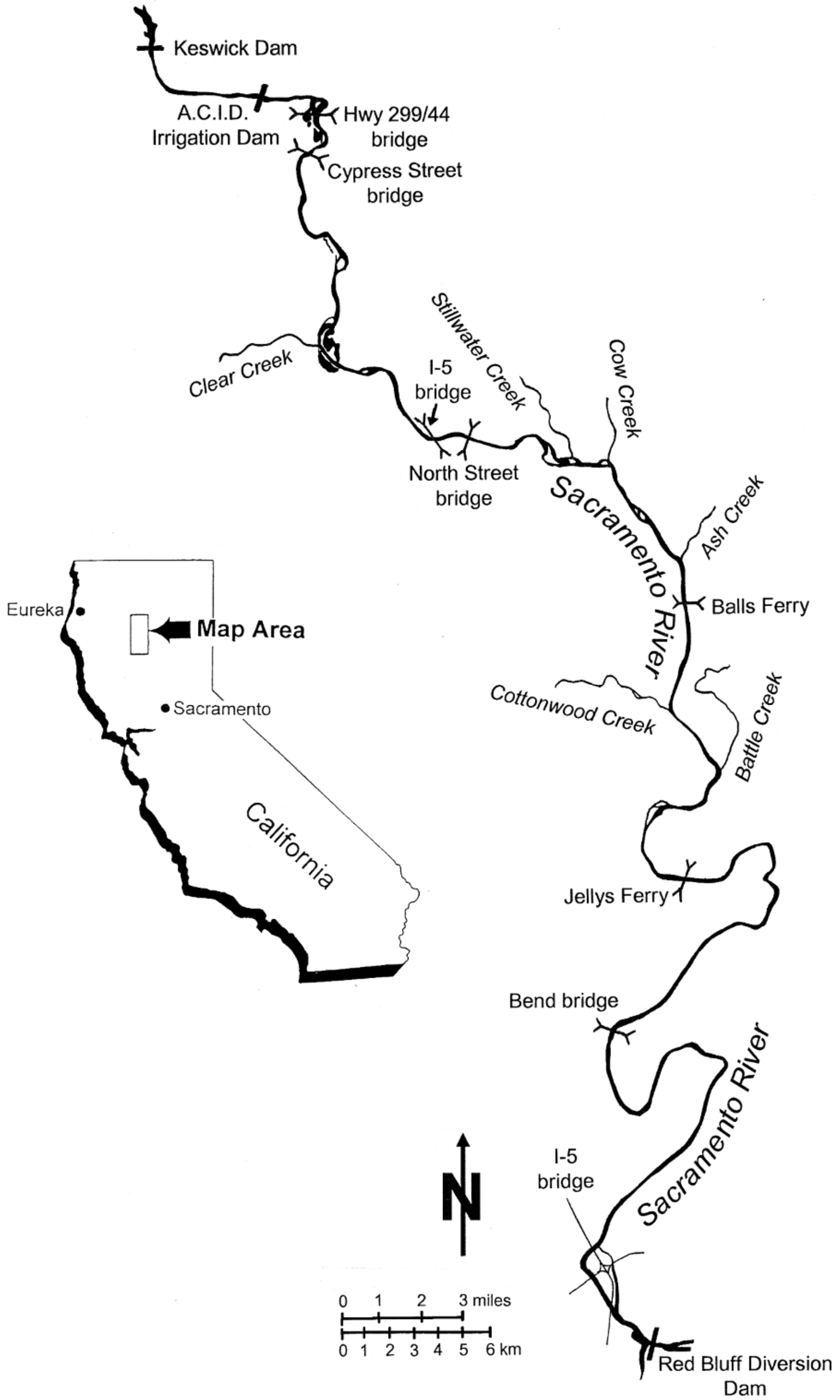
Physical Data

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 RBDD 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 RBDD 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 the RBDD is operated with spillway gates that alter the inundation pool's hydraulics. This pool has not been 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 Trinity Dam, Trinity River to Lewiston Dam, Lewiston Dam, Clear Creek Tunnel, Whiskeytown Dam, Spring Creek Tunnel, Shasta Dam, Keswick Dam, the Sacramento River from Keswick Dam to Knights Landing, Clear Creek below Whiskeytown, and the RBDD.   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 (cfs) and water temperature (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 inundation pool. 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 modeling study 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. Morhardt et al. (1983) 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 created by the RBDD. The inundated habitat within the inundation pool has not been satisfactorily measured hydraulically, and flash boards are in place only intermittently. 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 Lake section of the river were measured from the habitat map provided by USFWS (Gard 1995a, 1995b, 2001) using ARCGIS (v. 9.0). The distance from Keswick Dam to the beginning of the section from Battle Creek to Red Bluff Lake 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 Lake 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 the Red Bluff inundation pool, 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.

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-RBDD 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 1995a, 1995b, 2001), as was done in the previous model application. It was assumed that all computational units with spawning habitat were spawnable.

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.

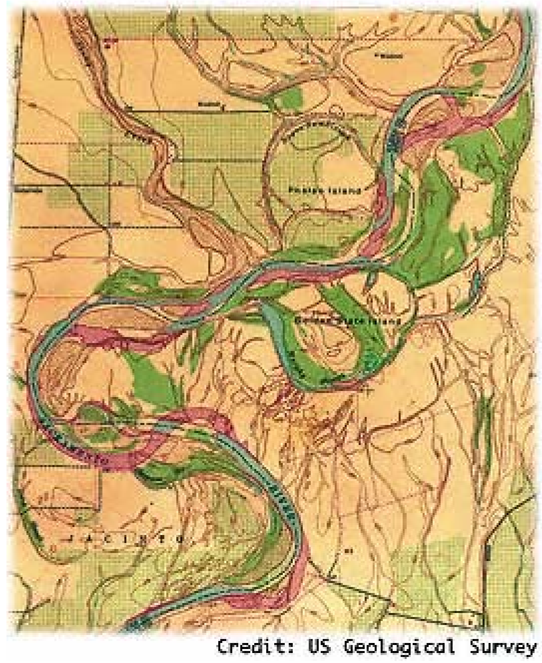
Microhabitat (WUA) Estimates for SALMOD Kent (1999) and Bartholow (2003) did not have WUA estimates for egg incubation habitat. Instead, they assumed that egg incubation habitat was essentially identical to spawning habitat by making them equivalent in SALMOD's WUA input file. On consultation with Mark 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. Some redd dune movement may occur and entomb egg pockets, even with flows in the range of up to 5,000 cfs, by moving surface materials over the tops of redds, affecting their hydraulic conditions and potential survival (Doug Killam, pers. comm. 2006).

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, an assumption supported by Chapman and Bjornn (1969), Fraser (1969), and Mundie (1974). 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 (Chapman and Bjornn 1969). 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.



Note:
Best viewed in color. Source is obscure. 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 1 weekly time step; in effect, this means that redds are defended for 1 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 m^2 (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 m^2 (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 m^2 in deference to DFG's 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 recent 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.

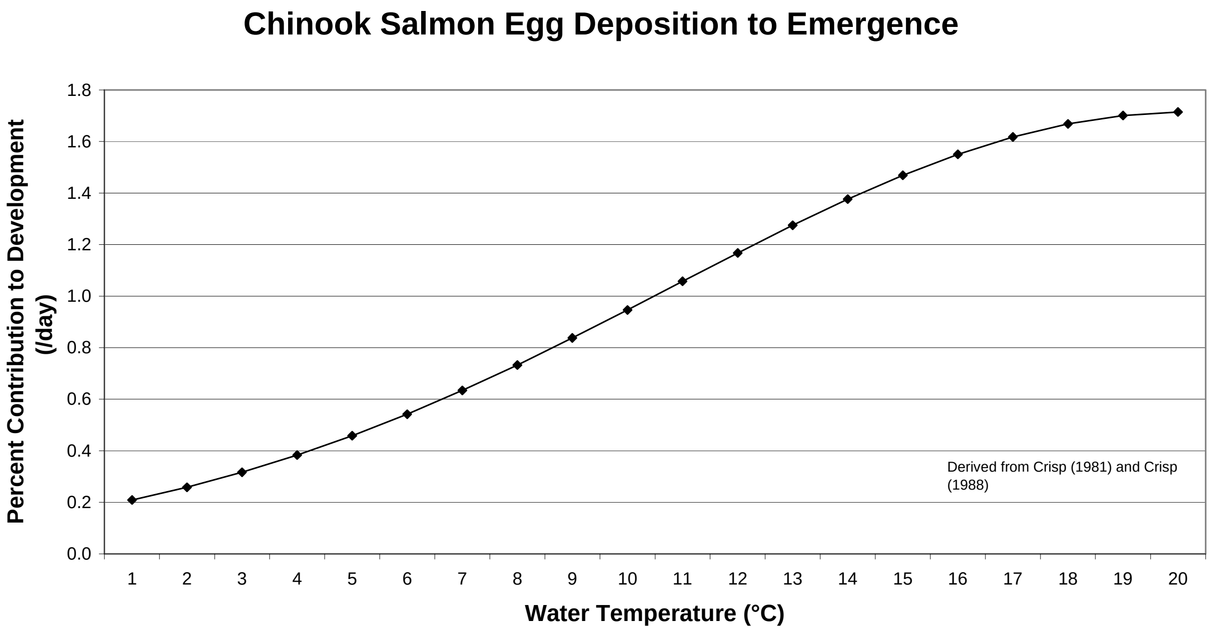
Table 5-8. Date and Fraction of Adults Converted to Spawners in Each Week of Their Respective Spawning Periods

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.

Thomas Quinn (pers. comm. 2006) believes there may indeed be a threshold emergence temperature, although it might vary from river to river or area to area. He cites anecdotal information related to ice-out conditions and to late-season temperatures being the best predictor of emergence timing. Nick Beer (pers. comm. 2006) believes that the suite of simultaneous environmental cues is difficult to decouple, but most likely fish will synchronize spawn timing to "optimize" production, and development rate is purely mechanistic. Ernie

Brannon (pers. comm. 2006) knows of no situation in the field or laboratory where there was an emergence threshold below which emergence would not occur. However, he also stated that, unlike other species, Chinook salmon can feed in the gravel and remain there after their yolk is absorbed "if conditions require it."

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.

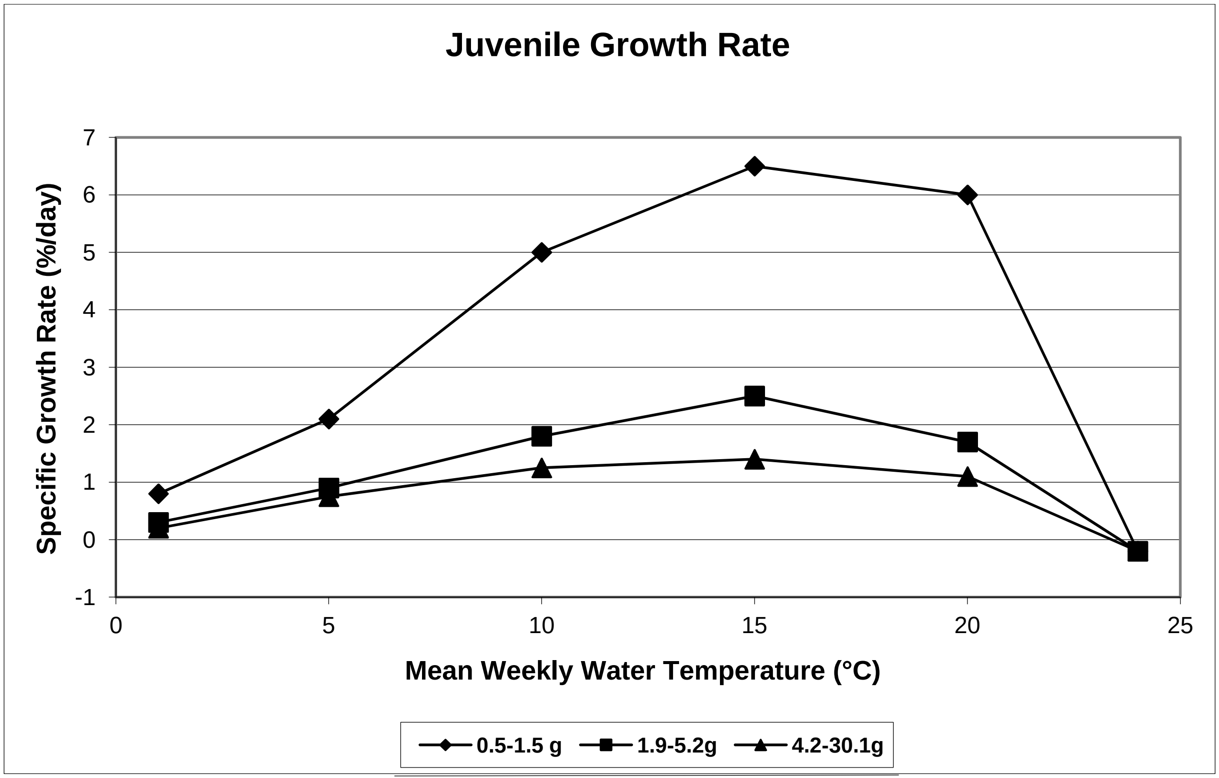
Emergent Length

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, 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

Freshet Movement

Freshets (sudden increases in discharge) have been associated with displacement of fry in some rivers (Godin 1981; 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.

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.

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.

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.

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 (USEPA 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 (1991) built a salmon mortality model parameterized with values supplied by USFWS (Richardson and Harrison 1990) in collaboration with DFG. 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 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 (M_{15}) = $1 - (1 - 0.0533)^{15} = 1 - 0.44 = 0.56$

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:

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

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:

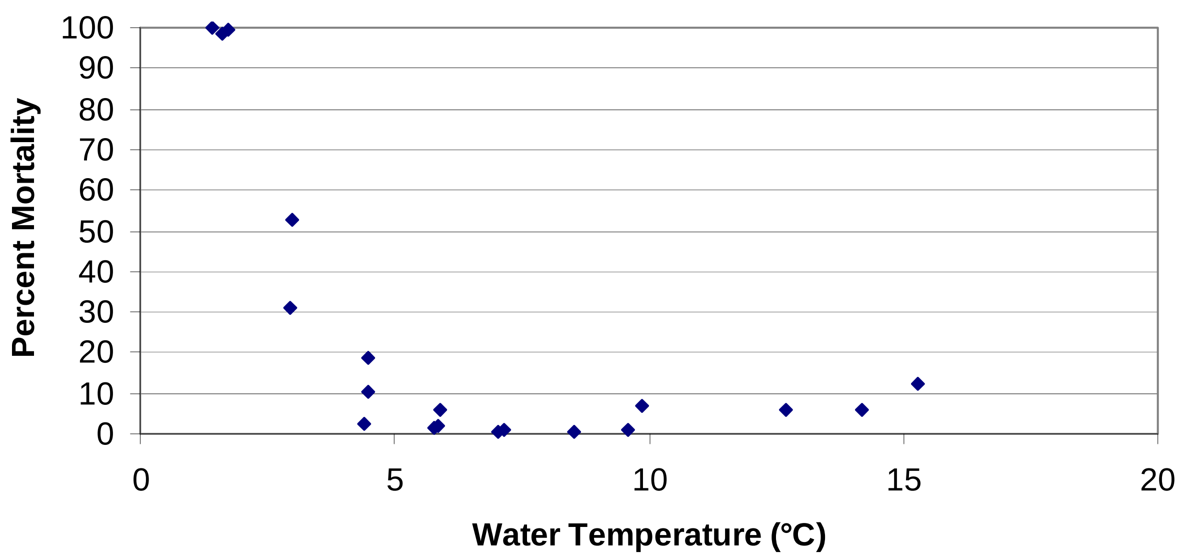
$$1 - (1 - M_1)^{12} = 0.99$$

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

$$M_1 = 1 - 0.6812 = 0.3187$$

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 Billard (1985, Figure 7), citing his own published work (but in French), Berman (1990), Berman and Quinn (1991), and Leitritz and Lewis (1980). Berman held adult spring-run Chinook salmon at 14°C (57.2°F) and 19°C (66.2°F). The group held at 19°C (66.2°F) produced a greater number of pre-hatch mortalities and developmental abnormalities as well as smaller eggs and alevins. As with Berman and Quinn (1991), 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:

$$\text{Survival rate} = \frac{1}{1 + e^{-a-bT}}$$

where

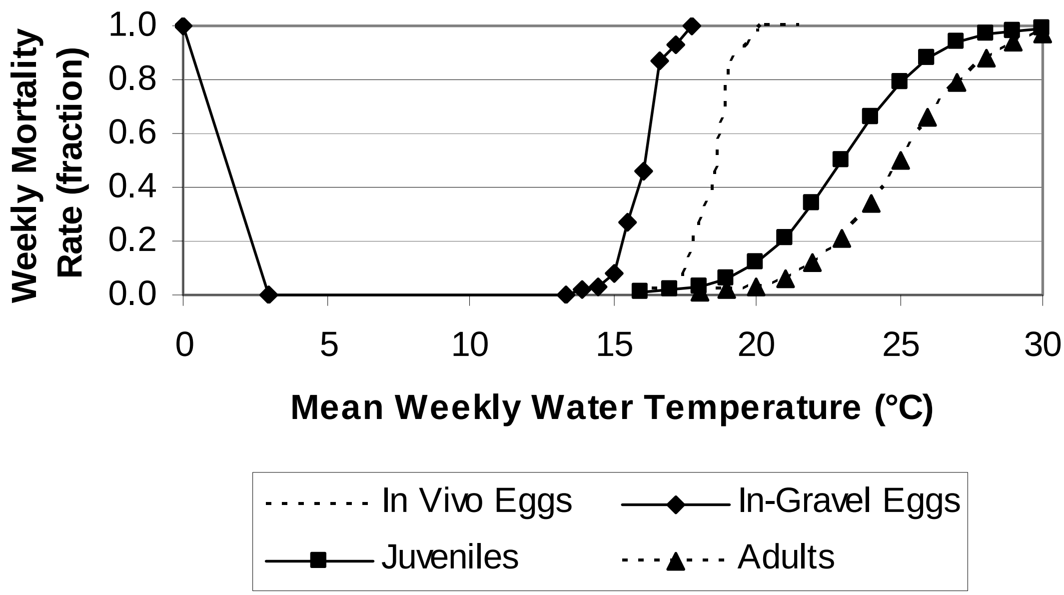
a = 15.56

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. (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); Berman (1990); 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:

^{0}C =degrees Celsius

^{0}F = degrees Fahrenheit

Myrick and Cech (2001) provide a recent 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.

Olson and Foster (1955) showed that Columbia River Chinook salmon eggs suffered a total of 79 percent mortality through the fingerling stage if initial incubation temperatures were 18.4°C (65.2°F), but only 10.4 percent mortality if the temperature was 16°C (60.9°F). The latest compilation of information appears in information assembled in support of thermal criteria developed by The Federal 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

Notes:
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:

$$1 \geq \frac{\text{minutes}}{10^{[a + b\,(\text{temperature }^\circ\text{C} + 2^\circ\text{C})]}}$$

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 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). For example, Allen (1969) cites an average salmonid density of 1.7 grams per cubic meter (g/m^2) for New Zealand rivers, an order of magnitude smaller than the values from Grant and Kramer (1990). 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 1995a, 1995b, 2001). 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 grams (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 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 DFG 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 DFG. 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 DFG'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 inundation pool.
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.
Habitat capacity movement rules	No	No	Based on literature and previous model.
Distance moved mortality rate	No	Yes	Derived initially from Bill Snider (DFG), but adjusted.

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
Exogenous production	Yes	Yes	Derived from Clear Creek; assumed Battle Creek was identical to Clear Creek; other tributaries and hatchery ignored.

Key:
DFG = California Department of Fish and Game
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 RBDD. 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.

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.

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 prior to 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

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

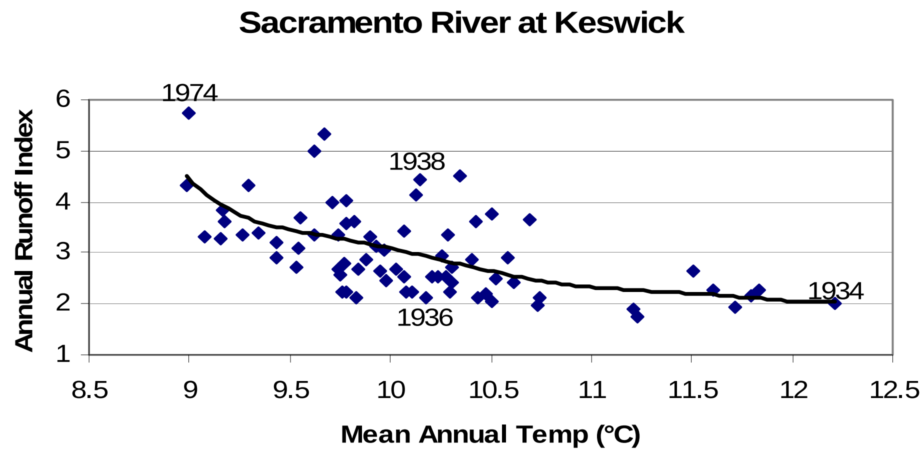
Model Constituent	Uncertainty	Sensitivity Range
Parameters (contd)		
Redd area	From measured data, but adjusted to minimize superimposition.	± 10 percent
Superimposition option	Set to “avoidance” to minimize superimposition.	Random/Avoidance
Egg development rate	Some uncertainty in hatch to emergent 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
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

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.



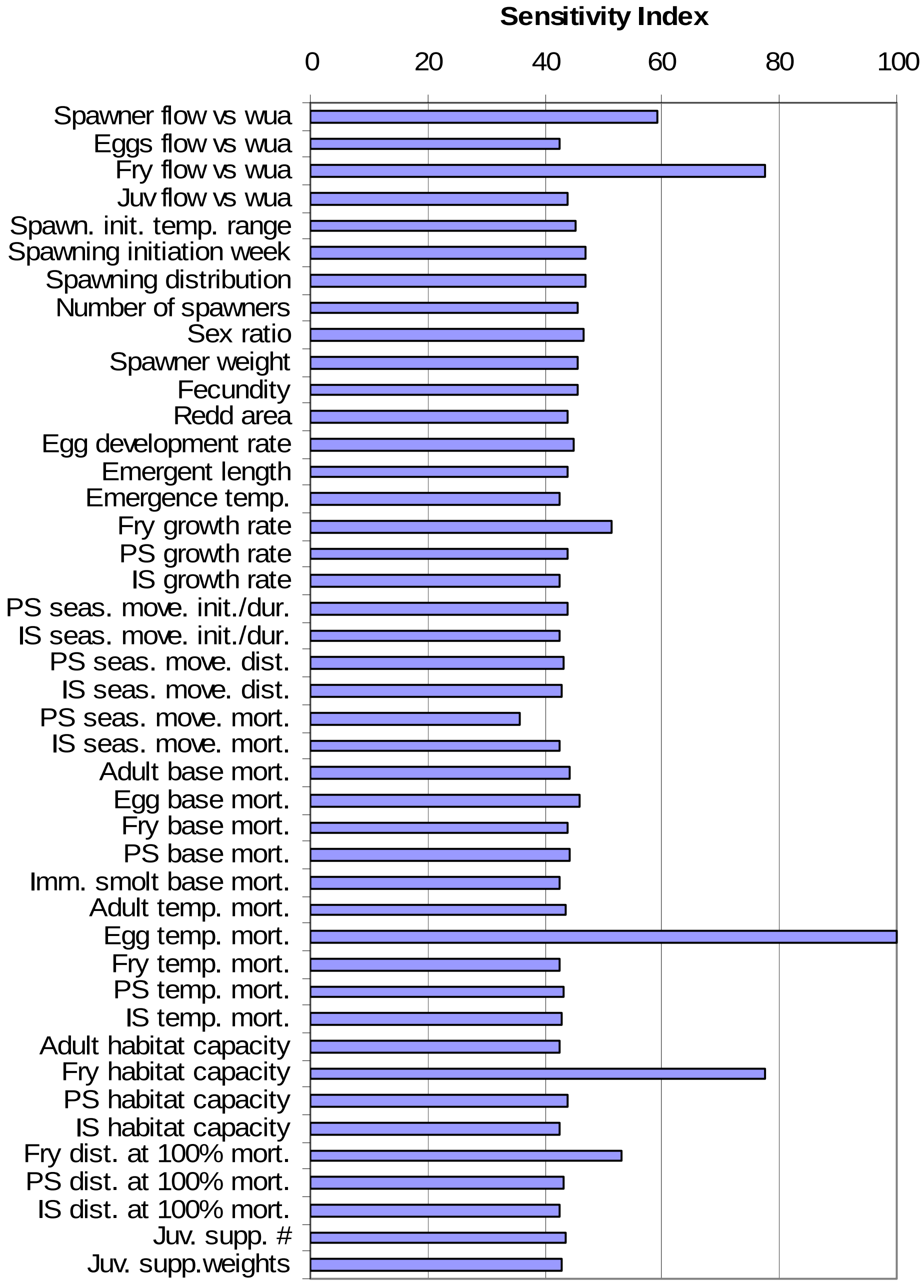
Notes:
1. Arrayed according to total annual runoff and mean annual water temperature downstream from Keswick Dam.
2. Solid line is simple polynomial fit, and four labeled points are the water years selected for sensitivity study.

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.

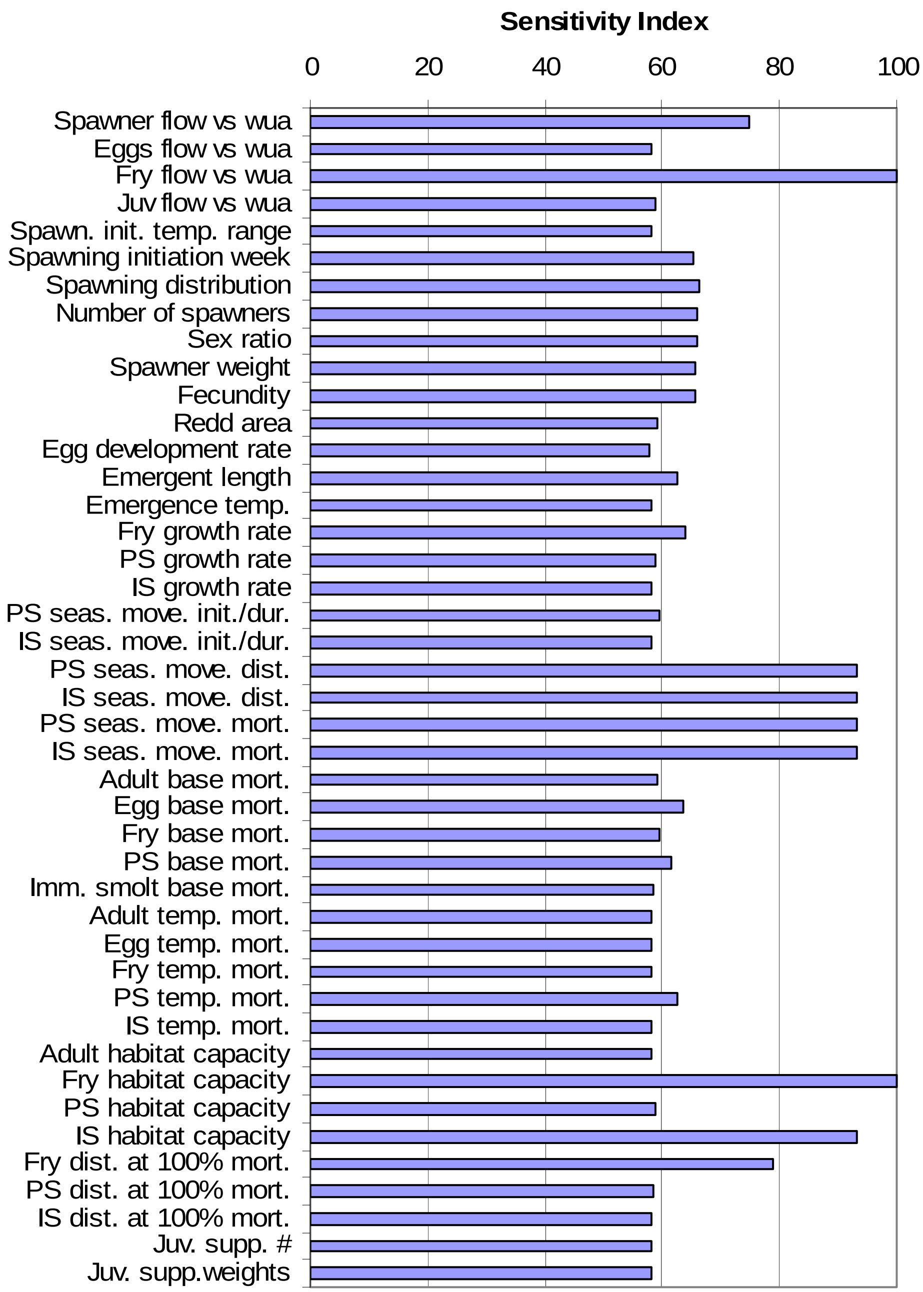
Sensitivity Analysis Findings

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.



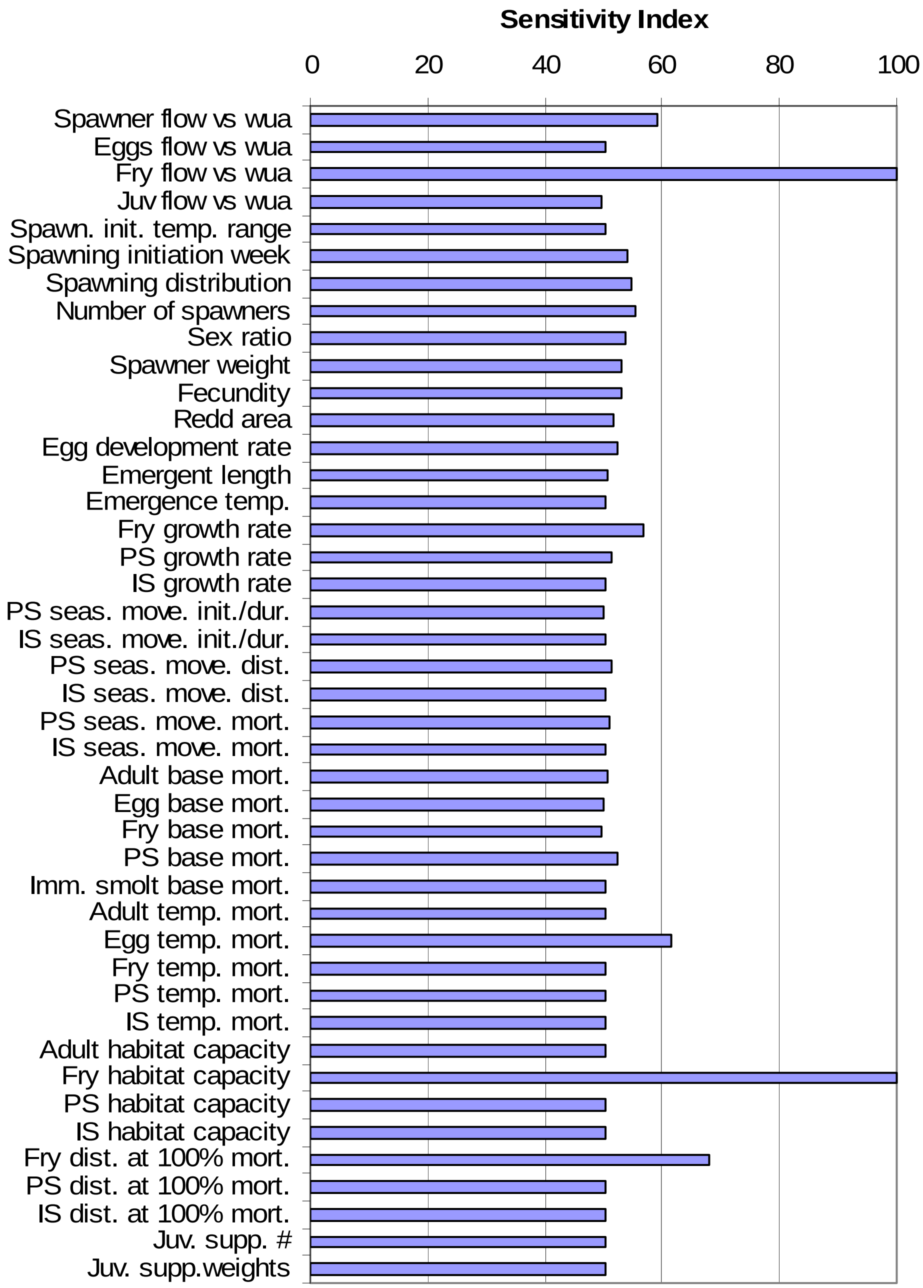
Note: Arranged from most sensitive at the top to least sensitive at the bottom

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



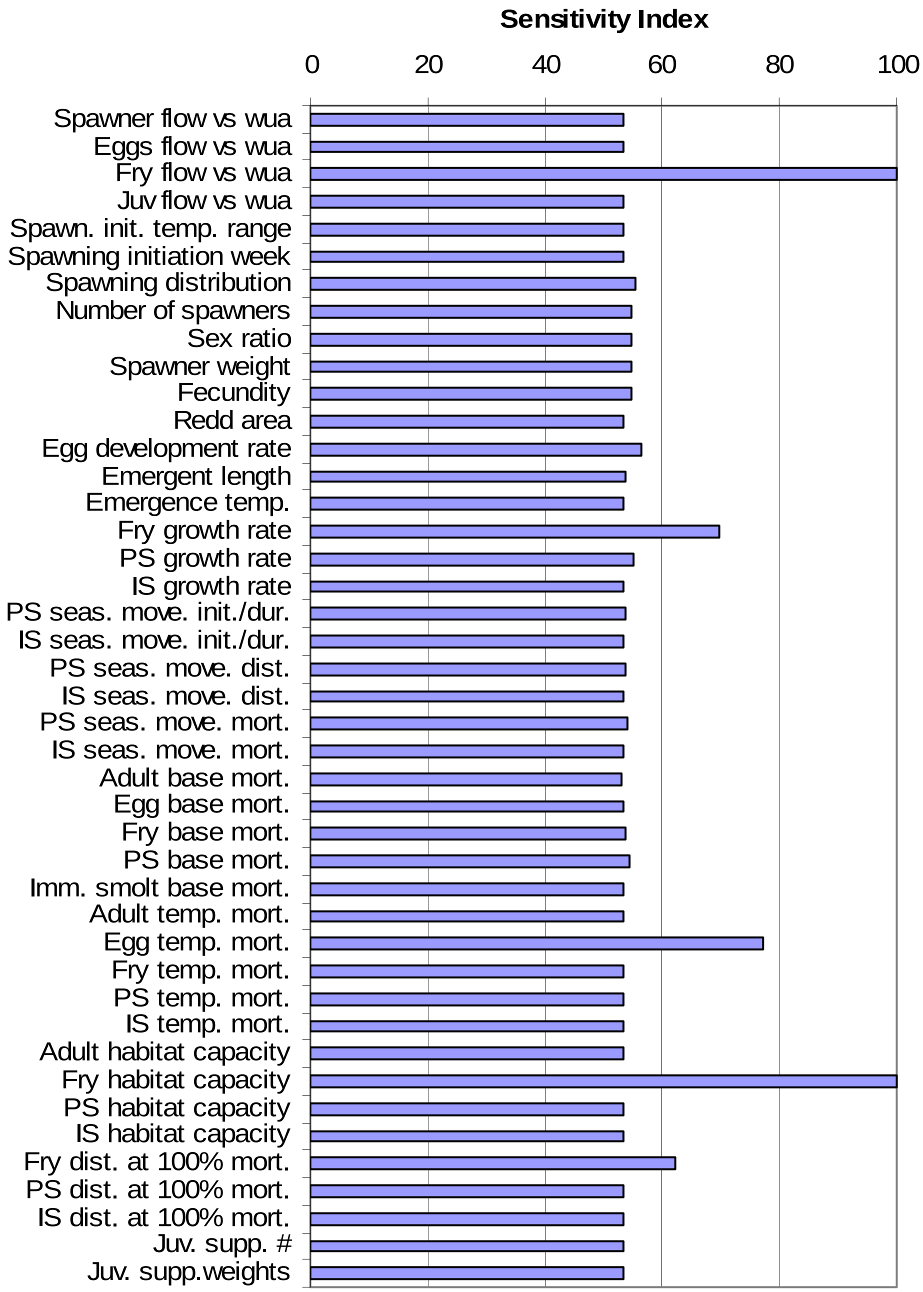
Note: Arranged from most sensitive at the top to least sensitive at the bottom.

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 RBDD, where other density-dependent phenomena may constrain the populations. 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

Walters (1986) reasons that 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, Walters (1986) further argues that 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.

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 is "calibratable") • 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 (Ahearn et al. 2005) 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 over 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.

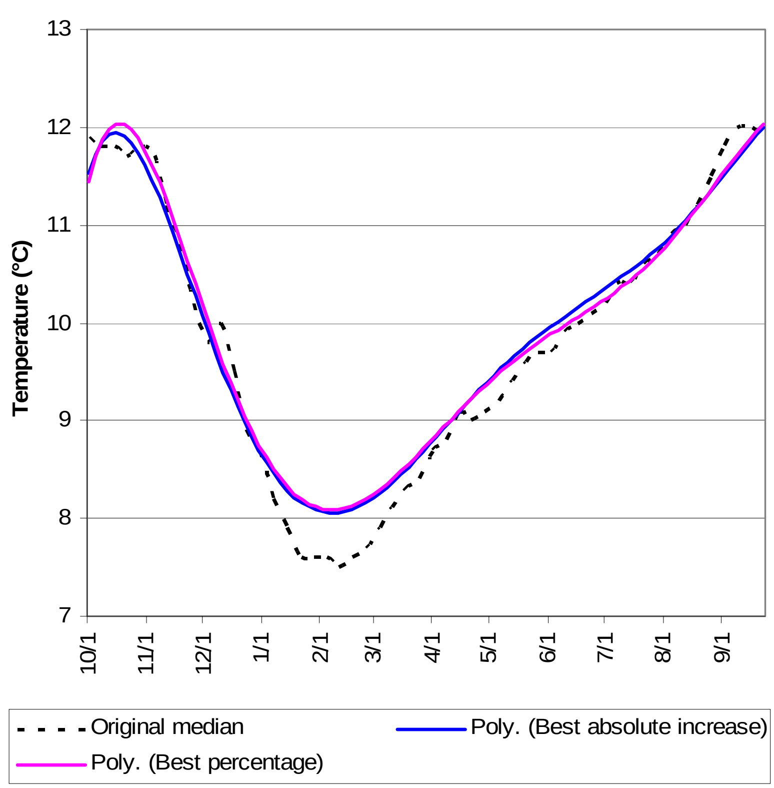


Figure 5-15. Idealized Annual (52-week) Thermal Regimes Compared to Median 18.5-foot Dam Water Temperatures

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Chapter 6
Urban Water Supply Economics Model (LCPSIM)

Least-Cost Planning Simulation Model

LCPSIM was the Urban Water Supply Economics Model used for the SLWRI, and is described in this chapter. Figures at the end of the chapter contain LCPSIM input and output data, LCPSIM interface screenshots, and smoothing analysis utility screens.

LCPSIM Objective

The objective of the use of LCPSIM with respect to the Integrated Storage Investigations Program is to be able to assign an economic value at the Delta for proposed water storage programs that will allow them to be compared on the basis of their contribution to urban water supply reliability.

LCPSIM Model Concept

LCPSIM is a yearly time step simulation/optimization model that was developed to assess the economic benefits and costs of enhancing urban water service reliability at the regional level. LCPSIM output includes the economically efficient level of adoption of reliability enhancement measures by type, including the cost of those measures. LCPSIM accounts for the ability of shortage management (contingency) measures, including water transfers, to mitigate regional costs and losses associated with shortage events, as well as the ability of long-run demand reduction and supply augmentation measures to reduce the frequency, magnitude, and duration of those shortage events.

In LCPSIM, a priority-based objective, mass balance-constrained linear programming solution is used to simulate regional water management operations on a yearly time step, including the operation of surface and groundwater carryover storage capacity assumed to be available to the region. The system operations context allows the evaluation of the reliability enhancement contribution of additional regional long-term water management measures, including increased carryover storage capacity, to account for any synergistic interactions between measures. The cost of adding those measures is determined using a quadratic-programming algorithm that minimizes the cost of each incremental addition.

LCPSIM is designed to be data-driven to easily represent different analytical circumstances without changing the model code. If unique situations require recoding, the source has been written with an emphasis on modularity.

Least-Cost Planning Strategy

The primary objective of LCPSIM is to develop an economically efficient regional water management plan based on the principle of least-cost planning. Under this principle, the total cost of reliability management is minimized. This total cost is itself the sum of two costs: the cost of reliability enhancement and the cost of unreliability, recognizing that the latter is inversely related to the former.

Using LCPSIM, an economic value can be assigned to a proposed program to augment imported supplies to a region; such an increase allows a region to develop a water management plan on least-cost planning principles that results in a lower total water management cost compared to the circumstances without the proposed augmentation program.

Foregone use is the most direct consequence of unreliability. Foregone use occurs when residential users or businesses, for example, establish a lifestyle or a level of economic production based on an expected level of water supply available for use and that expectation is not realized (i.e., a “shortage event”) in a particular year or sequence of years. Figure 6-1 illustrates the expected decrease in costs and losses associated with foregone use as regional water management options are adopted to enhance reliability. This enhancement may be obtained from either supply augmentation or demand reduction options.

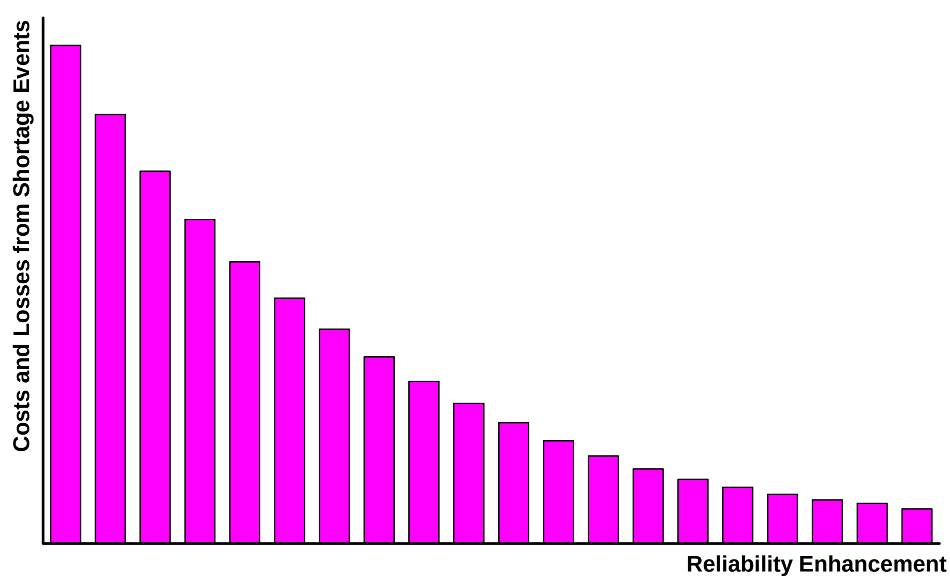

Figure 6-1. Effect of Increasing Reliability on Expected Costs and Losses

Figure 6-2 depicts the incremental effect of augmenting reliability on regional long-run water management costs. The assumption is made that options are adopted in an order inversely related to their unit cost; the least expensive options are expected to be adopted first.

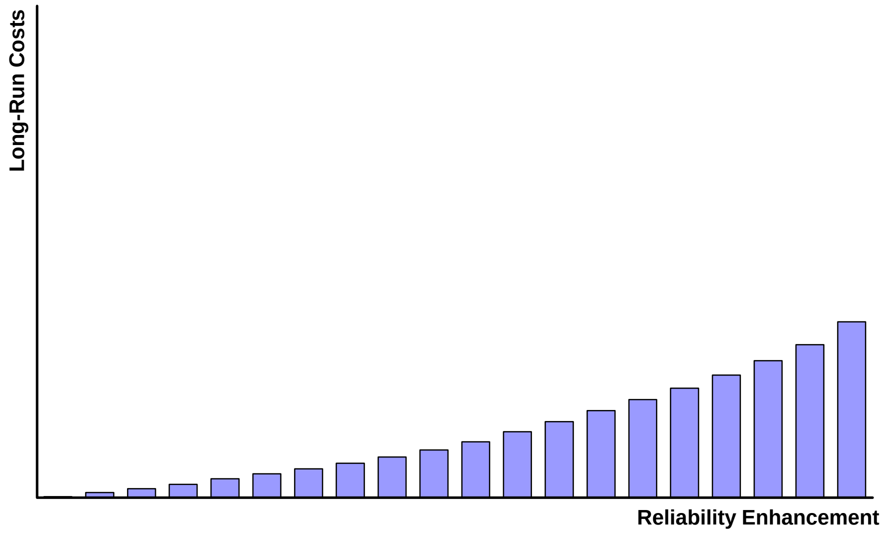

Figure 6-2. Effect of Increasing Reliability on Water Management Costs

Figure 6-3 shows the result of combining the information from Figures 6-1 and 6-2 into regional total water management costs tied to the level of reliability enhancement. The least-cost solution is economically efficient, meaning costs are accepted until additional investment equals the cost of actual shortages.

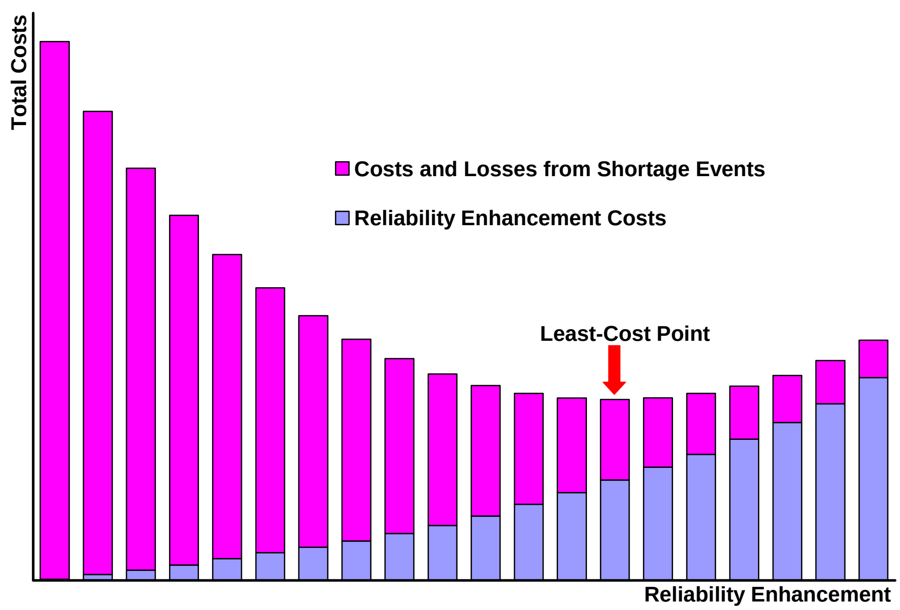

Figure 6-3. Effect of Increasing Reliability on Total Costs

LCPSIM as a Least-Cost Planning Tool

Modeled Relationships

At the least conceptually complex level, the relationship illustrated in Figure 6-3 relates the effect of adopting long-run water management options, such as recycling or toilet retrofit programs, on costs and losses associated with shortage events. At a more complex level, the availability and use of contingency measures to mitigate the economic impacts of shortage events, such as short-term water market transfers, use of supplies from carryover storage (conjunctive use), and water allocation programs can affect the economically efficient level of adoption of the long-term water management measures. Conversely, the level of adoption of long-term measures can influence the effectiveness of the contingency management measures and, therefore, their use.

Figure 6-4 depicts the primary planning interrelationships important for evaluating, from a least-cost perspective, the cost of alternative plans to increase the reliability of a hypothetical water service system. The link between the investment in long-term water management options and the size and frequency of shortages is shown, as is the link between shortage contingency management abilities and the costs and losses associated with foregone use; a greater investment in the ability to manage shortages will lessen the economic costs and losses due to foregone use when they occur.

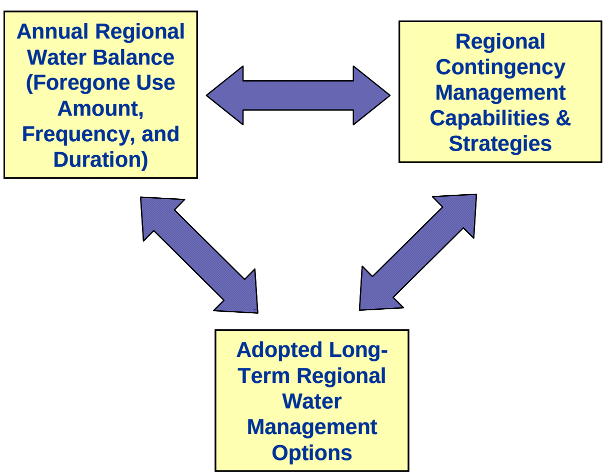

Figure 6-4. Reliability Management Linkages

The severity of these costs and losses are, in turn, linked to the willingness to invest in long-term water management options. Also, the larger the investment in long-term reliability enhancement, the less frequent and less severe the shortages experienced, reducing the need to invest in the ability to manage shortages. Capturing a system with multiple sources of feedback, such as those that characterize the system outlined in Figure 6-4, is a complex problem.

Basic Model Framework

Figure 6-5 shows the basic elements of LCPSIM used to generate the total costs and losses curve. This framework attempts to capture the interrelationships depicted in Figure 6-4 for the San Francisco Bay and South Coast hydrologic regions, recognizing the trade-off between reasonableness and both input data requirements and model complexity.

LCPSIM identifies the economically justified level of reliability enhancement provided by long-term water management measures in the context of regionally available contingency measures. Regional reliability management measures are divided into three categories: (1) shortage contingency demand management (including use reduction and reallocation of available supplies) and supply augmentation; (2) long-term demand reduction and supply enhancement; and (3) economic risk management. The latter strategy involves accepting a degree of economic risk from forgone use to avoid the use of other water management measures that are perceived to be even more costly. The least-cost combination of economic risk, regional long-term water management facilities and programs, and shortage management actions is identified within the model for each alternative water management plan being evaluated.

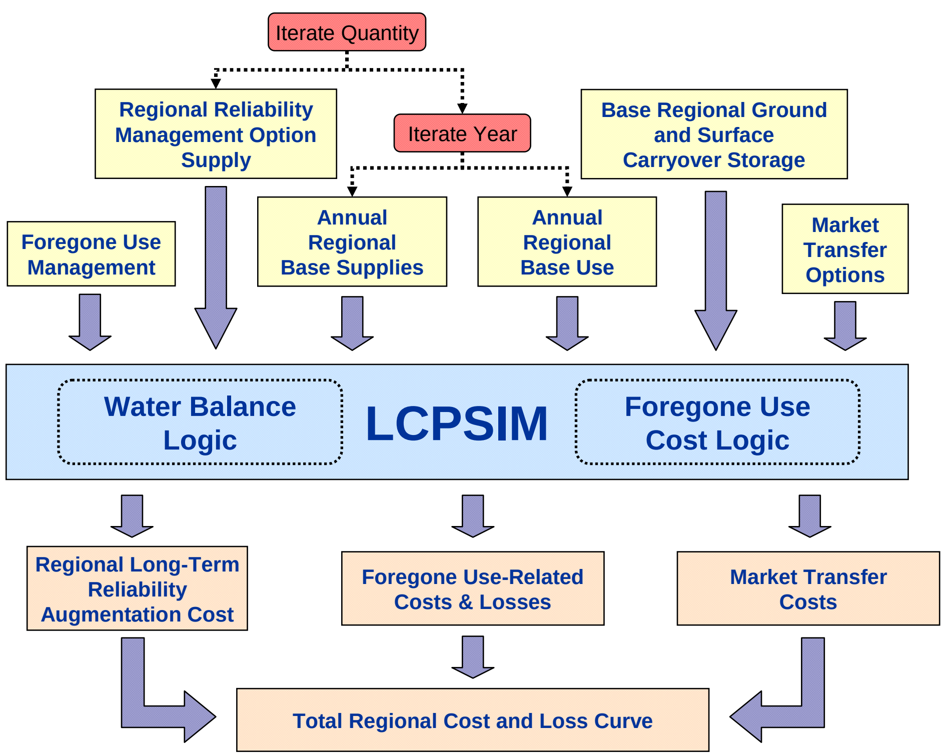

Figure 6-5. LCPSIM Basic Elements

Specific Water Agency Operations Modeled

Modeled operations include deliveries to users, deliveries to and from carryover storage, water transfers, and shortage-related conservation water allocation programs.

Carryover Storage Operations

Shortage contingency management measures include the augmentation of current year deliveries with previously stored delivery quantities. In LCPSIM, use of carryover storage is limited to that amount that has been previously placed in storage or declared to be in storage at the start of the simulation. Carryover storage capacity can exist both in surface reservoirs and groundwater basins. The ability to use this storage is modeled using capacity constraints for reservoir and groundwater operations, and annual fill (put) and withdrawal (take) rate constraints for groundwater operations. In general, regional surface storage carryover is withdrawn preferentially to groundwater storage carryover. LCPSIM can also use take capacity to stored supply ratios to dynamically set priorities for deliveries to carry over storage (puts) withdrawals from carryover storage (takes) (see "Annual Priority-Weighted Mass-Balance Constrained Linear Optimization," page 6-13).

Banked Groundwater A banking arrangement may involve an agreement between water agencies in two different regions of the State; for example allowing one agency to operate a specified portion of the other agency's groundwater storage capacity (e.g., the agreement between the Santa Clara Valley Water District and the Semitropic Water Storage District). The stored water is water that would otherwise be delivered for use under contract or water right but is stored for later delivery and use during shortage events. LCPSIM has the capability of simulating groundwater bank take constraints such as those agreed upon between Metropolitan Water District of Southern California (MWDSC) and the Semitropic Water Storage District and between MWDSC and the Arvin-Edison Water Storage District. The rules for simulating these constraints are stored as LCPSIM data files.

Regional Carryover Storage Regional carryover storage may be conjunctive use storage that is physically located within the region or it may be located outside of the region (e.g., MWDSC's Hayfield Project). Storage that uses a Federal contract service conveyance facility (e.g., the Colorado River Aqueduct) is constrained by the conveyance capacity available (Federal contract deliveries are given priority).

Reserve Storage SWP terminal reservoir storage in the South Coast Region can be used for shortage management per contractual agreement. LCPSIM can place strict rules on the use and refill of this storage (i.e., the last to be used and the first to be refilled).

SWP Carryover If storage is available in the San Luis Reservoir, SWP contractors can elect to have a portion of their SWP supplies stored for delivery in the following year when the stored quantities are always assumed to be used to augment SWP deliveries. Available San Luis Reservoir storage is determined using a file of time series (TS) data generated by the CALSIM.

Conservation and Rationing Operations

These operations are measures that are instituted during shortage events or when the total carryover storage quantity available to meet a shortage event, if it occurs in the following year (or years), is of serious concern.

Contingency Conservation Measures Examples of contingency conservation measures include: alternate day watering regulations, water waste patrols, emergency water pricing programs, and intensive public education campaigns. A specified reduction in use can be expected upon implementation of a program that includes such measures. LCPSIM assumes that such a program is instituted whenever there is a shortage in available water supplies compared to current use or in response to low carryover storage availability.

Curtailment of Interruptible Deliveries The economic losses assigned to users of interruptible supplies are assumed to be limited to the cost of those supplies in accordance with their usual water rate. Interruptible program deliveries are assumed to be cut back along with noninterruptible deliveries but at a higher rate relative to noninterruptible cutbacks.

Contingency Water Transfers Water transfers are modeled using constraints as well as costs by source. These constraints include conveyance capacity, carriage water, and other conveyance losses, and can be limited to the amount of water that can be transferred over a specified period or in consecutive years to emulate strategies for mitigating third-party impacts. If available, water costs by year type can be used.

Water transfers are also handled differently than other shortage contingency measures in the model. Using quadratic programming, a least-cost solution can be found for the sum of the economic losses to urban users and the total cost of the available supplies transferred. Alternatively, water can be transferred for shortage management using cost effectiveness. Water transfers for the purpose of alleviating depleted carryover storage conditions are always based on cost effectiveness.

Rationing In LCPSIM, "rationing" is shorthand for a water allocation method designed to minimize the overall economic costs of shortage by "balancing" the costs of shortage among customer classes. Above a specified threshold level, shortages are allocated to commercial users as a specified fraction of residential user shortages. Industrial users are allocated an even smaller specified fraction of the shortage allocated to residential users. The LCPSIM allocation method is intended to mimic water agencies either setting the allocation of the remaining supplies by user type or maintaining provisions for exemptions due to serious adverse economic impacts (e.g., layoffs) for businesses.

Economic Losses

A single residential user loss function is used for all user types to generate shortage event losses. Users in the commercial and industrial water use sectors–are, above a specified threshold shortage size, when their marginal losses are assumed to be substantially higher–allocated proportionately less of the overall forgone use during shortage events by the LCPSIM logic. This mimics the shortage contingency management programs used by local water agencies. These programs can be a preestablished cutback schedule by user type and/or a case-by-case cutback exemption program that is sensitive to avoidance of business income and job losses.

Elasticity of Demand

In LCPSIM, the cost of additional supply reliability and the cost of shortages (including the cost contingency supply and demand management measures) affect the level of the use of long-term conservation measures beyond those included in the base use values. This is because the economic optimization logic used in LCPSIM depends on comparing the marginal cost of regional long-term conservation measures, the marginal cost of regional supply reliability, and the marginal expected cost of shortages. Water use is therefore a function of the overall regional economic efficiency of water management. This is equivalent to the concept of price elasticity of demand but on an alternative marginal cost basis.

Demand Hardening

Long-term demand management measures that are adopted by water users can have a demand hardening effect. Although these measures can increase reliability by reducing the size, frequency, and duration of shortage events, they can make these events relatively more costly when they do occur. A hardening factor can be set in LCPSIM to simulate this effect (i.e., if conservation decreases demand by a specific percentage, then the economic impact of a shortage of a specified size is computed as if the shortage were greater based on the hardening factor).

Unused SWP Supplies

The CVP and SWP water deliveries used by the LCPSIM are generated by the CALSIM project operations model. CALSIM deliveries are driven by specified target delivery quantities which it tries to meet based on available inflows and storages in the CVP and SWP systems for each year of the hydrology used. Because these targets are set independently of the LCPSIM, an economically efficient water management plan can produce a level of reliance on regional supply and conservation measures that can result in the target deliveries for a region having been set too high for the wetter years. In these years, the capacity for deliveries to carryover storage can be exceeded, either because the volume to be stored exceeds the available space or the annual put rate is insufficient. This “excess” supply is assigned to the SWP because it is assumed by the LCPSIM to be the marginal supplier. This excess urban delivery quantity can be used to augment annual urban deliveries to other regions, to agricultural users, or used to reset the target deliveries in CalSim-II.

LCPSIM Simulation Logic

The following is a breakdown of the LCPSIM by its major logic elements.

Basic LCPSIM Water Management Simulation Elements

Figure 6-6 represents the basic water management operations simulation elements in LCPSIM.

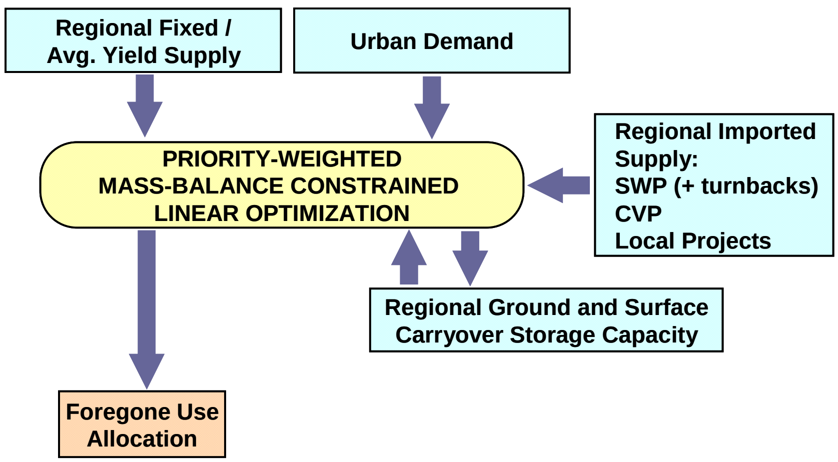

Figure 6-6. Basic LCPSIM Water Management Simulation Elements

Regional Fixed/Average Yield Supply Water supplies include within-region surface and groundwater supplies exclusive of carryover operations expected to be available for the study year level (e.g., 2030). These supplies include recycling and groundwater recovery. Because of a lack of information about the year to year availability of the supplies from within-region reservoir storage and groundwater operations, they are included as long-term averages unless otherwise noted.

Import Supply TS (Level 5) Annual deliveries from projects which import water from outside the region including the SWP, Federal service contract delivery projects, and regional projects. In the South Bay Area, the Federal service contract delivery sequence represents CVP deliveries for the South Coast Region, the sequence represents Federal deliveries made through the Colorado River Aqueduct.

Other Supply TS Other variable supplies available to the region are included as annual quantities over the hydrologic period being represented (e.g., the 82 years represented by the period 1922 to 2003).

If available, the data used are produced by hydrologic modeling studies. CVP and SWP deliveries are developed by using CalSim-II, DWR's project operations model for the CVP and the SWP. Colorado River Aqueduct Deliveries were sent a long-term average based on the recent Quantification Settlement Agreement.

For the South San Francisco Bay Area, the regional variable supply sequence is developed from modeling done by the East Bay Municipal Utility District (Mokelumne Aqueduct) and the San Francisco Water Department (Hetch-Hetchy Aqueduct). For the South Coast Region, the regional variable supply sequence results from modeling done by the Los Angeles Department of Water and Power (Los Angeles Aqueduct). If a TS of regional groundwater availability (exclusive of conjunctive use operations) is available, the quantities can be added to this file.

A fourth supply file of "excess" SWP deliveries can also be used. If a portion of the SWP supply available to a region exceeds both current quantity demanded and available carryover storage capacity, a TS file of the excess quantities can be generated by LCPSIM for that region and used to augment SWP deliveries to another region.

Priority Uses Uses that are assumed to be required to be met by regional supplies before the supplies are available for allocation to urban demands include noninterruptible agricultural use, environmental use, and conveyance losses. The supply needed to meet these uses is reduced by the regional reuse that occurs in the process of applying water for these purposes. LCPSIM uses a TS file of annual variation from average crop ETAW (Evapotranspiration of Applied Water) along with forecasted average applied water use from the parameter file to generate TS agricultural use data. Information on annual crop water use variation comes from a simulation model of unit crop ETAW that was developed to create a historical agricultural water use pattern for the 1922 to 2003 hydrologic period by water year (September through October). A reuse factor from the parameter file is used to generate the annual net agricultural use data used by LCPSIM.

Urban Demand TS The annual demand sequence consists of two components, noninterruptible, and interruptible demand. The demand sequence for noninterruptible urban deliveries is developed from a forecasted quantity demanded for the study level (e.g., 2030) being investigated. The annual interior and average annual exterior urban demand quantities are calculated using the interior and exterior urban demand share values from the parameter file. Interior demand is assumed to have the same value for all years. A value in the main parameter file allows for the separation of exterior use into two components, a fixed component, which is assumed to have the same value for all years, and a variable component, which is assumed to be directly proportional to the ETAW for each year.

A simulation model of urban turfgrass water use was developed to allow the creation of an annual ETAW variation TS for the 1922 to 2003 hydrologic period by water year (September through October). A variable exterior use component TS demand is generated using this TS and the average variable exterior demand. Adding the variable exterior demand TS to the sum of the fixed exterior demand component and interior demand produces the total urban applied water demand sequence.

Because the demand sequence consists of applied water quantities, they must be converted to net quantities for use in the mass balance logic. All of the variation in total applied water demand is assumed to arise from exterior applied water use. While the regional reuse associated with interior use is consequently constant, reuse associated with exterior applied water use varies from year to year. Interior and exterior reuse is calculated using factors from the parameter file.

The interruptible component of demand for the South Coast Region was developed from information contained in the annual financial reports of MWDSC. This component was held constant for the study period and the quantity specified assumes that other sources of supply will not be used in-lieu. No interruptible delivery program was assumed for the South San Francisco Bay Area.

Regional Ground and Surface Carryover Storage Capacities The carryover storage element of the basic water management simulation algorithm was developed from information published by agencies within the study regions as well as discussions with their staff. The information obtained was used to estimate the average amount of groundwater basin and reservoir storage capacities available for the purpose of storing currently available water for use in future years. The carryover storage capacities are the amounts over and above the capacities needed for regional intra-year operations. In the same manner, annual rate ceilings for deliveries to carryover storage (puts) and withdrawals from carryover storage (takes) were developed.

Carryover storage operations can involve storage capacities within the region or external to the region. Puts involving groundwater storage can be accomplished by injection wells, spreading basins, or in-lieu deliveries (water users normally pumping groundwater are switched to surface water supplies). Conversely, takes from groundwater storage either can be accomplished by groundwater pumping or by switching water users who normally take surface water to groundwater pumping, allowing the now unused surface supplies to be delivered elsewhere.

Information entered into LCPSIM for individual carryover storage operations includes the capacity that can be operated, the initial fill, the annual put capacity, the annual take capacity, the conveyance facilities that will be used for puts and takes, any losses associated with storage operations, the on-site unit cost of the put and take operations, and whether one or more storage operations operate the same physical storage space.

SWP project deliveries direct to San Joaquin Valley groundwater storage are also supported in LCPSIM. The stored water is then made available for delivery to the study region in subsequent years.

Additionally, LCPSIM can allow for water market transfers for the purpose of replenishing depleted carryover storage. A state of depletion is defined to exist if the total supply stored is less than the capacity to deliver that amount from carryover storage. An LCPSIM parameter setting determines the depletion threshold for this type of transfer to take place (e.g., carryover storage at 80 percent of the delivery capacity).

Takes from carryover storage are constrained in LCPSIM to amounts accrued from puts in previous periods, with an allowance for a specified initial fill. Takes from carryover storage can also be constrained by a hedging function within the model. This hedging function can be assigned to any or all carryover operations but only on a total capacity basis. Figure 6-7 depicts the functional form used.

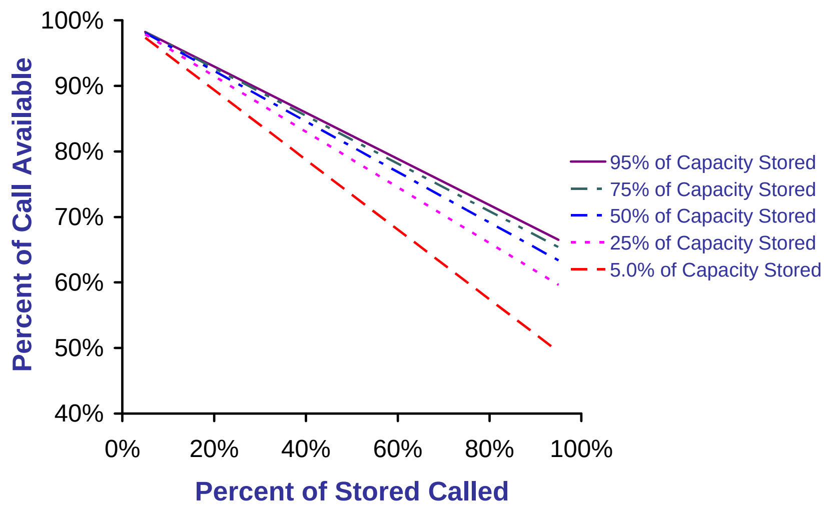

Figure 6-7. LCPSIM Hedging Function Example

From the example function shown, if the amount in storage is 50 percent of the total storage capacity of the operations selected to be hedged and 25 percent of the stored amount is needed to meet demand, 90 percent of the needed amount is supplied. If 75 percent of the stored amount is needed, 70 percent of the needed amount is made available. Three input parameters affect this function – the storage capacity ratio at which hedging is employed and two parameters which affect the absolute and relative slopes of the curves that relate quantity needed to quantity supplied.

Take constraints set in the reservoir carryover storage data file can also be used to represent a specific hedging strategy. LCPSIM also accepts water bank take constraint rules based on either reducing the allowed take in consecutive-year take situations (e.g., Arvin-Edison Water Storage District banking program), or on the project delivery received by the bank operator as a percentage of its contracted full-delivery quantity (e.g., Semitropic Water Storage District banking program).[1]

Annual Priority-Weighted Mass-Balance Constrained Linear Optimization
This model element is used to balance water use with water supply, simulating regional water management operations. Using the mass-balance logic requires that the demand data, which are applied water quantities, be converted to net quantities by accounting for regional reuse. Reuse is either fixed (e.g., recycling) or variable (e.g., in-region pumping of deep percolation). In LCPSIM, variable reuse arises primarily from deep percolation of exterior urban use (e.g., residential landscaping and public parks). The other variable source is interior urban wastewater that is deep percolated from septic tanks. For this conversion, interior use is assumed to be constant and any year-to-year variation in total use is assumed to arise from variation in exterior use due to weather (e.g., temperature and effective precipitation).

Storage operations are a critical component of the mass-balance logic. The put and take priorities for each storage operation are dynamically set by calculating the ratio of the stored supply to the take capacity for each storage operation for each annual time step. This ratio is then used to assign relative priorities for that time step: the lower the ratio, the lower the take priority and the higher the put priority. This strategy is designed to maximize supply availability from carryover storage when the desired deliveries to users exceed the supply available from other sources. Alternatively, these priorities can be set statically for each storage operation based on entries in the carryover storage data file.

Statically based priorities, in general, assume that when carryover supplies are needed to meet desired deliveries, water is preferentially taken from surface storage carryover supplies as opposed to groundwater storage carryover supplies. When supplies are available for refilling carryover storage, the supplies are preferentially used for groundwater storage carryover operations as opposed to surface storage carryover operations. Dynamically set put priorities are always used for water market transfers made to replenish depleted carryover storage, however.

If the water supply from the sources other than carryover storage is greater than desired deliveries to users, then this balance can be achieved by needed deliveries to carryover storage. Deliveries to carryover storage are constrained by annual put ceilings and available carryover storage capacity after adjusting

[1] Arvin-Edison Water Storage District's MWDSC take limit is reduced for each consecutive year for which a take is made. Semitropic Water Storage District's MWDSC take limit is equal to the bank's pumpback capacity plus the product of MWDSC's percentage share of the bank and Semitropic Water Storage District's SWP Contract Table A delivery after subtracting Semitropic Water Storage District's reserved amount of that allocation: Pumpback Capacity + Share of Bank * ((Table A Allotment * Percentage of Table A Delivered) - Reserved Table A).

for put efficiencies (if less than 100 percent). The amount of supply remaining subsequent to this balance due to these carryover storage delivery constraints is used to estimate how planned SWP operations might be reduced in specific years compared to the target deliveries sent in CalSim-II.

If the supply from the sources other than carryover storage is less than desired deliveries to users, this balance can be achieved by deliveries from carryover storage or by reducing use or both. Deliveries from carryover storage are constrained by the annual take ceilings and the amount of stored water available. Desired deliveries are separated into three categories: base use deliveries, deliveries for contingency conservation affected use, and interruptible use deliveries. Contingency conservation affected use is that amount of noninterruptible use, which can be expected to be eliminated on a short-term basis in response to programs such as drought alerts and conservation advice in the media, local agency water-waster patrols, alternate-day watering rules, etc.

Although a mass balance constraint is used to assure that supplies equal uses (aside from any supplies excess to the quantity demanded that can't be delivered to carryover storage), how this balance is achieved is set by assigning priority weights to affect how the water is moved. The algorithm maximizes quantities weighted by priorities subject to the imposed system constraints.

To assure that failing to meet the quantity demanded for current base consumptive use is a "last resort," meeting it has a high priority. Contingency conservation affected current consumptive use has a somewhat lower priority. Interruptible use has a relatively low priority compared to the other use categories. Even lower priorities are assigned to deliveries to carryover storage. Because of how it is used, however, a relatively high priority is given to reserve reservoir storage to ensure it is refilled as quickly as possible, even if contingency conservation is still in effect.

On the supply side, water delivered from sources other than carryover storage is assigned the lowest priority (i.e., the model uses this source first). Next in priority are deliveries from carryover storage, with the weight scheme giving preference to deliveries from reservoir carryover.

Overriding the allocations based on weights are contingency constraints that are implemented to reflect contingency shortage management programs. One such contingency constraint is a function relating interruptible program cutbacks to the level of the supply made available for delivery to the noninterruptible uses. An input parameter in the model determines the level of reduction in deliveries to the noninterruptible uses at which point the interruptible program is zeroed out.

Another contingency constraint keeps carryover supplies from being delivered from reserve reservoir storage facilities. This category of storage is available for use only if supplies delivered from sources other than carryover are less than that needed for base and interruptible use plus the amount needed to refill any available reserve reservoir storage capacity. A contingency constraint is also used to curtail supplies allocated to contingency conservation affected use. This represents the institution of a contingency conservation program and allows supplies that would have been directed to this category of use to be allocated elsewhere. Figure 6-8 shows the function used to implement this constraint. The take call ratio relates desired deliveries to supply availability, including the supply available from carryover storage but exclusive of water transfers that have a shortage threshold constraint imposed. The capacity use ratio relates the total amount of capacity available to store carryover supplies to the total amount of water in carryover storage. Both of these ratios are input parameters to LCPSIM.

Shortage   After the mass balance is performed, there may not be sufficient supplies available from current year supplies and withdrawals from carryover storage to meet the quantity demanded.   Before determining the economic losses from forgone use, the ability of contingency water market transfers to augment current year supply is simulated.

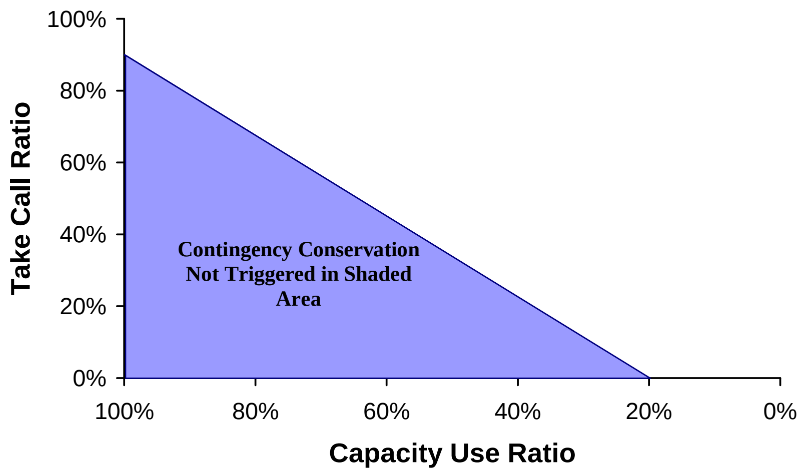

Figure 6-8. LCPSIM Trigger Function for Contingency Conservation

Regional Water Market Transfers and Economic Losses

Figure 6-9 shows the elements from Figure 6-8, with the addition of elements used to simulate water market transfers and an element used to determine economic losses from foregone use.

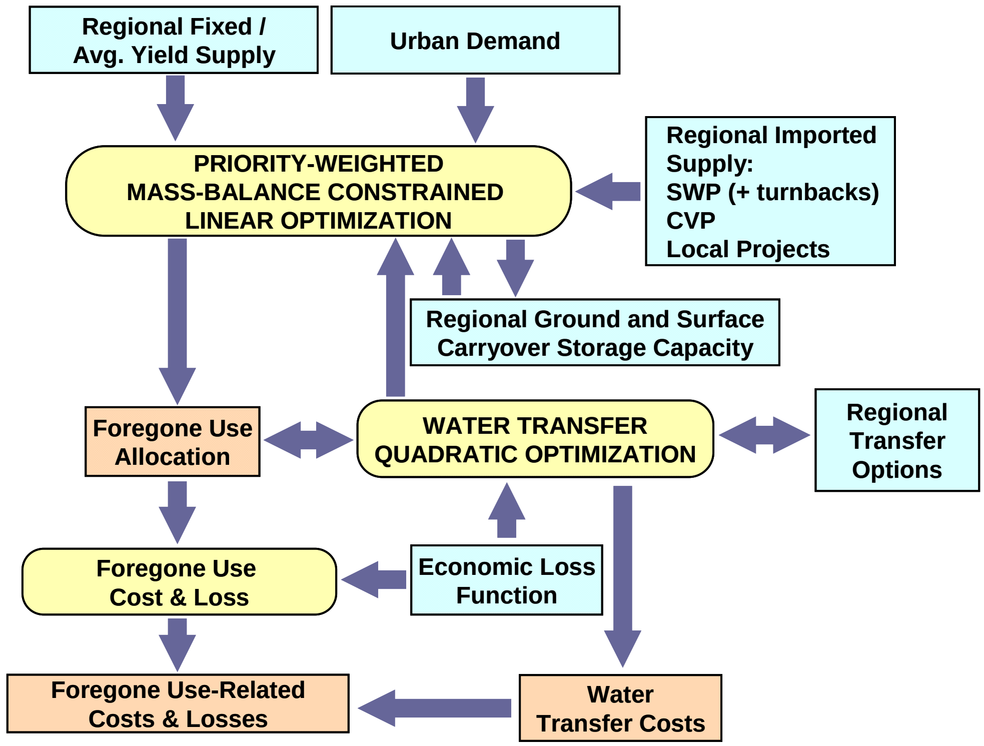

Figure 6-9. LCPSIM Regional Water Transfers and Economic Losses

Regional Water Market Transfer Options TS Water market transfer options are input into LCPSIM in terms of the quantity available from a specified source, the cost obtaining the water at the source, what facilities will be used to convey the transferred water, any losses during conveyance (e.g., carriage water for transfers involving the Delta), and any constraints on the frequency of use of the transferred water from that source. Multiple sources can be used. Also, transfers that have a forgone use threshold constraint can be specified. System conveyance capacity constraints and delivery efficiency factors for water market transfers in the form of TS files generated by CALSIM or other system models can be used by LCPSIM. LCPSIM can use such files for transfers from the either Sacramento Valley, the San Joaquin Valley, or both.

The cost of obtaining the transferred water can be entered as coefficients of a quadratic function, representing the situation where the unit price increases linearly as the amount purchased is increased. If available, the cost data can be entered as a file of cost coefficients by year type.

Identification of the conveyance facility is needed to determine what capacity remains for moving the water to be transferred and to determine the conveyance cost. If the conveyance facility is a federal service contract facility that is used to convey exchanged SWP Table A contract deliveries, then the aqueduct capacity for transfers is increased during those years when Table A deliveries are cut back. For example, MWDSC delivers Colorado River water to Desert

Water Agency and Coachella Valley Water District through the Colorado River Aqueduct in exchange for their SWP contact deliveries.

Frequency-of-use constraints can be used to represent the need to respect the potential for serious third-party impacts. These constraints are specified by source and are in the form of a limit on the maximum amount of water that may be transferred during consecutive years and in terms of the maximum quantity to be made available over a 10-year period. Both of these constraints are expressed as a percentage of the maximum to be made available during any single-year event. Another third-party impact mitigation mechanism is a constraint that can be placed on transfer sources that restrict their use to shortage events which exceed a specified percentage of regional use. These constraint parameters are overridden if TS transfer quantity constraint files are available.

Simulated water market transfers include not only those made for shortage event management but also those made to augment carryover storage. The latter type of transfer can be triggered when carryover storage is depleted (i.e., when the amount of stored supply is less than the available take capacity). The trigger can be set in the LCPSIM parameter file as a percentage of take capacity.

Forgone Use Allocation After accounting for water transfers, this model element is used to allocate forgone use resulting from the remaining shortage among the different user classes represented in the model: industrial users, commercial and governmental users, residential users, and large landscape users. This allocation is determined by input parameters for the nonresidential users. These parameters represent the respective fractions of the residential percentage of use forgone that will be allocated to them. For example, a parameter value of 25 percent for industrial users means that these users will be held to a forgone use equal to 25 percent of the percentage use forgone by residential users. This results in the residential users forgoing use, in percentage terms, larger than the overall forgone use. This effect can be moderated by specifying that deliveries to large landscape irrigators will be curtailed at a greater percentage rate compared to residential users. An input parameter determines the level of overall forgone use at which this allocation takes effect. This is intended to represent strategies used by water agencies to protect businesses and institutions from serious economic damage and job loss during shortage events. Some water agencies have explicit water allocation rules. Other agencies have hardship exemption programs that have a similar result.

Economic Loss Function This model element assigns economic losses to foregone use. The loss function is input into LCPSIM either as a coefficient of a polynomial function relating a percentage shortage to a total cost of that shortage or as the coefficient of a constant price elasticity of demand function.

LCPSIM has the ability to use a polynomial loss function because this functional form has the advantage of allowing "threshold effects" to be modeled. There is evidence from contingent valuation studies (e.g., SWRCB Bay-Delta Hearings, Exhibit 51 (1987)) that it is possible that the inconvenience of dealing with water agency policies during shortage events (e.g., alternate day watering and gutter flooder regulations, water waster patrols) is perceived as a hardship over and above the value associated with the amount of water no longer available for use. If real, this phenomenon can be represented by a loss function that, over a limited range, associates a higher marginal value of supply at lower shortage levels than at higher shortage levels.

The ability to use a constant price elasticity of demand (CPED) function is also provided as an alternative, more conventional, means of representing demand (i.e., there is no "threshold effect"). It has the advantage of using just two parameters that are readily available from most econometric studies of water demand. This specification of the loss function results in the acceptance of an appreciably greater number of small shortage events at the least-cost LCPSIM solution compared to the polynomial function. Tables 6-1 and 6-2 show a comparison of results produced by the two functional forms.

Table 6-1. Example LCPSIM Polynomial Loss Function Values

	Willingness to Pay to Avoid Event Acre-Foot Use/Year/Household		
Foregone Use	**0.75**	**0.65**	**0.55**
0%	$0	$0	$0
5%	$49	$43	$36
10%	$145	$126	$106
15%	$278	$241	$204
20%	$439	$380	$322
25%	$618	$535	$453
30%	$804	$697	$590
35%	$990	$858	$726

Table 6-2. Example LCPSIM CPED Loss Function Values

	Willingness to Pay to Avoid Event Acre-Foot Use/Year/Household		
Foregone Use	**0.75**	**0.65**	**0.55**
0%	$0	$0	$0
5%	$29	$25	$22
10%	$79	$69	$58
15%	$166	$14	$122
20%	$323	$280	$237
25%	$618	$535	$453
30%	$1,194	$1,034	$875
35%	$2,376	$2,059	$1,742

For comparison, the elasticity value of -0.10 used for the CPED function is set to replicate the foregone use losses at 25 percent, as determined by the polynomial function. (A 1996 elasticity study done for DWR Bulletin 160-98 found an average elasticity of -0.16 for urban residential users (DWR 1998)).

When calculated losses occur, they can be increased by a specified percentage amount to reflect the consequences of consecutive shortage events of a magnitude greater than another specified percentage amount. Both percentages are model input parameters. This effect falls off as a power function of the number of years between events and does not apply if the next loss event follows by more than 2 years.

The losses are also adjusted by the amount of demand hardening present in the system compared to the base. Hardening is computed from the ratio of the quantity of use reduction due to conservation to total quantity of use before that reduction and expressed as a percentage. This percentage is then multiplied by a percentage specified as a LCPSIM input parameter (the demand hardening adjustment factor) to get a shortage adjustment factor.

This latter value is used to adjust the magnitude of the shortage before the loss function is applied. For example, if the preadjustment shortage is 10 percent, the demand hardening percentage is 20 percent, and the demand hardening adjustment factor is 50 percent, then the shortage is increased to 11 percent for the purposes of determining economic losses.

The unit value of the losses incurred by interruptible supply customers is the same as the unit price paid for that supply. This is based on the assumption that the price reflects the value of that supply, discounted for unreliability, by knowledgeable users of that source of supply.

Market Transfer Quadratic Optimization If the mass balance algorithm results in supplies that are insufficient to meet desired deliveries, this model element is used to determine the total amount of water to be transferred to reduce the deficiency. Unit water purchase costs from each source are adjusted upward by their respective conveyance losses and augmented by their respective conveyance costs. The unit purchase costs from any source can be specified as coefficients of a quadratic function, representing a unit cost that increases linearly as the amount used is increased. Quantities available from each source are constrained by the applicable conveyance capacities. The quadratic programming solution that minimizes the sum of the forgone use-related costs and losses and the costs of transfers is used to determine the quantity transferred.

Expected Costs and Losses Curve

Figure 6-10 shows the elements from Figure 6-9 with the addition of iteration logic. The summation of water transfer costs and foregone use costs and losses produces foregone use-related costs and losses for an individual year. Iterating through the years in the hydrologic record produces expected costs and losses based on the level of adoption of regional long-term reliability augmentation options. Further iterating these expected values by incrementally increasing the level of adoption of regional long-term reliability augmentation options generates a downward sloping curve of expected costs and losses points, as shown in Figure 6-11.

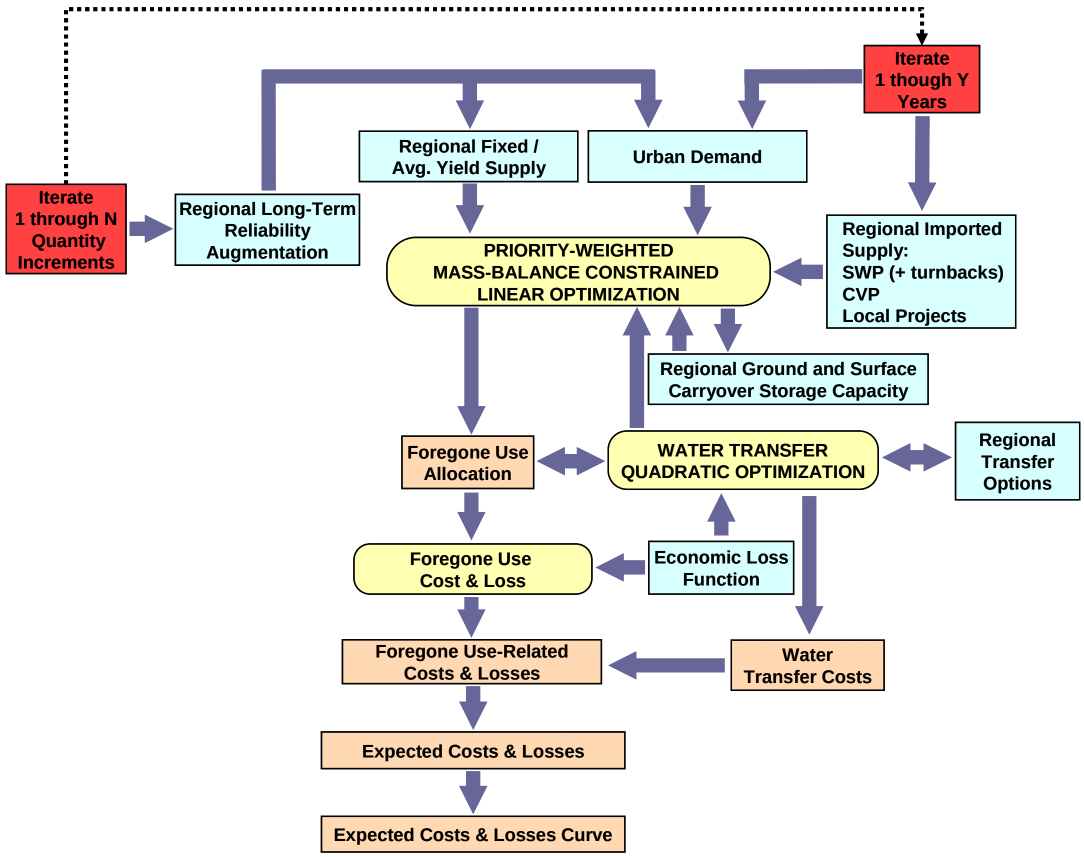

Figure 6-10. LCPSIM Expected Costs and Losses Curve Logic

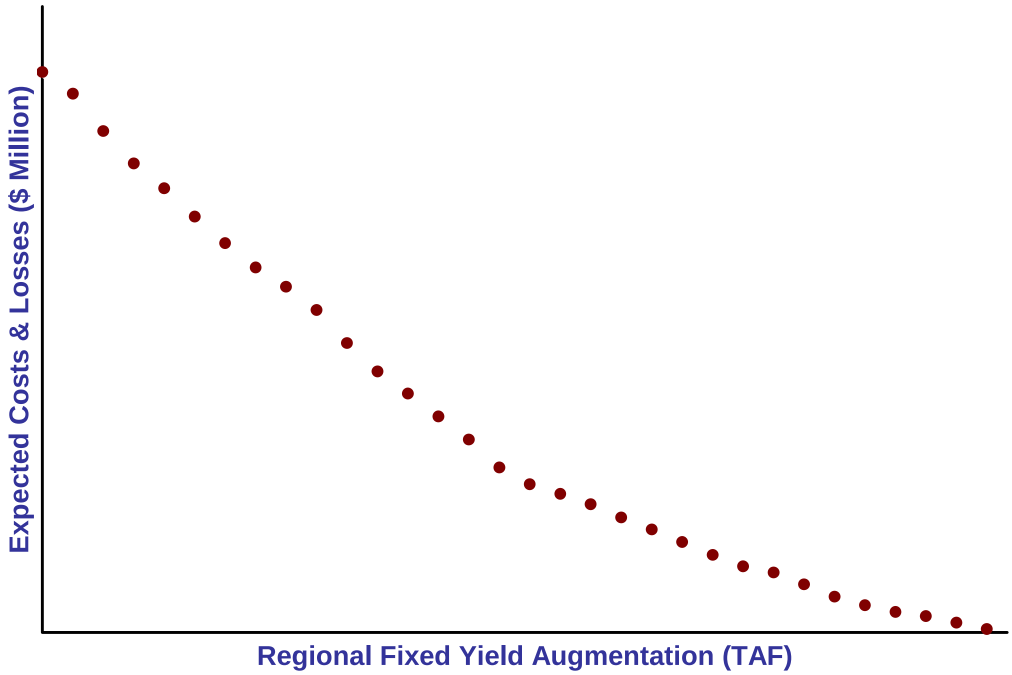

Figure 6-11. LCPSIM Expected Costs and Losses Curve

Total Regional Cost and Loss Curve

Shown in Figure 6-12 are the elements from Figure 6-9 with the addition of iteration logic. The summation of water transfer costs and forgone use costs and losses produces shortage-related costs and losses for an individual year. Iterating through the years in the hydrologic record produces expected costs and losses based on the level of adoption of regional long-term reliability augmentation options. Further iterating these expected values by incrementally increasing the level of adoption of regional long-term reliability augmentation options generates a downward sloping curve of expected costs and losses points as shown in Figure 6-13. Conveyance, potable and wastewater treatment, delivery, and carryover storage operations costs are included.

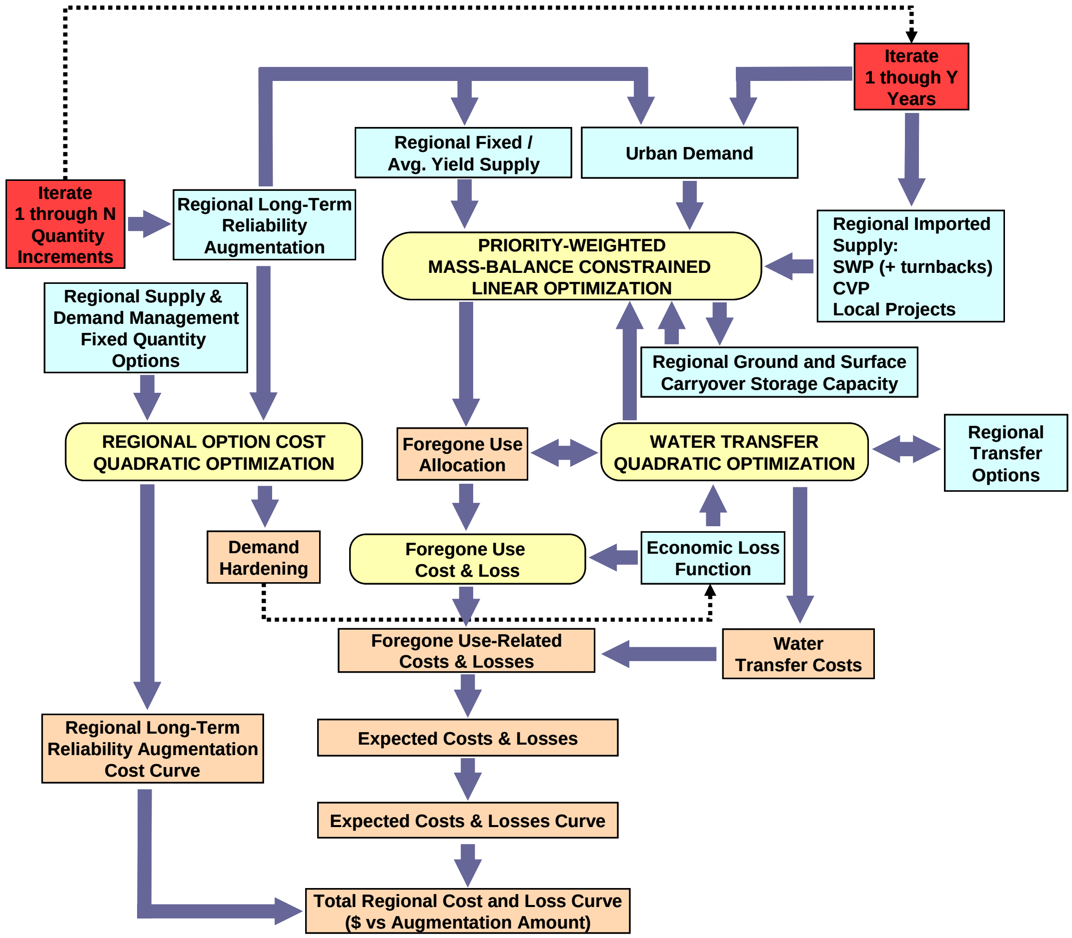

Figure 6-12. LCPSIM Total Regional Cost and Loss Curve Logic

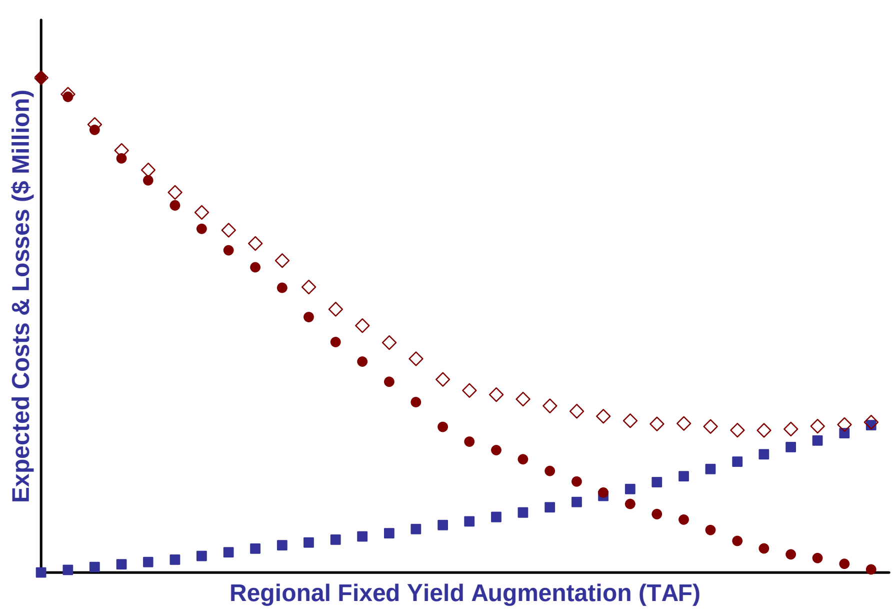

Figure 6-13. LCPSIM Total Regional Cost and Loss Curve

Regional Long-Term Reliability Augmentation with Regional Supply and Demand Management Options This element adds an increment of a specified constant size of regional option use which either augments the regional supply by a fixed annual yield or reduces demand by a fixed annual quantity or does some combination of both. Information on individual regional water management options used by LCPSIM includes the amount available from that that option, the unit annualized capital and O&M cost of that option, and the type of option.

The unit cost of any option can be specified as coefficients of a quadratic function, representing a unit price that increases linearly as the amount used is increased. The costs are from the perspective of statewide economic efficiency, and are lifecycle costs whenever possible. Conservation options, for example, are adjusted to reflect any energy costs savings which might accrue to the user.

The type of option is used to determine how the option would affect the mass balance. Options such as ocean water desalting augment supply, conservation options decrease applied water demand, and recycling options augment reuse. With one exception, these options are assumed to provide a fixed level of supply enhancement or demand reduction each year.

The type of option is also used to determine either the cost of regional potable water and wastewater treatment and distribution, or, in the case of conservation, that these costs don't apply. To determine the effect of conservation on wastewater treatment costs, interior and exterior conservation options are identified separately. If a recycling option has a dedicated distribution system (e.g., "purple pipe"), the capital and operations and maintenance (O&M) costs of that system must be included in the option data file as the cost of that option. The regional potable water treatment and distribution costs would not apply.

The applied water that is "lost" to surface return flows and deep percolation can help meet applied water demand through reuse. Conservation options, by definition, reduce this loss and, therefore reduce this source of applied water. To account for this, the parameter file includes percentage values to account for the effect of reuse on the ability of interior and exterior applied water conservation options to reduce the need for regional supplies and on the cost of achieving that reduction. Conservation options which reduce the amount of deep percolation are credited with their associated pumping cost savings in LCPSIM, reducing their effective cost.

The exception to fixed nature of the options used by LCPSIM is exterior conservation. The value in the main parameter file that sets the share of exterior use that is unaffected by ETAW is also used to separate the effect of exterior use conservation into a fixed component and a variable component. The variable component is assumed to be directly proportional to the amount of exterior use in any year and is intended to capture the effect of actions which, for example, reduce the amount of water applied through better irrigation management. In years dryer than average, the number of irrigations are likely to be higher, increasing the opportunity for better management to have a greater effect on use compared to wetter years. The quantity and cost entered into the options file is the average of the use reduction effect and cost of both conservation components.

The model logic incorporates circular references which require an iteration-based solution (e.g., the reuse of water applied to irrigate landscape is a function of the quantity applied; the need for applied water, in turn, is dependent on losses, a portion of which is reused as part of applied water requirement). After calibration, assumptions about future levels of water use efficiency and recycling can be used to develop base case conditions for LCPSIM parameters for 2030, for example, including the levels of supply-dependent interior and exterior uses; the effectiveness of interior and exterior conservation, respectively; and total regional reuse.

Regional Option Cost Quadratic Optimization This model element is used by the LCPSIM to relate the amount of option use to the total cost of that amount of option use. For a particular level of option use, the options are assumed to be implemented in manner that minimizes the cost of achieving that level of use when both annualized capital and O&M costs and regional treatment and distribution costs are considered. Because quadratic option costs can be entered, a particular level of use may be achieved by implementing less than the total amount specified as being available from any one option.

Demand Hardening The amount of conservation included by the optimization routine is tracked, and this information is used in the economic loss function element to adjust economic losses for demand hardening.

Incremental Regional Systems Operations Costs The economic costs and losses related to forgone use for the changes in regional systems operations costs realized as a consequence of implementing the use of the local supply augmentation and demand reduction options are adjusted for changes in regional water management operations costs. These costs include SWP conveyance costs to the region, conveyance costs on other affected aqueducts supplying the region, and regional potable water and wastewater treatment and distribution costs. The conveyance costs include the cost of wheeling transferred water.

Unit costs of aqueduct conveyance, regional potable water and wastewater treatment and distribution costs are entered as LCPSIM parameters. Also entered are per-capita costs to regional water agencies to manage and rationing programs along with the forgone use threshold at which it assumed a rationing program will be instituted. The contingency conservation program cost is imposed whenever the water management simulation logic in LCPSIM cuts deliveries to the contingency conservation affected use category. The cost of managing a water use reduction exemption program is an example of a cost that would be incurred in a rationing program.

Solving for the Least-Cost Use of Regional Water Management Options Figure 6-14 shows the result of applying a polynomial smoothing function to the total regional cost and loss curve points and then solving for the least-cost point (triangle).

LCPSIM also has the capability of solving for the point that meets specified hydrologic reliability criteria. This capability is useful for comparing the economic efficiency cost of planning on the basis of hydrologic reliability criteria instead of economic efficiency. The reliability criteria are entered in LCPSIM by specifying one or more shortage percentages and providing not-to-exceed frequencies for each shortage percentage specified.

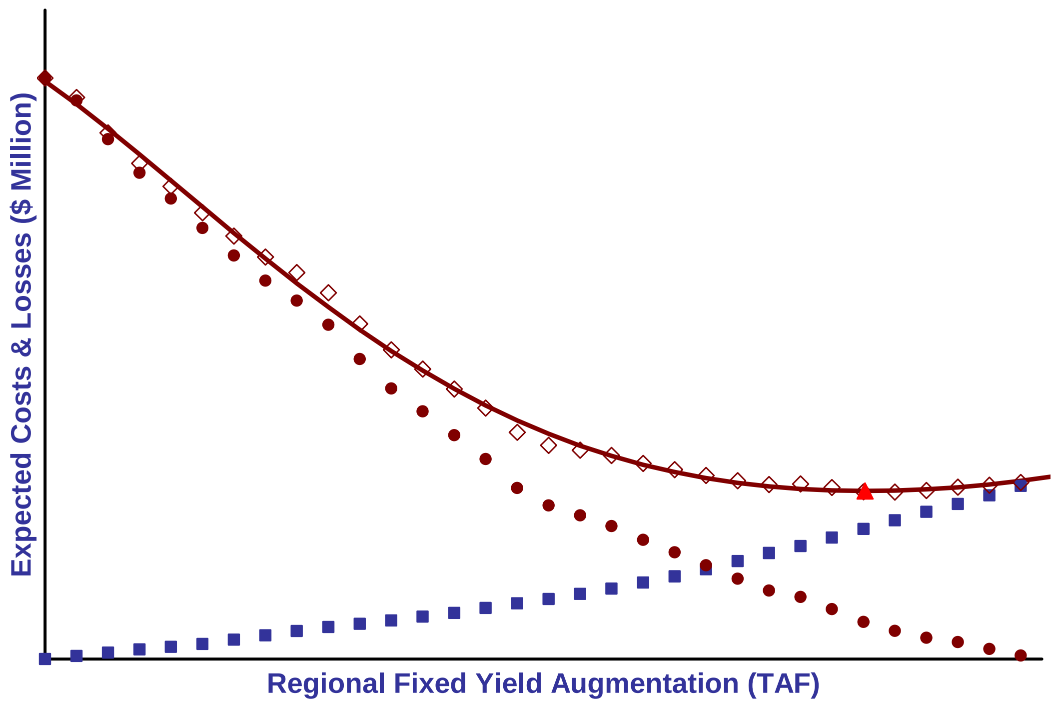

Figure 6-14. Least-Cost Solution Point

Results Available for Viewing and Saving Both incremental and summary results are available in tabular form.

- LCPSIM input data by year and water year type average
  - Supply by source
  - Use
  - Net supply

- Detailed data by regional water management option use increment and by year
  - Net supply
  - Carryover storage by location
  - Contingency conservation
  - Base and interruptible program use
  - Transfers by source
  - Percent shortage
  - Shortage costs and losses
  - Percent of available transfer supply transferred by source
- Summary data by regional water management option use increment
  - Option use cost
  - Costs and losses from foregone use and water transfer purchase costs
  - Regional system operations costs by cost component
  - Number of shortage events
  - Average sufficiency (1 – average shortage)
  - Total costs
  - Fitted total costs (fitted polynomial smoothing function)
  - Residual (total minus fitted total costs)
  - Marginal costs from fitted function
  - Quantity and frequency of transfers by source
- Summary data for least-cost solution
  - Comparison of alternative to base
  - Change in total costs and losses
  - Incremental CVP/SWP supply available for use or carryover storage
  - Hydrologic period average
  - Dry year average
  - Incremental unused CVP/SWP supply
  - Hydrologic period average
  - Dry year average
  - Total costs and losses

- Shortage costs and losses
- Fixed options cost
- Fixed option use
- Carryover option use
- Carryover option use
- Regional operations cost
- Shortage during 1990-1991drought period
- Total and average cost of transfers
- Supply transferred from all sources by source
- Cost of transfers by source
- Transfer value

• Data for the least-cost solution by year

- Net supply
- Carryover storage by location
- Regional carryover storage use
- Contingency conservation
- Base and interruptible program use
- Water available from all sources for transfer
- Supply transferred from all sources
- Cost of transfers
- Shortage quantity
- Percent shortage
- Shortage losses
- Unused SWP supply
- Regional system operations costs

• Data for the least-cost solution by water year type average

- Net supply
- Regional carryover storage use
- Transferred supply
- Incremental CVP delivery
- Incremental SWP delivery
- User shortage
- Shortage losses

- Cost of transfers

Data for the least-cost solution for the use of regional water management options are also available in graphical form. Data are also available for the hydrologic reliability solution criteria.

- Determination of least-cost point for regional water management option use
  - Sequence of net costs and losses from foregone use and water transfer purchase costs
  - Sequence of regional water management option costs
  - Sequence of total costs
  - Fitted polynomial smoothing function curve
  - Least cost point
  - Point at which hydrologic reliability criteria are met
  - Hydrologic reliability exceedence curve
- Trace of yearly regional water management operations
  - Net supply
  - Unused SWP supply
  - Carryover operations
  - Transfers
  - Contingency conservation
  - Foregone base and interruptible program use

LCPSIM Elements for Carryover Storage Augmentation Option

LCPSIM offers a limited ability to augment carryover storage capacity as an option. Only one existing carryover storage operation can be selected to be augmented. The augmentation assumes that annual put and take capacities are increased in proportion to the size of the augmentation. Information on which carryover storage operation is to be augmented and the cost of adding storage capacity to that operation is entered along with the data entered for the other regional management options. Shown in Figure 6-15 is the overall least-cost solution for the analysis of augmenting regional carryover storage capacity (triangle). Figure 6-16 depicts the LCPSIM logic used for the analysis of carryover storage capacity augmentation. Additional data applicable to the analysis of carryover storage capacity augmentation are available as results.

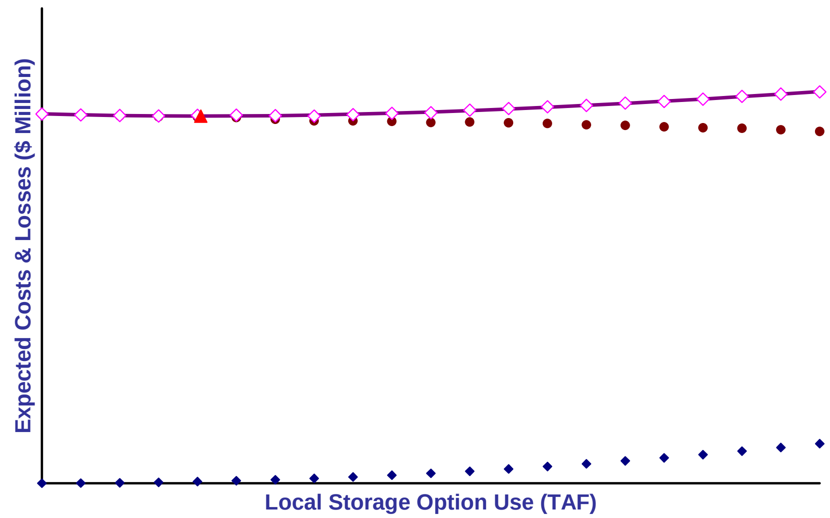

Figure 6-15. Overall Least-Cost Solution for Carryover Storage Augmentation

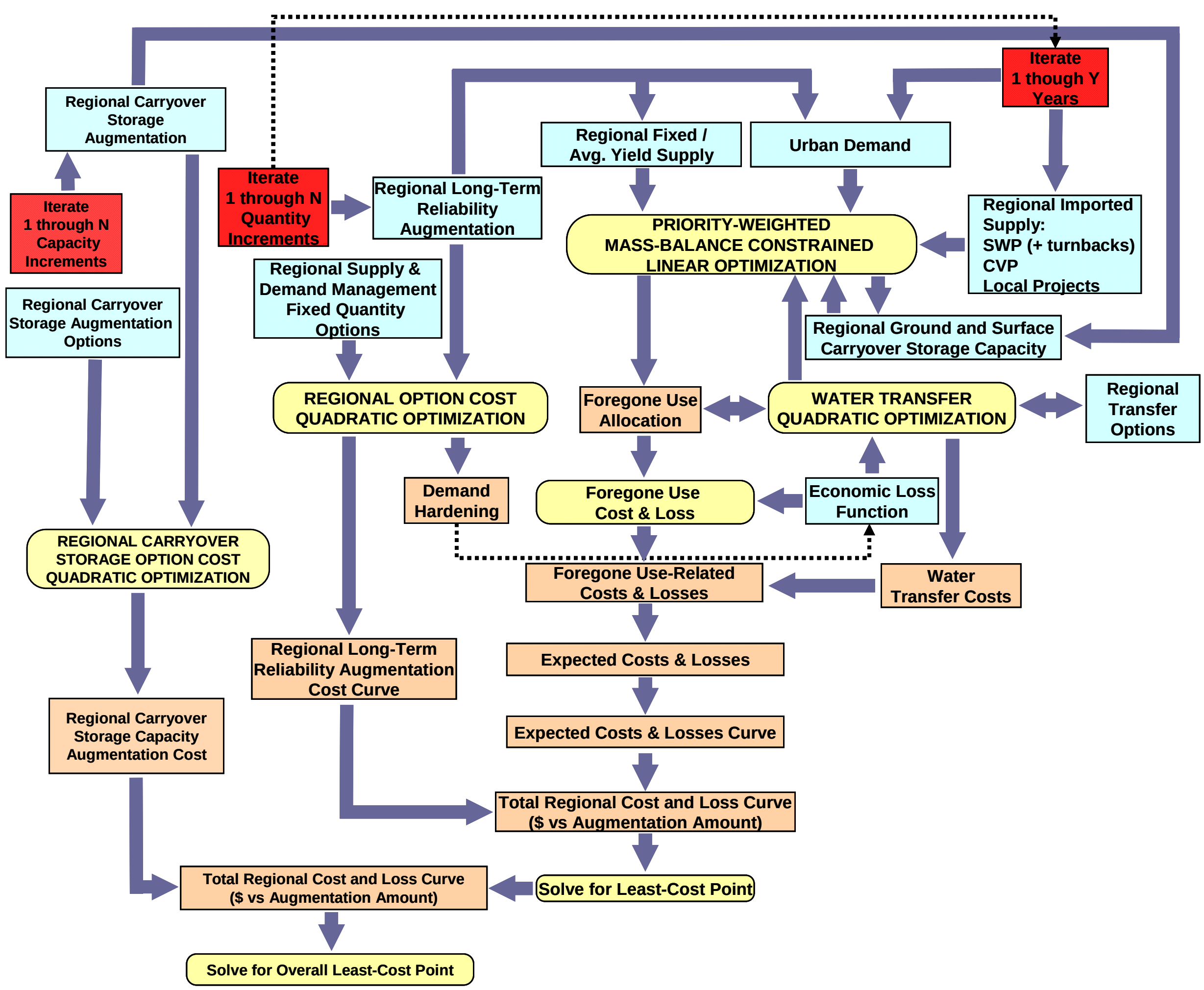

Figure 6-16. Analysis of Carryover Storage Augmentation

Regional Option Cost Minimization Analysis with LCPSIM

LCPSIM can also be used to determine if regional option use alone can provide at least the same hydrologic reliability or shortage-related cost and loss reduction benefits as a base scenario. For this type of analysis, the solution is least-cost only in the sense that the cost of regional option use is minimized. For the hydrologic reliability criterion, regional options are added to the alternative scenario at the point where the hydrologic exceedence curve of the base scenario is dominated (i.e., no point on the alternative curve falls below the base curve). For the economic reliability criterion, the same dominance strategy is used for an economic cost/loss reliability curve. For the expected value criterion, regional options are added to the alternative scenario at the point where the expected value of shortage-related costs and losses is equal to or lower than in the base scenario.

LCPSIM Limitations

LCPSIM is not appropriate for individual water agency management decisions because of the simplifying assumptions made about system operations. These assumptions keep the input data requirements and the complexity of the model logic at a level commensurate with the requirements of the regional level of the DWR studies for which it was designed.

In the LCPSIM, economic benefits are computed at specifically identified demand levels (e.g., 2020). The model thereby conforms to CALSIM hydrologic output, which is generated for specific study year levels and is tied to target deliveries and upstream depletions associated with those levels, rather than over a period of time. Because the economic life of the alternatives to be evaluated can be up to 50 years or more, benefit estimation is biased if only a single study year level is used and if, for the study period, LCPSIM results are not reasonably equivalent to the annualized sum of the discounted benefits before the year level used added to the discounted benefits subsequent to the year level used. Running LCPSIM for multiple year levels over the study period reduces the magnitude of this bias but requires large amounts of data.

LCPSIM uses regional operations studies for local imported supplies to obtain annual delivery information. Regional water supply sources that are not modeled on a year-to-year basis in LCPSIM are assumed to be held constant at their average year values. This simplifying assumption can bias the results by not capturing the costs and losses that may arise when deliveries from these regional supplies and the explicitly modeled imported supply systems are reduced concurrently and by not capturing the benefits of augmenting carryover storage when deliveries from both sources are at their highest levels concurrently.

The determination of reliability benefits is done in LCPSIM on the basis of a risk-neutral view of risk management. Risk-averse management (i.e., risk minimization) by regional agencies–which has been the predominant mode–would result in the justification of more costly water management measures than under the risk-neutral assumption. Also, LCPSIM is not as useful for water managers who base reliability investment decisions on the hydrologic performance (e.g., percentage of target delivery met) rather than economic performance of their systems over a specified drought sequence (e.g., 1928 to 1934). The loss function used could, however, be modified to more or less replicate this strategy.

LCPSIM assumes that the regions being evaluated have the facilities and institutional agreements in place to move water as needed to minimize the impact of shortages. For this reason, the use of LCPSIM on a regional basis is only appropriate for regions where this assumption is likely to be generally true within the time frame being modeled – the San Francisco Bay and South Coast regions.

In general, if interconnections and joint management do not realistically characterize a region, calculation of the benefits of additional reliability may be biased. For example, if the ability of the region to mitigate shortages with regional water allocation programs is significantly less than assumed in LCPSIM, a higher value may be assigned to useable deliveries from a reservoir supply alternative in a particular subregion but the actual amount of the useable supply may be reduced (i.e., the reservoir may be relegated to more of a peaking supply because the greater use of constant "yield" conservation and recycling measures may be justified for that subregion, reducing the usability of reservoir deliveries in wetter years). In any case, to extent that region-wide shortage contingency water allocation plans are expected to be put in place in the future, this bias will be reduced.

LCPSIM is designed to base urban use as estimated by the IWR-MAIN model. This use reflects the expected adoption of conservation measures, including those specified in Urban Best Management Practices (BMP), and incorporates water price elasticity effects on use. These base urban use amounts are not reduced further in LCPSIM in response to the higher urban user water prices that can be anticipated as regions use water pricing as a means of recovering the cost of increasing reliability. In accordance with the economic efficiency objective, use is reduced in LCPSIM based on the marginal cost of alternatives to that use reduction. If the water pricing strategy adopted by local agencies to recover costs reduces use differently than the use reduction logic in LCPSIM predicts, the model results will be biased.

The order of the polynomial smoothing function can be set by the model user based on the user's view of the trade-off between minimizing the rate of change in the slope of the function (i.e., a smoother function) and a function that is less smooth but more closely follows the path of the points (i.e., maximizes the goodness of fit). Selecting the starting and ending regional option use points for the simulation can also affect the results of smoothing. If the LCPSIM user feels that, on average, the real world operators would be unlikely to duplicate some of the threshold-based operating criteria incorporated in the model, then fitting the model-generated points too closely would be likely to bias the model results.

If Excel® is installed, selecting View Operations Trace in the LCPSIM Run/View Menu also makes available a spreadsheet smoothing analysis utility that can be used to select the order of the polynomial smoothing function and the range of option use results to smooth that the analyst feels best represent the model output. These parameters can then be used to rerun the LCPSIM to generate new results files.

The total cost/loss points generated by LCPSIM simulation as the model responds to added increments of regional water management option use are intended to plot out a cost/loss response path. This point path is mathematically converted to a continuous function by using polynomial smoothing. This function is then solved analytically to identify the least-cost solution consisting of a level of use of regional water management options and the total costs and losses associated with that level of use.

LCPSIM is set up to be a "best estimate" model. It is not intended to provide confidence intervals for statistical hypothesis purposes.

In addition to relying on a simplified representation of the physical configuration of a regional water management system, LCPSIM is based on determining a least-cost solution from the perspective of statewide economic efficiency for the purpose of identifying the level of statewide interest in the commitment of resources to a proposed project or program. Local planning decisions are likely to be influenced by local cost effectiveness and political concerns as well as additional factors of importance to regional water agency managers and water users that are not necessarily related to LCPSIM objective. Taking into consideration the context in which the results are to be used, LCPSIM results should be compared to local agency water management plans to help determine whether it would appropriate – or feasible – to modify the model to be more representative of the region from the local management perspective.

Exhibit 6A
LCPSIM Data

LCPSIM Input and Output Data

The information displayed in these example input data files is for the South Coast Region for a 2020 level of analysis. These numbers are for illustrative purposes only. The format of the files is ASCII and the data are stored without including the row headings.

Table 6A-1. Example LCPSIM Parameter File (*.prm)

Parameter	Value
Conveyance capacity available for Central Valley Imports (TAF)	3,243
Base average regional nontime series net M&I water availability (TAF)	1,438
Average year regional net M&I water use (TAF)	4,943
Standard deviation for regional net M&I water use (%)	2.9%
Number of years in precipitation ranking sequence	111
Base incremental M&I Conservation (%)	9.2%
Net Use Ratio (% of applied use)	91.0%
Interruptible program net use (TAF)	235
Federal service contract aqueduct capacity (TAF)	1,200
Cost of Federal service contract aqueduct conveyance ($/acre-feet)	$70.00
Cost of Federal service contract aqueduct use to GW bank ($/acre-feet)	$48.00
Cost of SWP aqueduct use to region ($/acre-feet)	$150.00
Cost of SWP aqueduct use to GW bank ($/acre-feet)	$22.00
Cost of regional M&I treatment and delivery ($/acre-feet)	$120.00
Cost of regional M&I delivery ($/acre-feet)	$40.00
Value of interruptible program water ($/acre-feet)	$231.00
Industrial customer size (% of total net use) [1]	6.1%
Commercial customer size (% of total net use) [2]	22.5%
Landscape customer size (% of total net use) [3]	5.7%
Fraction of interruptible supply treated (%)	46.0%
Cost/person for contingency conservation campaign	$0.25
Applied use reduction with contingency conservation (%)	5.0%
Take call ratio for using contingency conservation (%)[4]	100.0%
Capacity use ratio for using contingency conservation (%)[5]	20.0%
Industrial customer cut ratio (%)	25.0%
Commercial customer cut ratio (%)	50.0%
Landscape customer cut ratio (%)	200.0%
Threshold for shortage allocation (%)[6]	95.0%
Threshold to adjust loss value for proximate shortages (%)	0.0%
Loss value adjustment factor for consecutive shortages (%)	0.0%
Inverse power function exponent for loss value adjustment[7]	1.0%
Zero point for contingency reduction of interruptible program (%)[8]	35.0%
Shortage contingency water transfer threshold (%)[9]	90.0%
Depleted carryover storage water transfer threshold (%)[10]	80.0%

Table 6A-1. Example LCPSIM Parameter File (*.prm) (contd.)

Parameter	Value
Cost/person for rationing program	$0.50
Rationing program threshold (%)	80.0%
Regional urban population (thousands)	24,327
Price for CPED function	$567.00
Elasticity for CPED function	-0.16
Demand hardening adjustment factor (%)[11]	50.0%
Hedging point[12]	60.0%
Hedging call/storage factor	0.25
Hedging storage/capacity factor	0.25
Reserve reservoir storage hedging: 0: None, 1: Hedged[13]	0
Regional reservoir hedging: 0: None, 1: Hedged	0
Regional GW hedging: 0: None, 1: Hedged	0
Regional GW bank hedging: 0: None, 1: Hedged	0
SWP aqueduct GW bank hedging: 0: None, 1: Hedged	0
Regional aqueduct GW bank hedging: 0: None, 1: Hedged	0

Notes:

1 Proportion of user category for which use reduction is held to the industrial customer cut ratio compared to residential users.

2 Proportion of user category for which use reduction is held to the commercial customer cut ratio compared to residential users.

3 Proportion of user category for which use reduction is held to the landscape customer cut ratio compared to residential users.

4 Limit on the ratio of net current use to be met (including flexible storage refill, if any) to stored water available for current year use.

5 Limit on the fraction of carryover storage capacity filled before triggering contingency conservation

Subnote: 3&4 are used for triggering contingency conservation over and above a mass balance requirement for its use.

6 Below this point, all users experience the same percentage reduction.

7 Proximate losses are increased by a loss adjustment factor to account for residual damage effects.

8 At this point and above, interruptible deliveries are not made.

9 Used if a regional shortage has to exceed a specified percentage before transfers from this source type are allowed.

10 The ratio of supply in carryover storage to total carryover storage take capacity at which transfers are triggered.

11 The factor by which use reductions through conservation options as a percentage of initial use are used to adjust shortage size.

12 Parameters used for hedging logic: if storage is less than hedging point, then percent of storage made available is

13 Storage categories included for hedging purposes (hedging is applied to the total storage amount).

Key:
CPED = constant price elasticity of demand
GW = groundwater
LCPSIM = Least Cost Planning Simulation Model
M&I = municipal and industrial
SWP = State Water Project
TAF = thousand acre-feet

Table 6A-2. Example LCPSIM Regional Water Management Options File (*.opt)

Source[1]	Amount Avail (TAF)	Cost (Base) (%/acre-foot)	Cost (Incremental) ($/TAF)	Source[2] (type)	Description (alpha numeric)
1	262.0	$3.00	$2.10	2	Conservation Level I
2	76.0	$1,159.00	$4.30	2	Conservation Level II
3	171.0	$360.00	$2.00	1	Water Recycling Level I
4	212.0	$841.00	$1.70	1	Water Recycling Level II
5	208.0	$1,306.00	$1.10	1	Ocean Water Desalting Level I
6	10.0	$1,728.00	$0.00	1	Ocean Water Desalting Level II
7	1.0	$2,548.00	$0.00	1	Ocean Water Desalting Level III

Notes:

[1] Up to 20 supply/conservation and 20 carryover options can be entered. Only one carryover storage operation can be augmented, however, with put and take limits adjusted in proportion to the initial put/capacity and take/capacity ratios.)

[2] Used to identify source as storage or supply, to assign treatment and conveyance costs and for adjusting for demand hardening: 1=Local Production, 2=User Conservation, 3=System Conservation, 4=Local aqueduct, >10=Class of carryover storage being augmented +10.

Key:
AF = acre-feet
LCPSIM = Least Cost Planning Simulation Model
TAF = thousand acre-feet

Table 6A-3. Example LCPSIM Carryover Storage Operations File (*.stg)

Operation1	Capacity (TAF)	Init. Fill	Rech. Eff.	Put Limit (TAF)	Put Cost	Put Prty2	Take Limit3 (TAF)	Take Cost	Take Prty2	Class4	Type5	Opr. Rule6	Description
1	220.0	100%	100%	220.0	$0	2.0	220.0	$0	6.0	1	1	0	Reserve Reservoir Operations
2	600.0	50%	100%	860.0	$0	1.0	287.0	$0	3.0	2	1	0	In-Region Reservoir Operations
3	195.0	50%	100%	56.0	$65	3.0	75.0	$65	3.0	3	1	0	IRP GW Program
4	267.0	50%	90%	66.8	$0	3.0	89.0	$81	5.0	3	2	0	Prop 13 & Raymond Basin GW
5	210.0	50%	90%	55.0	$94	3.0	70.0	$94	5.0	4	1	0	North Las Posas Banking
6	75.0	50%	90%	20.0	$0	3.0	50.0	$79	5.0	4	1	0	San Bernardino Banking
7	800.0	50%	90%	150.0	$0	6.0	150.0	$34	2.0	5	4	0	Colo R. Aq. GW Banking Operations
8	310.0	50%	90%	155.5	$81	5.0	125.0	$44	4.0	6	3	4	Kern-Delta WD & North Kern WSD
9	350.0	50%	90%	31.7	$35	5.0	31.5	$33	4.0	6	3	1	Semitropic WSD
10	250.0	50%	90%	100.0	$62	5.0	75.0	$45	4.0	6	3	2	Arvin/Edison WSD
11	285.5	0%	100%	285.5	$0	4.0	285.5	$0	1.0	7	0	5	SWP Carryover Storage

Notes:

1 The LCPSIM code presently permits 20 storage operations to be entered

2 Highest priority = 1. (By default, the LCPSIM uses dynamic priorities; these priorities may be used instead by selecting "Use Static Priorities" on the Main Screen.)

3 These limits can be used for take operations and are always used for calculating storage depletion for the purpose of making market transfers for recharge. If either a Type 1 or Type 2 operating rule is indicated, these limits are overridden by the rule parameters entered in the respective parameter files for take operations.

[4] Storage class ID
1: Reserve reservoir
2: In-Region reservoir
3: In Region GW Storage
4: In-Region GW Bank
5: Federal service contract aqueduct GW Bank
6: External SWP aqueduct GW Bank
7: SWP reservoir carryover

[5] Used for conveyance and treatment costs for puts and takes:
1: Conveyance to region for puts
2: Conveyance to region and treatment costs for puts (spreading of treated water for GW recharge)
3: Conveyance to SWP aqueduct bank for puts, conveyance from SWP aqueduct bank to region for takes
4: Conveyance to Federal service aqueduct bank for puts, conveyance from Federal service aqueduct aqueduct bank to region for takes
5: Conveyance to SWP bank for puts, conveyance from Delta for takes
6: Conveyance to region for puts, conveyance from Federal service aqueduct for takes

[6] Type of operating rule:
1: Percentage Table A delivery take constraint
2: Consecutive use take constraint
3: Direct SWP SJV GW bank augmentation
4: Generic SJV storage
5 SWP carryover

Key:
Ag. = agriculture
Colo R. Aq. = Colorado River Aqueduct
Eff. = Efficiency
GW = groundwater
Init. = Initial
IRP = Integrated Resources Plan
LCPSIM = Least Cost Planning Simulation Model
Opr. = Operating
Prty = Party
Rech = Recharge
SWP = State Water Project
TAF = thousand acre-feet
WD = Water District
WSD = Water Storage District

Table 6A-4. Example LCPSIM Water Transfers Market File (*.mkt)

Source[1]	Amount Avail[2] (TAF)	Cost (Base) ($/acre-feet)	Cost (Incremental ($/TAF)	Conveyance[3] (type)	Max Interval[4] (% of available)	Max Sequential[5] (% of avail)	Deliv. Adj.[6] (%)	Description (alpha numeric)
1	650	$150.00	$0.00	4	1000%	200%	100%	Colo Riv Transfers
2	5000	$160.00	$0.00	2	1000%	200%	100%	SV Ag Transfers
3	5000	$268.00	$0.00	3	1000%	200%	100%	SJV Ag Transfers

Notes:

[1] Multiple transfer sources can be entered (up to 15).

[2] Overridden when time series files are found by the LCPSIM.

[3] Used for capacity and operational constraints and conveyance cost calculations:

1: No transfer constraint for transfer costs

2: Sacramento Valley transfers

3: San Joaquin Valley Transfers

4: Federal service contract conveyance transfers

[4] Maximum amount that can be transferred over any 10-year period

[5] Maximum that can be transferred in any 2 consecutive years (If Max Interval is 1,000% and Max Sequential is $200, then transfers are unrestricted.)

[6] Adjustment for conveyance losses (e.g., Delta carriage water requirement) (overridden when time series files are found by the LCPSIM.)

Key:

Ag. = agriculture
Avail = available
Colo. = Colorado
Deliv. = Delivery
LCPSIM = Least Cost Planning Simulation Model
Max = Maximum
Riv. = River
SJV = San Joaquin Valley
SV = Sacramento Valley
TAF = thousand acre-feet

Table 6A-5. Example LCPSIM Hydrologic Reliability Criteria File (*.hrc)

Criteria Step[1]	Shortage[2] (%)	Freq of Exceedence[3] (%)
1	15%	100%
2	10%	90%
3	0%	80%

Notes:
[1] Can be up to 4 steps.
[2] Shortage threshold.
[3] Maximum frequency with which a shortage exceeding the threshold occurs.
Key:
LCPSIM = Least Cost Planning Simulation Model

Table 6A-6. Example LCPSIM Polynomial Loss Function File (*.ply)

Coeff No.	Coefficient[1]
1	565.9284668
2	38655.50781
3	-134225.4844
4	188849.625

Note:
[1] Coefficients of loss function polynomial (can be up to a degree 3 as is the example).
Key:
Coeff. = coefficient
LCPSIM = Least Cost Planning Simulation Model

Table 6A-7. Example LCPSIM Percentage Delivery Constrained Take Rule File (*.pdc)

Rule Parameter	Value
Table A Allotment (TAF)[1]	155
Reserved Table A (TAF)[2]	22
Share of Bank (%)[3]	35%
Base Take Avail (TAF)[4]	31.5

Source: MWDSC Staff

Notes:

[1] SWP contract amount held by the agency operating the bank.

[2] Amount of SWP contract quantity reserved for local use by the agency operating the bank.

[3] Region's share of total bank capacity.

[4] Guaranteed minimum take. The take limit for MWDSC from the Semitropic WSD bank is equal to the bank's pumpback capacity (Base Take Avail) plus the product of MWDSC's percentage share of the bank and Semitropic WSD's SWP Contract Table A delivery after subtracting Semitropic WSD's reserved amount of that allocation: Base Take Avail + Share of Bank * ((Table A Allotment * percentage of Table A Delivered) - Reserved Table A).

The take limit for MWDSC from the Semitropic WSD bank is equal to the bank's pumpback capacity (Base Take Avail) plus the product of MWDSC's percentage share of the bank and Semitropic's SWP Contract Table A delivery after subtracting Semitropic's reserved amount of that allocation: Base Take Avail + Share of Bank * ((Table A Allotment * percentage of Table A Delivered) - Reserved Table A).

Key:
Avail. = available
LCPSIM = Least Cost Planning Simulation Model
MWDSC = Metropolitan Water District of Southern California
SWP = State Water Project
TAF = thousand acre-feet
WSD = Water Storage District

Table 6A-8. Example LCPSIM Consecutive Take Constrained Take Rule File (*.ctc)

Year No.[1]	Available[2]
1	100%
2	75%
3	70%
4	60%
5	40%
6	0%

Notes:

[1] Consecutive take sequence year number.

[2] Percentage of unconstrained take available.

LCPSIM Time Series Input Data Files

The following table contains a list of the hydrologic sequence time series data files used by LCPSIM and the file naming conventions expected by the model. The base files are vectors (single columns) while the scenario files can be matrices with the columns representing different scenarios.

Table 6A-9. LCPSIM Time Series Data Files

File Type	Description	Data Source	File-Naming Convention	
			Base Case[1]	Scenario[2]
Study ID	CALSIM study identification header text	Study name	*basefileid*.sid	*scnfileid*.sid
SWP Table A Delivery	CALSIM SWP Table A contractor deliveries	CALSIM	*basefileid*.tba	*scnfileid*.tba
SWP Article 21 Delivery	CALSIM SWP Article contractor deliveries	CALSIM	*basefileid*.a21	*scnfileid*.a21
Federal Contract Delivery	Deliveries based on Federal water service contracts (e.g., CALSIM CVP contractor deliveries)	CALSIM or regional model	*basefileid*.fcd	*scnfileid*.fcd
Regional Variable Supply	Regional supply unaffected by study scenarios	Regional model	*basefileid*.lvs	n/a[3]
SWP GW Augmentation	CALSIM GW augmentation deliveries	CALSIM	*basefileid*.exb	*scnfileid*.exb
Total Transfer Limit	CALSIM water market total transfer capacities	CALSIM	*basefileid*.tlm	*scnfileid*.tlm
SAC Transfer Limit	CALSIM Sacramento Valley water market transfer capacities	CALSIM	*basefileid*.tsv	*scnfileid*.tsv
SJV Transfer Limit	CALSIM San Joaquin Valley water market transfer capacities	CALSIM	*basefileid*.tsj	*scnfileid*.tsj
SAC Transfer Factor	CALSIM Sacramento Valley water market transfer efficiency factor	CALSIM	*basefileid*.fsv	*scnfileid*.fsv
SJV Transfer Factor	CALSIM San Joaquin Valley water market transfer efficiency factor	CALSIM	*basefileid*.fsj	*scnfileid*.fsj
Table A Percentage	CALSIM agricultural contractor deliveries as a percentage of Table A contract amounts	CALSIM	*basefileid*.tap	*scnfileid*.tap
SWP Carryover Storage	Capacity for undelivered water to be stored by SWP in San Luis Reservoir for delivery in following year	CALSIM	*basefileid*.slc	*scnfileid*.slc
Table A Turnbacks	SWP Table A deliveries assumed to be available due to inability to use them in another region	LCPSIM	*basefileid*.tat	*scnfileid*.tat
Article 21 Turnbacks	SWP Article 21 deliveries assumed to be available due to inability to use them in another region	LCPSIM	*basefileid*.a2t	*scnfileid*.a2t

Notes:
[1] These files must have the same primary file name (basefileid) and are required to be in the same directory.
[2] These files must have the same primary file name (scnfileid) and are required to be in the same directory.
[3] Applicable only if CALSIM generates different values for the scenarios.
Key:
CVP = Central Valley Project
GW = groundwater
ID = Irrigation District
LCPSIM = Least Cost Planning Simulation Model
n/a = not applicable
SAC = Sacramento
SJV = Jan Joaquin Valley
SWP = State Water Project

Selected LCPSIM Output Data

Table 6A-10. LCPSIM Summary Output Format

Annual Values / Increment >	Description of Results (Values are for least-cost solution operations)
Avg. Incremental Avail. Supply (TAF)	Average incremental supply made available to region by proposed project/program
Avg. Incremental Deliv. Supply (TAF)	Average amount of incremental supply that region can currently consume or store
Avg. Inc. Dry Period Avail. Sup. (TAF)	Average incremental dry period supply made available to region by proposed project/program
Avg. Inc. Deliv. Dry Period Sup. (TAF)	Average amount of incremental dry period supply that region can currently consume or store
Avoided Loss/Cost ($1,000)	Expected annual benefit of implementing proposed project/program
Total Loss/cost ($1,000)	Expected annual total costs and losses associated with shortage and regional options use
Shortage Loss/Cost ($1,000)	Expected annual shortage costs and losses
Regional Fixed Option Cost ($1,000)	Regression-fitted annualized costs of use of regional options
Regional Fixed Option Use (TAF)	Quantity of supply from regional options
Marg. Fixed Option Cost ($/AF)	Annualized cost of next increment of supply from regional supply options
Carryover Option Use (TAF)	Size of capacity added to regional carryover storage
Carryover Option Cost ($1,000)	Annualized cost of adding to regional carryover storage
Operations Cost ($1,000)	Cost of aqueduct conveyance, including wheeling of transfers and carryover storage, and other regional operations
Drought Shortage (90/91)	Shortage for 1990-1991 drought period
Total Transfer Quantity (TAF)	Total quantity transferred over hydrologic period
Ann. Avg. Transfer Quantity (TAF)	Average annual quantity transferred over hydrologic period
Total Transfer Cost ($1,000)	Total cost of transfers over hydrologic period
Ann. Avg. Transfer Cost ($1,000)	Average annual cost of transfers
(Output for each of the 5 water year-types plus dry period and no. of years represented)	
Water Year-Type	Name of water year type or period
SWP Delivery (TAF)	Average SWP delivery
Federal Svc Contract Deliv (TAF)	Average Federal service contract aqueduct delivery (e.g., CVP deliveries for SF Bay Region)
Net Supply (TAF)	Average supply above current consumptive use
Unallocated SWP Delivery (TAF)	Average incremental SWP delivery not allocatable to current consumptive use or regional carryover storage
Puts to Regional Storage (TAF)	Average puts to regional carryover storage facilities
Change in Storage (TAF)	Average change in regional carryover storage
Water Mkt Deliveries (TAF)	Average water market transfers
Net User Shortage (TAF)	Average user shortage after transfers
Total Loss/Cost ($1,000)	Average total costs and losses associated with shortage and regional options use
(Output for each regional option)	
Supply/Conservation Option	Name of regional supply/conservation option
Use (TAF)	Quantity of supply from regional option
Cost ($1,000)	Unfitted annualized cost of regional option use
(Output for each regional option)	
Carryover Storage Option	
Use (TAF)	Size of capacity added to regional carryover storage
Cost ($1,000)	Annualized cost of adding to regional carryover storage
(Output for each transfer source)	
Number of Transfers	Number of transfers during hydrologic period
Quantity (TAF)	Total quantity transferred during hydrologic period
Cost ($1,000)	Total costs of transfers during period of record
Avg. Quantity per Trf. (TAF)	Average quantity transferred per transfer event
Avg. Trf. Cost ($/acre-foot)	Average unit cost of transfers
Frequency	Frequency of transfer events during hydrologic period

Notes:

[1] Sum of "Shortage Cost/Loss," "Regional Fixed Option Cost," "Carryover Option Cost" (if used), and "Ann. Avg. Transfer Cost."

[2] Not be displayed if carryover storage options are not evaluated.

[3] Sum of the costs for specific options do not equal "Regional Fixed Option Cost" displayed above because the specific option costs represent the individual products of the unit costs of the options and the least-cost solution quantities identified, "Regional Fixed Option Cost" is a point on the cumulative option costs regression curve.

[4] Sum of the costs for specific options do not equal "Carryover Option cost" displayed above because the specific option costs represent the individual products of the unit costs of the options and the least-cost solution quantities identified, "Carryover Option Cost" is a point on the cumulative option costs regression curve.

Key:
Ann. = annual
Avail. = available
Avg. = average
Deliv. = delivery
Inc. = Incremental
Marg. = Marginal
Mkt = Market
No. = Number
SF = San Francisco
Sup. = Supply transfers
Svc = service
SWP = State Water Project
TAF = thousand acre-feet
Trf. = Transfers

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Table 6A-11. LCPSIM Least-Cost Solution Summary Output Format

Type of Value	Description of Results (values are for least-cost solution operations) (Output for each year in the hydrologic sequence, for the 5 hydrologic year-types, for the dry period, and for the average)
Net Supply	Supply available for delivery to carryover storage after netting out current year long-term conservation adjusted use target (negative value is deficit to be managed)
Opt Use Adj	Net adjustment to water balance from local long-term supply and conservation options implemented for least-cost solution
Flex Storage	Quantity stored in reserve carryover storage (last to release - first to refill)
Res Storage	Quantity stored in within-region surface carryover storage
GW Storage	Quantity stored in within-region groundwater storage
Loc Bank Stg	Quantity stored in within-region groundwater bank storage
CalAq Bank Stg	Quantity stored outside of region along the California Aqueduct in the San Joaquin Valley
LocAq Bank Stg	Quantity stored outside of region along the local aqueduct
Stg Use	Withdrawal from carryover storage for current year use
Cntgcy Consv	Conservation required to help balance supply and use in current year during shortage events or triggered by unfavorable carryover storage conditions
IPGM Use	Scheduled interruptible program cutback to help balance supply and use in current year during shortage events
Base Use	Cutback in current year use over and above contingency conservation
Trf Avail	Supply available for water market transfer based on conveyance capacity and third-party mitigation constraint rules
Transfers	Supply transferred to help meet current year use during shortage events
Pct Shortage	Cutback in current year conservation-adjusted use during shortage events
Short Losses	Economic losses from deliveries less than target long-term conservation-adjusted use
Unused Supply	Available imported supply in excess of current year use and carryover storage stock or flow capacity for puts
Sys Op Costs	Conveyance, distribution, treatment, and carryover storage operations costs for current year

Key:
LCPSIM = Least Cost Planning Simulation Model

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Exhibit 6B
LCPSIM Interface Screens

The following figures depict selected screens in LCPSIM.

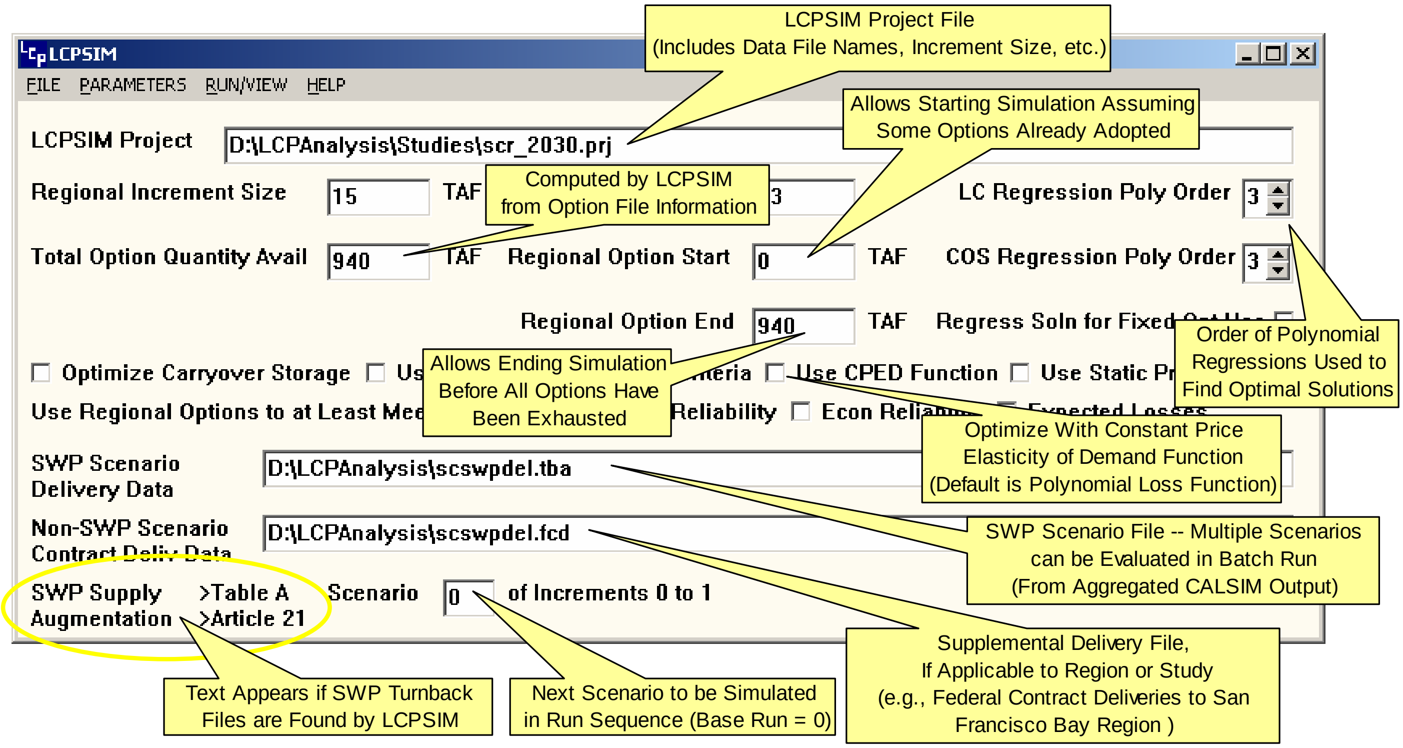


Figure 6B-1. LCPSIM Main Screen

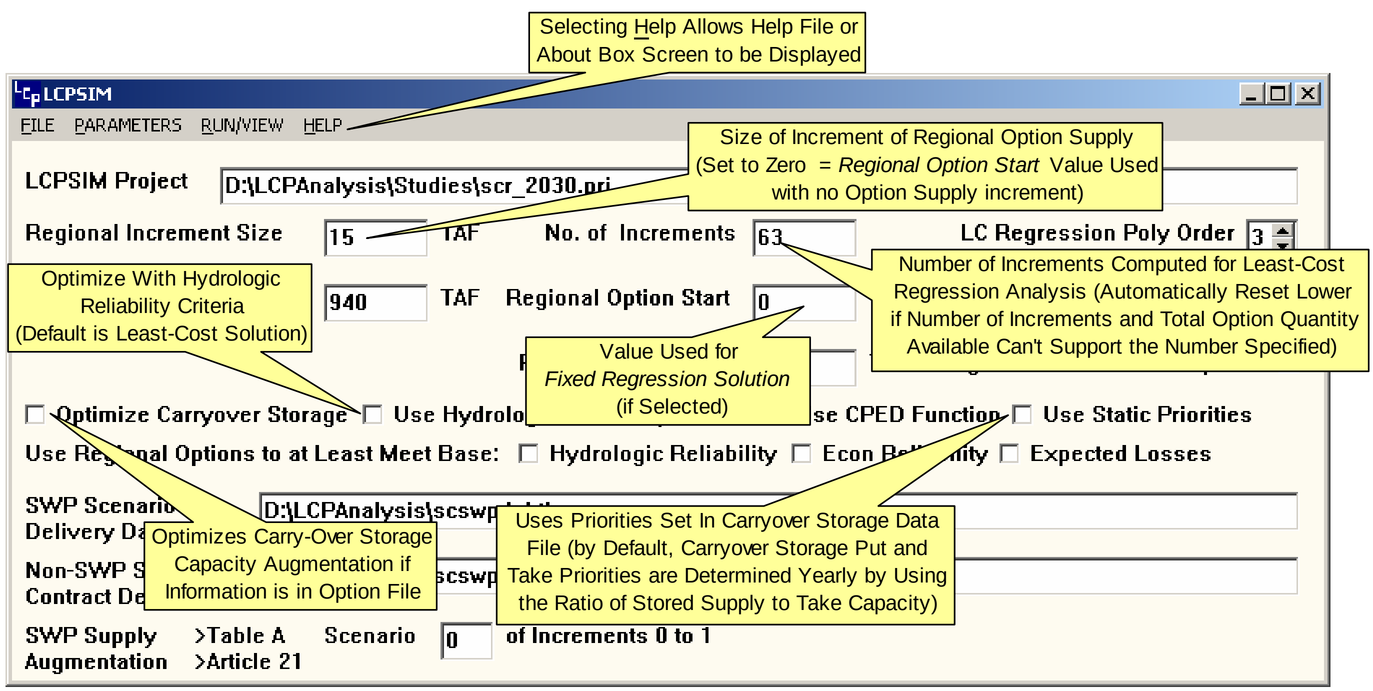


Figure 6B-2. LCPSIM Main Screen

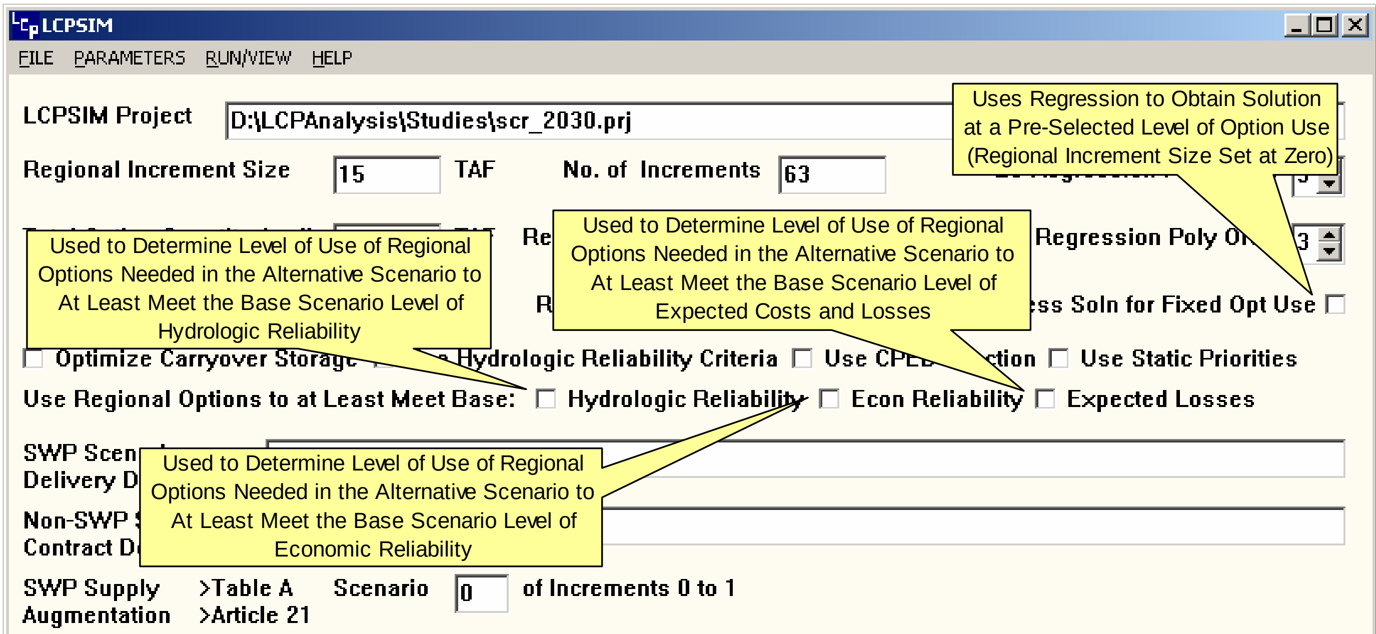


Figure 6B-3. LCPSIM Main Screen

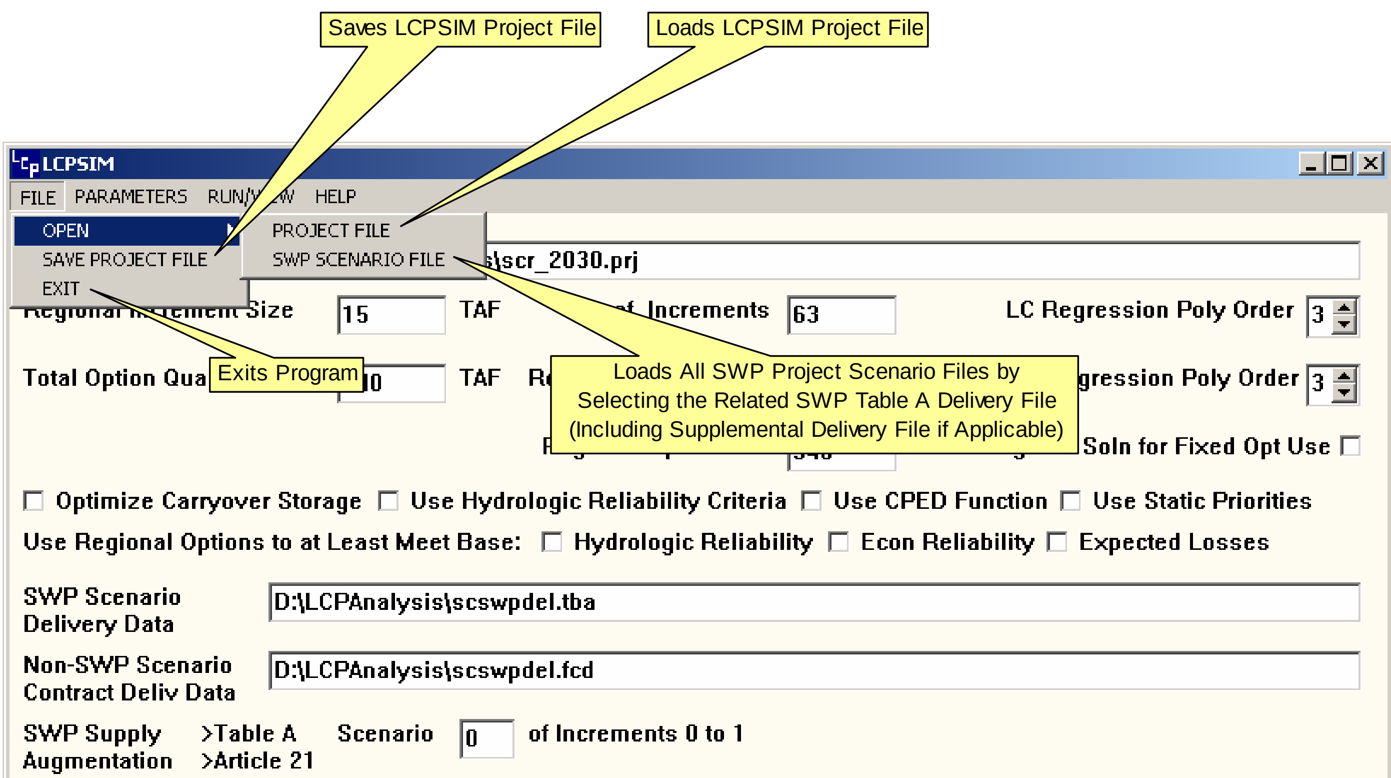


Figure 6B-4. LCPSIM File Menu

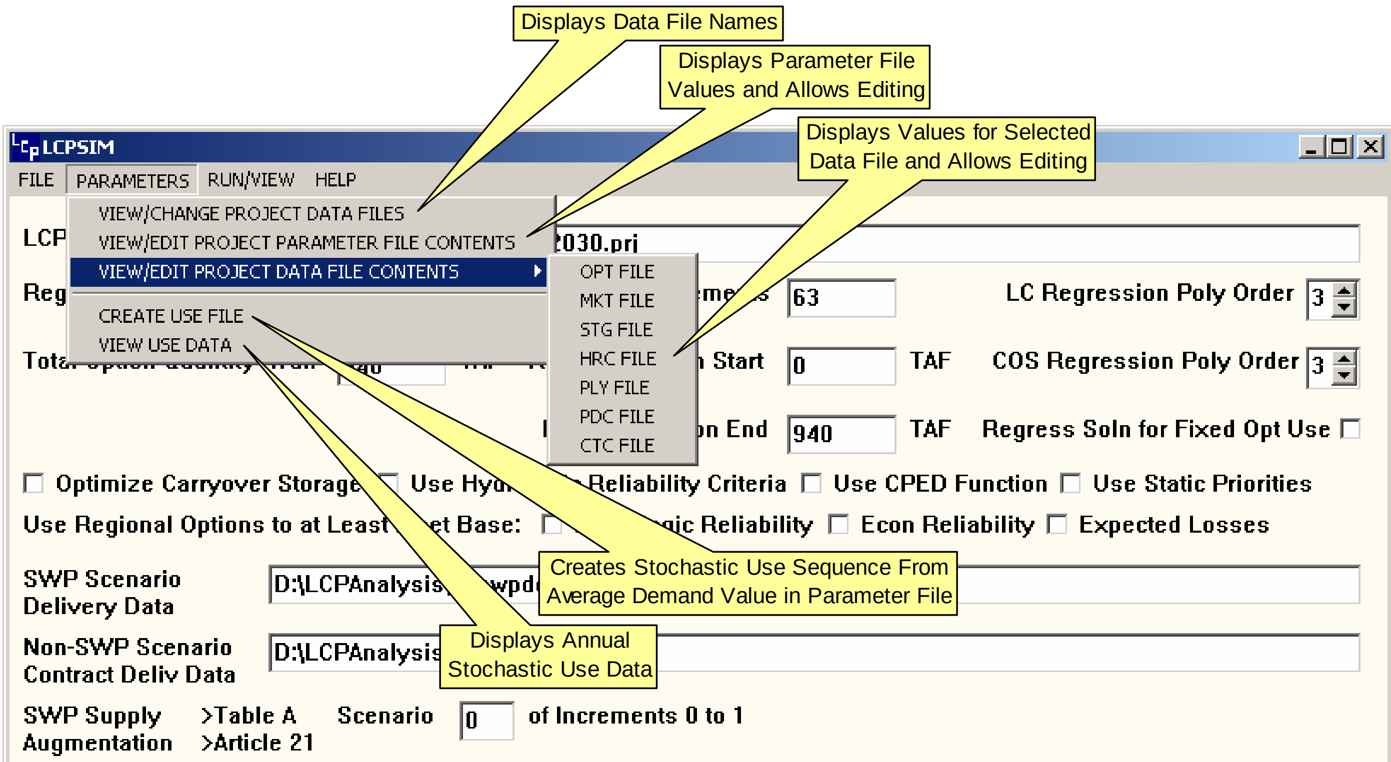


Figure 6B-5. LCPSIM Parameter Menu

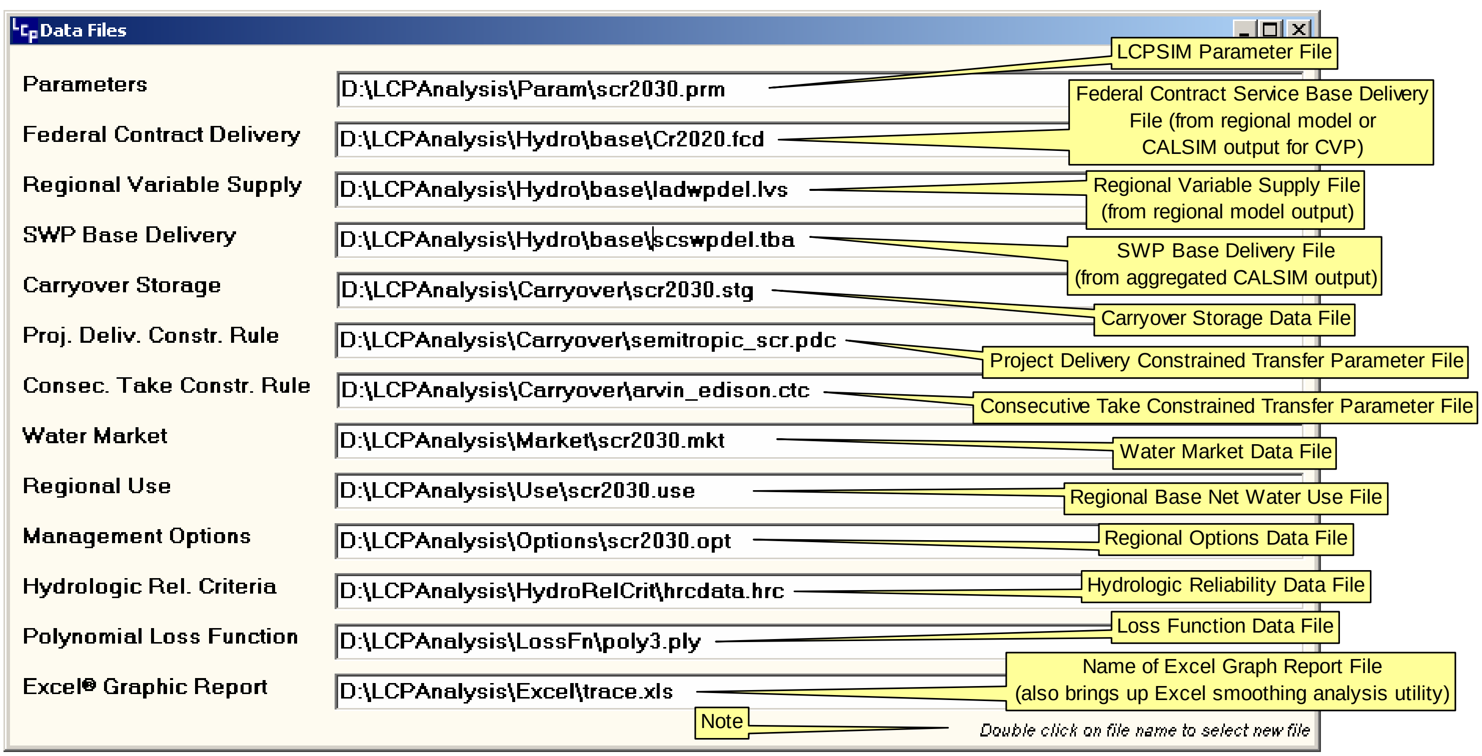


Figure 6B-6. LCPSIM Data File Screen

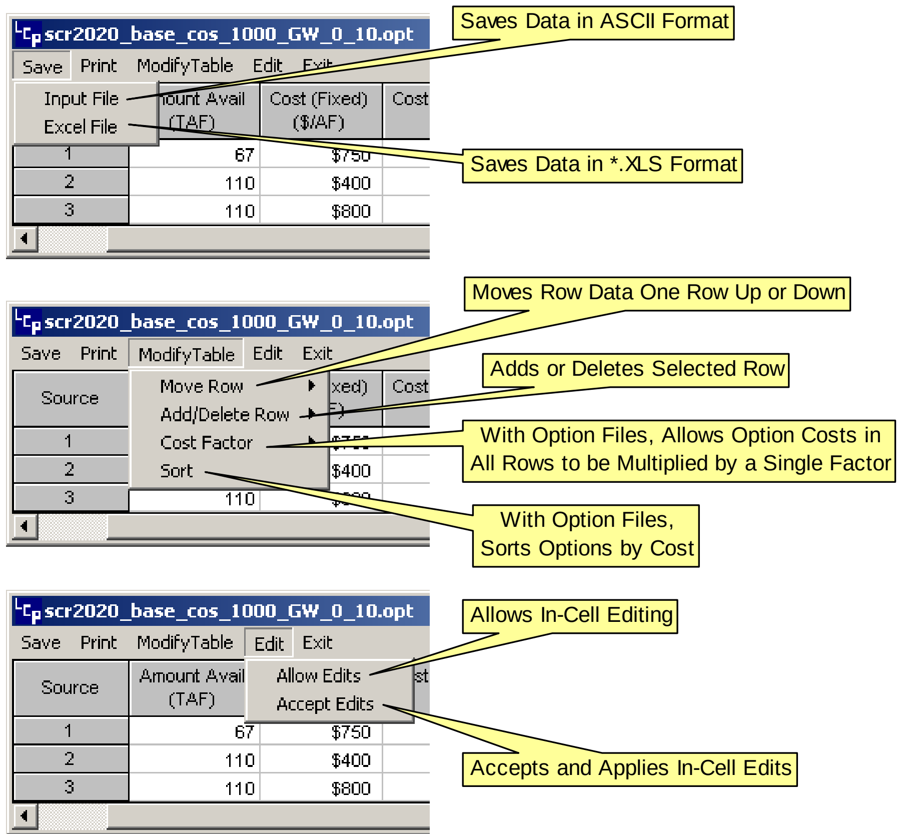
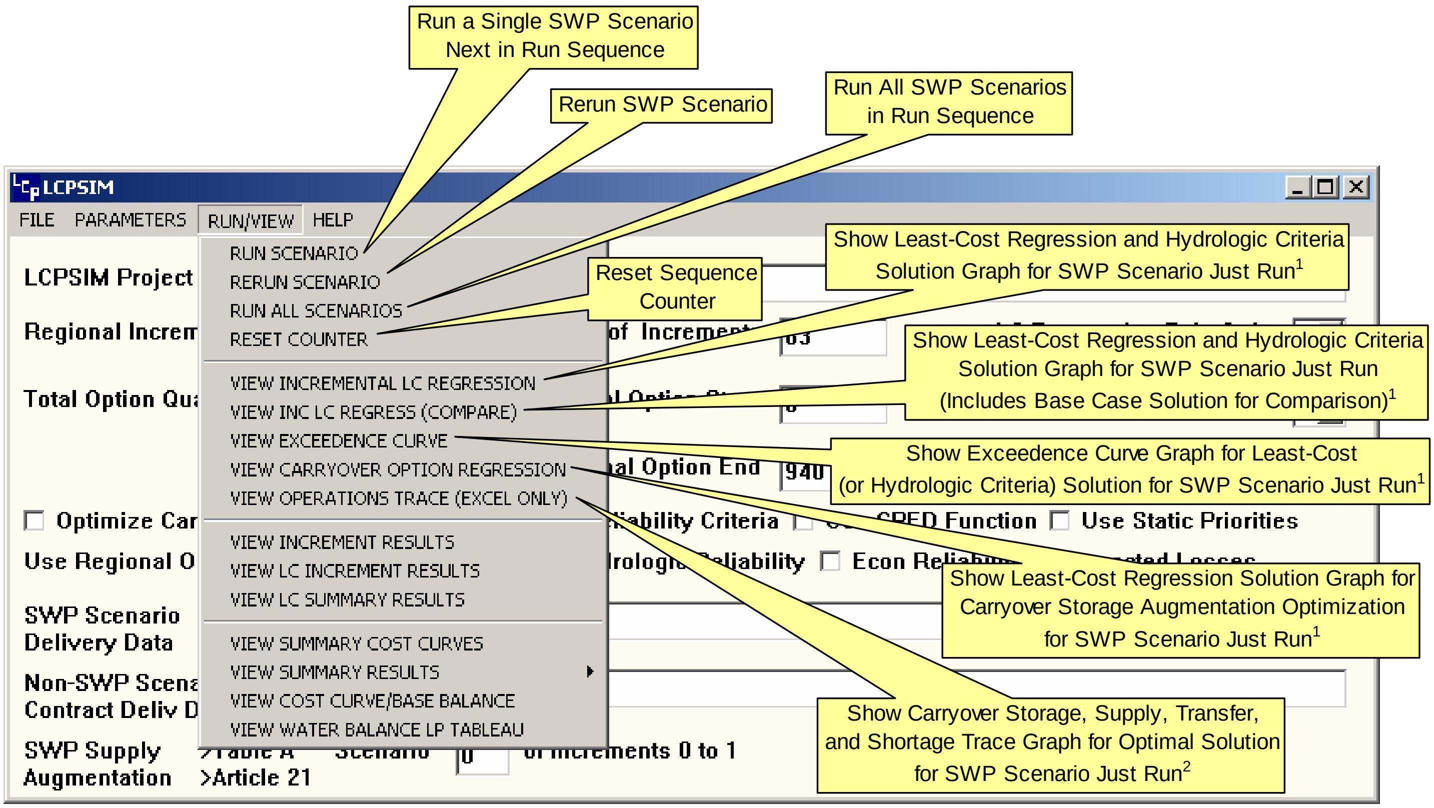


Figure 6B-7. LCPSIM Data File Edit Menu



Notes:

[1]Option to display in Microsoft Excel if the software is installed

[2]Will display only if Microsoft Excel is installed

Figure 6B-8. LCPSIM Run/View Menu

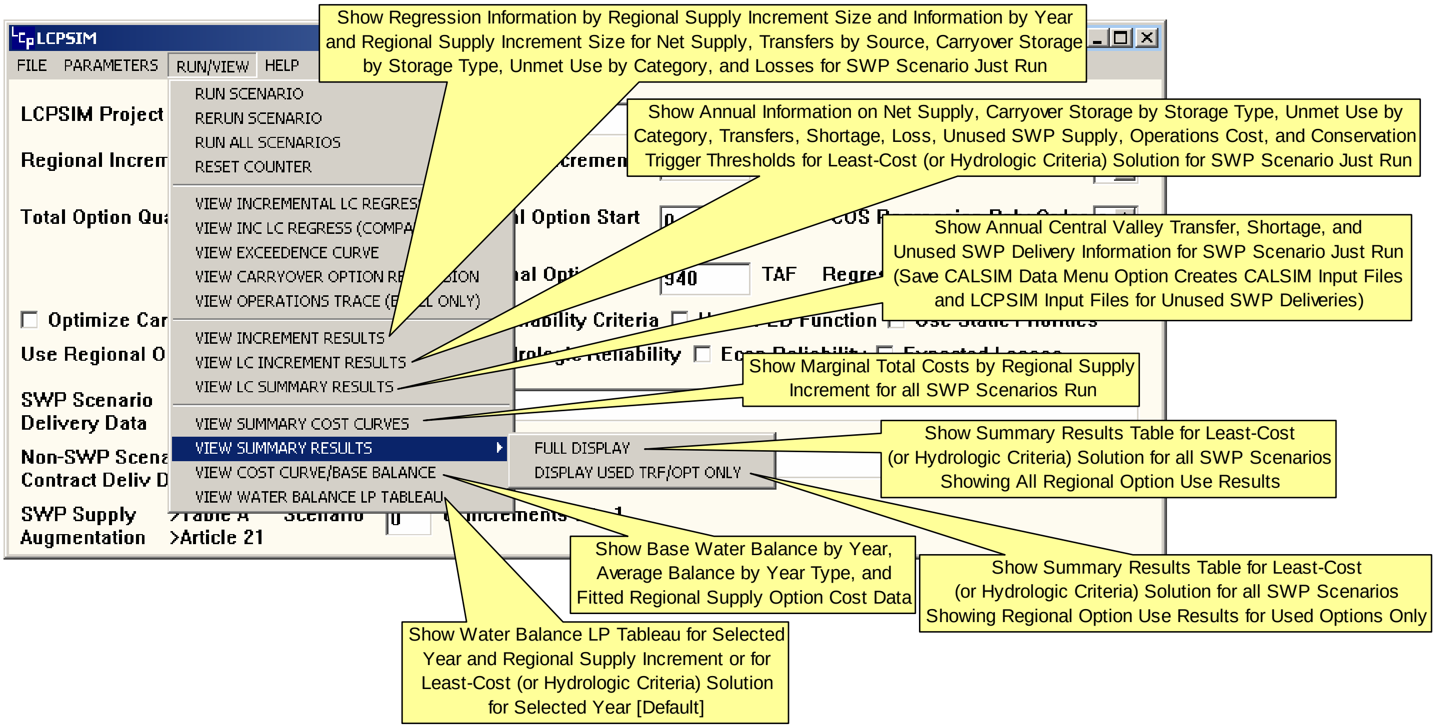


Figure 6B-9. LCPSIM Run/View Menu

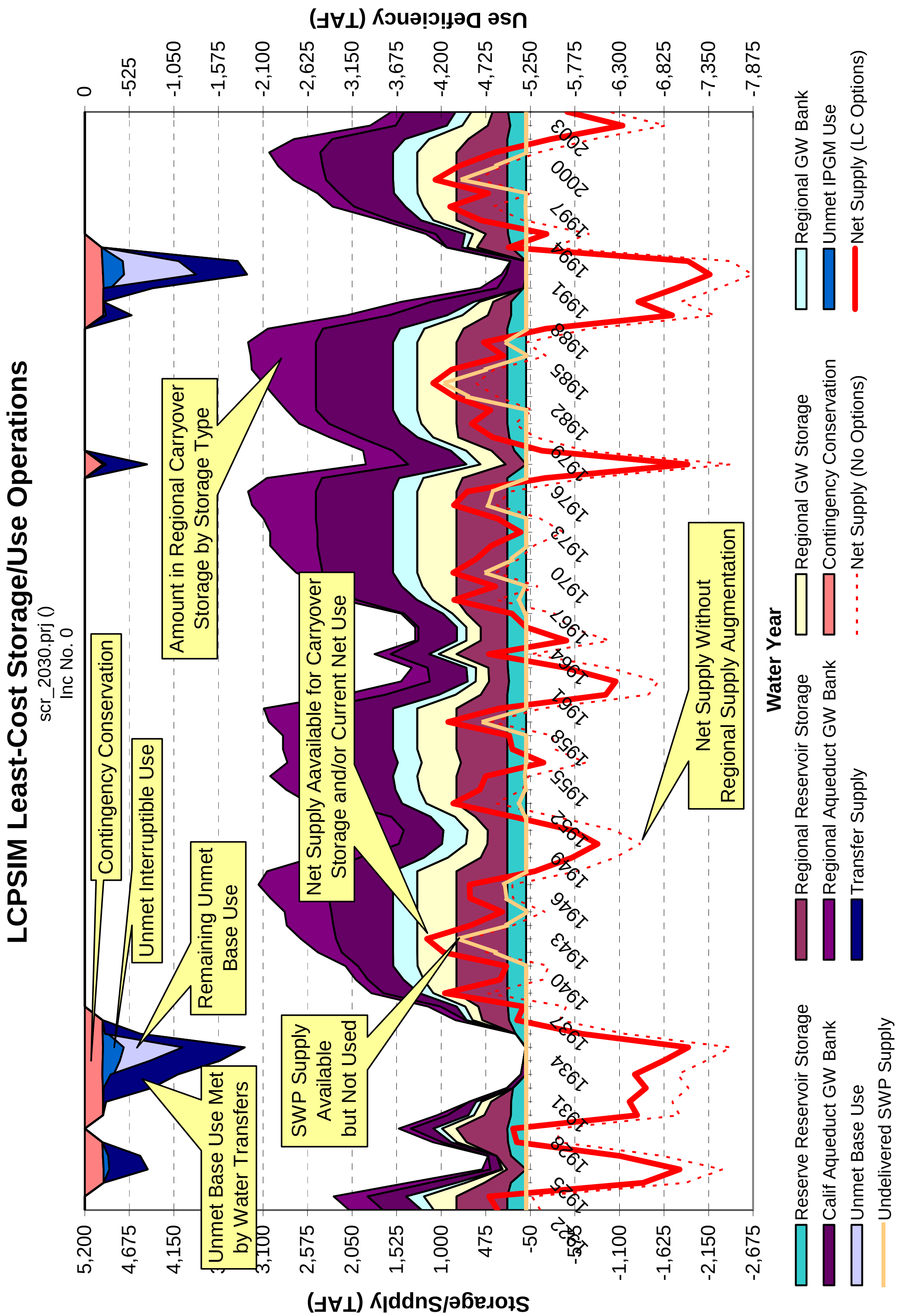


Figure 6B-10. Example LCPSIM Operations Trace Screen

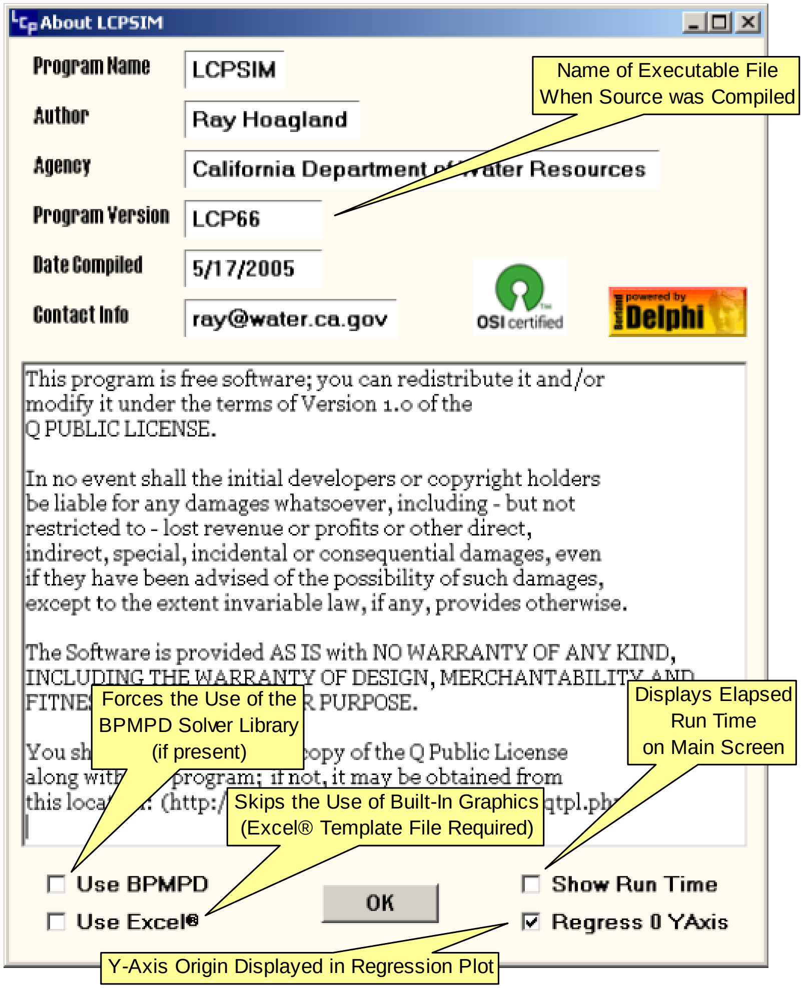


Figure 6B-11. LCPSIM About Box

Exhibit 6C
Smoothing Analysis Utility Screens

The following figures depict example screens in the Excel® smoothing analysis utility.

Smoothing Analysis

	startquan (TAF)	endquan (TAF)
range	600	900

	order
poly order	3

Polynomial Coefficients

	alt_coeff1	alt_coeff2	alt_coeff3	alt_coeff4	alt_coeff5	alt_coeff6	alt_coeff7	alt_coeff8
alternative	809.765715	-58.536988	-5.8739061	0.89713958	0	0	0	0
	base_coeff1	base_coeff2	base_coeff3	base_coeff4	base_coeff5	base_coeff6	base_coeff7	base_coeff8
base	287.426207	161.093276	-35.136466	2.17091769	0	0	0	0
	ben_coeff1	ben_coeff2	ben_coeff3	ben_coeff4	ben_coeff5	ben_coeff6	ben_coeff7	ben_coeff8
benefit	-522.33951	219.630264	-29.262559	1.27377811	0	0	0	0

	lc point (HTAF)	lc value ($Million)	Residual Variance
alternative	7.33	$418.41	19.39
base	7.49	$435.05	9.10
benefit		$16.64	21.76

Figure 6C-1. Example LCPSIM Main Spreadsheet Screen

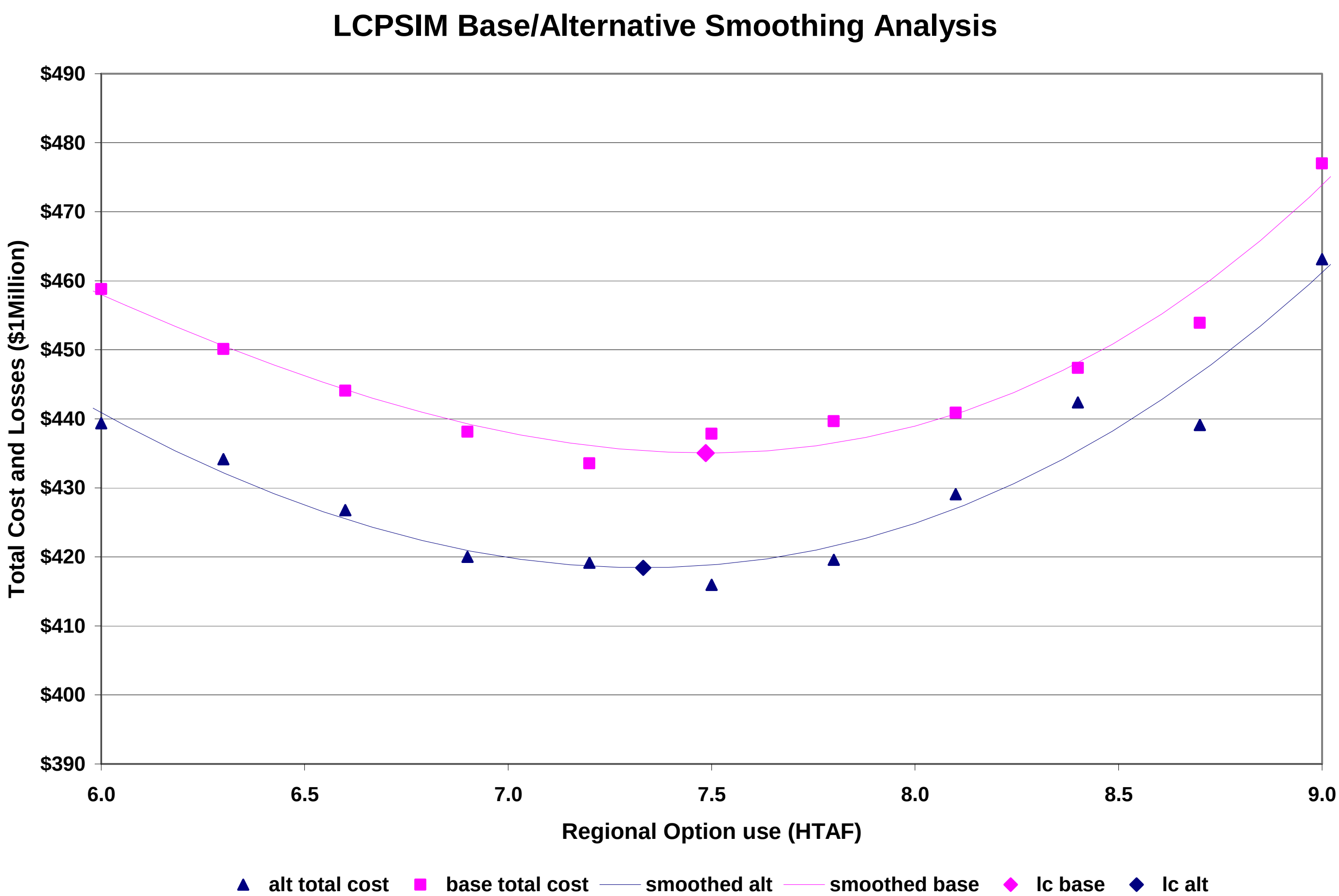


Figure 6C-2. Example LCPSIM Smoothing Analysis Results Graph

Chapter 7
Agricultural Water Supply Economics Model (CVPM)

Purpose and Need

The CVPM 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. A more complete description of the model's original development, calibration, and testing is provided as an appendix to Reclamation's PEIS for the CVPIA (Reclamation 1997).

Introduction

The CVPM is a regional model of irrigated agricultural production and economics that simulates the decisions of farmers in the Central Valley of California. CVPM assumes that farmers maximize profit subject to resource, technical, and market constraints. Farmers sell and buy in competitive markets, and no one farmer can affect or control the price of any commodity. To obtain a market solution, CVPM's objective function maximizes the sum of producers' surplus (net income) and consumers' surplus (net value of the agricultural products to consumers) subject to the following functions and constraints:

1. Linear, increasing marginal cost functions, estimated using the technique of positive mathematical programming, that incorporate acreage response elasticities that relate changes in crop acreage to changes in expected returns and other information.

2. Commodity demand functions that relate market price to the total quantity produced.

3. Irrigation technology tradeoff functions that describe the tradeoff between applied water and irrigation technology.

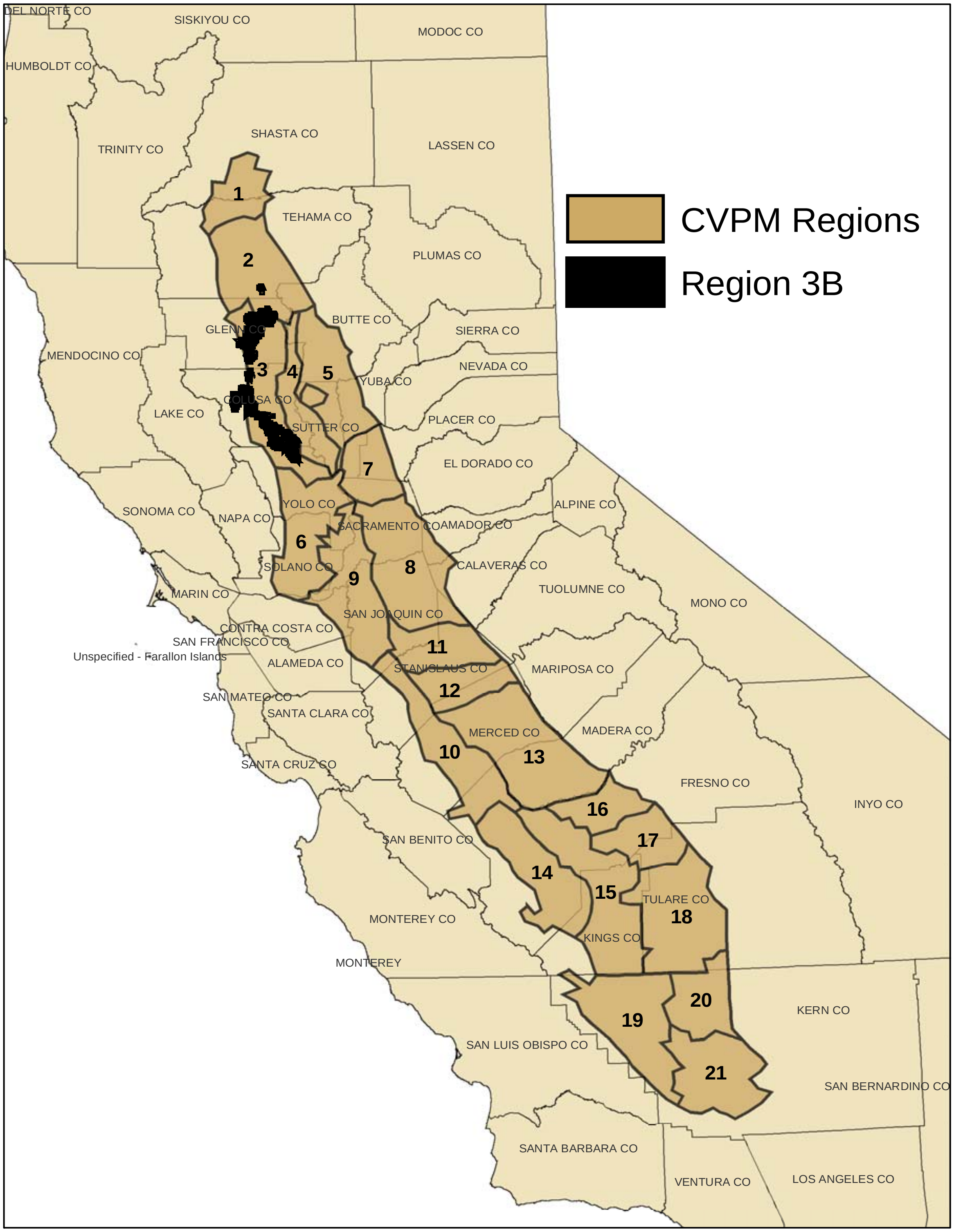
4. A variety of constraints involving land and water availability and other legal, physical, and economic limitations.

The model selects those crops, water supplies, and irrigation technology that maximize profit subject to these equations and constraints. From Component 1 above, cost per acre increases as production increases. Revenue is irrigated acreage, multiplied by crop yield per acre and crop price. From Component 2 above, crop price and revenue per acre decline as production increases. Component 3 affects costs and water use through the selection of the least-cost irrigation technology. Component 4 is used to analyze the impacts of the CALFED surface storage projects that change water availability and cost. Component 4 also ensures that the model incorporates real-world hydrologic, economic, technical, and institutional constraints.

Geographic Areas Considered

The model includes 22 crop production regions in the Central Valley and 20 categories of crops (Figure 7-1). Descriptions of each of the regions and crop types are provided in Tables 7-1 and 7-2, respectively.

This chapter describes the version of CVPM used in the SLWRI. Where appropriate, model inputs were adjusted to reflect changes in agricultural production and resource availability within production regions affected by water supply provided by the Investigation alternatives. A description of the changes in model inputs for the SLWRI is provided in the Economics Appendix.



Source: Reclamation, 1999

Figure 7-1. Agricultural Areas Modeled by Central Valley Production Model

Table 7-1. CVPM Regions and Descriptions

Region	Description of Major Agricultural Users
1	CVP users: Anderson Cottonwood, Clear Creek, Bella Vista, Sacramento River miscellaneous users
2	CVP users: Corning Canal, Kirkwood, Tehama, Sacramento River miscellaneous users.
3	CVP users: Glenn Colusa ID, Provident, Princeton-Codora, Maxwell, and Colusa Basin Drain MWC.
3b	Tehama-Colusa Canal Service Area. CVP Users: Orland-Artois WD, most of Colusa County, Davis, Dunnigan, Glide, Kanawha, La Grande, Westside WD.
4	CVP users: Princeton-Codora-Glenn, Colusa Irrigation Co., Meridian Farm WC, Pelger Mutual WC, Reclamation District 1004, Reclamation District 108, Roberts Ditch, Sartain M.D., Sutter MWC, Swinford Tract IC, Tisdale Irrigation, Sac River miscellaneous users.
5	Most Feather River region riparian and appropriative users.
6	Yolo, Solano Counties. CVP Users: Conaway Ranch, Sacramento River miscellaneous users.
7	Sacramento County north of American River. CVP users: Natomas Central MWC, Sacramento River miscellaneous users, Pleasant Grove-Verona, San Juan Suburban.
8	Sacramento Counties south of American River, San Joaquin County
9	Delta region. Direct diverters, CVP users: Banta Carbona, West Side, Plainview.
10	Delta-Mendota Canal. CVP Users: Panoche, Pacheco, Del Puerto, Hospital, Sunflower, West Stanislaus, Mustang, Orestimba, Patterson, Foothill, San Luis WD, Broadview, Eagle Field, Mercy Springs, Pool Exchange Contractors, Schedule II water rights, more.
11	Stanislaus River water rights: Modesto ID, Oakdale ID, South San Joaquin ID.
12	Turlock ID.
13	Merced ID. CVP users: Madera, Chowchilla, Gravelly Ford.
14	CVP users: Westlands WD.
15	Tulare Lake Bed. CVP users: Fresno Slough, James, Tranquility, Traction Ranch, Laguna, Reclamation District 1606.
16	Eastern Fresno Co. CVP users: Friant-Kern Canal. Fresno ID, Garfield, International.
17	CVP users: Friant-Kern Canal. Hills Valley, Tri-Valley Orange Cove.
18	CVP users: Friant-Kern Canal, County of Fresno, Lower Tule River ID, Pixley ID, portion of Rag Gulch, Ducor, Tulare County, most of Delano Earlimart, Exeter, Ivanhoe, Lewis Cr., Lindmore, Lindsay-Strathmore, Porterville, Sausalito, Stone Corral, Tea Pot Dome, Terra Bella, Tulare.
19	Kern County SWP service area.
20	CVP users: Friant-Kern Canal. Shafter-Wasco, South San Joaquin.
21	CVP users: Cross Valley Canal, Friant-Kern Canal. Arvin Edison.

Key:
CVP = Central Valley Project
CVPM = Central Valley Production Model
IC = Irrigation Company
ID = Irrigation District
MWC = Mutual Water Company
SWP = State Water Project
WD = Water District

Table 7-2. CVPM Crop Groupings

Category	Proxy Crop[1]	Unit of Measure
Grain	Wheat	Tons
Rice	Rice	Tons
Cotton	Cotton	Bales
Sugar Beets	Sugar Beets	Tons
Corn	Corn silage	Tons
Dry Beans	Dry Beans	Tons
Safflower	Safflower	Tons
Other Field	Sudan Grass	Tons
Alfalfa	Alfalfa Hay	Tons
Pasture	Irrigated Pasture	Acres
Processing Tomatoes	Processing Tomatoes	Tons
Fresh Tomatoes	Fresh Tomatoes	Tons
Cucurbits	Cantaloupe	Tons
Onions and Garlic	Dry Onions	Tons
Potatoes	White Potatoes	Tons
Other Truck	Broccoli	Tons
Almonds and Pistachios	Almonds	Tons
Other Deciduous	Walnuts	Tons
Sub Tropical	Oranges	Tons
Vine	Wine Grapes	Tons

Notes:
Acreage data for all crops in specific category summed with the proxy crop.
[1] Production costs, yields, and prices for this crop used in CVPM.
Key:
CVPM = Central Valley Production Model

Development History

The CVPM was developed by DWR in the early 1990s. It was substantially revised and updated for use in analyzing the impacts of the CVPIA. Important changes included geographic regions were revised to be consistent with water project operations planning models; more detail was included aggregation routines were added to allow the model to be run for subsets or groupings of regions and crops; and all data were revised with the best publicly available sources. The model has been further updated for the Common Assumptions analysis in cooperation with DWR and Reclamation. An important reason for selecting CVPM as a modeling tool for the Plan Formulation Common Model Package is that it is suitable for the development and refinement of a model that would be consistent with the Common Assumptions future planning and policy analyses. The model is based on an optimization technique known as positive mathematical programming. A description of the technique appears in Howitt (1995).

Several models of California agriculture based on the technique have contributed to the theory and application of the CVPM. These precursors have been used to estimate field crop losses caused by air pollution (Howitt and

Goodman 1989) and drought (Howitt 1994), demand functions for water (Howitt 1983), inter-regional water transfers (Vaux and Howitt 1984), impacts of changes in water supplies (Farnam 1994), and impacts of drainage control policies (Hatchett et al. 1991, Dinar et al. 1991). The technique has been applied to economic problems in many other settings.

Documentation and Review

CVPM underwent a series of revisions within DWR since its initial development, and no formal documentation of the model was made available to the public until the release of the CVPIA PEIS. A complete documentation of CVPM model structure, data, and use was prepared and published as part of the CVPIA PEIS (1977). As part of the analytical methods development for the CVPIA analysis, CVPM underwent a series of workshops and a formal peer review. Results and assumptions were also subject to review by the public and stakeholder groups during the CVPIA PEIS process and during subsequent environmental reviews of projects for which CVPM was used to assess impacts. The model's assumptions, structure, and data have again been assessed and revised by the Common Assumptions analytical team.

Qualifications on the Use of CVPM

CVPM is an optimization model that assumes agricultural decision-makers maximize long- or short-run profit based on a number of resource limitations. As a result, it derives the best possible response, as measured in profit, to changes in water supply conditions. Since actual decision-makers do not have access to perfect information on water supplies, prices, and markets, and do not have immediate access to financing to make the best possible adjustments to changes in conditions, actual responses will be less than optimal, so an optimization model tends to underestimate changes that reduce profit and overestimate changes that increase profit.

CVPM incorporates as much flexibility in the categories of adjustment allowed as conditions change. Changing crops, fallowing land, pumping groundwater, or adjusting irrigation efficiency are potential adjustments that may be implemented individually or in combination with one another. Depending on how these interact, errors in estimation of effects on profit may result in either an under- or overestimation of changes in these adjustment's individual categories. Other, simpler impact estimation methods not incorporating as much flexibility may overestimate reductions in profit.

The degree to which a decision-maker's response to a change in condition is optimal depends on information available, physical and financial flexibility, and the amount of time available for learning about and adjusting to the new circumstances. The primary impact analysis in the SLWRI uses 2030 as the basis for comparing conditions with and without implementing SLWRI alternatives. It is assumed that over the long run, decision-makers will learn and adjust to the SLWRI impacts. Impacts immediately following implementation are likely to be more pronounced because of the limited reaction time for decision-makers. Short-run adjustments to dry or wet conditions are assessed using a restricted form of the CVPM not allowing the flexibility of the long-run model.

Another qualification to the use of CVPM or any model used to estimate conditions in 2030 is the potential for structural and technological changes. Important changes that could occur between now and 2030 include international trade rules, consumer demand shifts, and agricultural and irrigation technology improvements. Trying to predict these changes is highly speculative, and revising CVPM to reflect these changes is beyond the scope of the SLWRI.

Core Modeling Assumptions

Positive Mathematical Programming and Model Calibration

Traditional optimization models, such as linear programming (LP) models, rely on data based on observed average conditions (e.g., average production costs, yields, and prices), which are expressed as fixed coefficients. As a result, these models tend to select crops with the highest average returns until resources (land, water, capital) are exhausted. The predicted crop mix is therefore less diverse than observed in reality. The most widespread reason for diversity of crop mix is the underlying diversity in growing conditions and market conditions. Not all farms and plots of land produce under the average set of conditions, therefore the marginal cost and revenue curves do not coincide with average cost and revenue curves.

Economic theory suggests economic decisions are based on marginal conditions, and these differ from average conditions. Positive Mathematical Programming (PMP) is a modeling technique developed to incorporate both marginal and average conditions into an optimization model. In the conventional case of diminishing economic returns, productivity declines as output increases. Therefore, the marginal cost of producing another unit of crop increases as production increases and the marginal cost exceeds the average cost. PMP uses this concept to reproduce the variety of crops observed in the data. The PMP technique uses this idea to reproduce the variety of crops observed in the data.

Several possible or combined reasons for crop diversity include the following: diverse growing conditions causing a variation in production costs or yield, crop diversity to manage and reduce risk, and constraints in marketing or processing capacity. CVPM assumes that the diversity of crop mix is caused by factors that can be represented as increasing marginal production cost for each crop at a regional level. For example, CVPM costs per acre increase for cotton farmers as they expand production onto more acreage. The PMP approach used in CVPM uses empirical information on acreage responses and shadow prices – implicit prices of resources – based on standard linear programming techniques and a calibration period data set. The acreage response coefficients and shadow prices are used to calculate parameters of a quadratic cost function that is consistent with economic theory. The calibrated model will then predict the original calibration data set, and can be used to predict effects of specified policy changes such as changes in water supplies.

Calibration refers to the calculation of some model parameters in such a way that the model will predict a given set of target data. The CVPM is calibrated against two categories of information: irrigated acreage by crop and by region and applied water (or irrigation efficiency) by crop and by region. Each category represents the target parameter (e.g., acres by crop by region) and has one or more calibration parameters calculated or adjusted in order for the model to match the target. The years 1998, 2000, and 2001 are used. At the time the Common Assumptions analysis was being designed, these years provided the most recent, available data on cropping patterns and prices. For calibrating to crop acreage, the calibration parameters are the coefficients of the quadratic total cost (linear marginal cost) function. The derivation of these parameters guarantees that the model will duplicate the calibration period crop acreage if no other data are changed. In addition, the calibration parameters for crop acres are calculated in such a way that the calculated net revenue in the calibration period equals the observed net revenue for that period. In other words, the acreage calibration parameters change the marginal costs but not the average or total costs in the calibration period. The other piece of information used to calculate the calibration parameters is the acreage response elasticity, described below.

Acreage Response Elasticities and PMP Coefficients

Acreage response elasticities show how farmers change their planted acreage in response to changes in expected price, revenue, or profit. Acreage response elasticity is defined here as the percent change in acreage of a crop due to a percent change in expected revenue per acre. The CVPM incorporates acreage response elasticities directly within the linear marginal cost functions as part of the PMP calculations. The shadow prices calculated as part of the PMP procedure indicate the deviation between marginal and average cost, but they do not provide information on the slope of the marginal cost function. This is the role of the acreage response elasticity. The elasticities used are provided in Table7-3.

Table 7-3. California Demand Flexibility, Share of California Production from the Central Valley, and Long- and Short-Run Acreage Response Elasticities

			Acreage Response	
Crop	**Demand Flexibility**	**Share from Central Valley**	**Long Run**	**Short Run**
Alfalfa	-0.5	0.63	0.51	0.24
Almonds and Pistachios	-0.7	1	0.11	0.03
Subtropical	-0.8	0.7	0.5	0.03
Corn	0	0.5	0.45	0.21
Cotton	-0.05	0.97	0.64	0.36
Dry Beans	-0.2	0.85	0.17	0.13
Fresh Tomatoes	-0.62	0.5	0.31	0.16
Cucurbits	-0.2	0.7	0.05	0.05
Other Field	-0.2	0.63	1.89	0.63
Other Truck	-0.2	0.35	0.19	0.11
Safflower	-0.2	0.9	0.34	0.34
Onions and Garlic	-0.21	0.58	0.19	0.11
Pasture	-0.5	0.66	0.51	0.24
Potato	-0.1	0.75	0.19	0.11
Processing Tomatoes	-0.17	1	0.28	0.15
Rice	-0.05	1	0.3	0.96
Sugar Beets	-0.1	0.8	0.19	0.11
Other Deciduous	-0.25	0.93	0.11	0.03
Vine	-0.8	0.55	0.11	0.03
Grain	0	0.5	0.38	0.36

Commodity Demand Functions and Price Flexibilities

Commodity demand functions show the price buyers are willing to pay for agricultural goods as a function of the total quantity put up for sale. The CVPM uses linear commodity demand functions derived from secondary information in the form of price flexibilities. Price flexibility is defined as the percent change in market price caused by a percent change in sales.

Price flexibilities must be appropriate to the region being analyzed, in this case the Central Valley. The CVPM is set up to read in California-wide flexibilities and then adjust them for Central Valley-only flexibilities. The Central Valley price flexibility is equal to the statewide flexibility times the proportion of California production of the commodity grown in the Central Valley. These proportions were obtained from DWR. California flexibilities and the share of California production from the Central Valley as used in the CVPM are provided in Table 7-3.

Existing estimates of California price flexibilities from the agricultural economics literature were used. Commodities that could not be found in existing studies were approximated using values for similar kinds of commodities.

Price data from 1998 to 2002 and production data from 1998, 2000, and 2001 are combined with the price flexibility to construct a linear demand function. As CVPM commodity production changes because of changes in water supplies, the model predicts changes in market price.

In general, price changes are not an important impact of changes in water supplies because the commodities most likely to be idled by water shortages are produced for national or international markets and have small California price flexibilities. One exception to this generalization is alfalfa. Local production declines can cause significant local price increases because of inelastic demands for feed, especially for horses and dairy cattle, and large transportation costs.

Irrigation Technology Adjustments

Cost functions derived with PMP govern changes in acreage of different crops as conditions change. Those functions do not affect the mix of inputs used to grow a crop. Inputs used to produce an acre of an irrigated crop include labor, water, irrigation system investments, other capital investments, fertilizer, and chemicals. Although any of these inputs could be adjusted in response to a change in water policy, water use and irrigation system investments are of particular interest for this effort.

CVPM includes tradeoff functions between water use and irrigation system cost. For purposes of CVPM irrigation tradeoff functions, water use is defined as applied water (AW) divided by ETAW. This ratio is referred to as Relative AW, and is the inverse of the most commonly used measure of field-level irrigation efficiency. Because ETAW varies regionally, using the ratio of AW to

ETAW in the estimation allows the parameters of the tradeoff functions to be more site independent.

To estimate the tradeoff functions, data on irrigation system cost and performance were updated from an earlier study prepared for Reclamation (CH2M HILL 1991). The updated study was prepared in 1994 (CH2M HILL 1994).

In CVPM, both applied water and irrigation system cost are decision (endogenous) variables. Profit maximizing (or cost minimizing) conditions require that the ratio of water price to irrigation technology price be equal to the ratio of the marginal products of water and irrigation technology. Given an estimate of the tradeoff function, an observed Relative AW also defines the irrigation system cost.

There are several ways of calibrating CVPM to observed applied water. The current version of CVPM uses the estimated tradeoff function parameters and assumes that the observed water use-irrigation technology mix is cost minimizing, and CVPM calculates the implied irrigation technology price needed for this to be true.

Short-Run Versus Long-Run Analysis

As previously mentioned, CVPM is designed to analyze both short- and long-run responses to changes in water resource conditions. The purpose of the long-run analysis is to estimate economic conditions after farmers have made permanent adjustments to changes in hydrologic and economic conditions. The purpose of the short-run analysis is to estimate acreage, crop mix, and water use during a drought, given farmers' best possible responses to the temporary situation.

The two analyses have several important differences involving farmer behavior and the extent to which certain technologies, crops, and costs can be affected in the short run.

- Variable and fixed costs can be avoided in the long run, but only variable costs can be avoided in the short run. Therefore, only variable costs affect decisions in the short run. Fixed costs are subtracted from net returns after CVPM has decided the best short-run response. Both variable and fixed costs affect decisions in the long run because all factors of production can be adjusted.

- CVPM differentiates short- and long-run acreage response elasticities. Short-term elasticities represent the willingness of growers to change acreage of a crop on a year-to-year basis. Long-run elasticities represent more permanent or long-run changes in crop mix.

- The long-run analysis includes limitations on perennial crop acreage determined by running CVPM with dry-year hydrology to ensure that perennial acreage cannot exceed that which can be supported during drought conditions.

- Investment in irrigation technology is determined by its long-run average profitability. CVPM holds irrigation technology constant in the short run.

- The water use required for nonbearing perennial acreage is included in the long-run analysis to account for the average replacement rate of these crops. Production costs, yields, and water use all represent the average over the production cycle. Alfalfa and pasture are on a 4- or 5-year cycle; trees and vines are on a 20- to 40-year cycle (see Table 7B-1 in Exhibit 7B).

Other Resource Constraints

CVPM includes several other constraints to account for limited resources.

CVPM constrains water supplies and allows economics to determine the farmer's best use of them. CVPM can include as many distinct water sources and costs as are appropriate for a production region. The current model identifies CVP water service contract supply, CVP water rights settlement and exchange supply, SWP supply, local surface supply, and groundwater as potential sources available in each region.

CVPM can also impose an upper limit on irrigable land. Currently, this limit is set at 120 percent of the irrigated acreage during full water supply conditions. This assumption accounts for the maximum irrigable acreage given current facilities, and for purposes of the SLWRI analysis, prevents land from becoming a limiting resource.

CVPM Data Handling and Sources for Calibration Run

CVPM was calibrated using data for 1998, 2000, and 2001. These years were chosen because DWR has prepared full water balance and land use estimates for the coverage area as part of the California Water Plan Update (DWR 2005). The calibration run uses this information to estimate the calibration parameters as described above.

Water Supplies

CVP: Reclamation operations data provided the total amounts of CVP water delivered by region. Contract deliveries were obtained from Reclamation (1998, 2000, 2001). The difference between total deliveries and contract deliveries indicates deliveries for water rights settlement.

SWP: SWP deliveries were obtained from DWR Bulletin 132 (DWR, various years).

Local Surface: Local surface water is estimated using applied water rates per region from DWR. CVP and SWP deliveries are subtracted from the applied water use to identify local surface and groundwater supplies. Historical local surface and groundwater proportions are used to estimate local surface water totals.

Groundwater: Groundwater is estimated using applied water rates per region from DWR. CVP and SWP deliveries are subtracted from the applied water use to identify local surface and groundwater supplies. Historical local surface and groundwater proportions are used to estimate groundwater totals.

A summary of surface water supplies used in the calibration run is provided in Table 7-4.

Table 7-4. 1998, 2000, and 2001 Average Surface Water Supplies by Region

Region	Central Valley Project Contract Water (TAF)	Central Valley Project Settlement Water (TAF)	State Water Project (TAF)	Local Surface Water (TAF)	Groundwater (TAF)
1	2.53	104	0	0	48.17
2	18	0	0	80.9	437.3
3	101	626	0	19.5	398.8
3b	198	0	0	0	58.4
4	119	377	0	0	331.2
5	0.4	1.6	0	1230	528.9
6	5.1	20.5	0	291.2	473.6
7	16.1	70.4	0	185.7	263
8	0	0	0	113.8	715.1
9	10.1	0	0	1092	108.6
10	264	661	3.7	62.7	252.9
11	0	0	0	755.3	35.33
12	0	0	0	563.1	207.2
13	146	70.2	0	438.4	807.1
14	971	0	0	161.9	118.4
15	60.7	0	143.2	340.9	1247
16	24.4	0	0	293.7	65.5
17	31	0	0	281.2	430.8
18	280	0	0	339.1	1214
19	0	0	532.2	26	354.1
20	281	0	41.57	50.97	182.3
21	68.2	0	257.8	153.4	641.2
Total	2597	1930	978.4	6480	8920

Key:
TAF = thousand acre-feet

Crop Acreage and Crop Mix

Three primary sources of crop acreage data are available, including district-level reports, County Agricultural Commissioner Reports, and DWR land use estimates. Because of the need for a consistent and annual data set that covers all irrigated lands in the Central Valley, CVPM uses County Agricultural Commissioner (CAC) crop reports of harvested acreage as the primary data source (California Department of Food and Agriculture 1984 to 1993). County-level electronic data were obtained. Crop acreage was apportioned to CVPM regions using DWR's 1990 land use estimates, which are available by detailed analysis unit (DAU). Additional information obtained from individual districts was used, as available, to adjust these estimates. Kern County Water Agency (KCWA) annual water supply reports provided crop acreage for Kern County, and Westlands Water District (WWD) provided data for CVPM Region 14 (KCWA various years, WWD various years).

The county crop data include dryland acreage of wheat, miscellaneous grains, miscellaneous hay, and oilseeds. The proportion of this acreage that was not irrigated was estimated based on U.S. agricultural census data (U.S. Department of Commerce, Bureau of the Census 1987). Adjusting for dryland production gives an estimate of lands that are harvested and irrigated. CVPM accounts for all irrigated land, even if it is not harvested (nonharvested lands include nonbearing orchards and vines, cover crops, and crop failures). A second adjustment occurs within CVPM so that water use depends on irrigated acreage whereas production depends on harvested acreage. The ratio of harvested and irrigated to all irrigated is based on a crop and regional comparison of DWR’s 1990 irrigated acreage estimates with the dryland-adjusted 1990 CAC estimates.

Table 7-5 displays the average calibration period crop acreage by subregion. These data represent lands harvested and irrigated. For analysis of 2030 conditions, crops supplies and demands are scaled to match DWR’s projected 2030 acreage.

Crop Water Use and On-Farm Irrigation Efficiency

DWR has made estimates by DAU of AW and the crop use of AW (ETAW) for 14 crop categories. CVPM uses these estimates in all but a few cases. A few of the estimates implied unrealistically high irrigation efficiency, and were adjusted slightly. Crop water use estimates appear in Tables 7-6 and 7-7.

Crop Prices and Yields

CAC reports provided estimates of prices and yields. The data sometimes showed large, and probably unrealistic, variations in prices or yields between some adjacent counties, possibly because of small samples. Tables 7-5 and 7-6 provide crop price and yield data.

Table 7-5. Average Acres (1998, 2000, and 2001) by Region and Crop

Region	Pasture	Alfalfa	Sugar Beets	Other Field	Rice	Other Truck	Fresh Tomatoes	Other Deciduous	Grain	Vines	Cotton	Subtropical
	(thousand acres)											
1	24.47	0.87	0.00	0.13	0.00	0.67	0.00	2.97	1.03	0.07	0.00	0.90
2	35.70	7.63	0.10	2.20	2.00	0.47	0.00	47.80	8.07	0.00	0.00	22.40
3	9.23	11.90	0.80	6.47	150.37	0.50	0.90	4.97	22.43	3.80	8.90	0.93
3b	3.30	5.27	0.73	3.30	9.27	0.33	0.00	3.03	7.07	3.53	4.07	1.13
4	1.57	6.13	0.67	5.97	96.50	1.03	0.43	24.30	18.53	0.00	1.07	0.00
5	25.73	5.33	0.00	2.97	181.77	1.77	0.00	111.03	6.40	0.30	0.53	5.03
6	11.50	48.13	2.13	15.93	12.50	2.80	1.73	23.83	50.43	5.50	1.00	0.23
7	21.43	3.17	1.43	1.40	61.73	0.43	0.00	10.87	8.93	0.00	0.00	0.20
8	41.80	15.03	1.50	4.17	3.13	5.93	5.00	51.60	28.33	86.60	0.00	0.33
9	31.93	58.50	3.93	10.17	0.73	21.73	7.70	18.07	53.63	22.47	0.00	0.03
10	13.40	79.13	8.47	10.77	6.63	15.17	5.87	23.90	42.47	1.90	98.03	0.67
11	49.53	8.93	0.00	0.77	5.47	6.80	0.20	25.87	13.33	12.07	0.00	0.30
12	22.50	22.03	0.13	4.73	0.00	10.73	0.23	17.73	14.87	15.00	0.00	0.20
13	38.10	69.43	4.77	5.03	3.80	11.13	8.43	27.03	57.40	105.23	47.63	5.77
14	1.73	18.33	7.80	2.27	0.00	32.13	3.37	3.80	48.97	9.43	198.10	0.83
15	6.17	114.93	6.10	6.27	0.00	2.47	1.20	25.37	122.73	57.20	205.07	0.73
16	8.00	9.03	0.00	0.00	0.00	10.60	0.00	13.03	3.07	73.33	6.50	11.53
17	6.67	8.87	0.00	0.67	0.00	2.77	0.20	78.13	9.60	109.80	3.27	38.23
18	5.20	96.93	6.33	8.83	0.00	5.53	1.20	61.27	92.97	57.17	81.07	104.57
19	2.03	45.33	2.63	5.77	0.00	6.33	0.90	2.33	41.07	9.40	92.13	2.17
20	0.10	16.43	0.93	1.43	0.00	11.30	0.00	7.30	11.17	45.03	12.37	28.87
21	1.20	51.77	0.67	5.03	0.00	27.83	0.87	9.80	36.83	40.73	74.87	19.40

Table 7-5. Average Acres (1998, 2000, and 2001) by Region and Crop (contd.)

Region	Corn	Dry Beans	Safflower	Processed Tomatoes	Cucurbits	Onion and Garlic	Potato	Almonds and Pistachios	Total
	(thousand acres)								
1	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.20	31.40
2	5.03	1.47	0.83	0.00	0.93	0.00	0.00	35.63	170.27
3	9.43	3.83	3.87	19.20	9.03	1.63	0.00	16.37	284.57
3b	7.90	1.40	0.40	7.83	0.00	0.00	0.00	33.90	92.47
4	14.30	13.83	31.97	28.93	11.43	0.10	0.00	4.37	261.13
5	1.17	2.90	2.90	0.93	2.70	0.00	0.00	29.37	380.83
6	27.30	5.53	9.10	36.60	2.77	0.20	0.00	6.03	263.27
7	4.57	0.67	1.67	0.60	0.17	0.07	0.00	0.13	117.47
8	33.77	7.20	1.10	14.27	2.03	0.40	0.00	2.93	305.13
9	113.43	9.20	33.83	33.10	5.10	0.47	4.07	1.73	429.83
10	23.23	21.33	2.17	33.17	28.13	2.77	0.07	18.10	435.37
11	29.87	1.10	0.23	0.63	1.03	0.57	0.00	60.97	217.67
12	50.53	2.43	0.40	0.00	1.37	0.10	0.00	84.57	247.57
13	52.70	2.67	0.90	10.53	2.33	1.40	0.00	121.57	575.87
14	4.90	8.87	3.43	89.57	21.63	30.80	0.00	37.60	523.57
15	58.03	7.67	18.43	4.17	1.40	2.80	0.00	29.77	670.50
16	4.80	1.27	0.00	0.00	0.43	0.10	0.00	15.10	156.80
17	8.07	1.43	0.00	0.27	0.33	0.20	0.00	6.27	274.77
18	124.33	6.60	2.67	1.50	1.23	1.77	0.33	25.23	684.73
19	7.23	1.60	0.97	3.53	0.53	2.87	0.00	68.60	295.43
20	4.03	2.17	0.00	0.00	0.23	1.07	1.93	64.23	208.60
21	34.40	2.30	5.87	3.57	5.43	7.37	18.43	17.03	363.40

Source: DWR

Table 7-6. Applied Water (1998, 2000, and 2001) per Acre by Region and Crop

Region	Pasture	Alfalfa	Sugar Beets	Other Field	Rice	Other Truck	Fresh Tomatoes	Other Deciduous	Grain	Vines	Cotton	Subtropical
	Acre-feet per acre											
1	3.42	3.60	0.00	1.62	0.00	1.97	0.00	2.83	0.29	1.60	0.00	2.02
2	4.02	3.73	2.76	1.70	5.14	1.99	0.00	2.76	0.37	0.00	0.00	1.99
3	3.99	4.26	2.80	1.94	5.32	2.94	2.80	3.08	0.75	1.79	2.92	2.38
3b	3.97	4.13	2.76	1.87	5.32	2.68	2.80	3.08	0.72	1.79	2.92	2.38
4	3.64	4.14	2.85	1.90	5.19	2.52	2.75	3.08	0.74	0.00	2.71	0.00
5	4.81	4.31	1.18	2.12	5.29	2.71	0.00	3.61	0.81	1.70	3.10	2.58
6	5.45	5.05	3.21	2.38	5.24	3.83	2.86	3.83	1.09	1.40	2.99	3.08
7	5.14	4.46	3.21	2.42	5.10	3.21	0.00	3.65	0.92	1.17	0.00	3.09
8	5.22	4.52	2.99	2.66	5.20	3.48	1.96	3.40	0.56	1.37	0.00	2.77
9	5.66	5.05	3.28	2.67	5.64	2.41	2.26	4.12	0.96	1.68	0.00	2.91
10	4.67	4.63	1.76	2.65	5.21	1.25	2.40	3.31	1.13	2.07	2.74	2.52
11	4.56	4.53	0.00	2.57	5.28	1.64	2.22	3.46	0.94	1.66	0.00	3.12
12	4.36	4.35	1.49	2.34	0.00	1.25	2.31	3.29	1.03	1.81	0.00	2.68
13	4.35	4.15	1.46	2.33	5.26	1.25	2.33	3.25	1.01	2.07	2.88	2.54
14	4.00	3.86	3.41	2.26	0.00	1.59	2.06	3.88	1.36	2.35	2.67	3.05
15	4.34	4.37	1.71	2.54	0.00	1.47	2.41	3.62	1.26	1.99	2.89	2.99
16	4.50	4.50	0.00	1.00	0.00	1.27	0.90	3.27	1.16	2.04	2.82	2.57
17	4.49	4.69	0.00	2.76	0.00	1.39	2.42	3.42	1.12	2.05	2.92	2.43
18	4.64	4.59	1.69	2.73	0.00	1.73	2.45	3.34	1.19	2.21	2.87	2.75
19	4.65	4.60	2.03	2.78	0.00	1.63	2.49	3.32	1.31	2.14	2.76	3.05
20	4.91	4.95	2.08	2.89	0.00	1.58	0.00	3.35	1.30	2.39	2.81	2.96
21	4.95	4.65	2.16	2.88	0.00	1.64	2.45	3.39	1.52	2.57	3.14	3.24

Table 7-6. Applied Water (1998, 2000, and 2001) per Acre by Region and Crop (contd.)

Region	Corn	Dry Beans	Safflower	Processed Tomatoes	Cucurbits	Onion and Garlic	Potato	Almonds and Pistachios
	Acre-feet per acre							
1	0.00	0.00	0.48	0.00	0.00	0.00	0.00	2.76
2	2.25	1.76	0.47	0.00	1.22	0.00	0.00	2.85
3	2.40	2.07	0.45	2.80	1.28	3.22	0.00	2.99
3b	2.34	2.00	0.45	2.80	1.26	3.22	0.00	2.99
4	2.41	2.10	0.45	2.80	1.45	3.63	0.00	2.91
5	2.80	2.36	0.62	2.91	1.67	0.00	0.00	3.20
6	2.77	2.41	0.59	2.96	1.64	3.93	0.00	4.06
7	2.78	2.27	0.62	2.89	1.69	4.17	0.00	3.62
8	2.53	2.17	0.68	2.63	1.64	2.10	0.00	3.40
9	2.81	2.38	0.69	3.07	1.87	2.61	2.96	3.62
10	2.61	2.22	1.48	2.90	2.36	3.73	2.24	3.30
11	2.51	2.09	1.15	2.87	2.04	2.19	0.00	3.39
12	2.33	1.91	1.14	0.90	2.41	3.69	0.00	3.00
13	2.38	1.95	1.08	3.01	2.27	3.69	0.00	3.14
14	2.43	1.94	1.23	2.29	2.04	2.72	0.00	3.49
15	2.69	2.32	1.32	3.05	2.58	3.83	0.00	3.37
16	2.44	2.04	0.00	0.00	2.46	3.95	0.77	3.00
17	3.00	2.32	0.00	3.15	2.49	3.88	0.00	3.27
18	3.13	3.02	1.09	3.16	2.39	3.95	2.05	3.45
19	3.34	3.16	1.19	3.13	2.39	3.52	0.00	3.57
20	3.38	3.15	0.00	0.00	2.50	3.59	2.34	4.02
21	3.43	3.28	1.47	3.06	2.48	3.61	2.11	4.18

Source: DWR

Table 7-7. Average ET of Applied Water (1998, 2000, and 2001) by Region and Crop

Region	Pasture	Alfalfa	Sugar Beets	Other Field	Rice	Other Truck	Fresh Tomatoes	Other Deciduous	Grain	Vines	Cotton	Subtropical
	Acre-feet per acre											
1	2.31	2.57	0.00	1.23	0.00	1.42	0.00	2.13	0.22	1.17	0.00	1.47
2	2.83	2.70	2.10	1.23	2.93	1.49	0.00	2.14	0.27	0.00	0.00	1.63
3	2.80	2.99	1.99	1.35	3.03	2.00	1.93	2.27	0.52	1.43	2.01	1.79
3b	2.80	2.99	1.89	1.33	3.03	2.00	1.93	2.27	0.52	1.43	2.01	1.79
4	2.57	2.91	2.03	1.32	2.94	1.74	1.90	2.28	0.50	0.00	1.94	0.00
5	3.14	2.98	0.80	1.48	3.00	1.85	0.00	2.56	0.55	1.36	2.11	1.90
6	3.50	3.44	2.60	1.62	2.93	2.59	1.97	2.69	0.73	1.12	2.03	2.19
7	3.26	3.03	2.61	1.65	2.86	2.18	0.00	2.55	0.61	0.93	0.00	2.17
8	3.38	3.08	2.34	1.73	2.89	2.33	1.35	2.38	0.39	1.09	0.00	1.96
9	3.62	3.43	2.70	1.81	3.16	1.71	1.56	2.89	0.65	1.35	0.00	2.33
10	3.12	2.94	1.32	1.67	3.10	0.80	1.73	2.57	0.80	1.55	2.30	1.99
11	3.07	3.04	0.00	1.65	3.05	1.11	1.53	2.56	0.65	1.27	0.00	2.14
12	3.00	2.80	1.10	1.47	0.00	0.80	1.73	2.50	0.70	1.40	0.00	1.90
13	3.00	2.81	1.11	1.47	3.10	0.80	1.73	2.54	0.70	1.46	2.15	1.90
14	3.13	3.10	2.56	1.79	0.00	0.99	1.51	2.93	0.96	1.89	2.05	2.26
15	3.11	2.97	1.23	1.66	0.00	0.94	1.73	2.67	0.84	1.48	2.25	2.19
16	3.01	2.83	0.00	0.60	0.00	0.80	0.63	2.53	0.73	1.47	2.17	1.90
17	3.06	3.06	0.00	1.68	0.00	0.90	1.73	2.55	0.73	1.48	2.16	1.78
18	3.36	3.17	1.27	1.69	0.00	1.17	1.73	2.60	0.78	1.63	2.23	2.09
19	3.54	3.38	1.50	1.83	0.00	1.17	1.70	2.78	0.91	1.62	2.28	2.33
20	3.53	3.37	1.50	1.82	0.00	1.17	0.00	2.75	0.89	1.81	2.33	2.19
21	3.60	3.47	1.60	1.93	0.00	1.17	1.73	2.82	1.03	1.93	2.43	2.40

Table 7-7. Average ET of Applied Water (1998, 2000, and 2001) by Region and Crop (contd.)

Region	Corn	Dry Beans	Safflower	Processed Tomatoes	Cucurbits	Onion and Garlic	Potato	Almonds and Pistachios
	Acre-feet per acre							
1	0.00	0.00	0.33	0.00	0.00	0.00	0.00	2.15
2	1.61	1.27	0.34	0.00	0.86	0.00	0.00	2.24
3	1.67	1.45	0.34	1.93	0.89	2.19	0.00	2.39
3b	1.67	1.45	0.35	1.95	0.89	2.19	0.00	2.39
4	1.70	1.45	0.34	1.93	0.99	2.43	0.00	2.30
5	1.94	1.61	0.47	2.02	1.13	0.00	0.00	2.39
6	1.91	1.64	0.46	2.05	1.11	2.63	0.00	2.80
7	1.91	1.54	0.48	1.99	1.13	2.93	0.00	2.50
8	1.74	1.41	0.52	1.81	1.10	1.47	0.00	2.31
9	1.94	1.62	0.54	2.12	1.33	1.85	2.10	2.50
10	1.77	1.50	1.19	2.20	1.59	2.80	1.43	2.46
11	1.68	1.49	0.90	1.99	1.36	1.47	0.00	2.40
12	1.63	1.43	0.91	0.70	1.60	2.80	0.00	2.35
13	1.65	1.45	0.87	2.20	1.60	2.80	0.00	2.38
14	1.91	1.60	0.99	1.88	1.39	1.96	0.00	2.53
15	1.81	1.71	1.05	2.22	1.60	2.80	0.00	2.56
16	1.63	1.47	0.00	0.00	1.60	2.80	0.50	2.40
17	2.02	1.65	0.00	2.33	1.62	2.82	0.00	2.44
18	2.13	2.22	0.87	2.23	1.60	2.80	1.33	2.82
19	2.27	2.37	0.95	2.23	1.60	2.80	0.00	2.69
20	2.27	2.33	0.00	0.00	1.60	2.80	1.33	3.03
21	2.33	2.43	1.17	2.23	1.60	2.80	1.33	3.12

Source: DWR
Key:
ET = evapotranspiration

Table 7-8. Average Crop Prices from 1998 – 2002 by Region and Crop

Region	Pasture	Alfalfa	Sugar Beets	Other Field	Rice	Other Truck	Fresh Tomatoes	Other Deciduous	Grain	Vines	Cotton	Subtropical
	(dollars per ton)											
1	123	104	0	93	0	507	0	1095	91	321	0	383
2	123	96	36	92	319	507	0	1117	91	0	0	383
3	132	95	36	93	270	507	427	1089	94	561	348	383
3b	132	95	36	93	270	507	0	1089	94	561	348	383
4	127	94	36	92	271	507	427	1116	94	0	357	0
5	123	105	36	92	270	507	0	1167	92	561	333	383
6	120	99	36	94	254	507	427	1060	95	752	333	383
7	120	103	36	94	272	507	0	1153	96	505	0	383
8	131	117	36	94	272	507	462	1167	99	525	0	383
9	113	114	36	94	263	507	463	1152	98	600	0	383
10	158	120	36	84	263	507	408	1191	99	339	391	362
11	138	119	0	84	263	507	432	1233	99	399	0	380
12	148	120	36	84	0	507	382	1172	99	312	0	380
13	154	116	36	84	264	507	431	1047	99	343	367	382
14	124	110	37	84	0	507	412	1086	127	241	399	362
15	122	109	37	84	0	507	373	1086	124	241	393	375
16	124	110	0	84	0	507	421	1086	127	244	401	362
17	123	106	0	84	0	507	259	1073	124	244	380	374
18	121	104	32	84	0	507	255	1057	124	244	373	382
19	141	98	37	84	0	507	396	1057	116	244	373	383
20	141	98	37	84	0	507	0	1057	116	244	373	383
21	141	98	37	84	0	507	396	1057	116	244	373	383

Table 7-8. Average Crop Prices from 1998 – 2002 by Region and Crop (contd.)

Region	Corn	Dry Beans	Safflower	Processed Tomatoes	Cucurbits	Onion and Garlic	Potato	Almonds and Pistachios
	(dollars per ton)							
1	0	0	272	0	0	0	0	2190
2	23	681	268	0	288	0	0	2167
3	23	664	271	55	288	104	0	2181
3b	23	664	271	55	288	0	0	2181
4	23	632	272	55	288	104	0	2138
5	23	601	271	55	288	0	0	2105
6	23	601	269	54	288	104	0	2080
7	23	601	256	55	288	104	0	1978
8	23	626	252	55	288	104	0	2107
9	23	625	256	55	288	104	237	2164
10	22	651	240	55	255	104	237	2168
11	22	656	240	55	288	104	0	2145
12	22	646	240	55	288	104	0	2154
13	21	599	240	54	283	104	0	2187
14	23	599	240	54	226	104	0	2374
15	20	599	240	53	226	104	0	2350
16	24	599	0	0	224	104	197	2388
17	21	599	0	51	236	104	0	2357
18	21	599	259	51	247	104	197	2163
19	21	599	259	56	287	98	0	2159
20	21	599	0	0	287	98	197	2159
21	21	599	259	56	287	98	197	2159

Source: DWR

Table 7-9. Average Crop Yield from 1998-2002 by Region and Crop

Region	Pasture	Alfalfa	Sugar Beets	Other Field	Rice	Other Truck	Fresh Tomatoes	Other Deciduous	Grain	Vines	Cotton	Subtropical
	(tons per acre)											
1	5.41	0	3.59	0	5.75	0	2.7	2.52	8.16	0	12.87	5.41
2	6.28	31.96	3.46	3.71	5.75	0	2.7	2.52	0	0	12.87	6.28
3	6.53	31.96	3.69	3.96	5.75	13.1	2.7	2.52	7	2.42	12.87	6.53
3b	6.53	31.96	3.69	3.96	5.75	0	2.7	2.52	7	2.42	12.87	6.53
4	6.46	31.96	3.55	3.93	5.75	13.1	2.7	2.52	0	2.55	0	6.46
5	5.84	31.96	3.46	3.95	5.75	0	2.7	2.52	7	2.55	12.87	5.84
6	6.33	31.96	3.99	3.73	5.75	13.1	2.4	2.52	7	2.2	12.87	6.33
7	6.32	31.96	3.99	3.9	5.75	0	2.59	2.52	7	0	12.87	6.32
8	6.57	31.96	3.99	3.73	5.75	9.71	2.02	2.54	7	0	12.87	6.57
9	6.5	31.96	3.99	4.09	5.75	9.64	2.66	2.52	7	0	12.87	6.5
10	7.34	31.73	4.17	3.71	5.75	15.72	2	2.65	8.04	2.78	12.87	7.34
11	7.05	0	4.17	3.7	5.75	12.57	2	2.65	7.91	0	12.87	7.05
12	7.55	29.35	4.17	0	5.75	17.35	2	2.65	8.45	0	12.87	7.55
13	7.18	29.35	4.17	3.53	5.75	12.78	2	2.65	7.84	2.67	12.87	7.18
14	7.41	33.69	4.17	0	5.75	16.25	2	2.82	8.8	2.71	12.87	7.41
15	7.06	33.68	4.17	0	5.75	17.46	2	2.64	8.76	2.51	12.87	7.06
16	7.61	0	4.17	0	5.75	16.02	2	2.84	8.66	2.76	12.87	7.61
17	7.89	0	4.17	0	5.75	20.86	2	2.56	8.71	2.6	12.87	7.89
18	8.15	30.24	4.17	0	5.75	20.98	2	2.56	8.67	2.55	12.87	8.15
19	7.78	32.49	4.17	0	5.75	16.92	2	2.91	8.66	2.61	12.87	7.78
20	7.78	32.49	4.17	0	5.75	0	2	2.92	8.66	2.61	12.87	7.78
21	7.78	32.49	4.17	0	5.75	16.92	2	2.92	8.66	2.61	12.87	7.78

Table 7-9. Average Crop Yield from 1998-2002 by Region and Crop (contd.)

Region	Corn	Dry Beans	Safflower	Processed Tomatoes	Cucurbits	Onion and Garlic	Potato	Almonds and Pistachios
	(tons per acre)							
1	0	0	1.07	0	0	0	0	1
2	31.7	0.88	0.71	0	11.32	0	0	1
3	31.7	0.85	1.05	34.85	11.32	18	0	1
3b	31.7	0.85	1.05	34.85	11.32	0	0	1
4	31.7	0.87	1.08	34.16	11.32	18	0	1
5	31.7	0.86	1.11	33.32	11.32	0	0	1
6	30.02	0.91	1.11	33.73	11.32	18	0	1
7	31.7	0.86	1.08	32.79	11.32	18	0	1
8	28.09	1.01	1.15	35.72	11.32	18	0	1
9	27.63	1.01	1.28	35	11.32	18	16.9	1
10	26.24	1.14	1.75	37.87	12.41	18	16.9	1.12
11	25.3	1.17	1.52	36.5	11.32	18	0	1
12	25.88	1.12	1.73	37.53	11.32	18	0	1.16
13	26.46	1.12	1.73	37.8	11.5	18	0	1.4
14	24.5	1.18	1.76	38.53	13.54	18	0	1.4
15	23.99	1.18	1.76	38.01	13.53	18	0	1.4
16	24.62	1.18	0	0	13.45	18	21.01	1.4
17	24.37	1.28	0	36.58	14.02	18	0	1.4
18	24.39	1.34	1.63	36.52	14.45	18	21.01	1.4
19	24.28	1.3	1.22	35.77	14.11	18.24	0	1.4
20	24.28	1.3	0	0	14.11	18.24	21.01	1.4
21	24.28	1.3	1.22	35.77	14.11	18.24	21.01	1.4

Source: DWR

Water Costs

Water prices in CVPM have two components, a project charge and a district charge. The project charge is the price per acre-foot paid by the district (or contractor) to either the CVP or the SWP. This unit cost is analogous to a wholesale cost, and is zero for water rights supplies. These data were obtained from Reclamation (1993, 1994) and DWR (various years), respectively.

In addition, surface water has a district charge associated with the cost of delivering the water from the source to the farms. The district charge is the amount that local districts charge to recover their costs, and this charge applies to CVP, SWP, or local water.

The district charge is divided into a water charge, or markup, (in dollars per acre-foot) and a land assessment (in dollars per acre), sometimes called a standby charge. Districts with more than one source of water may charge everyone the same markup and assessment or may vary the charge to reflect internal delivery cost differences. CVPM is defined by region, so district charges are averaged over a region and do not vary by source. The cost per acre-foot of water charged to growers is the sum of the wholesale cost and the markup. Standby charges do not vary based on water used, but are included in the overall cost and net revenue calculations. District charges and land assessments were obtained from a direct survey of more than 50 Central Valley water districts.

CVPM calculates groundwater costs using information on depth to groundwater, drawdown, and total cost per acre-foot per foot of lift. All three are data inputs that the user can change if desired. The groundwater depths are data inputs to CVPM. Drawdown is assumed to be affected by the rate of pumping, so that as pumping rates increase, drawdown increases. Because of lack of data for estimation, CVPM assumes only minor changes in drawdown, with a linear relationship between pumping rate and drawdown. Water price data and current depth to groundwater are provided in Table 7-10.

It is important to recognize that CVPM is not a groundwater model. The groundwater costs represent currently available information and current conditions. When using CVPM for analysis in which groundwater conditions may change, it is important to use a separate groundwater model or analysis in conjunction with CVPM.

Table 7-10. Water Cost and Price Data

Region	Local Water Costs		GW Lift (feet)
	Per Acre	Plus Per Acre-Foot	
1	64		130
2	17.81	28.75	120
3	52		85
3b	18.35	25.33	110
4	30	60	60
5	30	75	75
6	15.25	16	70
7	30	95	95
8		15	110
9	30	80	80
10	10	40	60
11		3.6	75
12	14	90	90
13	24	13.75	125
14	16	64	350
15		44	210
16	25		130
17		25	130
18		25	200
19	32.5	44	310
20	20	44	310
21	57	50	310

Source: Survey of districts, Reclamation, DWR (various years).
Key:
GW = groundwater

Crop Production Costs

Production costs are based primarily on budgets prepared by the University of California Extension Service (various years). DWR compiled the budgets for various crops and counties, and created a crop net revenue model covering all subregions within CVPM. Crop production cost data appear in Tables 7-11 and 7-12.

Table 7-11. Crop Harvest Cost Estimates Used in CVPM

Region	Pasture	Alfalfa	Sugar Beets	Other Field	Rice	Other Truck	Fresh Tomatoes	Other Deciduous	Grain	Vines	Cotton	Subtropical
	(dollars per acre)											
1	23	305	0	228	0	2,155	0	1,237	141	1,121	0	2,288
2	23	340	742	222	465	2,155	0	1,190	143	0	0	2,288
3	23	382	742	232	532	2,155	4,040	1,193	153	1,621	596	2,288
3b	23	382	742	232	532	2,155	0	1,193	153	1,621	596	2,288
4	23	401	742	226	527	2,155	4,040	1,193	152	0	636	0
5	23	333	742	222	507	2,155	0	1,193	145	1,695	577	2,288
6	23	394	742	245	487	2,155	4,040	1,161	154	1,950	533	2,288
7	22	349	742	245	497	2,155	0	1,188	149	1,690	0	2,288
8	22	345	742	245	489	2,155	3,361	1,063	181	1,606	0	2,288
9	23	353	742	245	503	2,155	3,341	1,076	173	1,752	0	2,288
10	23	353	741	257	472	2,156	4,697	1,078	187	1,160	541	2,232
11	23	351	0	257	488	2,155	4,119	1,072	187	1,305	0	2,218
12	23	359	596	257	0	2,155	5,386	1,080	187	1,016	0	2,218
13	23	344	719	257	477	2,155	4,198	1,087	187	982	528	2,224
14	24	353	758	257	0	2,155	4,347	1,105	197	1,009	540	2,232
15	24	344	758	257	0	2,155	4,486	1,105	192	1,008	535	2,266
16	24	358	0	257	0	2,155	4,320	1,105	197	1,003	541	2,232
17	24	365	0	257	0	2,155	4,875	1,109	190	1,005	534	2,264
18	24	371	722	257	0	2,155	4,889	1,114	190	1,004	531	2,288
19	24	360	750	257	0	2,155	4,634	1,114	193	1,003	527	2,288
20	24	361	750	257	0	2,155	0	1,114	193	1,003	527	2,288
21	24	360	750	257	0	2,155	4,634	1,114	193	1,003	527	2,288

Table 7-11. Crop Harvest Cost Estimates Used in CVPM (contd.)

Region	Corn	Dry Beans	Safflower	Processed Tomatoes	Cucurbits	Onion and Garlic	Potato	Almonds and Pistachios
	(dollars per acre)							
1	0	0	156	0	0	0	0	1,077
2	414	315	142	0	2,689	0	0	1,049
3	414	315	157	1,222	2,689	1,003	0	1,066
3b	414	315	157	1,222	2,689	0	0	1,066
4	414	336	157	1,187	2,689	1,003	0	1,052
5	414	341	150	1,146	2,689	0	0	1,050
6	402	434	154	1,195	2,689	1,003	0	1,125
7	414	341	154	1,160	2,689	1,003	0	1,168
8	389	345	155	1,185	2,689	1,003	0	1,193
9	386	347	159	1,190	2,689	1,003	3,213	1,193
10	377	378	171	1,211	2,597	1,003	3,213	1,222
11	369	388	160	1,194	2,689	1,003	0	1,196
12	370	370	170	1,207	2,689	1,003	0	1,232
13	367	269	170	1,186	2,674	1,003	0	1,264
14	427	340	172	1,227	2,567	1,003	0	1,293
15	422	340	172	1,217	2,563	1,003	0	1,294
16	428	340	0	0	2,509	1,003	3,403	1,293
17	424	350	0	1,189	2,875	1,003	0	1,288
18	424	356	170	1,188	3,150	1,003	3,403	1,257
19	424	345	163	1,191	3,171	1,003	0	1,306
20	424	345	0	0	3,171	1,003	3,403	1,306
21								

Source: DWR
Key:
CVPM = Central Valley production Model

Table 7-12. Crop Fixed Cost Estimates Used in CVPM

Region	Pasture	Alfalfa	Sugar Beets	Other Field	Rice	Other Truck	Fresh Tomatoes	Other Deciduous	Grain	Vines	Cotton	Subtropical
	(dollars per acre)											
1	207	286	0	108	0	176	0	1,007	136	1,159	0	1,600
2	210	286	275	105	322	176	0	1,015	136	0	0	1,600
3	213	292	275	109	322	176	429	1,046	138	1,767	249	1,600
3B	213	292	275	109	322	176	0	1,046	138	1,767	249	1,600
4	223	294	275	107	323	176	429	1,044	137	0	251	0
5	211	287	275	105	322	176	0	1,040	137	1,877	240	1,600
6	206	297	275	115	322	176	429	1,071	139	2,082	247	1,600
7	213	293	275	115	322	176	0	1,040	137	1,884	0	1,600
8	203	359	275	115	299	176	428	1,160	124	1,841	0	1,600
9	205	352	275	115	321	176	428	1,148	129	1,963	0	1,600
10	204	384	274	120	295	176	430	1,174	121	1,229	256	1,589
11	200	373	0	120	298	176	429	1,170	121	1,473	0	1,599
12	202	381	225	120	0	176	432	1,173	121	1,121	0	1,599
13	203	379	271	120	297	176	435	1,174	121	1,090	253	1,600
14	200	388	277	120	0	176	427	1,254	119	953	256	1,589
15	200	386	277	120	0	176	422	1,254	119	953	256	1,596
16	200	388	0	120	0	176	428	1,253	119	953	256	1,589
17	200	385	0	120	0	176	410	1,254	118	953	255	1,595
18	199	384	274	120	0	176	409	1,254	118	953	255	1,600
19	199	378	279	120	0	176	431	1,254	119	953	252	1,600
20	199	378	279	120	0	176	0	1,254	119	953	252	1,600
21	199	378	279	120	0	176	431	1,254	119	953	252	1,600

Table 7-12. Crop Fixed Cost Estimates Used in CVPM (contd.)

Region	Corn	Dry Beans	Safflower	Processed Tomatoes	Cucurbits	Onion and Garlic	Potato	Almonds and Pistachios
	(dollars per acre)							
1	0	0	130	0	0	0	0	807
2	169	184	123	0	242	0	0	792
3	169	183	133	423	242	326	0	821
3B	169	183	133	423	242	0	0	821
4	169	184	130	432	242	326	0	796
5	169	176	129	438	242	0	0	793
6	163	178	137	417	242	326	0	865
7	169	176	143	403	242	325	0	884
8	157	205	150	345	242	325	0	1,025
9	156	204	154	368	242	325	281	1,051
10	145	221	205	328	246	325	281	1,062
11	148	218	177	337	242	325	0	1,058
12	147	222	202	328	242	325	0	1,065
13	142	219	202	328	243	325	0	1,075
14	140	211	206	325	248	325	0	1,056
15	137	211	206	325	248	325	0	1,057
16	141	211	0	0	249	325	278	1,056
17	137	208	0	323	243	325	0	1,061
18	136	206	207	323	239	325	278	1,094
19	137	208	207	313	249	316	0	1,035
20	137	208	0	0	249	316	278	1,035
21	137	208	207	313	249	316	278	1,035

Source: DWR
Key:
CVPM = Central Valley Production Model

CVPM Model Structure

CVPM consists of four modules, including:

- A data file that includes information on irrigated crop production, irrigation water supplies, and other baseline data and parameters
- An aggregation routine that allows the user to aggregate regions and/or crops as needed
- The basic set of mathematical relationships that constitute CVPM
- A user-modifiable policy change file that includes output tables to present model results

An additional file to create additional output tables can also follow the policy change file.

Variability, Risk, and Uncertainty

Economists and farmers have long recognized there are economic costs associated with risk and uncertainty in agricultural production. The SLWRI may influence agricultural decisions through effects on variability, risk, and uncertainty. Risk is created when the future cannot be known with certainty but there is a known probability distribution of potential outcomes. The probability distribution is typically estimated based on historical values. The probability of a critical or dry year type can be estimated based on historical records.

Uncertainty is associated with an unknown probability distribution. The distribution may be unknown because the source of uncertainty has no historical record, or factors are expected to change in a way that cannot be predicted. The uncertainties created by new laws or changing technology are examples.

Several approaches for incorporating risk into the analysis of CALFED surface storage projects have been considered:

1. Incorporate risk directly as an argument in the producers' objective function. The most widespread approach is to incorporate variability of crop revenue as a cost in the objective function, with an appropriate cost coefficient (called the risk aversion coefficient).

2. Incorporate constraints that reflect risk aversion or downside risk aversion. For example, a constraint can prevent perennial crop acreage from exceeding the amount supported by the water supply available in the driest year.

3. Assess impacts for different categories of water delivery (water year-types), and show how the pattern of impacts varies between alternatives. One way to do this is to define year types by ranges of

water delivery, and then assess the change in probability that water supply will fall in different year-types. Another approach is to identify several particular years or sets of years that represent a range of hydrologic conditions. For each year or set of years, estimate how the water delivery changes from the No-Action Alternative compared to an alternative. The cost of adjusting to this change is one measure of the cost of water supply variability.

The analysis of the CALFED surface storage projects uses a combination of Approaches 2 and 3. Within the CVPM analysis, perennial crop acreage is not allowed to exceed the water supply available during the dry and critically dry periods. Also, each alternative is assessed for three water year-types defined as overall average, average dry, and average wet. Irrigated acreage, water use, value of production, and net income are compared for each year-type. In addition to this CALFED surface storage projects analysis, the cost of additional water supply variability is estimated by calculating the cost of well capacity needed to eliminate the additional surface supply shortage in the driest 1-, 2-, and 3-year periods.

Cost of Groundwater Pumped

The cost to pump groundwater includes well development or well deepening cost, the cost of power to pump, and other well O&M. Pumping power cost, in dollars per acre-foot per foot of lift, equals 1.02 x c/PE, where c is the cost per kilowatt-hour (kWh) of power, and PE is the effective efficiency of the well and pump. Pumping lift is equal to the regional groundwater depth plus effective drawdown. Additional capital, operation and maintenance costs must be added to the cost of power to pump. The model currently assumes a total variable cost of 20 cents per acre-foot per foot of lift, plus an additional per acre-foot cost to recover capital costs of well installation. The well installation cost is subregion specific and reflects the relative depth of typical wells in each subregion.

Baseline Model Run

For the baseline condition, CVPM is used to estimate 2030 conditions on crop acreage and production, income, water use, and irrigation efficiency in the Central Valley. Baseline water deliveries are provided by CalSim-II.

CVPM is not run for each year of an 82-year sequence. Rather, CVPM uses water year-types developed from CALSIM model runs. Based on CALSIM results, a baseline CVPM run develops a long-run condition and a set of short run conditions to estimate how producers would respond to short-run changes in water supply conditions (e.g., dry or wet years).

CalSim-II provides changes in project water supply (CVP water service contract delivery, CVP settlement and exchange contract delivery, and SWP contract delivery) for the baseline analysis. The CALSIM diversion output is converted into water supply available for on-farm delivery – this is done by the CalSim-II-CVPM Conversion Tool.

Changes in other water resources can also be made for the 2030 baseline run. These include the following:

- Changes in other, nonproject surface water supplies.
- Changes in groundwater pumping lift or limits on groundwater pumping (either hydrologic capacity limits or policy constraints).

The current, interim version of the CVPM model does not impose changes in these water sources. Ultimately, a comprehensive surface and groundwater model, such as C2VSIM, will be used to provide such input.

Prices, yields, and production costs are not changed for the 2030 baseline run. Though it is certain that all of these will change, no consistent methodology has been undertaken to predict such changes. Therefore, a conservative assumption is maintained that yields and relative prices are unchanged.

Baseline crop acreage for 2030 is developed from hydrologic region aggregate projections reported in the California State Water Plan Update (DWR 2005). It is important for the user of CVPM to understand that the model is not a crop demand forecasting tool. Rather, CVPM is used to estimate changes in crop water use and acreage to changes in water supply or economic conditions. In other words, CVPM does not forecast 2030 baseline acreage – this is estimated external to the model. CVPM then estimates changes from 2030 conditions that result from new projects, operations, or other policy parameters.

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Exhibit 7A
CVPM Technical Description

The Central Valley Production Model (CVPM) is a regional agricultural production model developed by DWR. It is a policy tool to assess regional effects on agricultural production from changes in water (or other resource) supplies, resource pricing, commodity market conditions, and regulatory controls. CVPM simulates the decisions of agricultural producers in the Central Valley of California. The model assumes that farmers act to maximize profits of their enterprises subject to resource constraints, production technology, and market conditions. The model assumes that farmers operate within a competitive market in the sense that no one farmer can affect or control the price of any commodity. Therefore the model's objective function maximizes consumer profit and surplus (CPS), defined as the sum of consumers' surplus (net value of the products to consumers) and producers' surplus (profit). CVPM maximizes CPS subject to available land, water from various sources, and three types of economic response functions: a set of commodity demand functions relating total quantity produced to the market price; a set of acreage response functions, relating changes in crop acreage to changes in net returns and other cost information; and a set of functions describing the tradeoff between applied water and irrigation technology.

Commodity Demand Functions and Price Flexibilities

The CVPM incorporates estimated price flexibilities into linear commodity demand functions. The calibration period price and output is combined with the price flexibility to construct a linear demand function. As output changes due to changes in water policy, the model predicts changes in market price based on the price flexibility.

Price flexibility is defined as the percent change in market price caused by a percent change in output. Price flexibilities must be appropriate to the region being analyzed, in this case the Central Valley. For example, a flexibility estimated for California as a whole must be adjusted for the proportion of California production that occurs in the Central Valley. The CVPM is set up to read in California-wide flexibilities and then adjust them for Central Valley-only flexibilities, using DWR estimates of the proportion of California production that occurs in the Central Valley.

Let Fc be the California-wide estimate of price flexibility for a commodity, defined as the percent change in price per percent change in California production:

$$Fc = (dPc/dQc) \cdot (Qc/Pc)$$

Then the appropriate price flexibility for Central Valley production is adjusted by the proportion of California production grown in the Central Valley, $k = Qcv/Qc$. Assume that quantity produced outside the Central

Valley is unchanged, so $dQc = dQcv$. To simplify the analysis of commodity price changes, the model assumes that the base market price for each commodity is the same across the state, with regional variation accounted for as deviations from the base market price. The commodity demand equations (and therefore the price flexibilities) apply to the base price. If Pc is the base price and mr is the deviation from the base price in region r, then actual price in region r is $Pr,c = Pc + mr$. To derive the Central Valley price flexibility from the California-wide estimate:

$$Fc = (dPc/Pc) \bullet (Qc/dQc) = (dPc/Pc) \bullet (Qcv/dQcv) \bullet 1/k.$$

Because $Pc = Pcv$, the first two terms on the right hand side equal Fcv, so solving for Fcv:

$$Fcv = Fc \bullet k,$$

or the Central Valley price flexibility is equal to the statewide flexibility times the proportion of the commodity grown in the Central Valley.

CVPM uses the baseline conditions of price and quantity along with the estimated Central Valley price flexibility to calculate changes in commodity price caused by a change in quantity produced. The model approximates dPc as Pc(base) - Pc(new) and dQcv as Qcv(base) - Qcv(new). Substituting these into the price flexibility equation and solving for Pc(new),

$$Pc(new) = Pc(base) \bullet [1 - Fcv \bullet (Qcv(base) - Qcv(new))/Qcv(base)].$$

Existing estimates of California price flexibilities from the agricultural economics literature were used for the model. Commodities that could not be found in existing studies were approximated using values for similar kinds of commodities.

Positive Mathematical Programming

PMP is a technique developed to incorporate both marginal and average conditions into a regional optimization model (Howitt 1995). Traditional regional models have relied on data based on observed average conditions (e.g., average production costs, yields, and prices). According to economic theory, the short- or long-run equilibrium level of activities is determined by marginal conditions. PMP is a technique whereby information on the marginal value of resources (derived from shadow prices) is used to augment the average cost/revenue information and calibrate a regional model to a baseline condition. This allows the model to predict a more diverse set of activities than would be possible with a simple linear framework.

A number of economic or market conditions can influence the marginal tradeoffs among crops and therefore the observed crop mix.

- Willingness of the market to buy additional amounts of a given commodity (i.e., the commodity demand function) declines as more is produced.

- Risk considerations – crop diversification is a known strategy for reducing downside risk.

- Crop rotations can improve yields or reduce costs.

- Marketing/processing constraints – cotton ginning capacity, for example, may be limited in the short run, although over the long run this would not be limiting.

- Government farm programs may encourage some crops and limit production of others.

- Other resource constraints – restrictions on water, labor, or capital can force a crop mix that does not appear to be the most profitable.

Regional models can accommodate all of these constraints in various ways. Perhaps the most widespread reason for crop diversity is the underlying diversity in growing conditions and market conditions. All farms and plots of land do not produce the same, average set of conditions, and therefore the marginal cost and revenue curves do not coincide with the average cost and revenue curves. A linear programming model based on average costs and returns does not capture this. PMP uses information about the average and the marginal conditions to generate appropriate marginal cost and/or revenue functions that can predict the observed diversity of activities.

To illustrate, consider a two-crop (wheat and cotton) regional production model. Let the average observed net return to wheat be $50 per acre (as estimated from county-wide yields and prices and estimated production cost budgets), and let the average net return to cotton be $100 per acre. With 100 acres of land available, a simple linear programming model would obviously allocate all 100 acres to cotton and none to wheat, based on the average costs and returns. In fact, however, we observe that 40 acres are growing wheat and 60 are growing cotton. In the absence of externalities or other market-distorting considerations, economic theory requires that the equilibrium condition allow the same net return, at the margin, to either crop. Otherwise total net return could be increased by shifting an acre to the crop yielding the greater net return.

To create a condition of marginal equality, PMP augments the linear total cost (or revenue) function with quadratic terms that guarantee the marginal equality conditions will hold at the observed crop mix. For the example above, a difference of $50 per acre between marginal and average net return to cotton would explain the apparent suboptimal solution observed. A simple PMP model could add a linear marginal cost of production to cotton such that, at the observed acreage, cotton's average net return is $100 but its marginal net return is only $50. Because the marginal cost is rising, additional cotton acreage beyond its observed level would be less profitable than wheat acreage, while cotton acreage below the observed level would be more profitable than wheat acreage. Under this structure, predicted cotton and wheat acreage would exactly match the observed values.

This simple example can be generalized mathematically. The objective of the standard programming approach is to maximize net revenue, defined as:

$$NR = (py - AC) \cdot X,$$

where p is a vector of prices per unit, y is a vector of yield in units per acre, AC is a vector of average production costs per acre, and X is a vector of acres. This expresses net revenue (NR) in terms of average revenues and costs. PMP augments this linear specification with a nonlinear function of acreage by crop, f(X):

$$NRA = (py - AC)\, X + f\,(X).$$

The nonlinear function is quadratic in the case of CVPM. Calculated properly, the augmented, nonlinear objective function can produce the same level of NR as the linear function at the baseline acreage, but can create marginal conditions that also satisfy the profit-maximizing first order conditions at the baseline acreage.

The PMP procedure is mathematically equivalent to adding a nonlinear adjustment cost function onto the linear NR specification, although the rationale and interpretation are quite different.

The variability in marginal NR embodied in the PMP function can represent variation in production cost, variation in yield, variation in crop quality (which affects the crop price), or a combination of all three. These possibilities can be classified into revenue effects (yield and/or price) and production cost effects. Let a, b, and c be parameters of a quadratic revenue function and d, f, and g be parameters of a quadratic cost function. Assuming farmers use the land best suited to a given crop first and expand to less suited land as total production increases, then marginal revenue declines and/or marginal cost increases as X increases, so:

$b \le 0$ and $g \ge 0$.

Gross revenue becomes $GR = p \cdot y \cdot X + (c + a \cdot X + .5\ b \cdot X2)$,

and total cost becomes $TC = AC \cdot X + (d + f \cdot X + .5\ g \cdot X2)$.

Then, $NRA = p \cdot y \cdot X + (c + a \cdot X + .5\ b \cdot X2) - AC \cdot X - (d + f \cdot X + .5\ g \cdot X2)$

Marginal net revenue can be broken into average net revenue (which is constant with respect to acreage) and the components of the marginal revenue and marginal cost functions (which exhibit declining marginal net revenue).

$$MNR = p \cdot y - AC + [(a - f) + (b - g) \cdot X] \quad \text{or}$$

$$MNR = p \cdot y - AC + [\alpha + \beta \cdot X]$$

The PMP approach can attempt to account for the revenue and cost components separately; it can simply combine them and not distinguish whether the parameters represent cost effects or revenue effects; or it can combine them and assume that the marginal function represents either falling marginal revenue or rising marginal cost. Although the choice of assumption does not affect the mathematical form of the net revenue function, it does affect how results of the model are interpreted. For example, if the PMP augmenting function is assumed to represent falling marginal yield, then changes in acreage will affect commodity prices both directly (acreage changes) and indirectly (yield changes), and these effects will somewhat offset each other. Alternatively, if the PMP augmenting function is assumed to represent rising marginal cost, then only the acreage change affects commodity prices.

The CVPM assumes that the marginal function represents increasing marginal production cost. This assumption affects how the PMP parameters, α and β, are estimated. The next section derives the approach used for estimating the PMP parameters.

Acreage Response Elasticities and PMP Coefficients

The example in the section above showed how a point estimate of the difference between marginal and average conditions can be used to calibrate a model to observed crop mix. Essentially the calibration condition provides one point on the marginal cost function. Additional assumptions or information are needed to determine the slope of the marginal cost function. The CVPM addresses this need by incorporating acreage response elasticities directly in the linear marginal cost functions. Acreage elasticity is defined as the percent change in acreage of a crop due to a percent change in expected revenue. Basically, this is an acreage supply elasticity with per-acre revenue acting as the unit price received for an acre of production. Because the CVPM will be used primarily to assess long-term, permanent changes in water supply and prices, long-run supply elasticities are generally appropriate. The following derivation can be used with either long-run or short-run elasticities.

The total cost of production in the CVPM objective function includes both an observed cost per acre derived from cost-of-production analyses (denoted AC), and a quadratic component in acreage of crop c. In matrix notation, the total cost for all crops is:

$$C = AC \cdot X + (K \cdot \iota + A \cdot X + .5 \cdot X' \cdot \Gamma \cdot X)$$

where AC is a vector of observable production costs per acre, X is a vector of crop acres, ι is a vector of ones, and K, A, and Γ are parameters of the imputed cost function.

The following derivation of PMP coefficients assumes that Γ is diagonal, i.e., that the total or marginal cost of crop c is unaffected by the acreage of any other crop. This assumption is maintained in CVPM, but could be relaxed if sufficient data were available to estimate off-diagonal (cross-crop) effects. The total cost of crop c is:

$$Cc = ACc \cdot Xc + (Kc + \alpha c \cdot Xc + .5 \cdot \gamma c \cdot Xc2).$$

Then, $MCc = ACc + \alpha c + \gamma c \cdot Xc$.

Set MCc = marginal revenue, pcyc and solve for

$$Xc = (pcyc - ACc - \alpha c)/\gamma c.$$

Then, $dXc/d(pcyc) = 1/\gamma c$,

so the acreage elasticity is $ec = (1/\gamma c) \cdot (pcyc/Xc)$, evaluated at observed Xc, pc, and yc.

This shows the relationship between elasticity and γ, which combines with the other conditions needed for calibration to define the quadratic PMP function. The conditions described below must hold at the observed acreage for each crop, Xo:

The exogenously determined acreage supply elasticity determines the slope of the MC function, as derived above: $\gamma c = 1/ec \cdot pcyc/Xc$.

In order to calibrate to observed acreage by crop, the marginal cost of an acre of production must equal the observed portion (AC) plus the unobserved portion, indicated by the shadow price from the calibration model (λ). The shadow price represents the deviation between average and marginal cost. Therefore, using the derivation of MC above:

$$MCc = ACc + \lambda c \text{ implies } \alpha c = \lambda c - \gamma c \bullet Xc = \lambda c - pcyc/ec$$

In order to calibrate to observed production cost and net revenue, the unobserved portion of total cost must equal zero at the observed acreage. Therefore using the total cost notation above:

$$TCc = ACc \bullet Xc \text{ implies } Kc + \alpha c \bullet Xc + .5 \bullet \gamma c \bullet Xc2 = 0,$$

$$\text{so, } Kc = -(\lambda c - pcyc/ec) \bullet Xc - .5(1/ec \bullet pcyc/Xc) \bullet Xc2 = (.5pcyc/ec - \lambda c) \bullet Xc$$

Cost function parameters calculated in this way are largely governed by exogenously determined acreage response elasticities, with the shadow price information used to shift the intercept of the marginal and total cost functions so that the model calibrates to a particular set of base conditions.

Irrigation Technology Adjustments

CVPM allows agricultural producers to shift irrigation technology in response to changing conditions. Technology is defined as a combination of irrigation system cost and the associated applied water or irrigation efficiency. Data on irrigation system cost and performance were updated from an earlier study prepared for the U.S. Bureau of Reclamation (CH2M HILL 1991).

For each crop category and region, the feasible technology-management combinations were plotted graphically. Some irrigation systems were clearly inefficient and dominated by at least one other system that could provide similar efficiency at much lower cost or similar cost at a much better efficiency. Such irrigation systems were eliminated from the analysis. The remaining data points were fitted to a Constant Elasticity of Substitution (CES) isoquant, having the form:

$$a \bullet [b \bullet W\rho + (1-b) \bullet IC\rho] (1/\rho) = 1$$

where W is the measure of relative water use, AW/ETAW, and IC is the annual irrigation system cost per acre. The parameters a, b, and ρ were estimated using nonlinear least squares.

In the CVPM, both applied water and irrigation system cost are decision (endogenous) variables. The CES isoquants act as nonlinear constraints in the optimization.

Profit maximizing (or cost minimizing) conditions require that the ratio of water price to irrigation technology price be equal to the ratio of the marginal products of water and irrigation technology. Given an estimate of the isoquant, an observed relative applied water also defines the irrigation system cost. For the model to calibrate (i.e., to replicate the observed applied water), either the price ratio or the isoquant parameters must be adjusted.

For calibrating to observed applied water, the CVPM offers the user four alternatives.

Applied Water Calibration Method 1: One way to adjust the effective price ratio is to calculate the irrigation technology price needed for the observed water use-irrigation technology mix to be cost minimizing. Using the first order conditions for minimizing cost subject to the estimated CES isoquant and then solving for irrigation technology cost gives:

$$ICprice = \theta \bullet ETAW \bullet ((1-b)/b) \bullet (IC/W)(-1/\sigma),$$

where ICprice is the calculated irrigation technology price, θ is the imputed price of water applied to the crop, and σ is the elasticity of substitution.

CVPM uses this approach. The rationale is that, although CVPM includes an estimate of irrigation system cost, it is based on an average cost for each irrigation technology. A number of factors other than the average system cost affect a grower's choice of irrigation system. These include unique growing conditions such as soil slope and texture; drainage problems; federal, state, or district requirements and programs to improve irrigation efficiency; and grower preferences and experience. This calibration approach imputes an adjustment to system cost that accounts for these differences.

Applied Water Calibration Method 2: A second way to adjust the effective price ratio is to calculate the water price needed for the observed water use-irrigation technology mix to be cost minimizing. Using the first order conditions for minimizing cost subject to the estimated CES isoquant and then solving for irrigation technology cost gives:

$$Wprice = (1/ETAW) \bullet (b/(1-b)) \bullet (IC/W)(-1/\sigma) - WRprice,$$

where WRprice is regional marginal value of water, and Wprice is a crop-specific imputed value of water.

Applied Water Calibration Method 3: A third way to calibrate CVPM to observed water use is to use the PMP function with cross-products between water use and acreage.

Applied Water Calibration Method 4: A fourth way to calibrate to observed water use is to adjust the parameters of the CES function so that the marginal rate of substitution equals the observed price ratio. The estimated CES substitution parameters are kept but the share and scale parameters (a and b in the CES equation) are calculated to force the marginal optimality condition to hold:

$$b = \theta *ETAW*(IC/W)(-1/\sigma)/(1+\theta*ETAW*(IC/W)(-1/\sigma))$$

$$a = 1/(b*W\rho + (1-b)*IC\rho)(1/\rho)$$

All four of these approaches have been coded into CVPM and all will calibrate the model to water use, acres, and net revenue. The first two approaches have the advantage of using estimated scale and distribution parameters (rather than calibrated from a single data point), but they require some modification to prices or costs.

Harvested and Irrigated Acres

CVPM distinguishes between total irrigated acreage, total harvested acreage (including dryland production), and the portion of irrigated acreage that is harvested. The data from the County Agricultural Commissioner's reports total harvested acreage and yield. The ratio of total harvested to harvested and irrigated acreage is based on Census of Agriculture estimates. Representing this ratio for a given crop as t, and the ratio of irrigated yield to harvested crop yield as s, the CAC data can be adjusted to reflect only irrigated yields. Overall observed production, YO*XO, is the sum of dryland production and irrigated production:

YO*XO = YI*XI + YD*XD.

Substitute YI = s*YD , XI = t*XO , and XD = (1-t)*XO and solve for YI:

YI = (s*YO) / (1-(1-s)*t).

Scaling the Model to 2020 Conditions

One of the assumptions in the analysis for the CVPIA was the use of the year 2020 as the basis for comparison of alternatives. Bulletin 160-93 (DWR 1993) was used to determine projected land use in 2020. Two problems arose because of this. First, the water supply assumptions of DWR's projections are not consistent with the conditions for the CVPIA No-Action Alternative. Second, Bulletin 160-93 (DWR 1993) irrigated crop acres were not supported by the economic demands, prices, and costs determined from the calibration database in CVPM. DWR used a demand and supply forecasting procedure to develop 2020 crop acres, and these forecasts estimated significant shifts in demands and supplies between 1990 and 2020. Because of these shifts, production of vegetables and orchards increased while field crops (especially pasture and alfalfa) declined.

To provide analysis that is reasonably consistent with DWR projections and yet incorporates the changes in water supply conditions imposed by the CVPIA and the Bay-Delta Accord, a three step procedure is used in CVPM. The first step calibrates the economic parameters to the average 1987-1990 conditions from the calibration database. The second step scales (i.e., shifts) the crop demand and supply functions so that relative prices and costs are maintained as calibrated, but the model approximates the 2020 crop mix projected by DWR. The scaling procedure also maintains the price flexibilities at their estimated values. The third step imposes the changes in water supply conditions and other policies as appropriate for the No-Action Alternative or one of the action alternatives.

Model Convexity

Convexity is a mathematical characteristic of constrained optimization problems that guarantees that any local optimum found by a mathematical search algorithm will also be the global optimum. The mathematical structure of CVPM is constrained optimization, or nonlinear programming, which has the general form:

(NLP) Maximize $F(x)$

Subject to $g(x)=0$

$h(x)<=0$

$X>=0$.

For CVPM, x is a vector of decision variables: irrigated acres, applied water per acre, irrigation cost per acre, water use by source, and endogenous crop price. A well-known theorem of mathematical programming, the Kuhn-Tucker sufficiency theorem, states that, subject to constraint qualification, if F(x) is concave and g(x) and h(x) are convex (including linear), then any local maximum point is a global maximum point. A local maximum is defined as a point that satisfies the Karush-Kuhn-Tucker first-order maximum conditions. Another theorem, known as the Arrow-Enthoven Theorem states that, if F(x) is quasiconcave over the feasible region and the functions g(x) and h(x) are quasiconvex, then any local maximum of Non-Linear Programming (NLP) is a global maximum (see for example, Chiang 1984). Both of these theorems provide sufficient conditions for assuring that a well-designed search algorithm will find a global maximum. Because they are sufficient but not necessary conditions, there exists a potentially large set of NLP structures that may satisfy neither set of conditions yet are convex in the sense that any local maximum is also a global maximum.

In addition, a well-designed search algorithm may consistently find the true global maximum even though the NLP is not globally convex. There is, however, no way of proving that this is so; the appropriate procedure in cases where the NLP cannot be proven convex is to provide a good starting point for the search algorithm, often by first solving a convex approximation of the NLP and by placing reasonable bounds on the feasible set. Global optimality can be further tested by comparing the solution using a number of different starting points.

CVPM maximizes a nonlinear objective function subject to a set of linear constraints (both equality and inequality) and a set of nonlinear equality constraints allowing substitution between irrigation system cost and efficiency. The quadratic terms in the objective function represent increasing marginal cost and declining marginal revenue (for some crops). The Hessian matrix associated with these terms is diagonal and negative semidefinite, therefore this portion of the objective function is easily shown to be concave (and therefore also quasiconcave). If irrigation technology is held constant, the remaining terms of the objective function and all of the constraints would be linear, resulting in a convex model. However, the irrigation technology functions, having the form known as CES, are nonlinear (though convex). The decision variables in these functions, applied water per acre and irrigation cost per acre, also appear as cross product terms with crop acres in the objective function. As a result, proving global optimality of solutions to the model with variable irrigation technology has not yet been possible.

Two strategies are used to improve the likelihood that the solution from a particular model run is a global optimum. First, the policy changes are first implemented in a fixed-technology version of CVPM. As described above, this model version satisfies the sufficient conditions for convexity and global optimality. This provides an excellent starting point for the full, nonlinear solution of CVPM. The second strategy compares the results achieved from the good starting point against results from a number of other starting points. If results are the same for each starting point, then a high probability exists that the result is globally optimal. This was done for each of the main alternatives. Table 7-A-1 illustrates results from an 11-region version of a Preliminary Alternative that was considered but not evaluated further in the PEIS.

Table 7A-1. Test of Different Starting Points

Region	Crop	Different Starting Points				
		Original Solution (1,000 acres)	CHG12 Difference (1,000 acres)	CHG13 Difference (1,000 acres)	CHG14 Difference (1,000 acres)	CHG15 Difference (1,000 acres)
REG1	IRRPAST	20.609	-0.000	-0.000	-0.000	0.000
REG1	ALFHAY	8.507	0.000	0.000	0.000	0.000
REG1	SBEETS	3.300	-0.000	0.000	-0.000	0.000
REG1	FIELD	14.211	-0.000	0.000	-0.000	0.000
REG1	RICE1	3.144	0.000	0.000	-0.000	0.000
REG1	TRUCK	12.531	-0.000	0.000	-0.000	0.000
REG1	ORCHARD	77.965	0.000	0.000	-0.000	0.000
REG1	GRAIN	11.142	0.000	0.000	-0.000	0.000
REG1	SUBTROP	7.263	0.000	0.000	0.000	0.000
REG2	IRRPAST	0.001	0.000	0.000	0.000	0.000
REG2	ALFHAY	6.067	-0.000	-0.000	0.000	0.000
REG2	SBEETS	18.108	0.000	0.000	-0.000	0.000
REG2	FIELD	23.786	0.000	0.000	-0.000	0.000
REG2	RICE1	19.080	-0.000	-0.000	-0.000	0.000
REG2	TRUCK	34.139	0.000	0.000	-0.000	0.000
REG2	TOMATO	56.605	0.000	0.000	-0.000	0.000
REG2	ORCHARD	64.098	0.000	0.000	0.000	0.000
REG2	GRAIN	40.427	-0.000	0.000	-0.000	0.000
REG2	SUBTROP	0.703	0.000	0.000	0.000	0.000
REG3	IRRPAST	0.001	0.000	0.000	0.000	0.000
REG3	ALFHAY	.383	0.000	0.000	0.000	0.000
REG3	SBEETS	3.255	0.000	0.000	0.000	0.000
REG3	FIELD	7.960	-0.000	-0.000	-0.000	0.000
REG3	RICE1	40.399	-0.000	-0.000	-0.000	0.000
REG3	TRUCK	5.507	0.000	0.000	0.000	0.000
REG3	TOMATO	1.831	-0.000	-0.000	-0.000	0.000
REG3	ORCHARD	111.170	0.000	-0.000	0.000	0.000
REG3	GRAIN	16.569	0.000	0.000	0.000	0.000
REG3	GRAPES	0.151	-0.000	-0.000	0.000	0.000
REG3	SUBTROP	1.761	0.000	0.000	0.000	0.000
REG4	IRRPAST	0.001	0.000	0.000	0.000	0.000
REG4	ALFHAY	0.001	0.000	0.000	0.000	0.000
REG4	SBEETS	26.920	-0.000	-0.000	-0.000	0.000
REG4	FIELD	0.001	0.000	0.000	0.000	0.000
REG4	RICE1	0.001	0.000	0.000	0.000	0.000
REG4	TRUCK	38.132	-0.000	-0.000	-0.000	0.000
REG4	TOMATO	65.608	0.000	0.000	0.000	0.000

Table 7A-1. Test of Different Starting Points (contd.)

Region	Crop	Different Starting Points				
		Original Solution (1,000 acres)	CHG12 Difference (1,000 acres)	CHG13 Difference (1,000 acres)	CHG14 Difference (1,000 acres)	CHG15 Difference (1,000 acres)
REG4	ORCHARD	37.812	0.000	0.000	0.000	0.000
REG4	GRAIN	37.176	-0.000	0.000	0.000	0.000
REG4	GRAPES	10.055	-0.000	-0.000	0.000	0.000
REG5	IRRPAST	40.323	-0.000	0.000	0.000	0.000
REG5	ALFHAY	12.193	-0.000	-0.000	0.000	0.000
REG5	SBEETS	11.009	0.000	0.000	-0.000	0.000
REG5	FIELD	38.365	-0.000	-0.000	-0.000	0.000
REG5	RICE1	3.893	0.000	0.000	0.000	0.000
REG5	TRUCK	13.894	0.000	0.000	0.000	0.000
REG5	TOMATO	12.544	0.000	0.000	-0.000	0.000
REG5	ORCHARD	40.989	-0.000	-0.000	-0.000	0.000
REG5	GRAIN	21.501	0.000	0.000	-0.000	0.000
REG5	GRAPES	45.775	-0.000	-0.000	-0.000	0.000
REG6	IRRPAST	0.001	0.000	0.000	0.000	0.000
REG6	ALFHAY	0.001	0.000	0.000	0.000	0.000
REG6	SBEETS	8.984	0.000	0.000	-0.000	0.000
REG6	FIELD	20.403	-0.000	0.000	-0.000	0.000
REG6	RICE1	0.001	0.000	0.000	0.000	0.000
REG6	TRUCK	123.206	-0.000	-0.000	-0.000	0.000
REG6	TOMATO	29.563	0.000	-0.000	-0.000	0.000
REG6	ORCHARD	31.669	0.000	0.000	0.000	0.000
REG6	GRAIN	11.032	-0.000	-0.000	-0.000	0.000
REG6	GRAPES	0.872	-0.000	-0.000	0.000	0.000
REG6	COTTON1	13.896	0.000	-0.000	0.000	0.000
REG6	SUBTROP	0.100	0.000	0.000	0.000	0.000
REG7	IRRPAST	0.001	0.000	0.000	0.000	0.000
REG7	ALFHAY	0.001	0.000	0.000	0.000	0.000
REG7	SBEETS	0.001	0.000	0.000	0.000	0.000
REG7	FIELD	0.001	0.000	0.000	0.000	.000
REG7	RICE1	0.001	0.000	0.000	0.000	0.000
REG7	TRUCK	6.751	-0.000	-0.000	-0.000	0.000
REG7	TOMATO	0.001	0.000	0.000	0.000	0.000
REG7	ORCHARD	59.999	0.000	0.000	-0.000	0.000
REG7	GRAIN	0.001	0.000	0.000	0.000	0.000
REG7	GRAPES	1.945	-0.000	-0.000	0.000	0.000
REG7	COTTON1	0.001	0.000	0.000	0.000	0.000

Table 7A-1. Test of Different Starting Points (contd.)

Region	Crop	Different Starting Points				
		Original Solution (1,000 acres)	CHG12 Difference (1,000 acres)	CHG13 Difference (1,000 acres)	CHG14 Difference (1,000 acres)	CHG15 Difference (1,000 acres)
REG7	SUBTROP	0.805	0.000	0.000	0.000	0.000
REG8	IRRPAST	0.001	0.000	0.000	0.000	0.000
REG8	ALFHAY	10.305	0.000	0.000	0.000	0.000
REG8	SBEETS	3.710	0.000	0.000	-0.000	0.000
REG8	FIELD	38.536	-0.000	-0.000	-0.000	0.000
REG8	RICE1	0.375	-0.000	-0.000	-0.000	0.000
REG8	TRUCK	19.717	0.000	0.000	-0.000	0.000
REG8	TOMATO	5.683	-0.000	-0.000	-0.000	0.000
REG8	ORCHARD	118.707	0.000	0.000	-0.000	0.000
REG8	GRAIN	50.967	-0.000	-0.000	-0.000	0.000
REG8	GRAPES	88.299	-0.000	-0.000	0.000	0.000
REG8	COTTON1	34.589	-0.000	-0.000	-0.000	0.000
REG8	SUBTROP	9.989	0.000	0.000	0.000	0.000
REG9	IRRPAST	0.001	0.000	0.000	0.000	0.000
REG9	ALFHAY	0.001	0.000	0.000	0.000	0.000
REG9	SBEETS	3.229	-0.000	-0.000	-0.000	0.000
REG9	FIELD	9.967	0.000	0.000	-0.000	0.000
REG9	TRUCK	148.730	0.000	0.000	-0.000	0.000
REG9	TOMATO	58.943	0.000	0.000	-0.000	0.000
REG9	ORCHARD	21.758	-0.000	-0.000	-0.000	0.000
REG9	GRAIN	9.714	-0.000	-0.000	-0.000	0.000
REG9	GRAPES	6.176	-0.000	-0.000	0.000	0.000
REG9	COTTON1	70.654	0.000	0.000	0.000	0.000
REG9	SUBTROP	1.006	0.000	0.000	0.000	0.000
REG10	IRRPAST	18.875	-0.000	0.000	-0.000	0.000
REG10	ALFHAY	130.748	0.000	0.000	-0.002	0.000
REG10	SBEETS	5.999	-0.000	0.000	-0.000	0.000
REG10	FIELD	203.422	-0.000	-0.000	-0.002	0.000
REG10	RICE1	0.072	-0.000	-0.000	0.001	0.000
REG10	TRUCK	44.250	0.000	-0.000	-0.000	0.000
REG10	TOMATO	2.708	-0.000	-0.000	-0.000	0.000
REG10	ORCHARD	175.165	-0.000	0.000	-0.000	0.000
REG10	GRAIN	157.082	0.000	0.000	-0.001	0.000
REG10	GRAPES	252.737	-0.000	0.000	-0.000	0.000
REG10	COTTON1	390.264	-0.000	0.000	-0.003	0.000
REG10	SUBTROP	144.036	0.000	0.000	-0.000	0.000
REG11	IRRPAST	0.001	0.000	0.000	0.000	0.000
REG11	ALFHAY	7.122	0.000	0.000	0.000	0.000
REG11	SBEETS	9.097	-0.000	-0.000	-0.000	0.000
REG11	FIELD	18.165	-0.000	-0.000	-0.000	0.000

Table 7A-1. Test of Different Starting Points (contd.)

Region	Crop	Different Starting Points				
		Original Solution (1,000 acres)	CHG12 Difference (1,000 acres)	CHG13 Difference (1,000 acres)	CHG14 Difference (1,000 acres)	CHG15 Difference (1,000 acres)
REG11	RICE1	0.001	0.000	0.000	0.000	0.000
REG11	TRUCK	188.964	-0.000	-0.000	-0.000	0.000
REG11	TOMATO	2.356	-0.000	-0.000	-0.000	0.000
REG11	ORCHARD	112.207	-0.000	-0.000	-0.000	0.000
REG11	GRAIN	9.397	-0.000	-0.000	-0.000	0.000
REG11	GRAPES	71.928	-0.000	-0.000	-0.000	0.000
REG11	COTTON1	116.732	-0.000	-0.000	-0.000	0.000
REG11	SUBTROP	45.385	0.000	0.000	-0.000	0.000

Notes:

CHG12 Change from AVA5, using starting point at 50% of base acres

CHG13 Change from AVA5, using starting point at 120% of base acres

CHG14 Change from AVA5, using starting point at maximum achievable efficiency

CHG15 Change from AVA5, using starting point at low irrig. efficiency (AW 10% higher than base)

This discarded alternative is used here because it imposes the greatest change on the model inputs and is probably the most likely to cause numerical difficulty in finding a global optimum. The 11-region results were the same regardless of the starting point used, as was the case for each of the PEIS alternatives.

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Exhibit 7B
Estimation and Sources of Economic Parameters Used in CVPM

Price Flexibilities

A survey of existing literature was conducted to obtain the price flexibility estimates provided in Table 7B-1. Not all crops were represented in the literature, and much of the available literature is somewhat dated. Therefore, some crops were grouped into categories (such as fresh vegetables) with a consistent flexibility assigned to the category. Flexibilities estimated for California as a whole were adjusted to apply to the Central Valley, using the valley's proportion of statewide production, as described in Exhibit 7A.

Wheat, miscellaneous grains, and corn are given price flexibilities of zero in the CVPM: there is no farm-level price response to quantity produced in the Central Valley. The reason for this is that California production of these crops is a small share of total production. Rice and cotton are given only small flexibilities of -0.05 for the same reasons. There is some response because both commodities are produced partially for specialized export markets in which California production can affect price. Sugar beet production also occurs for a national market but is affected by local milling capacity. A small value of 0.10 is used in the CVPM.

No usable empirical information was available for most field and forage crops. Pasture, miscellaneous hay, dry beans, alfalfa seed, and oil seed crops were all assigned a price flexibility of -0.2. Several empirical studies (Knapp 1990, for example) suggest that alfalfa should be given a higher flexibility. A value of -0.5 is used in the CVPM.

For vegetables, important information was obtained from Nuckton (1980) and King, Adams and Johnston (1978). Both studies suggest that California vegetable price flexibilities are generally small. King, Adams and Johnston (1978) estimated a flexibility of -0.12 to -0.13 for fresh tomatoes. For onions, they estimated a flexibility of -0.18. For crops in the miscellaneous vegetable group they estimated lettuce flexibilities of -0.10 to -1.39, depending on season of sale. For carrots, values ranged from -0.11 to -0.58. For cantaloupe, they provide flexibilities of -0.19 to 0.38, depending on season of sale. The CVPM uses a value of -0.2 for all of these vegetable groups (fresh tomatoes, onions, melons, and miscellaneous vegetables).

For potatoes, King, Adams and Johnston (1978) estimated a California flexibility of -0.45 to -1.03 depending on season of sale. Nuckton's review shows flexibilities of -0.65 to -1.24. The CVPM uses a value of -0.5. For processing tomatoes, one 1975 study estimated a flexibility of 0.27. The CVPM uses a value of -0.25.

Tree fruit and vine crops have generally showed higher price flexibilities. For pears, Masud, O'Rourke and Harrington (undated) found price flexibilities of -1.67 and -0.94 for fresh market and processing pears, respectively. Nuckton's (1978) most recent price flexibilities from the literature and the flexibilities used in the CVPM are summarized in Table 7B-1.

Table 7B-1. Orchard and Vine Crop Price Flexibilities

	Literature Value	Used in CVPM
Plums and prunes	-0.63 to -1.13	-0.80
Walnuts	-0.25	-0.25
Almonds	-0.49	-0.50
Peaches	-0.36 to -0.63	-0.50
Oranges	-0.89	-0.80
Olives	-0.40	-0.50
Grapes	-0.98	-0.80

Acreage Response Elasticities

Acreage response elasticities were estimated using crosssectional TS for the years 1985 through 1992. Each crop was estimated using a partial adjustment model. The form of the estimation equation was:

$$\ln(ACt) = a + b(\ln ACt\text{-}1) + c(\ln GRt\text{-}1) + d(\ln Wt)$$

where

AC is acreage

ACt-1 is acreage lagged one year

GRt-1 is lagged per acre gross revenue

Wt is surface water supply

a,b,c and d are estimated coefficients

The partial adjustment specification implies that acreage decisions are based on a geometric lag in observed revenues and water supplies. Because current year revenues are not yet realized when cropping decisions are made, the initial value in the gross revenue series is lagged and therefore predetermined. Both long- and short-run acreage response elasticities can be estimated from this specification. The short-run elasticity is the partial response to a change in the most recent observed revenue, whereas the long-run elasticity captures the full adjustment over time to a permanent change in revenue. Due to the lagged gross revenue and acreage variables, only 7 years were available for estimation. Results were provided in Table II-1 of this technical appendix.

County Agricultural Commissioners do not report the unit value of pasture, so its acreage elasticity could not be estimated. In the CVPM, pasture is assigned the same short- and long-run values (0.24 and 0.51, respectively) as estimated for alfalfa. For oil seed and alfalfa seed, a short-run and long run elasticity of 0.34 is used in the CVPM corresponding to the long-run value estimated for safflower, an oil seed crop. Potatoes, miscellaneous vegetables, and sugar beets were all given short- and long-run response elasticities of 0.11 and 0.19, respectively, which were the values estimated for onions. The regression estimates for cotton were not significant, so elasticity estimates for cotton were obtained from Duffey et. al (1987).

For tree and vine crops, estimates from the above model were not expected to be as reliable because of the long delay between planting, production and revenue, and planting decisions. Therefore, tree and vine acreage response elasticities were estimated using a longer TS. Data on bearing and nonbearing acreage, yields, and prices were obtained from the California Agricultural Statistics Service for the years 1978 through 1992. Bearing and nonbearing acreage were added together to get total acreage. With the lagged variables and some missing data in 1992, 14 observations were generally available. The natural log of all data were used.

Estimated coefficients generally showed the expected signs, but neither the own-price nor the revenue variable were significant for almonds, walnuts, prunes, olives, or wine grapes. One or the other was significant for peaches, oranges and raisin grapes.

Crop Budget Analysis

A crop budget analysis was prepared to estimate the variable and fixed production costs for the selected crops in the model. Crop production cost information was obtained from the University of California Cooperative Extension Service county crop budgets, Reclamation crop budgets prepared for the CVP Cost Allocation Study (March 1992) and updated for this study, DWR existing input into CVPM plus supplemental survey data on crop costs, and cost estimates included in the California Agricultural Resources Model. This information was then compiled on a crop by crop basis. These cost estimates were then reviewed with Reclamation and DWR to select the most representative costs for a given crop. The costs reflect typical growing conditions and typically sized farms for each crop but do not necessarily represent average conditions in a statistical sense.

In general, the farm budgets prepared by Reclamation were selected as the basis for the production cost estimates. Other sources were used if Reclamation budgets were not available for the crop or crop variety. Fixed costs were calculated using Reclamation farm budget instructions. It should be noted that the fixed costs do not contain any land rents, interest, or opportunity cost; therefore, net returns represent returns to land and water. Also, irrigation costs are accounted for separately so are not included.

Variable costs are further separated into preharvest and harvest costs, which vary by subregion based on yield. This cost information was then compiled with price, yield, water use, and irrigation cost data to reflect net returns to water.

Irrigation Technology and Cost

Irrigation technology is represented in CVPM by functional relationships between irrigation efficiency and irrigation system cost. The nonlinear functions were estimated from irrigation system performance data prepared as an update to earlier work by CH2M HILL (1991). The updated study, "Irrigation Cost and Performance" (CH2M HILL 1994), estimated irrigation costs and performance characteristics (including irrigation efficiency) for eight crop categories, 15 irrigation systems, three management levels, and three regions within the Central Valley. Not all combinations of these parameters were investigated – some combinations such as drip irrigation on grain or linear-move sprinklers on orchards simply are not sensible and were excluded. For each crop category and region, the feasible technology-management combinations were plotted graphically. Any irrigation system that was clearly inferior was eliminated from the analysis. (A dominant system could provide similar efficiency at much lower cost or similar cost at a much better efficiency.) The remaining data points were fitted to a CES isoquant using nonlinear least squares. Exhibit 7A provided the functional form. Each data point was assumed to produce equivalent yield normalized at 1 acre.

Chapter 8
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 (electroconductivity (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 Delta Simulation Model 2 (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. Recent 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, SWRCB, 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

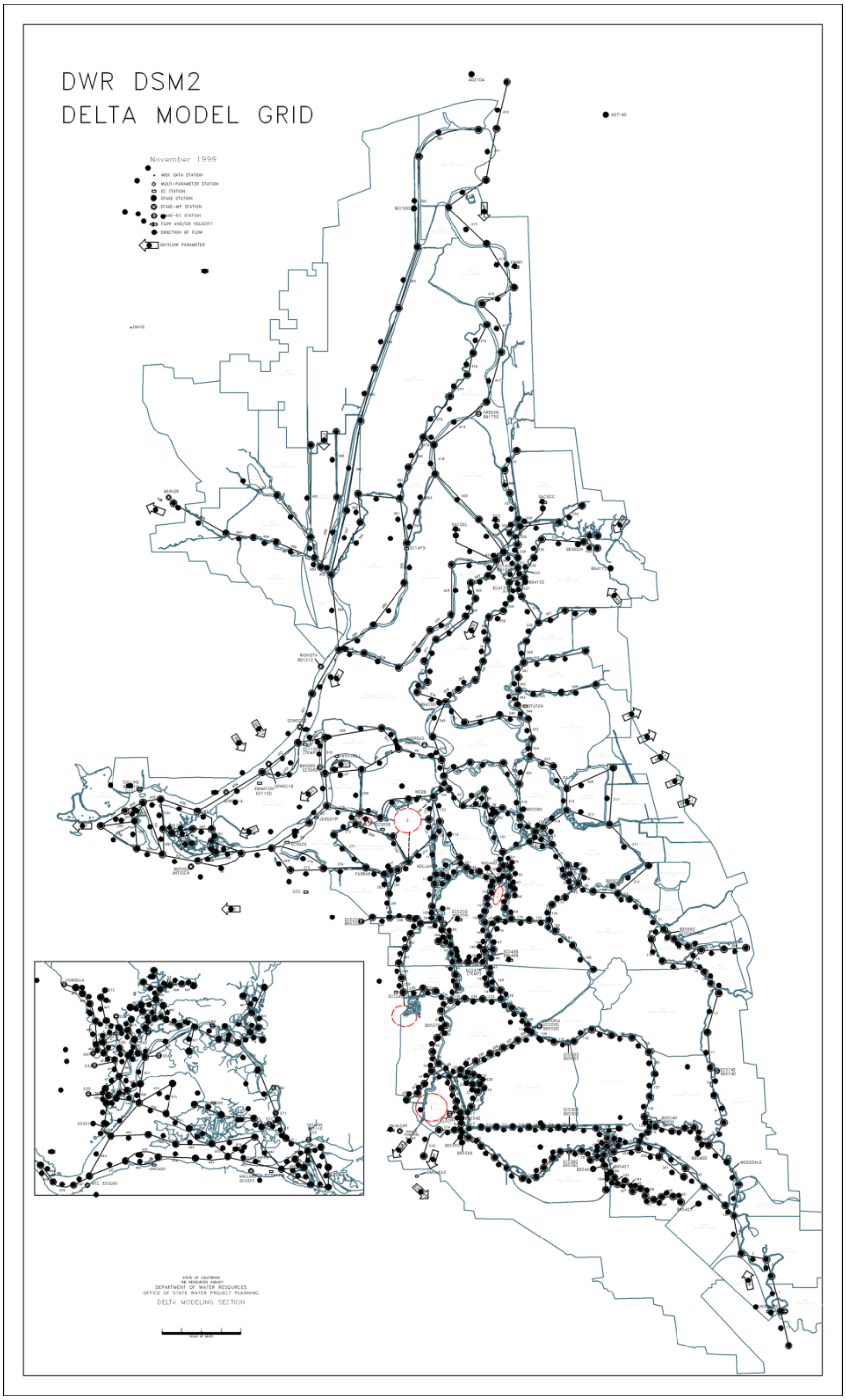
Various mathematical models have been developed to estimate hydrodynamic and water quality conditions in the Delta under different hydrologic conditions. A tidal hydraulic model of the Delta channels was first developed by DWR in 1969 (based on the Water Resources Engineers "Dynamic Estuary" link-node 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/Resource Management Associates (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 EIR documentation of alternatives. The models (MFLOW and MQUAL) were soon modified by Dr. Fischer for DWR to simulate the entire Delta (Fischer 1982). 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 SWRCB, Methodology for flow and salinity estimates in the Sacramento-San Joaquin Delta and Suisun Marsh, by the Delta Modeling Section of DWR.

The DSM2 schematic is shown in Figure 8-1. Key DSM2 inputs include tidal stage, boundary inflow and salinity concentration, and operation of flow control structures. Table 8-1 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 8-1. Illustration of DSM2 Schematic

Table 8-1. 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
EC = Electroconductivity
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 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 (California Department of Water Resources 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).

As part of the Common Assumptions effort, 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 (MWQI) 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 level of development (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 WQCP (SWRCB 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, DFG 1601 Permit, and various Temporary Entry Permits required from landowners and local reclamation districts. Table 8-2 gives the assumed temporary barrier operation for modeling existing conditions.

Table 8-2. 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 (CCC PP) 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 8-3.

Table 8-3. 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

Chapter 9 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 LongTermGen (LTG) and SWP Power California (CA Power) were used to simulate energy generation and consumption for CVP and SWP facilities, respectively. These two tools were originally CALFED Common Assumptions Power tools. This chapter provides an overview of modeling methodology used in LTG and CA Power.[1]

Methods and Assumptions

For each SLWRI alternative, outputs from CalSim-II simulation were inputs to LTG and CA Power 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 LTG and CA Power are monthly models. Their simulation periods are from October 31, 1921, to September 30, 2003, the same simulation periods used in CalSim-II.

In LTG and CA Power, 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

LTG 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, Delta-Mendota Canal, and

[1] Refer to documentation of the Common Assumptions Common Modeling Package Version 8D for details of LTG and CA Power.

Tehama-Colusa relift pumping plants; O'Neill and the CVP portion of Gianelli pumping-generating plants. Table 9-1 summarizes LTG simulated CVP energy facilities and their corresponding CalSim-II inputs.

Functions and parameters assumed in LTG were mostly provided by the Western Area Power Authority (Western) of the U.S. Department of the Interior, which is responsible for managing energy generated from the CVP system.

Table 9-1. CVP Facilities Simulated in LongTermGen 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

Notes:
[1] It is assumed that no energy is generated at Lewiston Powerplant.
Key:
CVP = Central Valley Project
N/A = not applicable

Energy Generation

Using CalSim-II outputs as LTG input, general modeling procedures and assumptions for monthly energy generation calculation in LTG are as follows:

- Convert CalSim-II storage (TAF) to reservoir water surface elevation (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. LTG 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 kilowatt-hour 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, LTG 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 LTG.

Energy Consumption

The general modeling procedures and assumptions for the monthly calculation of CVP energy consumption in LTG are as follows:

- Convert the CalSim-II pumping rate (cfs) into a monthly volume (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 LTG.

- 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

CA Power 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 9-2 summarizes CA Power simulated SWP energy facilities and their corresponding CalSim-II inputs.

CA Power uses a methodology to calculate SWP energy generation and consumption that is very similar to LTG's. Functions and parameters in CA Power were provided by the State Operations Control Office (OCO).

Table 9-2. SWP Facilities Simulated in LongTermGen 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

Notes:
[1] CalSim-II storage numbers are used in the calculation of tailrace elevation.
Key:
N/A = Not applicable
SWP – State Water Project

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Chapter 10
Hydrologic Modeling

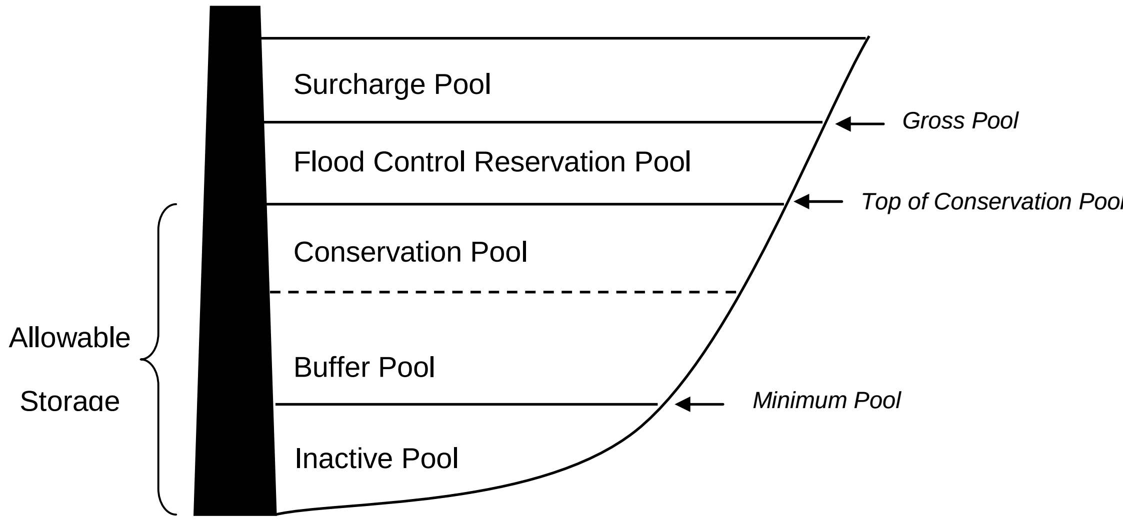
SLWRI alternatives could affect releases from Lake Shasta during flood events. HEC-5 was used to simulate the reservoir releases for the different alternatives. This chapter provides an overview of the modelings methodology used for the HEC-5 analysis.

Background and Methodology

HEC-5, a computer program first developed and distributed in 1973, was designed by the USACE Hydrologic Engineering Center (HEC) to offer guidance in real-time reservoir release decisions and to aid in planning studies for proposed reservoirs, operation alternatives, and flood space allocation based on specified project demands and constraints. It can simulate a dendritic reservoir system configuration of streams, weirs, bypasses, and storage areas. The program accepts criteria related to flood operations, hydropower generation, river routings, diversions, and low-flow operations. Simulations can be performed using time steps ranging from 5 minutes to 1 month.

With support from the USACE Water Management Section of the Sacramento District, HEC constructed working HEC-5 models for flood damage reduction reservoirs within the Central Valley. The Water Management Section began detailed modeling in 1999 to expand the working models into calibrated models capable of performing reservoir simulations for the entire watershed under different storm centers with different return frequencies.

HEC-5 routes flow through reservoirs based on operational criteria provided by the modeler. Operational criteria in the HEC-5 baseline models strictly observe guidelines established within each reservoir's water control manual and focus on flood damage reduction operations, as well as winter operations for water supply and hydropower. Figure 10-1 shows the basic operational zones of a reservoir in HEC-5.



Adapted from: (Hickey et.al, 2003)

Inactive Pool – Storage in this pool may be zero or a minimum pool.
Buffer Pool – This is part of the conservation pool; when the water level drops into the buffer pool, only essential demands will be met.
Conservation Pool – Space is reserved for the various water demands on the reservoir (e.g., agricultural, municipal).
Flood Control Reservation Pool – Water is stored in this pool when it cannot be safely passed downstream within objective flow targets.
Surcharge Pool – Water in this zone is above the emergency spillway; outflows are determined by the spillway capacity or Emergency Spillway Release Diagram.

Figure 10-1. Basic Operational Zones of a Reservoir in HEC-5

Under normal conditions, when reservoir storage encroaches into the flood pool (i.e., storage exceeds the top of conservation pool), reservoir outflow is ramped up to the objective release to evacuate water from the flood pool. The objective release is based on downstream channel capacity and reservoir outlet capacity. If inflow into the reservoir is greater than outflow, the volume of water in the reservoir continues to increase and emergency spillway releases (which are greater than objective releases) begin when storage reaches the gross pool.

Four separate HEC-5 models were developed: two for the Sacramento River system and two for the San Joaquin River system. Each system has one model that represents the headwater reservoirs and a second model for the lower basin flood control facilities. The headwater model for each basin generally contains reservoirs located upstream from flood damage reduction projects. Lower basin models contain flood reduction projects as well as water supply, recreation, and hydropower facilities. Reservoirs simulated in the HEC-5 models either have existing flood damage reduction functions or maintain an active storage greater that 10,000 acre-feet and regulate a significant natural drainage area.

These models were run for various storm centerings. Storm centerings are defined according to the location in the basin where the highest intensity flood flows occur, but the storm may occur throughout the basin. The process used to analyze each storm centering was as follows (additional description is provided in later sections):

1. Simulate headwater models.

2. Use resulting storage time series for headwater facilities to compute top of conservation storage for flood reduction projects in the lower basin models based on established credit space agreements.

3. Use results from Steps 1 and 2 to simulate the lower basin models. The simulated regulated outflow time series from the lower basin models are inputs for hydraulic models (UNET and FLO-2D) to perform detailed routing of flows through floodplains and channels in the foothills and valley floor.

In the lower basin models, HEC-5 applies Muskingum routing (hydrologic routing) to simulate river routing that delays and attenuates flows as water travels downstream from the reservoir through river reaches. Travel times and attenuation factors were determined through past studies, comparison with historical flood hydrographs, communication with local water agencies, and channel characteristics.

Figure 10-2 is the HEC-5 lower basin model schematics for the Sacramento River Basins. The triangle symbols represent reservoirs and dummy reservoir control point; circles represent other control points. HEC-5 requires a reservoir to be located at the most upstream location in a subreach, hence dummy reservoirs were added to the models. Dummy reservoirs do not model physical reservoirs, nor do they have any storage; they are locations that receive diverted flows and flows simply pass through this location without any regulation. Table 10-1 lists reservoirs, as well as important notes and assumptions, simulated in the HEC-5 lower basin model for the Sacramento River Basin.

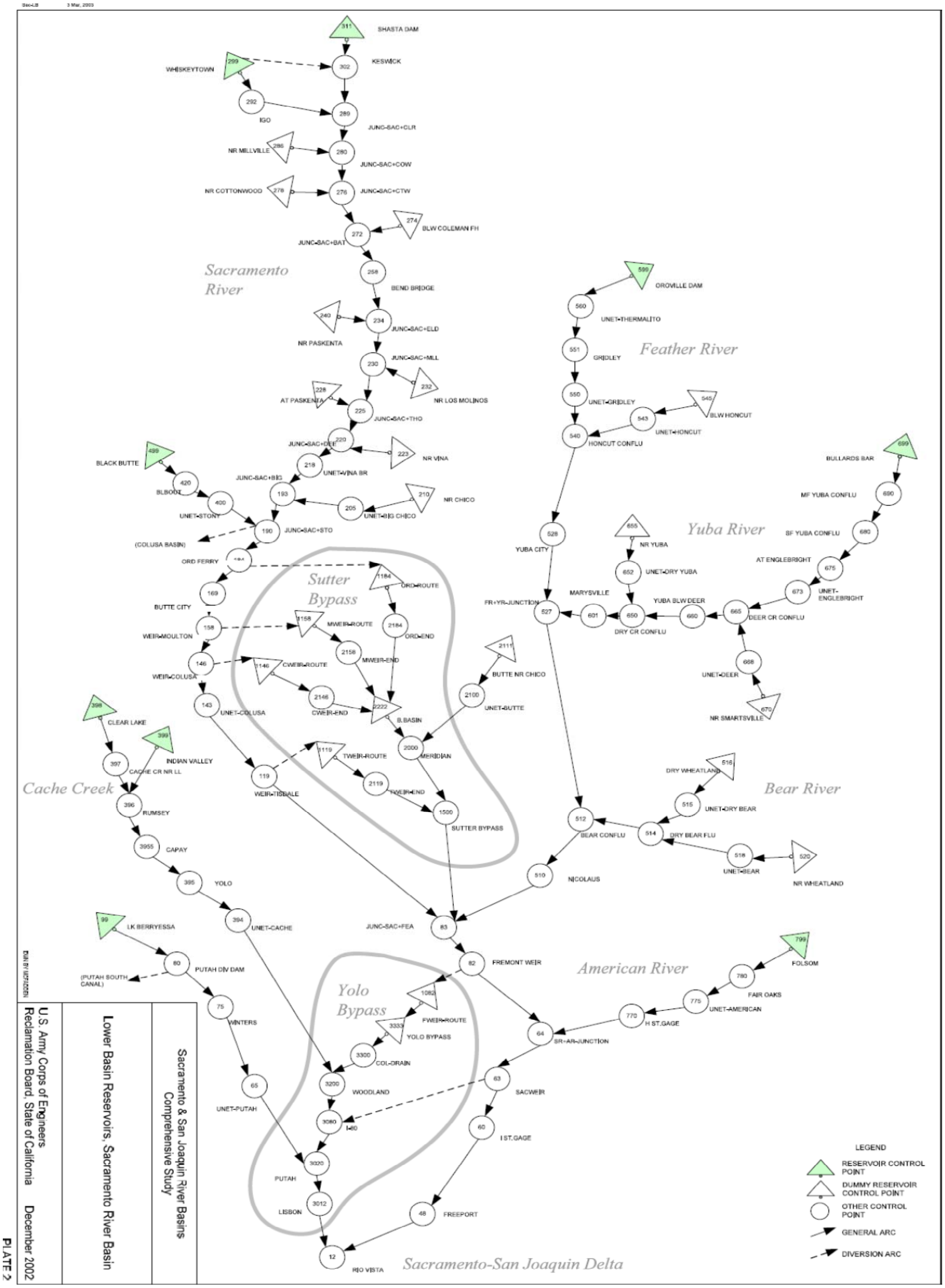


Figure 10-2. HEC-5 Schematic for the Sacramento River Basin

Table 10-1. HEC-5 Sacramento Lower Basin Reservoirs

Reservoir	Owner	Objective Flow	Gross Pool Storage (TAF)	Maximum Flood Space (TAF)	Notes
Shasta Dam and Lake	Reclamation	Below dam – 79,000 cfs Bend Bridge – 100,000 cfs	4,552	1,300	
Whiskeytown Dam and Lake	Reclamation	N/A	241	N/A	No formalized flood space
Black Butte Dam and Lake	USACE	Below dam – 15,000 cfs	144	136	Up to 40 TAF of storage can be transferred based on storage in East Park and Stony Gorge
Oroville Dam and Lake Oroville	DWR	Below dam – 150,000 cfs Gridley – 150,000 cfs Yuba City – 180,000 cfs Feather - Yuba River Junction – 300,000 cfs Nicolaus – 320,000 cfs	3,538	750	
New Bullards Bar Dam and Reservoir	YCWA	Below dam – 50,000 cfs Marysville at Yuba River – 180,000 cfs	970	170	
Folsom Dam and Lake	Reclamation	Below dam – 115,000 cfs	975	670	Up to 200 TAF of storage can be transferred based on storage in French Meadows, Hell Hole, and Union Valley
Clear Lake and Cache Creek Dam	YCFC&WCD	N/A	314	150	No formalized flood space, but YCFC&WCD holds appropriative rights for up to 150 TAF per year.
Indian Valley Dam and Reservoir	YCFC&WCD	Below dam – 10,000 cfs Rumsey – 20,000 cfs	301	40	
Monticello Dam and Lake Berryessa	Reclamation	Below dam – 16,000 cfs	1,564	N/A	No formalized flood space

Key:
cfs = cubic feet per second
DWR = California Department of Water Resources
N/A = Not applicable, no specified objective releases or flood control storage
Reclamation = U.S. Department of the Interior, Bureau of Reclamation
TAF = thousand acre-feet
USACE = U.S. Army Corps of Engineers
YCFC&WCD = Yolo County Flood Control & Water Conservation District

Expectations of Use

The HEC-5 baseline models represent current (2000) reservoir operations within existing flood management systems of the Sacramento and San Joaquin river basins.

The hydrologic routing of HEC-5 allows modeling of flood flow conditions along the river mainstem below the reservoirs. More detailed hydraulic models are required to predict site-specific flow conditions. However, the HEC-5 models provide reconnaissance-level flow evaluation of river mainstems for pre-feasibility studies.

The HEC-5 models developed for the Comprehensive Study were created with the following key assumptions and limitations:

- Models were developed for use only with the synthetic hourly hydrographs from January 1 through February 4. To simulate other time steps or series, adjustments may need to be made.
- Headwater reservoir starting storage values were based on the average storage during the 1986, 1995, and 1997 storm events.
- For the lower basin reservoirs, the starting storage is at the top of conservation pool. This assumes a maximum basin wetness to assure the maximum available flood space.
- It is assumed that all channels have infinite capacity (i.e., all magnitudes of flows would be routed through the channels even if channel capacity is exceeded). No losses, such as evaporation, seepage, and overbank flow due to levee breaks, were simulated.

For more information about the capabilities of the HEC-5 simulation program and its basic assumptions and limitations, refer to the October 1998 User's Manual (USACE 1998) and the December 2002 Comprehensive Study Reservoir Operation Models User's Guide (USACE 2002b).

Storm Centerings

The Comprehensive Study hydrology was formulated within the context of the "Composite Floodplain" concept that a frequency-based floodplain is not created by a single flood event, but by a combination of several events, each of which shapes the floodplain at different locations. To construct the Composite Floodplain, a series of storm centerings, which is a set of storms with different return periods assigned to a set of tributaries, was developed to characterize flooding in different parts of the basin (Hickey et. al. 2003).

The models simulated flood events with the following return periods:

- 2 years (50-percent exceedence)
- 10 years (10-percent exceedence)
- 25 years (4-percent exceedence)
- 50 years (2-percent exceedence)
- 100 years (1-percent exceedence)
- 200 years (0.5-percent exceedence)
- 500 years (0.2-percent exceedence)

Synthetic hydrology was developed to ensure that the Composite Floodplain represents the maximum extent of inundation possible at all locations for any of the simulated seven synthetic return period storm events (USACE 2002a).

Synthetic storm runoff centerings for the Central Valley were generated based on the analysis of 19 historical storms. The center of the storm is the location in the system with the highest intensity and is defined as a set of tributaries. Two basic types of storm runoff centerings were developed: mainstem (basin-wide storms that stress the system on a regional basis) and tributary (storms that generate extremely large floods on individual tributaries). Mainstem centerings in the Sacramento River Basin were prepared at Ord Ferry, and Sacramento (USACE 2002b).

In the HEC-5 Sacramento River Basin model, the following storm centers were used to develop alternatives for operational changes to lower basin reservoirs:

- Shasta Lake to Ord Ferry (Shasta centered)
- Sacramento River at latitude of Ord Ferry2 (Ord Ferry centered)
- Yuba River near Marysville (Yuba centered)
- Feather River at Oroville (Oroville centered)
- Sacramento River at latitude of Sacramento (Sacramento centered)
- American River at Fair Oaks (American centered)

[2] All “at latitude” locations represent mainstem storm runoff centerings.

SLWRI Hydrologic Analysis

The primary objective of the SLWRI hydrologic analysis was to observe the potential effects of the SLWRI alternatives on Lake Shasta releases and downstream flow. This section describes the changes made to the Sacramento River Basin HEC-5 model in order to simulate the effects of the SLWRI alternatives on reservoir releases and downstream flow.

Model Modifications

Only the upstream portion of the Sacramento River Basin HEC-5 model, from Lake Shasta to Sacramento River at Bend Bridge, was used in this analysis.

A starting storage of 3,152,100 acre-feet at Lake Shasta was used for all alternatives. This starting storage was selected because it is 100 TAF below the bottom of the existing flood pool and allows all alternatives to begin the simulation under normal operating conditions (i.e., not under flood operations).

Table 10-2 lists the gross pool and surcharge pool (maximum) storage and elevations for each of the alternatives. Enlarging Lake Shasta did not change the size of the flood control reservation pool; the bottom of the flood control reservation pool was 1.3 MAF below the gross pool for all alternatives.

Table 10-2. Modifications to HEC-5 Model

Alternative	Storage Increase (TAF)	Gross Pool Storage (acre-feet)	Gross Pool Elevation (feet)	Maximum Storage (acre-feet)	Maximum Elevation (feet)
Existing Condition	0	4,552,100	1067	4,854,755	1076.2
CP1	256	4,808,000	1075.5	5,105,858	1084
CP2	442	4,995,000	1081.5	5,299,228	1090
CP3	634	5,186,000	1087.5	5,496,881	1096

Notes:
Values rounded for use in HEC-5 model.
Key:
TAF = thousand acre-feet

Other assumptions made for this analysis include the following:

- Reservoir emergency spillway operations do not change.
- Maximum release capacity is the same for all alternatives.
- Reservoir area increases linearly for each alternative.

Storm Events

The Shasta centered storm was used because this storm is on the mainstem Sacramento River and the highest intentisty of this storm is centered at Lake Shasta. Storm return periods applied in this analysis were the following:

- 2 years (50-percent exceedence)
- 10 years (10-percent exceedence)
- 25 years (4-percent exceedence)

These events were selected based on the assumption that most of the effects on releases would occur during the smaller, more frequent storm events.

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