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Upper Sacramento River Water Quality Modeling with HEC-5Q: Model Calibration and Validation

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UPPER SACRAMENTO RIVER WATER QUALITY MODELING WITH HEC-5Q: MODEL CALIBRATION AND VALIDATION

EXECUTIVE SUMMARY

An HEC-5Q model was developed to simulate the thermal regime of reservoirs and river reaches of the Upper Sacramento River system including Shasta, Trinity, Lewiston, Whiskeytown, Keswick and Black Butte Reservoirs; Trinity River; Clear Creek; Upper Sacramento River from Shasta to Knights Landing; and Stony Creek. The objectives of this effort were to develop and calibrate a model capable of simulating the water temperature responses in the Upper Sacramento River and associated reservoirs. The model is designed to provide an evaluation of temperature impacts of alternative conditions such as enlarged Shasta or construction of the North of Delta Storage Options alternative including Sites Reservoir. These alternative scenarios will be discussed in a separate report.

The TCD algorithm was modified specifically for Shasta and embedded in HEC-5Q. TCD gates were operated to achieve temperature targets given flood control, penstock and leakage flows. Relationships were developed between outflow rate and leakage for each of seven different leakage zones. The leakage zones were delineated to represent different leakage flows that occur at different elevations. Temperature was adjusted by thermal balance for leakage flow and simulated temperature. Relationships were developed between outflow rate and proportional discharge from gates for selection of the best gate setting. Combined discharge temperatures were computed for all outflows.

The models were calibrated against average ambient stream temperature time series data and reservoir temperature profile data collected during January 1998 through November 2002. Tributary inflow temperatures were developed as a function of the typical seasonal variation (same for all years) and 6-hour equilibrium temperature (variable by year). Correlation of inflow temperature to meteorology is necessary to extend historical ambient temperature data to the entire simulation period (1921 through 2002). The model results are in good agreement with observed data in all of the upper reservoirs and streams, and throughout the Upper Sacramento River.

A model validation simulation was performed for the period of January 1990 through January 1997. The Shasta TCD was not in place during this time period, therefore, historical flood control and power generation rates were specified with a single penstock intake elevation. Model results were compared with average ambient stream temperature time series and Lake Shasta temperature profiles. The validation exercise verified that the model adequately represents the thermal responses of the Upper Sacramento River stream and reservoir system.

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1 INTRODUCTION

An 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, Red Bluff diversion Dam, Black Butte Dam, and downstream Stony Creek. This model was then modified and extended to include the North of Delta Offstream Storage (NODOS) options for the purpose of evaluating the impacts of the creation of Sites Reservoir and accompanying diversions on temperature and water quality. The NODOS model extends from Keswick Dam to Knights Landing and includes the Sacramento River, Red Bluff diversion Dam, 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 USGS USACE and USBR data sources were input to the model. Meteorological data from CIMIS and the National Weather Service and ambient water temperatures from DWR, USBR and CDEC were input. Similar data sources were used for model validation. All flow data are daily averaged and meteorology and inflow temperatures are defined at six-hour intervals. All temperature simulations utilized 6-hour time steps with daily average flows.

HEC-5Q is an integral component of the "Temperature Modeling System (USBR-TMS) software developed previously (RMA, 2003). Therefore, calibration of the temperature model supports the HEC-5Q application within TMS.

Further alternative operations, based on CALSIM II hydrologic inputs and outputs, were performed using the Upper Sacramento River model. A pre-processor program (described in Appendix 6.1) was developed to convert CALSIM II monthly averages into daily values based on historical hydrologic patterns and operation constraints. The meteorology and inflow temperatures were correlated with historical air temperature and extrapolated to the entire 1921 – 1994 CALSIM II simulation period.

Only the calibration and validation of the Upper Sacramento River model will be discussed in this report.

1.1 BACKGROUND

The Bureau of Reclamation initiated the development of the "Temperature Modeling System (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 in the introduction. Under the current phase of this work RMA has further developed the water temperature model, 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 proposed enlarged Lake Shasta; and utilizing HEC-5Q modeling capability to enhance procedures for determining control releases in CALSIM II.

1.2 PROJECT OBJECTIVES

The objectives of this phase of the modeling study were to:

- update HEC-5Q model geometry based on RMA model cross-section data;
- refine tributary temperature relationships using all available time series data from CDEC, DWR and USBR;
- modify the HEC-5Q temperature model and data to better represent Shasta TCD operation;
- calibrate the HEC-5Q temperature model of Upper Sacramento River (including river and reservoir temperatures, and TCD algorithm) to January 1998 through November 2002 data;
- validate the HEC-5Q temperature model of Upper Sacramento River using January 1990 through January 1997 data for Sacramento River and Lake Shasta; and
- develop software to convert monthly CALSIM II monthly averages in to daily values based on historical hydrologic patterns and operation constraints as required by HEC-5Q.

Additional project objectives, which will be discussed in a separate report, are:

- develop and calibrate North of Delta Storage Options model (NODOS) with proposed Sites Reservoir, and
- perform alternative operations simulations using the Upper Sacramento River and NODOS models for 1921 through 1994 based on CALSIM II hydrologic inputs and outputs.

2 MODEL DESCRIPTION

The water quality simulation module (HEC-5Q) was developed so that temperature, and conservative and non-conservative water quality constituents could be readily included as a consideration in system planning and management. Using system flows computed by HEC-5, HEC-5Q computes the distribution of temperature in the reservoirs and in the 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 provides an approximation of diurnal variations in temperature. For the Upper Sacramento River system, flow and temperature within the Colusa and Yolo bypasses were not simulated since 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 the system. Examples of applications of the flow simulation model include examination of reservoir capacities (e.g., impacts of the proposed enlarged Lake Shasta) for flood control, hydropower and reservoir release requirements to meet water supply and in-stream flow requirements (e.g. CALSIM II operation scenarios). The model can be used in applications including evaluation of in-stream temperatures and constituent concentrations at critical locations in the 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 Shasta spillway, flood control outlets and TCD gates to meet tailwater temperature targets

HEC-5Q can be used to simulate concentrations of various combinations of the water quality constituents, many of which may be coupled with other water quality constituents. The following can be simulated.

- Temperature
- TDS or conservative tracer
- Ammonia (NH_3) – Nitrogen
- Nitrate (NO_3) - Nitrogen
- Phosphate (PO_4) - Phosphorus
- Phytoplankton
- Dissolved oxygen
- Dissolved and particulate organic material
- Suspended sediments
- Chloride
- Alkalinity
- Total inorganic carbon and pH
- Water column and sediment heavy metals

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The HEC-5Q North of Delta Storage Options model includes all of these parameters however, the Upper Sacramento River model calibration and validation utilized only temperature and the conservative tracer (for mass continuity checking). A brief description of the processes affecting these two parameters is provided below.

Temperature

The 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 utilized 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 the overlying atmosphere is zero. The coefficient of surface heat exchange is the rate at which the heat transfer process progresses. The 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. The heat exchange with the bottom is a function of conductance and the heat capacity of the bottom sediment.

Conservative parameter / tracer

The conservative parameter is unaffected by decay, settling, etc. This parameter was used to check mass continuity by setting the quality of all inflows to a constant value and then checking to see that the simulation results did not deviate from that value.

2.1 MODEL REPRESENTATION OF THE PHYSICAL SYSTEM

For this application of HEC-5 and HEC-5Q, rivers and reservoirs comprising 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 control point.

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)
- Red Bluff Diversion Dam 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 2-1.

In HEC-5, flows and other hydraulic information are computed at each control point. In the HEC-5 context, control points 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 control points. Reservoirs are partitioned into vertical and/or longitudinal computational elements to represent the significant thermal gradients. Within each element, uniform temperature is assumed; therefore the element size determines the spatial resolution. The model representation of streams and reservoirs is summarized below.

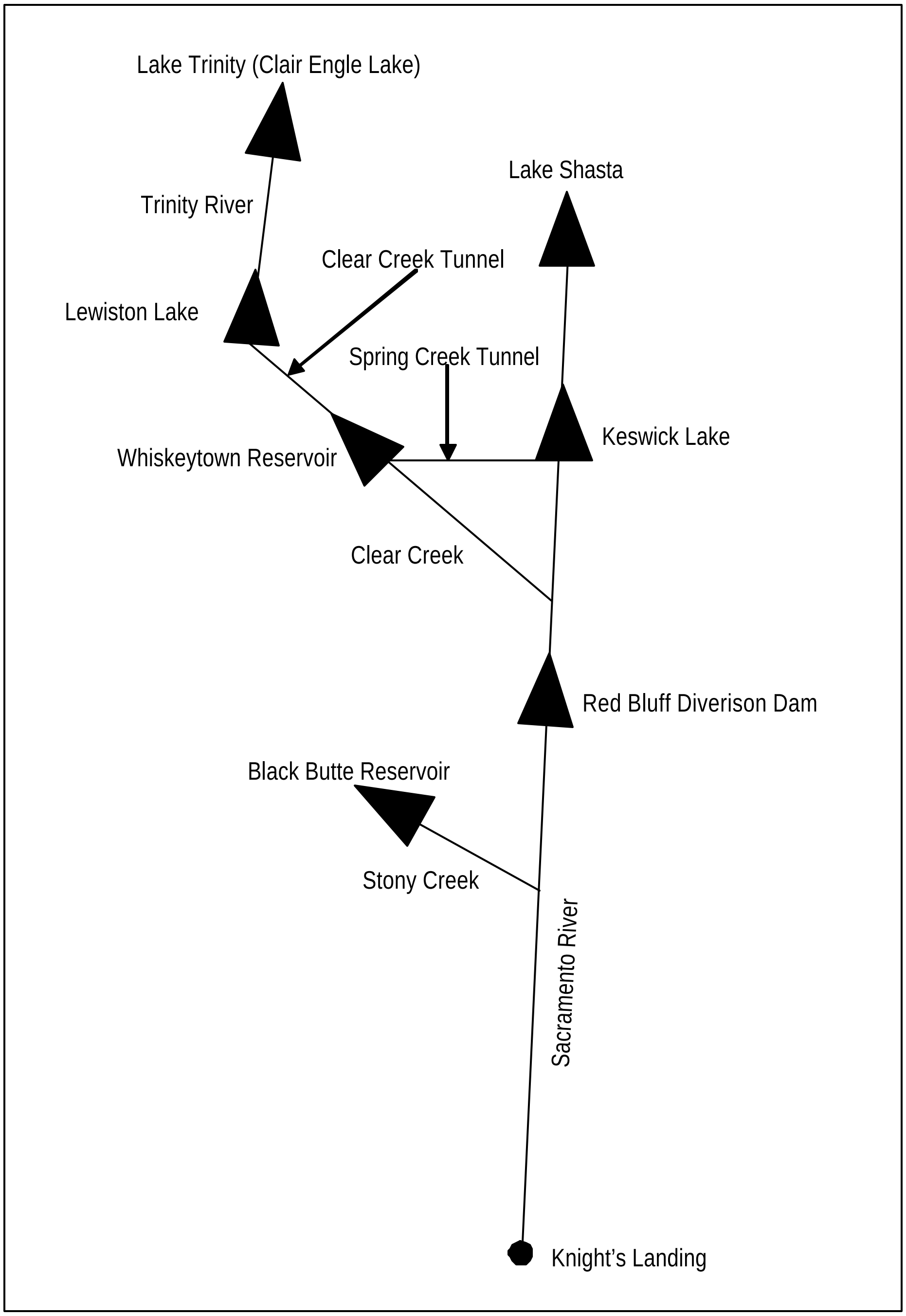


Figure 2-1 Schematic of the HEC-5Q Upper Sacramento River model.

2.2 MODEL REPRESENTATION OF RESERVOIRS

For the Upper Sacramento River model, Shasta, Trinity, Whiskeytown and Black Butte Reservoirs were geometrically discretized and represented as vertically segmented water bodies with 3.28' thick layers. In Whiskeytown, the Oak Bottom curtain near the Judge Francis Carr Powerhouse tailrace was 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 are represented as vertically layered and longitudinally segmented reservoirs. Lewiston has nine segments each with 9 layers. Keswick has 13 segments each with 5 layers. Red Bluff Diversion Dam is represented as a longitudinally segmented reservoir with 2 segments and seasonal elevation constraints. In Lewiston, 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 one-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 inter-element 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, as the cross-sectional area of all layers are 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 non-point 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 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.

2.3 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 control points. The port selection algorithm of the water quality module uses non-linear mathematical optimization techniques to determine appropriate port openings and flow rates to satisfy downstream water quality objectives, subject to the different system hydraulic constraints. The solution method is described in the HEC-5 Appendix on Water Quality Analysis [RMA, 1998].

Control point target values can be specified for several water quality constituents. The 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 control point 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 non-upper 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, which is described in Appendix 6.2, contains a summary of the TCD operation including the 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 three-dimensional hydrodynamic model results provided by the Bureau (USBR, 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 2.1. These leakage zones coincide with the three-dimensional model output summaries. The greatest leakage flow occurs from zone 6, which 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 2-2.

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 2.1. The table also includes the average leakage rate, average absolute difference between the 3-D 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-D model leakage is 5.2% of the total power flow.

No assessment of the accuracy of the 3-D model is made herein; therefore it is difficult to assess the ramifications of the 5.2% 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 above elevation 1000', all flow goes through the upper gate. If the target temperature is below 804', all flow goes through the bottom gate. At intermediate locations, the following relationships between proportional discharges from adjacent gates were developed from the 3-D model results (note that only two gate levels are used to assign outflow fractions).

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

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

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

Where: Qg = residual total gate flow (power flow less leakage),
Qm = flow through middle gate,
Qb = flow through the lower gate,
Nt = number of upper gates,
Nm = number of middle gates, and
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 2-3 shows the relationship that was developed between penstock level gate flow and middle gate flow.

Within the TCD algorithm, all combinations of gate openings (Nt, Np and Nm varying between 1 and 5 gates) for the two gate levels that bracket the adjusted target temperature were computed. 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 tailwater temperatures and target tailwater temperatures (see Section 3, Figure 3-57) is a function of the simulated Shasta reservoir temperatures and the operation of the Shasta Dam TCD. We believe that the quality of the Lake Shasta temperature calibration (profiles and tailwater) attests to the adequacy of the TCD for alternative evaluation.

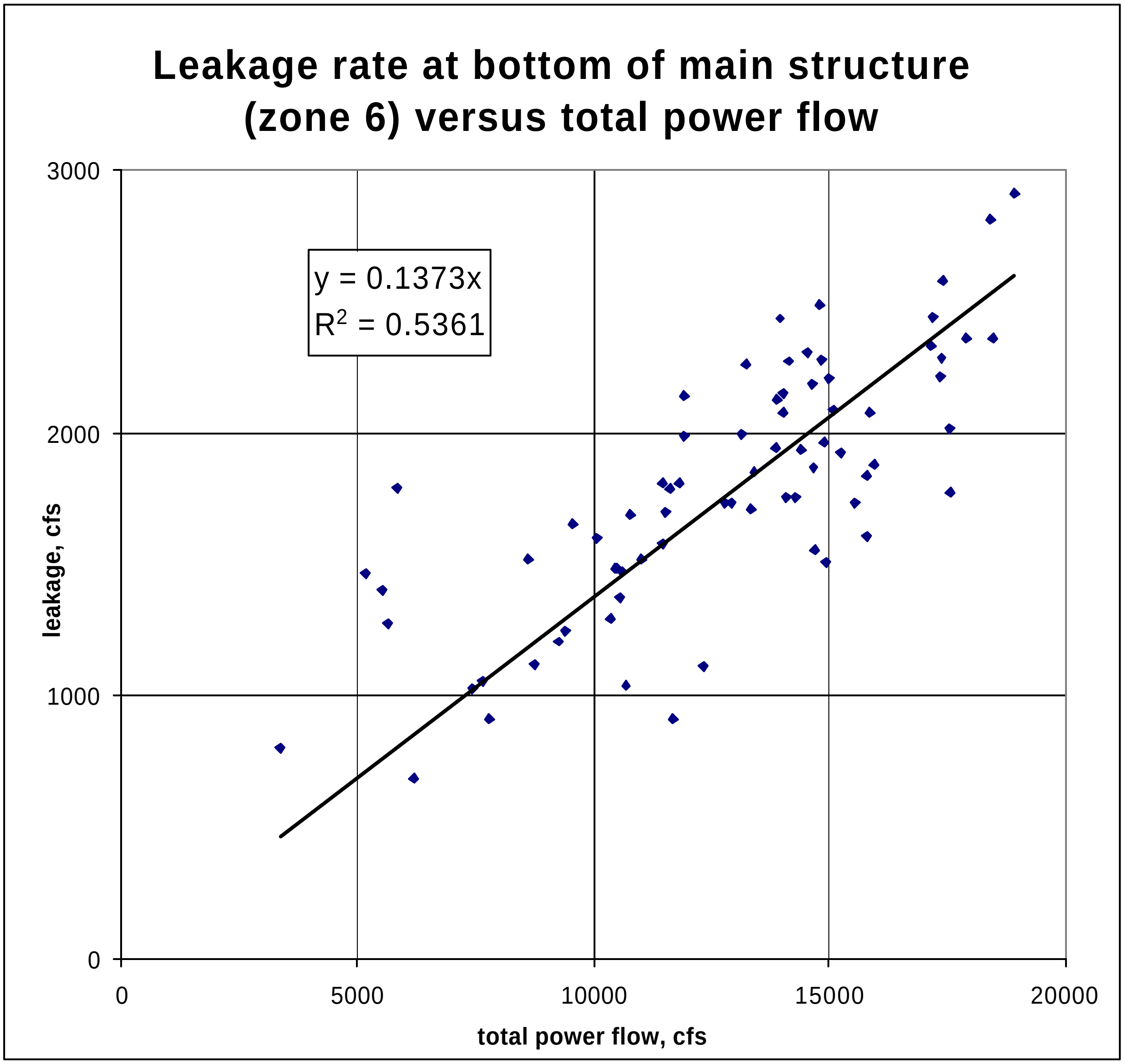


Figure 2-2 Shasta Dam leakage rate at bottom of gate structure (zone 6) versus total power flow.

Table 2.1 Leakage statistics and equation coefficients.

Zone	Elevation (feet)	K_f	Average Leakage (cfs)	Absolute difference, comp. vs. obs. total Q	
				cfs	%
1	Above 1000 (includes over top)	0.0306	356	133	1.07
2	1000-945	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	1785	245	2.36
7	780-750 (leakage of low level access)	0.0047	65	8	0.06
	Total		3052	664	5.2

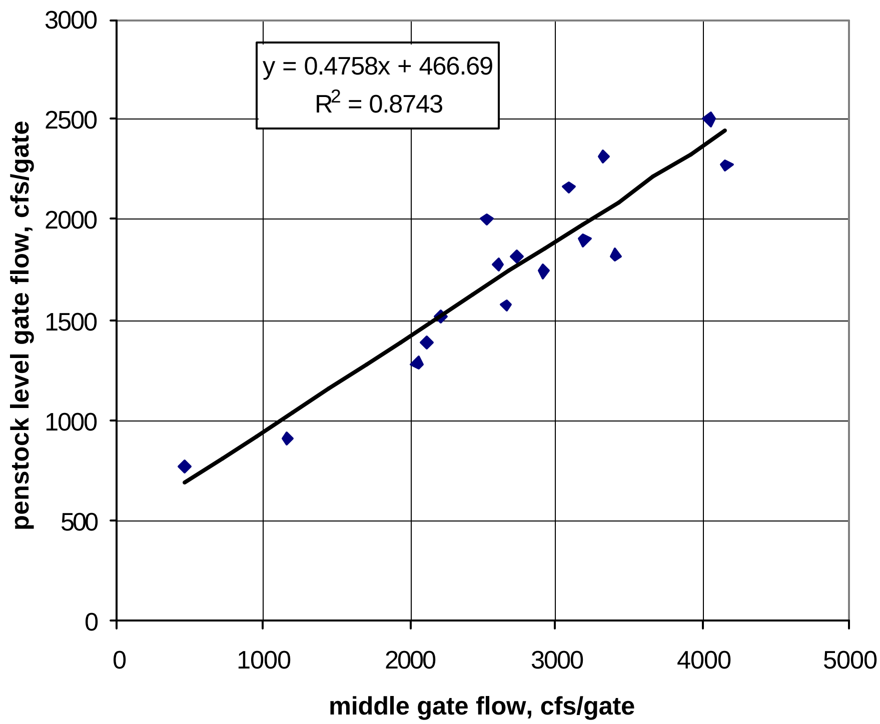


Figure 2-3 Shasta Dam penstock level gate flow versus middle gate flow.

2.4 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 control points and at intermediate locations when data are available. The flow versus depth relation 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 Upper Sacramento River was originally developed and calibrated by UC Davis and refined through work sponsored by USGS. To develop flow versus depth relations from this model, a series of simulations was performed with a range of constant inflows at the upstream boundary. Flow depths were then extracted from the model results to correspond to the different flow rates that defined the 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 control points 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 2.2. Within HEC-5, incremental local flows (i.e., inflow between adjacent control points) are assumed deposited at the control point. 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 control points). A flow balance is used to determine the flow rate at all element boundaries.

Inflows or withdrawals may include any point or non-point flow. Distributed flows such as groundwater accretions and non-specific 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 inter-element 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 one-half mile in length were used in this study.

Table 2.2 Flow routing times.

Location	Flow routing time (hrs)
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

2.5 HYDROLOGIC BOUNDARY CONDITIONS

The 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 USBR data sources were used to develop boundary conditions.

2.6 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 as defined by HEC-5.

Water temperature was simulated by HEC-5Q using tributary stream inflow temperatures developed from DWR, USBR 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 snow melt 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 Lake Trinity (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; and
- Sacramento River tributary (cool): Battle Creek.

The three major tributaries to Shasta, 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 2.3.

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 2.3.

Table 2.3 Reservoir inflow data availability.

Tributary	Available Reservoir Inflow Data		
	Start	End	# 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 2.4.

Figure 2-4 shows daily average, seasonal distribution and computed trib utary inflow temperature for Battle Creek. This plot is intended to show the typical temporal variations in the 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 resource for river temperature control during the summer and fall seasons.

Table 2.4 Sacramento River tributary temperature assignments and data availability.

Sacramento River Tributary	Temperature Assignment	Available Temperature Data		
		Start	End	# 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 Cr.	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

2.7 METEOROLOGICAL DATA

Meteorological data were available from CIMIS and the US Weather Service (USWS) at several locations within the Sacramento Valley. The Gerber station was selected as the primary CIMIS meteorological data record as 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 US Weather Service 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 since was the nearest station with data dating back to 1921.

The extrapolation procedure consists of searching the Gerber CIMIS data record to find the air temperature range that most closely matches 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 – 1985 period. From 1985 on, the unadjusted CIMIS data were used.

The 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, the 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.

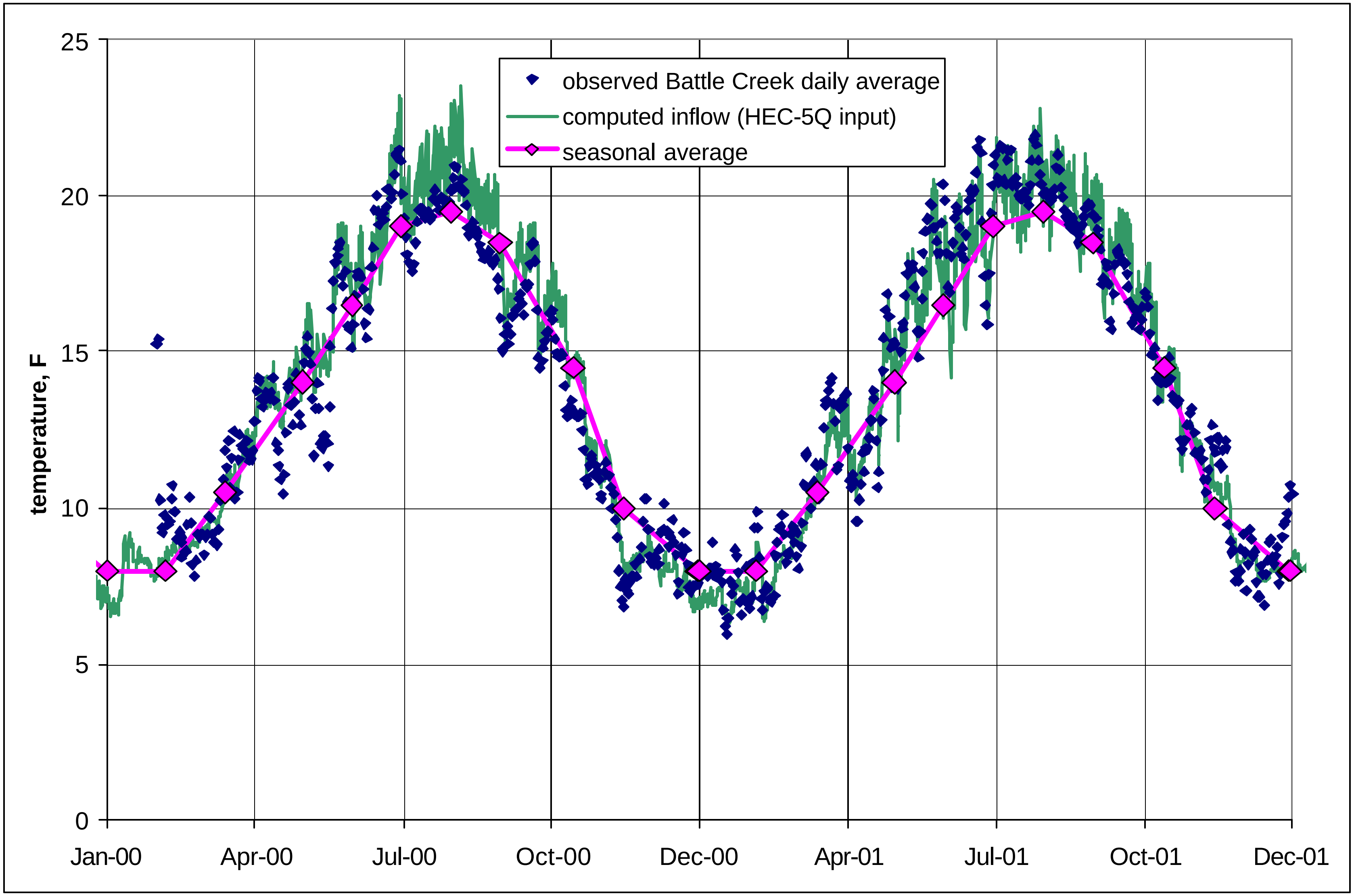


Figure 2-4 Daily average, seasonal average, and computed tributary inflow temperature for Battle Creek.

3 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 utilized.

- CDEC water temperature time series;
- DWR water temperature time series;
- Reservoir temperature profiles (Shasta, Trinity, Lewiston and Whiskeytown) provided by USBR; and
- US Army Corps of Engineers Black Butte Reservoir temperature profiles.

The hydrology, meteorology, and inflow water quality conditions described in Chapter 2 were assumed.

The intent of the model calibration exercise was to adjust the model parameters to minimize the 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. The model is spinning up during 1998, and TCD operation to meet downstream temperature targets did not begin until the spring of 1999, therefore reservoir temperature profile plots are provide from 1999 on.

3.1 HEC-5Q CALIBRATION RESULTS

The following sections provide a brief discussion of the calibration results for reservoirs and streams.

3.1.1 Reservoir Temperature Calibration Results

Computed and observed vertical reservoir temperature profiles are plotted for numerous dates during 1999 through 2002 in Figures 3-1 through 3-56.

Shasta profiles are plotted in Figures 3-1 through 3-16. There is excellent agreement between computed and observed data for all of the profiles. In several of the profiles there is a 2 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. 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 profiles are plotted in Figures 3-17 through 3-32. The calibrated mixing coefficients reflect current facilities that include the temperature control curtain near the Clear Creek Tunnel discharge and the 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. On May 12, 1999 and July 7, 1999 in Figures 3-17 and 3-18, the computed profiles show slightly more stratification than the observed data, however the surface and hypolimnion temperatures are still within 2 to 3° F of observed on both dates. On November 22, 1999 (Figure 3-20) computed hypolimnion temperatures are as much as 4° F lower than observed. On May 19, 2000 in Figure 3-21, the computed surface temperature is 4° F higher than observed and on June 25, 2001 in Figure 3-26, the computed surface temperature is 2.5° F higher than observed. On July 11, 2001 in Figure 3-27, the computed surface temperature is almost 6° F higher than observed. 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 five 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 3-50) and the discrepancies noted do not appear to adversely impact the discharge temperature calibration.

Trinity temperature profiles are shown in Figures 3–33 through 3-40. 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 temperature profiles are shown in Figures 3–41 through 3-48. Computed temperature profiles tend to be 0 to 2° F cooler than observed. Discrepancies in temperatures may be influenced by the presence of the Clear Creek Intake Tunnel curtain. Lewiston temperatures were not adjusted to correct for this minor discrepancy as it would have adversely affected the calibration of Spring Creek Powerhouse temperatures (see Figure 3-58, Section 3.1.2).

Although not included in the original Upper Sacramento River model, Black Butte Reservoir was added to the model in an attempt to provide a better estimate of temperature at the confluence of Stony Creek and the Sacramento River, and to provide inflow quality to the conveyance facilities being considered in various North of Delta storage options. Black Butte Reservoir temperature profiles are shown in Figures 3-49 through 3-56. Calibration of Black Butte Reservoir is preliminary as sufficient data have not been obtained to configure the reservoir and outlet structure in the model. The reservoir geometry was developed using the 1999 area capacity curve. Computed temperatures differ from observed data by as much as 4 to 8° F and in some cases the thermocline location is not well represented. On July 31, 2000 there appears to be a problem with the reservoir elevation data.

Black Butte Reservoir receives summertime releases from Stony Gorge Reservoir located several miles upstream on Stony Creek. Heating within the stream channel results in elevated inflow temperatures to Black Butte reservoir. The elevated summertime inflow temperatures coupled with small reservoir volume relative to the inflow rate results in relatively short hydraulic residence time and total depletion of cool water within the reservoir by mid summer. Comprehensive modeling including the two upstream reservoirs and connecting creek segments is likely necessary to more realistically simulate the thermal responses of the Black Butte / Stony Creek system.

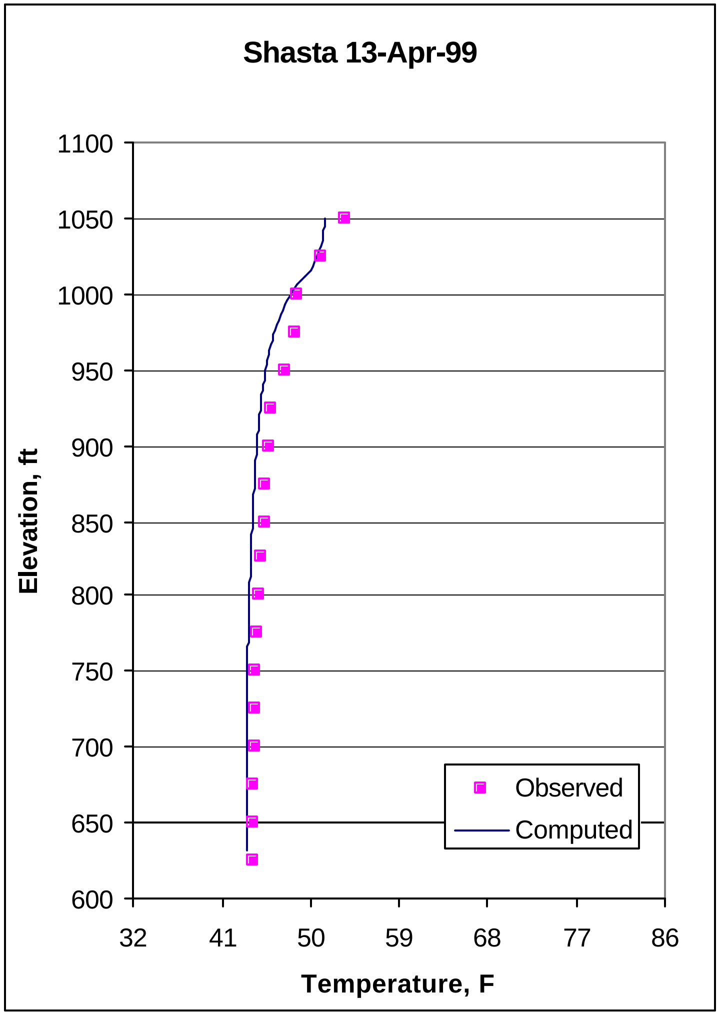
3.1.2 Stream Temperature Calibration Results

Computed and observed temperature time series for locations throughout the Upper Sacramento River system are plotted in Figures 3.57 – 3.73 and summarized in Table 3.1. Computed values are plotted at 6-hour intervals at 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 furthest 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.

Table 3.1 Summary of stream temperature calibration results.

Figure	Location	Description
3-57	Shasta Dam tailwater	Computed temperatures within 1° F or less of average observed data throughout most of calibration period.
3-58	Lewiston Fish Hatchery	Average computed temperatures are 0 to 1° F lower than average observed temperatures. This discrepancy also seen in Lewiston reservoir temperature profile in Section 3.1.1.
3-59	Spring Creek Powerhouse	Computed temperatures are within less than 1° F of average observed data throughout most of calibration period.
3-60	Sac. R. below Keswick Dam	Computed temperatures are within less than 1° F of average observed data throughout most of the calibration period.
3-61	Sac. R at Clear Creek	Average computed temperatures are within 1° F or less of average observed data throughout the calibration period.
3-62	Sac. R at Balls Ferry	Average computed temperatures are within 1° F or less ofaverage observed except during January 199 and January 2002 when there is as much as 2° F difference.
3-63	Sac. R at Jellys Ferry	Average computed temperatures are within 1° F or less of average observed data throughout the calibration period.
3-64	Sac. R at Bend Bridge	Average computed temperatures are within 1° F or less of average observed data throughout most of the calibration period.
3-65	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 is as much as 2° F difference.
3-66	Sac. R at Tehama	Average computed temperatures are within 1° F or less of available average observed data throughout most of the calibration period.
3-67	Sac. R at Woodson Bridge	Average computed temperatures are within 2° F or less of available average observed data throughout the calibration period.
3-68	Sac. R at Hamilton City	Average computed temperatures are within 2° F or less of available average observed data throughout the calibration period.
3-69	Sac. R at Butte City	Average computed temperatures are within 2° F or less of available average observed data throughout most of the calibration period.
3-70	Sac. R at Colusa	Average computed temperatures are within 2° F or less of available average observed data throughout the calibration period.
3-71	Sac. R above Colusa Basin Drain	Average computed temperatures are within 2° F or less of available average observed data throughout most of the calibration period.
3-72	Black Butte Dam	Excellent agreement between computed and observed temperatures during February through May and September through November of each year. During December and January of each year computed temperatures tend to be about 1° F lower than observed. In June through August computed temperatures are 2 to 3° F higher than observed.
3-73	Stony Creek at Tehama Colusa Canal	Average computed values are within 2° F or less of available average observed data during September through November of each year. Slightly larger discrepancies occur during the remainder of the year with the largest differences (as much as 5° F) occur during June and July of 1999.



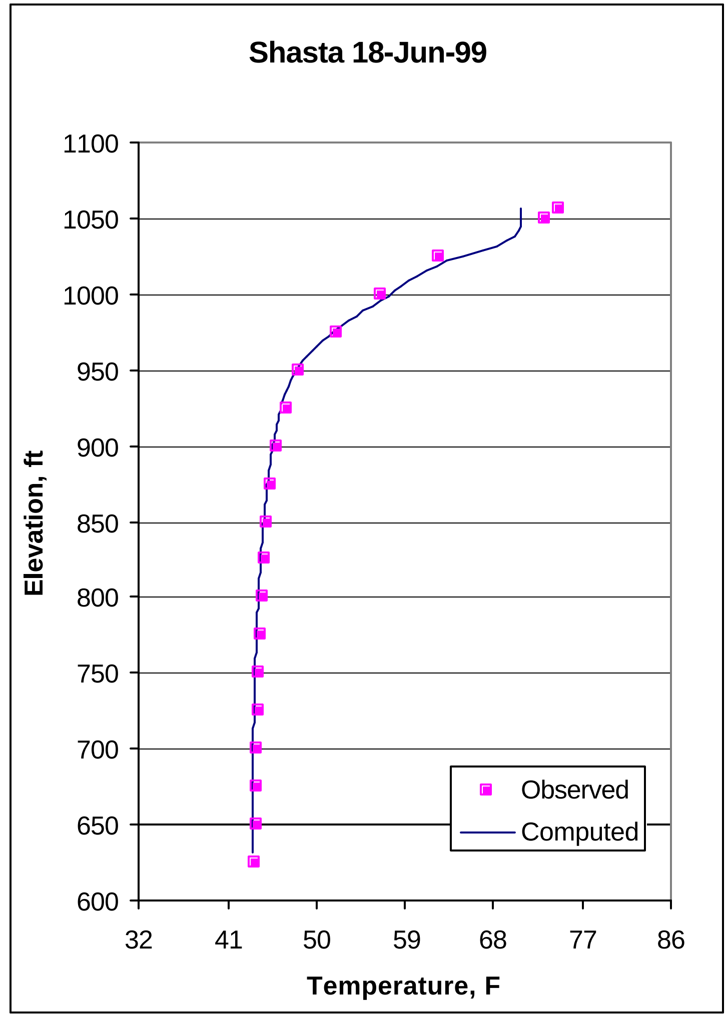


Figure 3-1 Computed and observed temperature profiles in Shasta Reservoir on April 13, 1999.

Figure 3-2 Computed and observed temperature profiles in Shasta Reservoir on June 18, 1999.

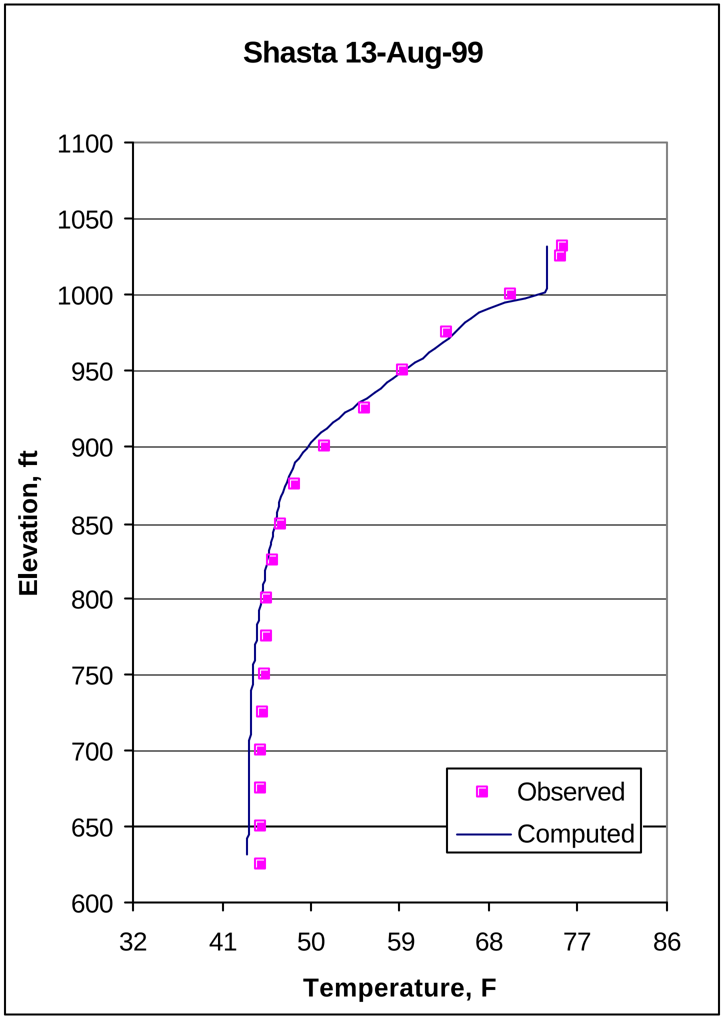


Figure 3-3 Computed and observed temperature profiles in Shasta Reservoir on August 13, 1999.

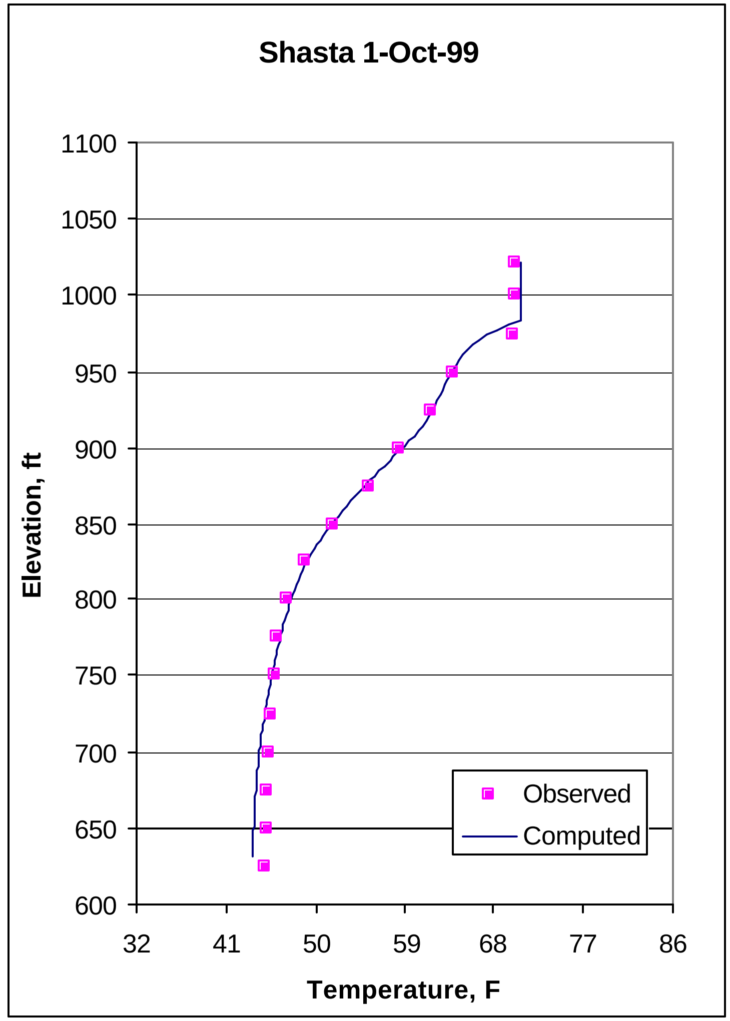


Figure 3-4 Computed and observed temperature profiles in Shasta Reservoir on October 1, 1999.

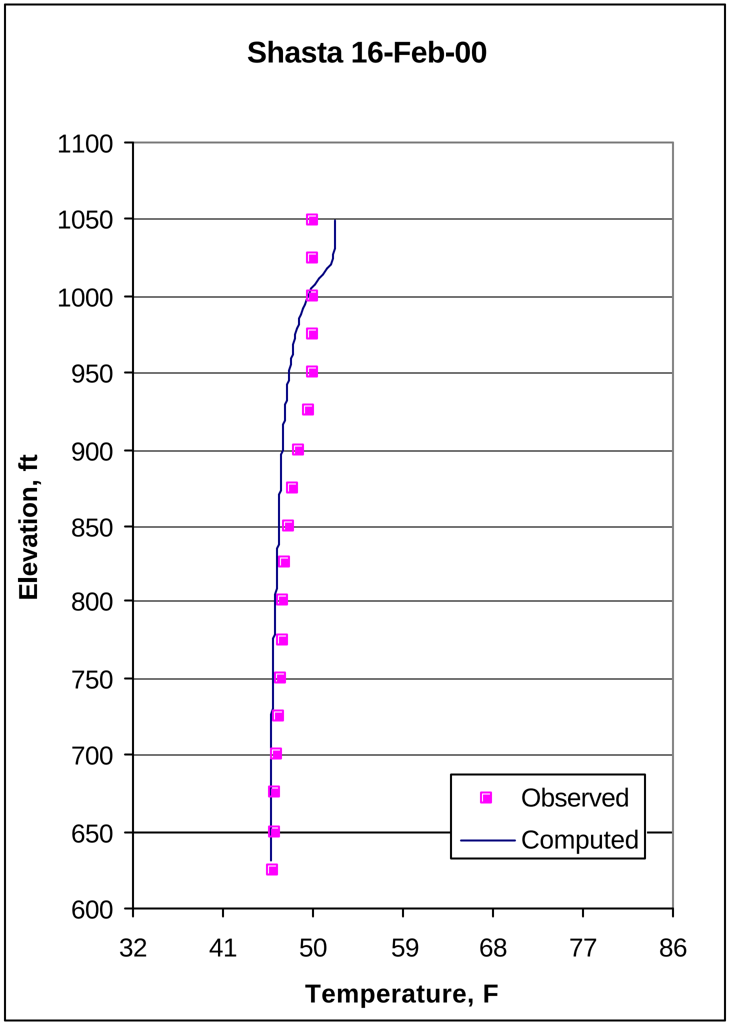


Figure 3-5 Computed and observed temperature profiles in Shasta Reservoir on February 16, 2000.

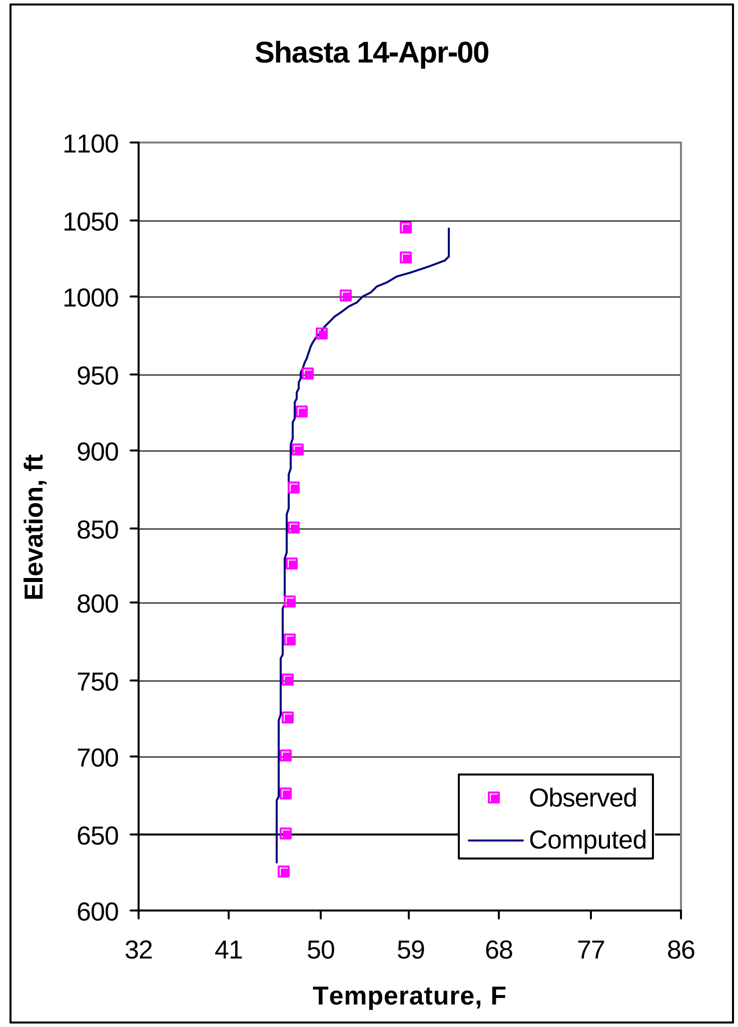


Figure 3-6 Computed and observed temperature profiles in Shasta Reservoir on April 14, 2000.

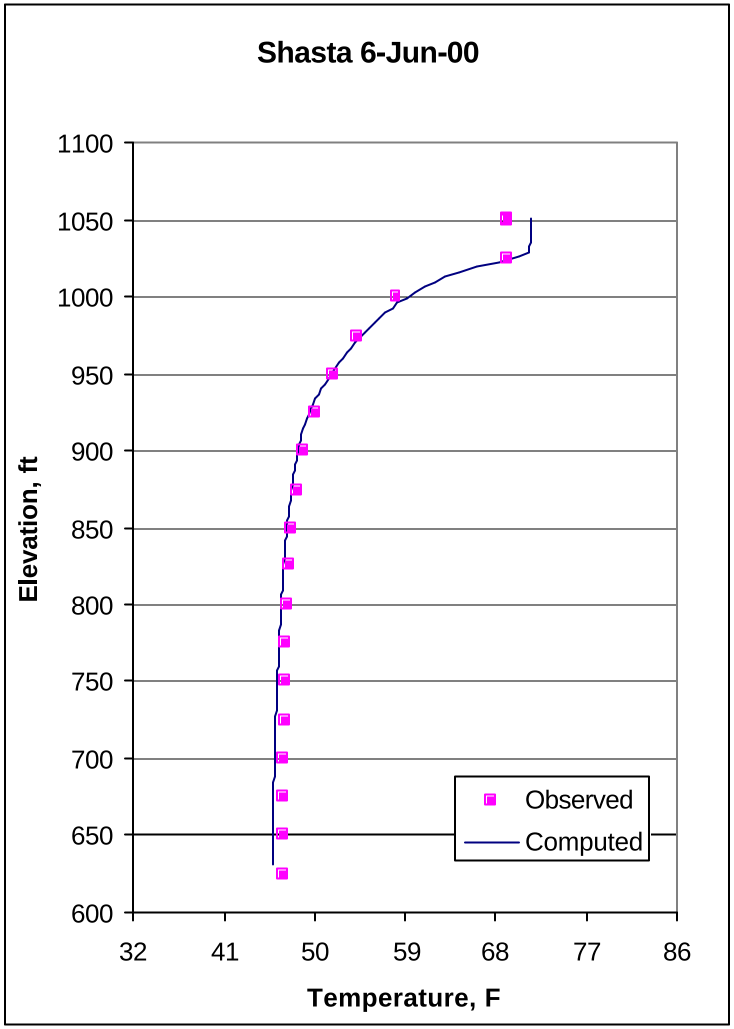


Figure 3-7 Computed and observed temperature profiles in Shasta Reservoir on June 6, 2000.

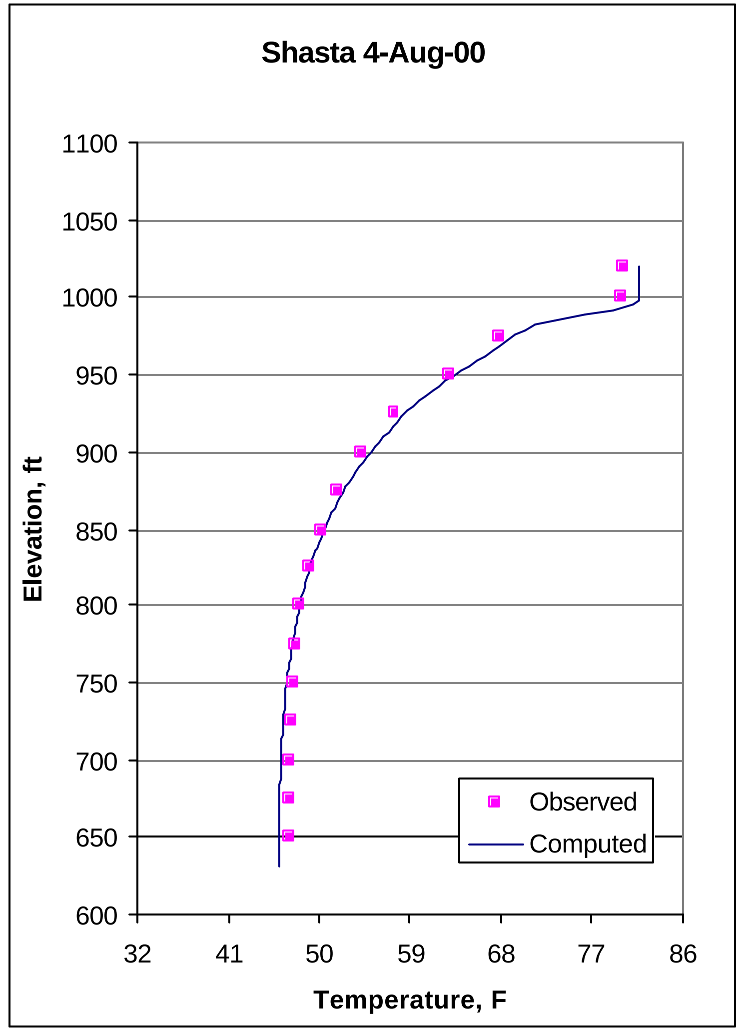


Figure 3-8 Computed and observed temperature profiles in Shasta Reservoir on August 4, 2000.

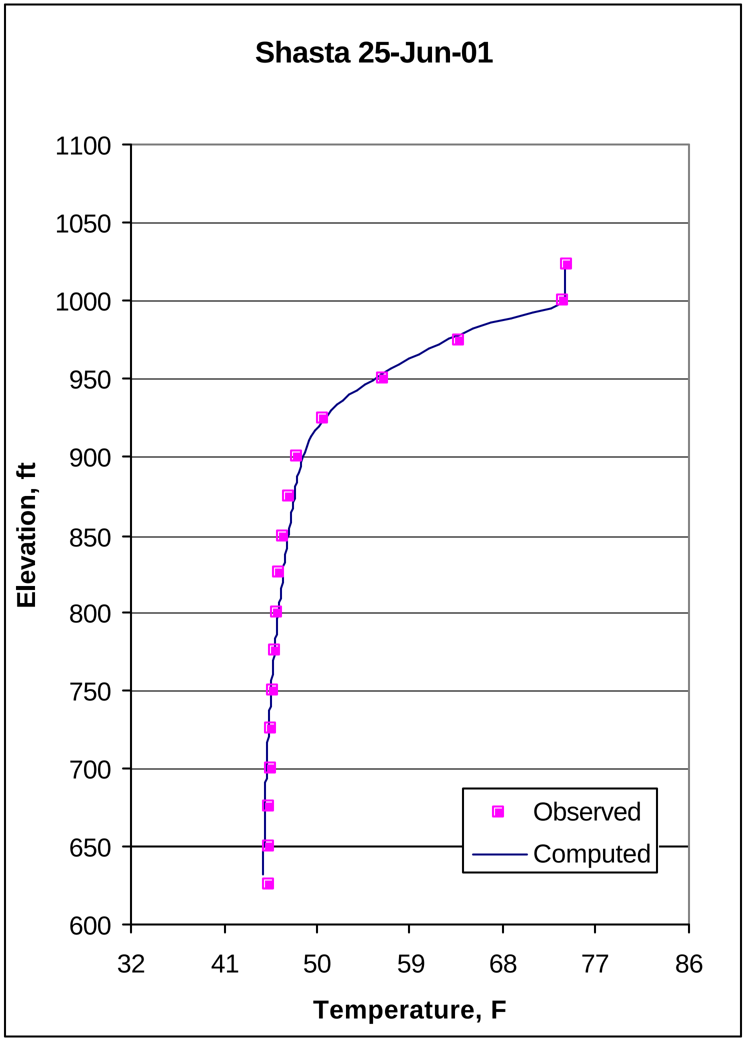


Figure 3-9 Computed and observed temperature profiles in Shasta Reservoir on June 25, 2001.

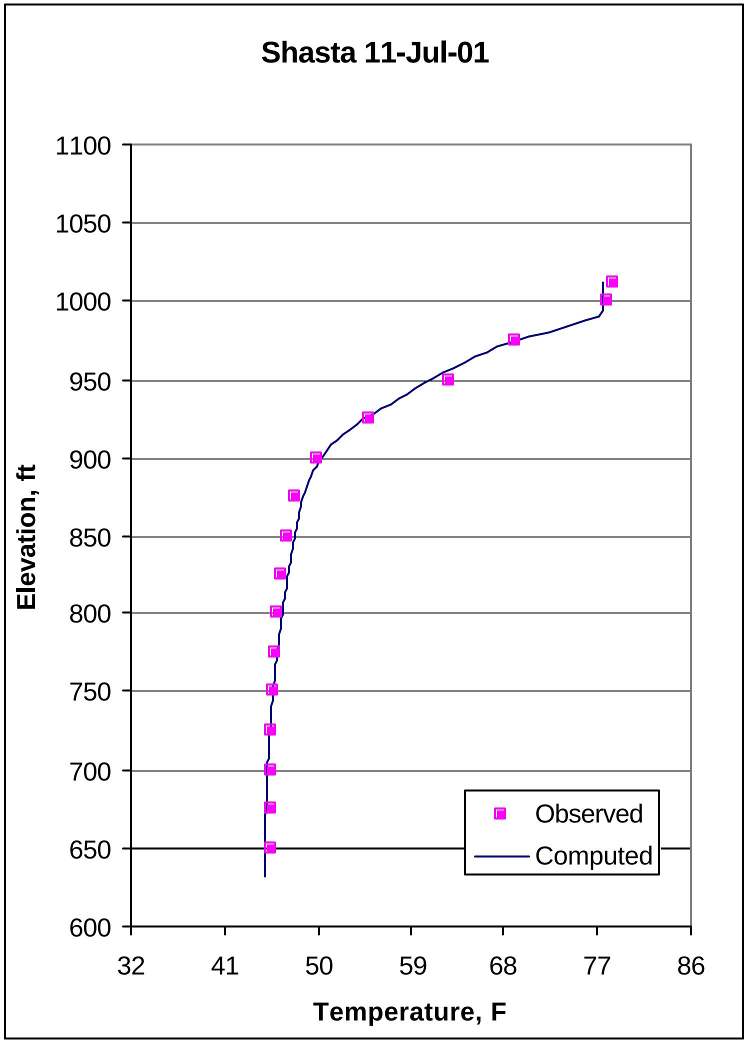


Figure 3-10 Computed and observed temperature profiles in Shasta Reservoir on July 11, 2001.

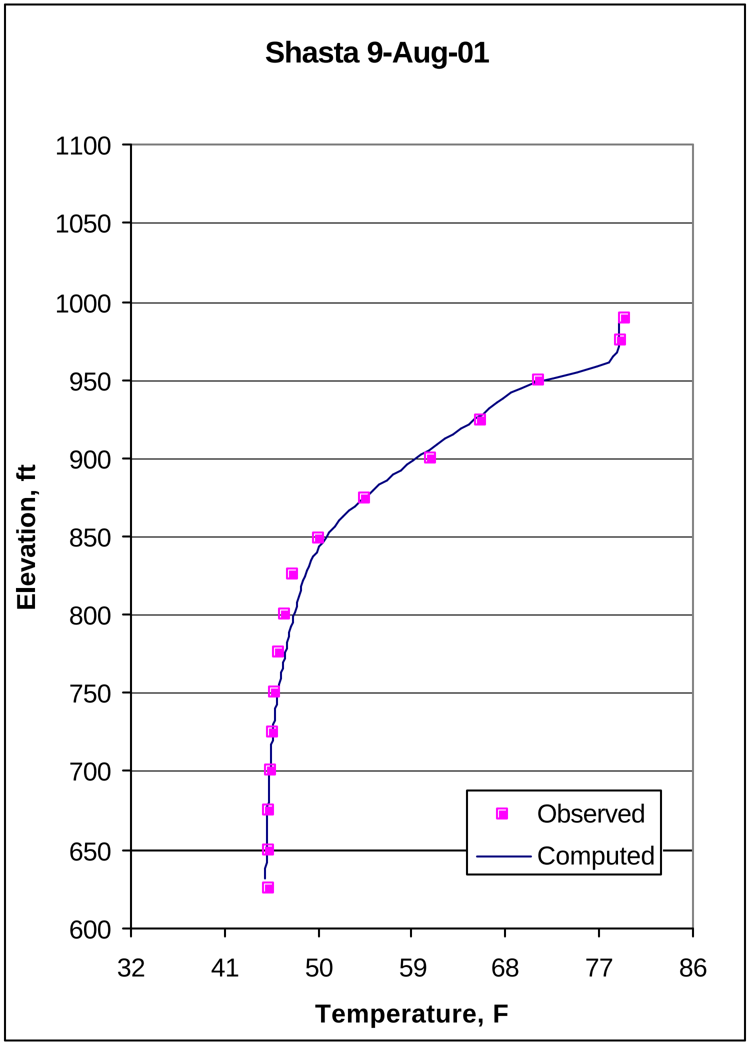


Figure 3-11 Computed and observed temperature profiles in Shasta Reservoir on August 9, 2001.

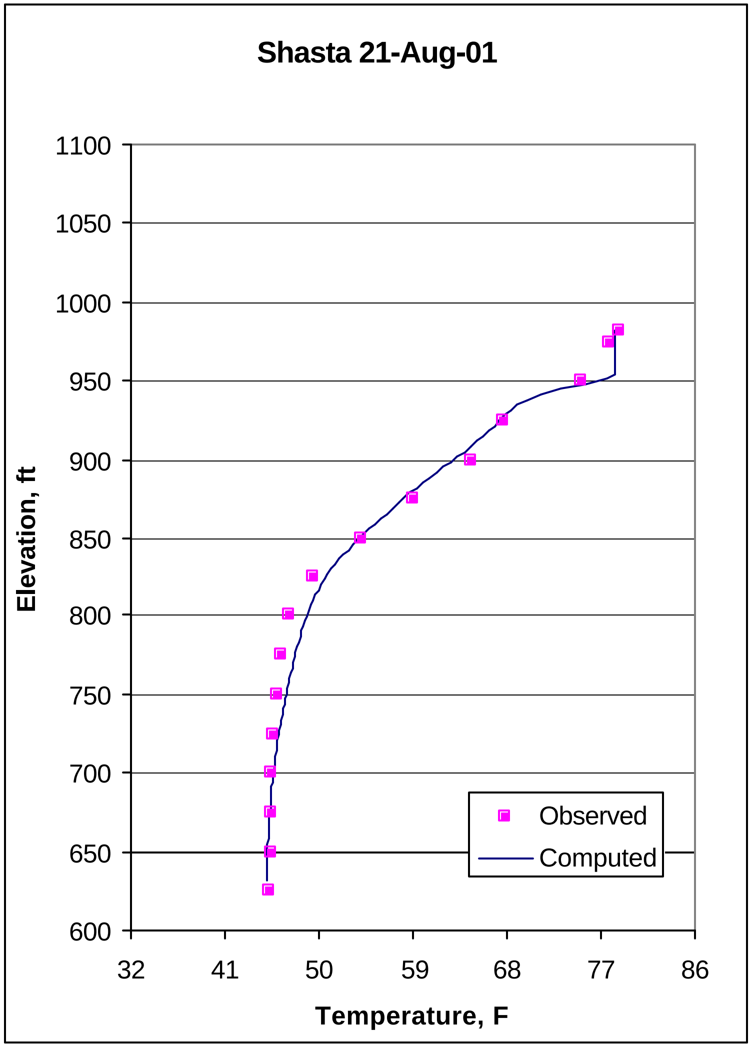


Figure 3-12 Computed and observed temperature profiles in Shasta Reservoir on August 21, 2001.

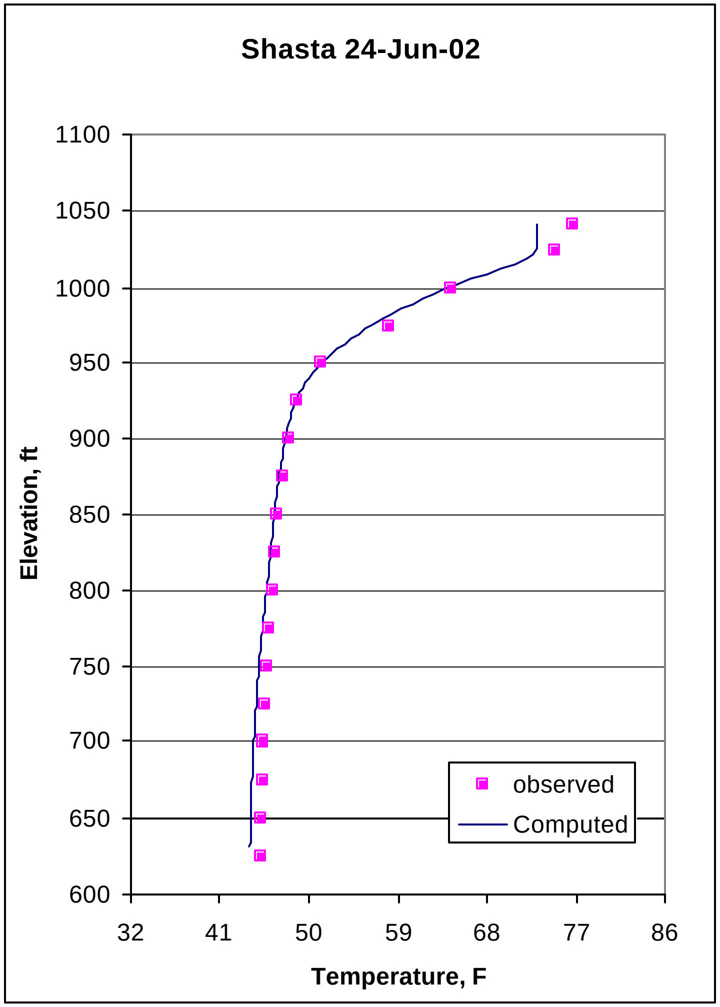


Figure 3-13 Computed and observed temperature profiles in Shasta Reservoir on June 24, 2002.

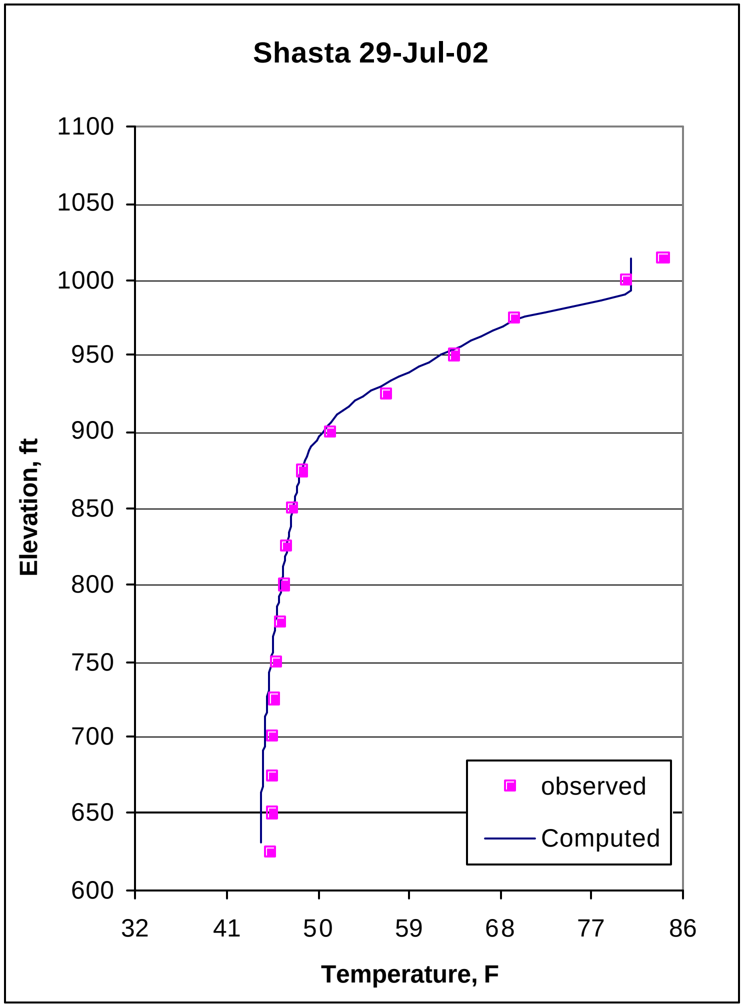


Figure 3-14 Computed and observed temperature profiles in Shasta Reservoir on July 29, 2002.

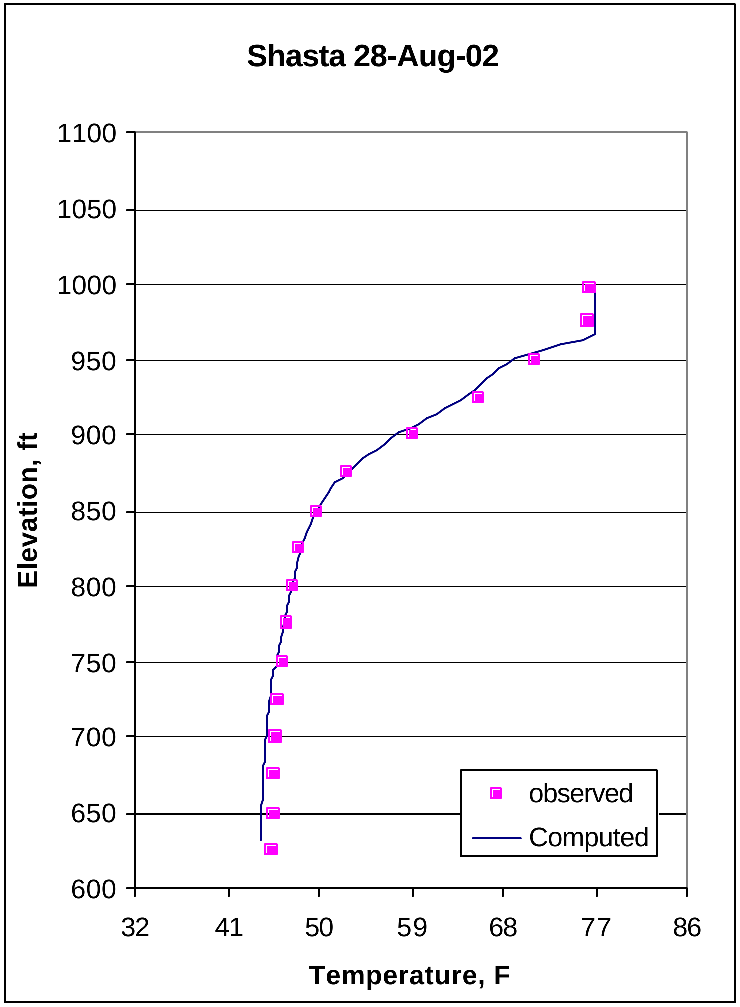


Figure 3-15 Computed and observed temperature profiles in Shasta Reservoir on August 28, 2002.

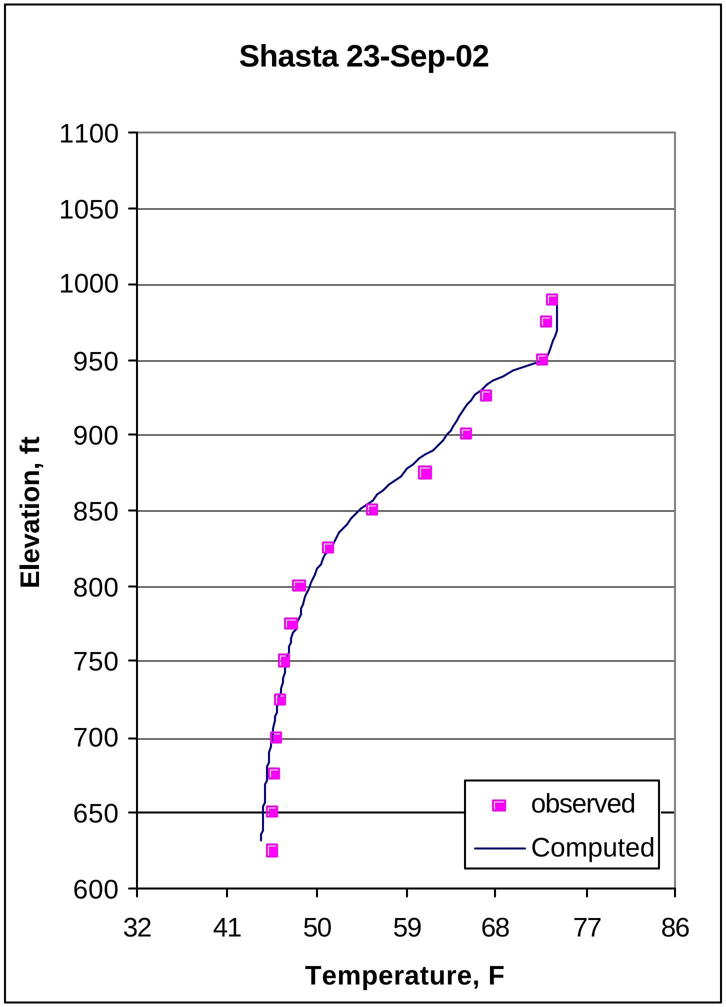


Figure 3-16 Computed and observed temperature profiles in Shasta Reservoir on September 23, 2002.

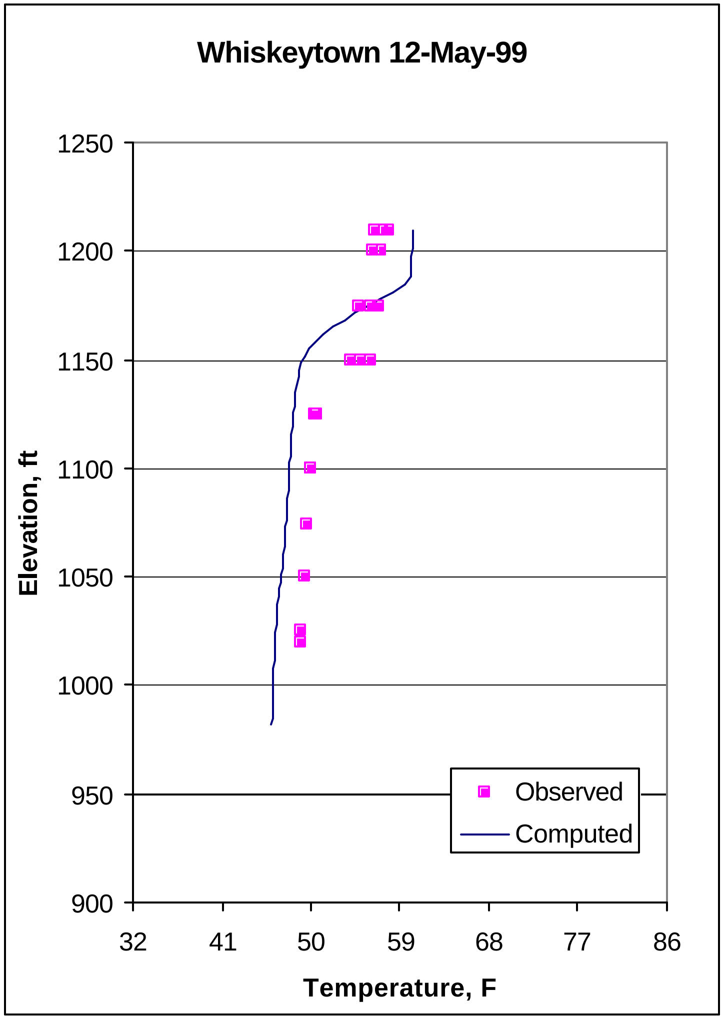


Figure 3-17 Computed and observed temperature profiles in Whiskeytown Reservoir on May 12, 1999.

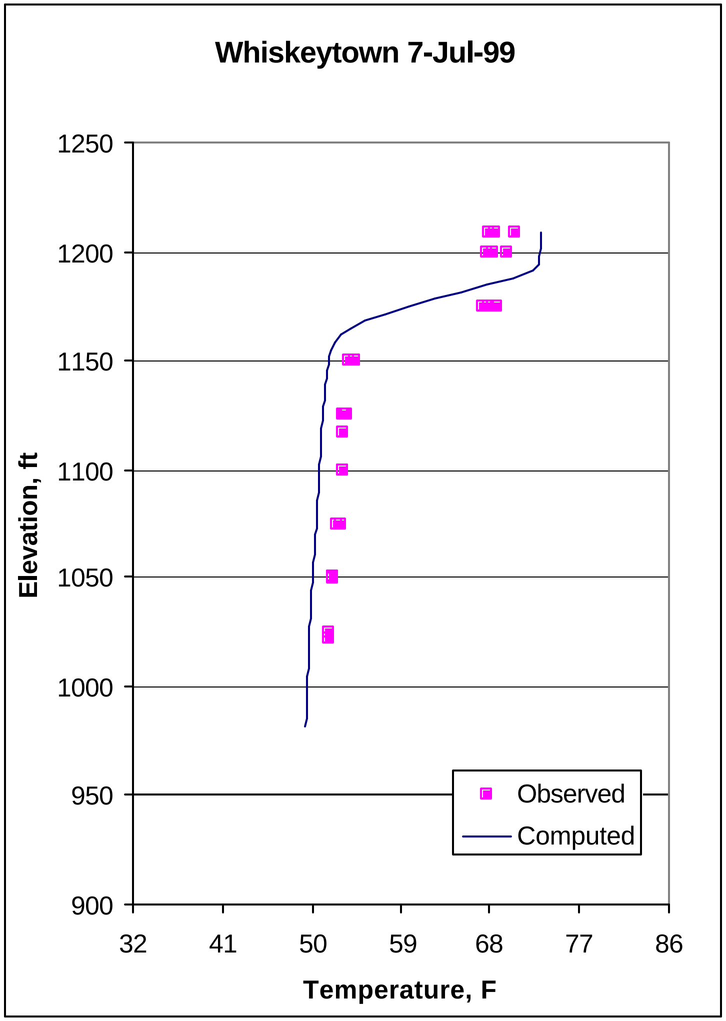


Figure 3-18 Computed and observed temperature profiles in Whiskeytown Reservoir on July 7, 1999.

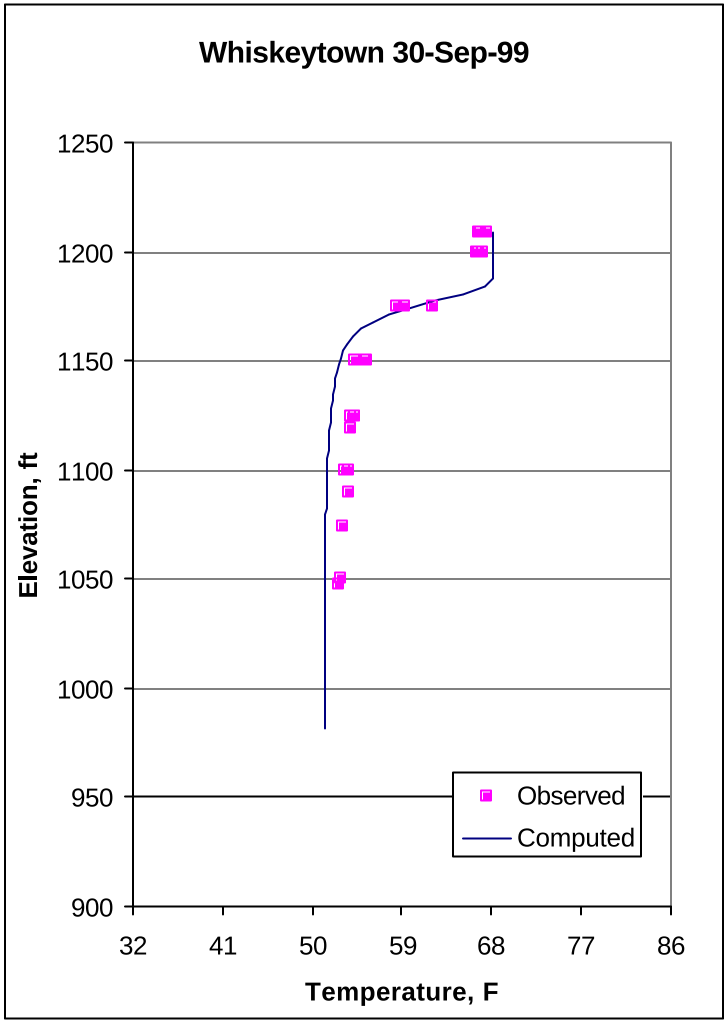


Figure 3-19 Computed and observed temperature profiles in Whiskeytown Reservoir on September 30, 1999.

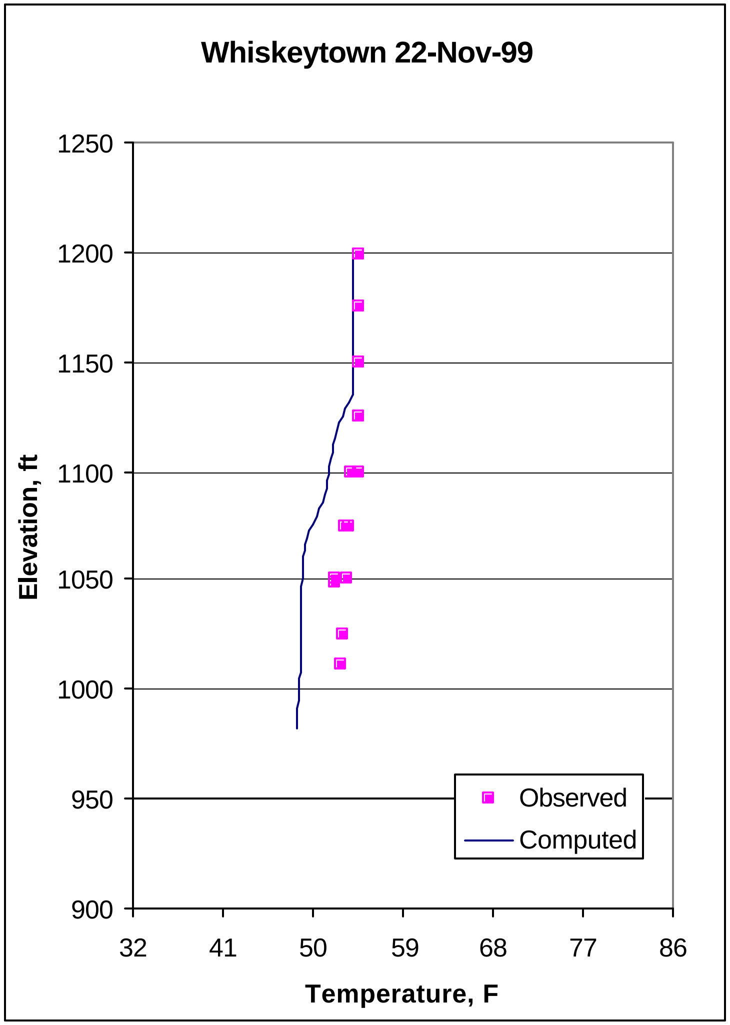


Figure 3-20 Computed and observed temperature profiles in Whiskeytown Reservoir on November 22, 1999.

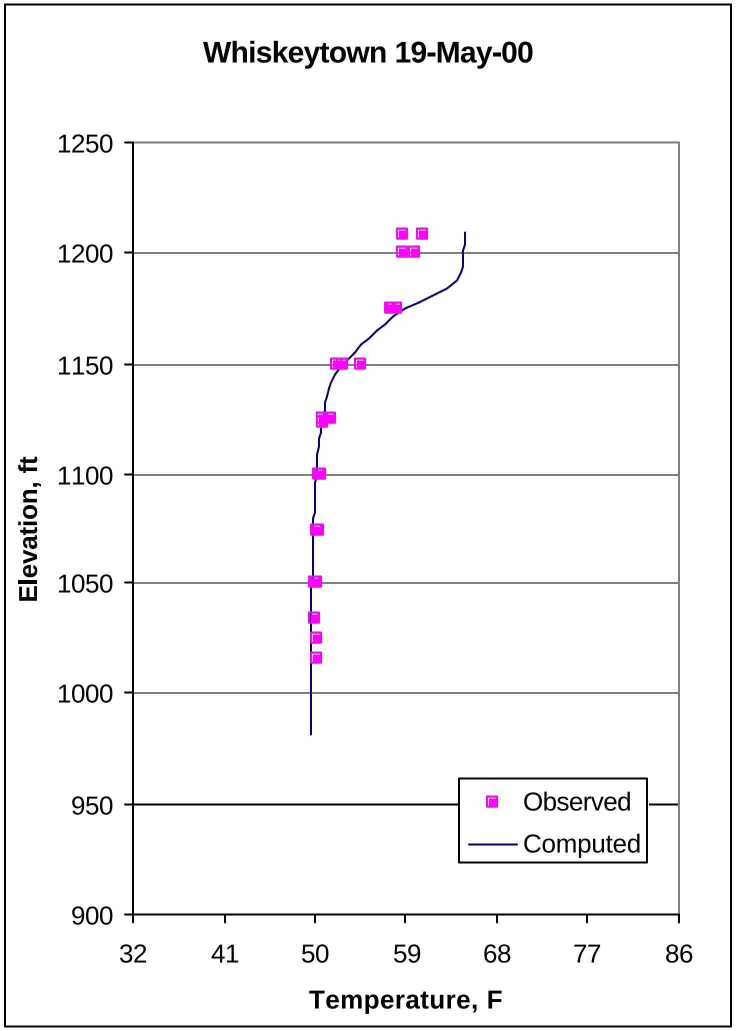


Figure 3-21 Computed and observed temperature profiles in Whiskeytown Reservoir on May 19, 2000.

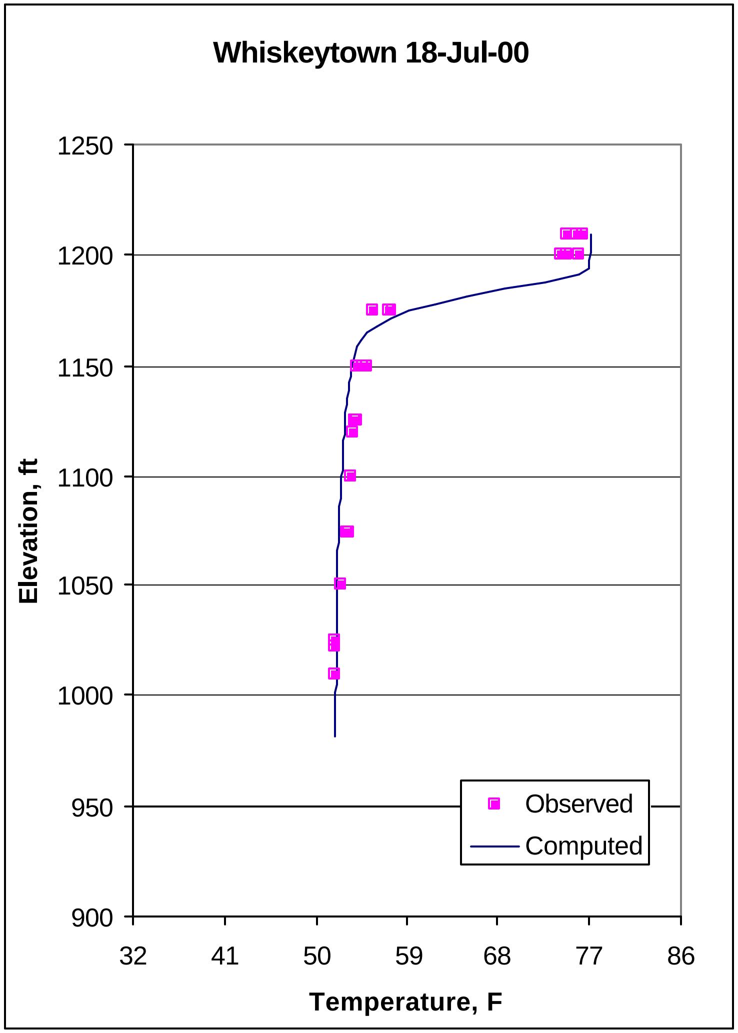


Figure 3-22 Computed and observed temperature profiles in Whiskeytown Reservoir on July 18, 2000.

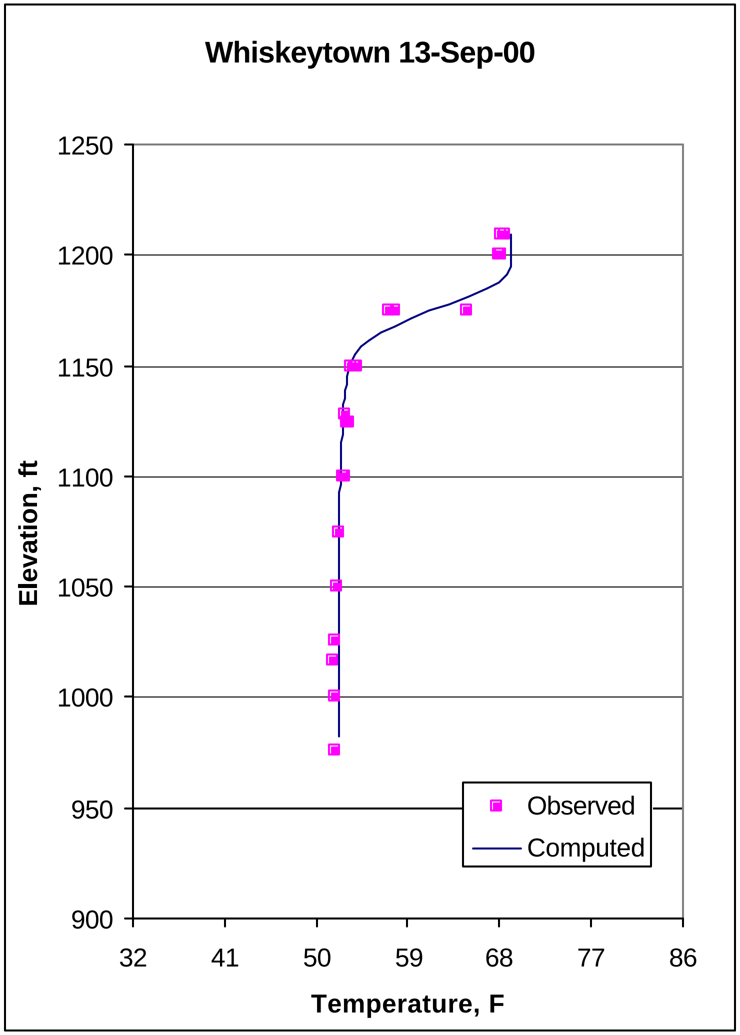


Figure 3-23 Computed and observed temperature profiles in Whiskeytown Reservoir on September 13, 2000.

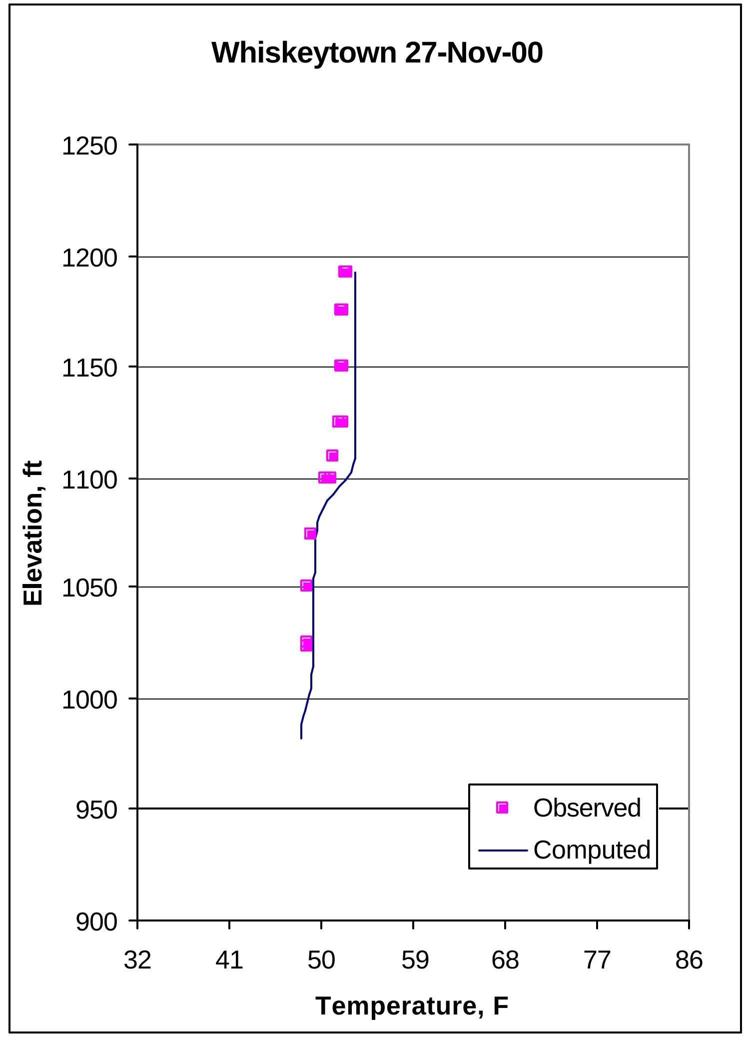


Figure 3-24 Computed and observed temperature profiles in Whiskeytown Reservoir on November 27, 2000.

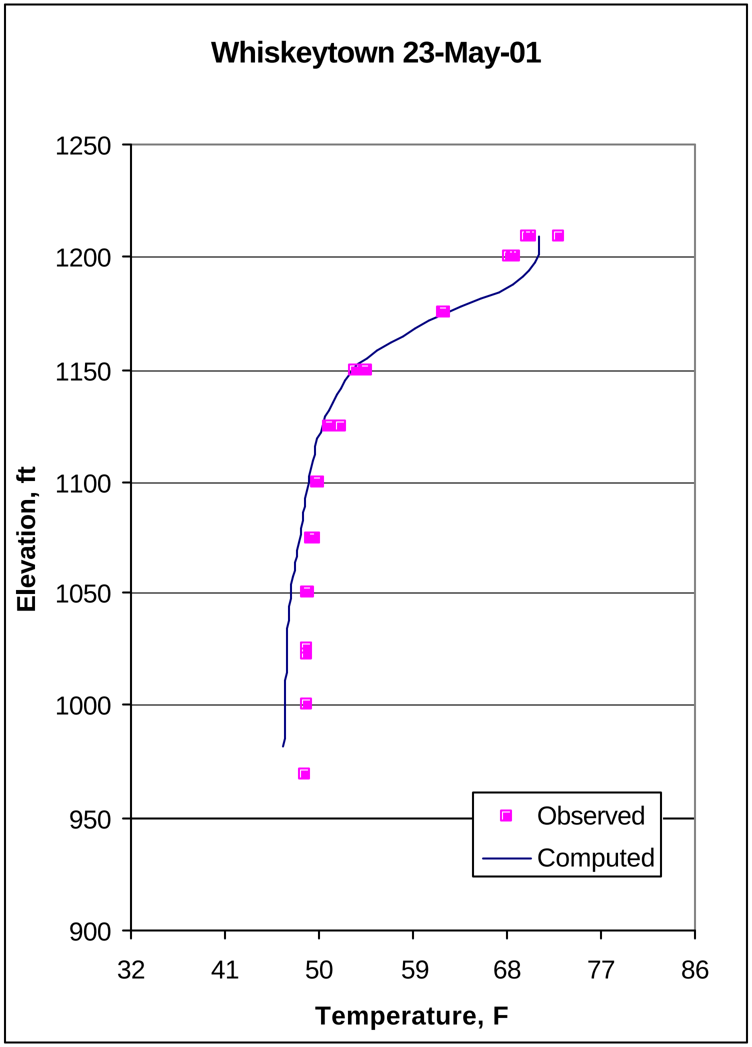


Figure 3-25 Computed and observed temperature profiles in Whiskeytown Reservoir on May 23, 2001.

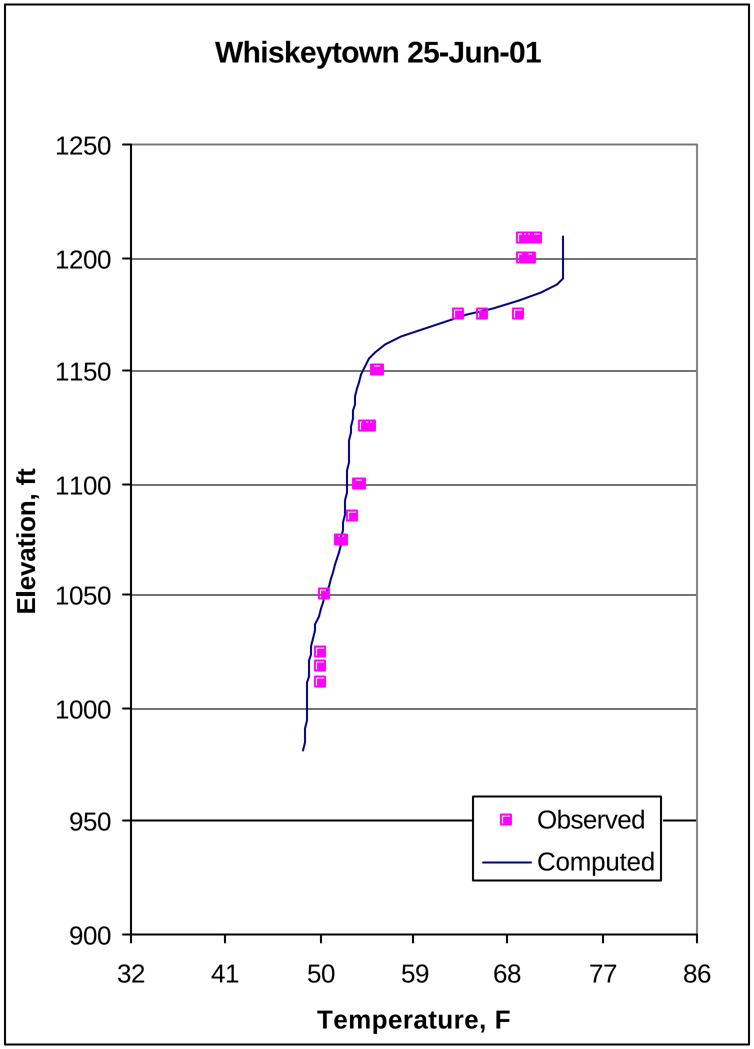


Figure 3-26 Computed and observed temperature profiles in Whiskeytown Reservoir on June 25, 2001.

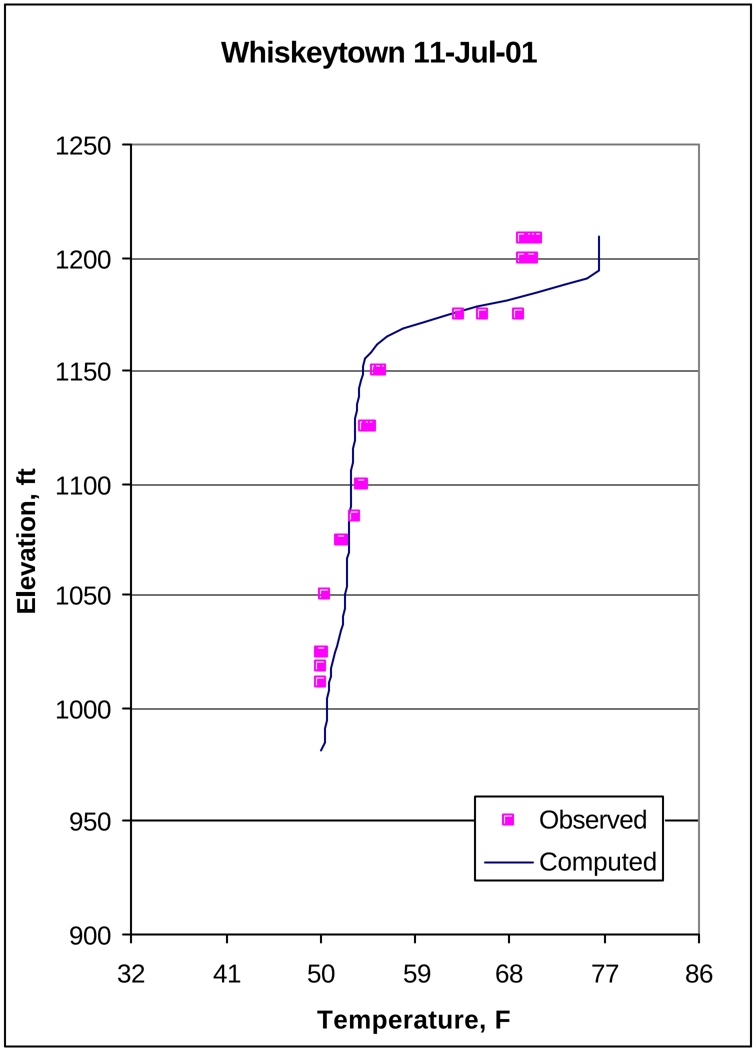


Figure 3-27 Computed and observed temperature profiles in Whiskeytown Reservoir on July 11, 2001.

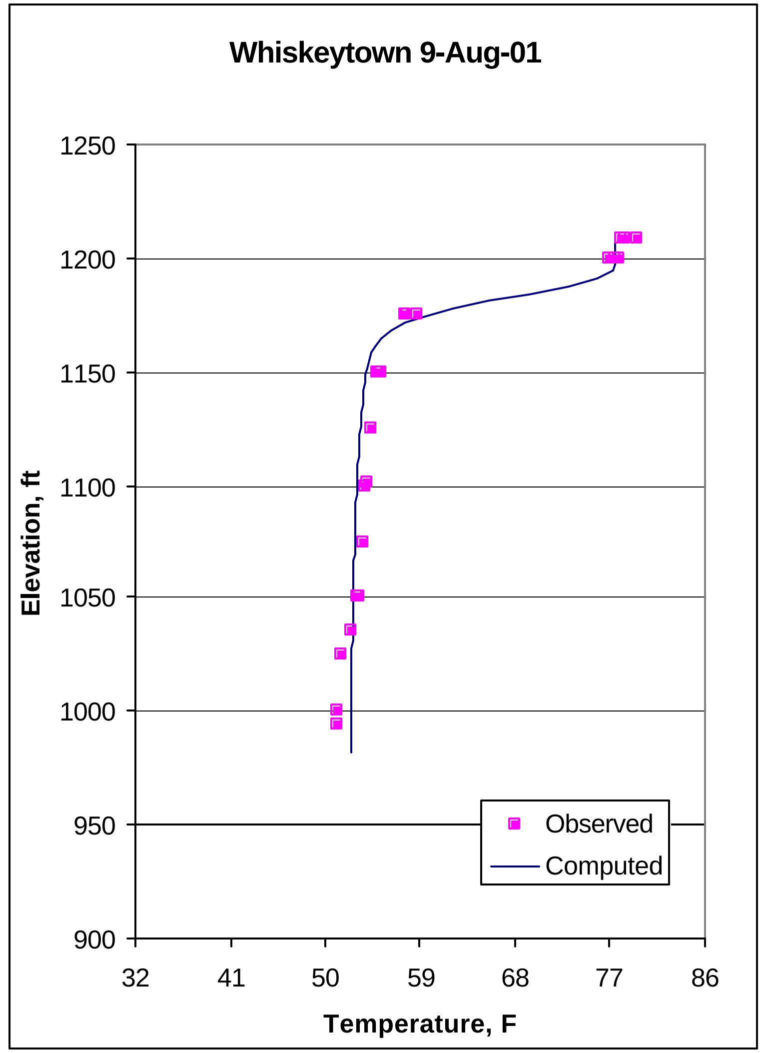


Figure 3-28 Computed and observed temperature profiles in Whiskeytown Reservoir on August 9, 2001.

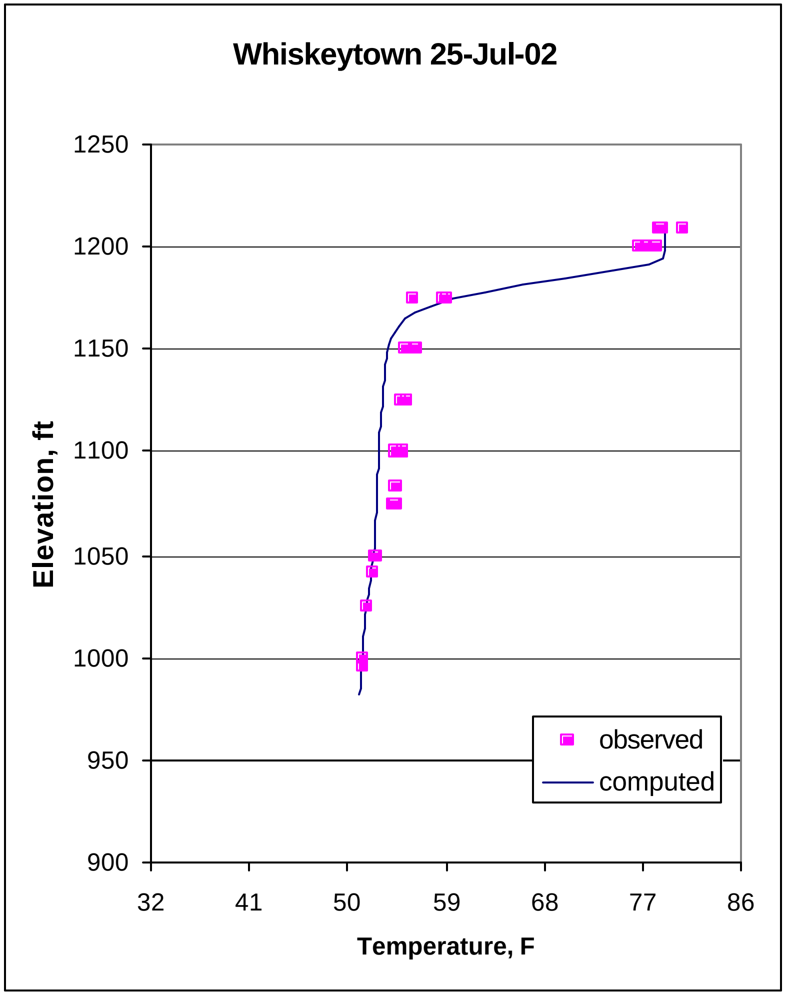


Figure 3-29 Computed and observed temperature profiles in Whiskeytown Reservoir on July 25, 2002.

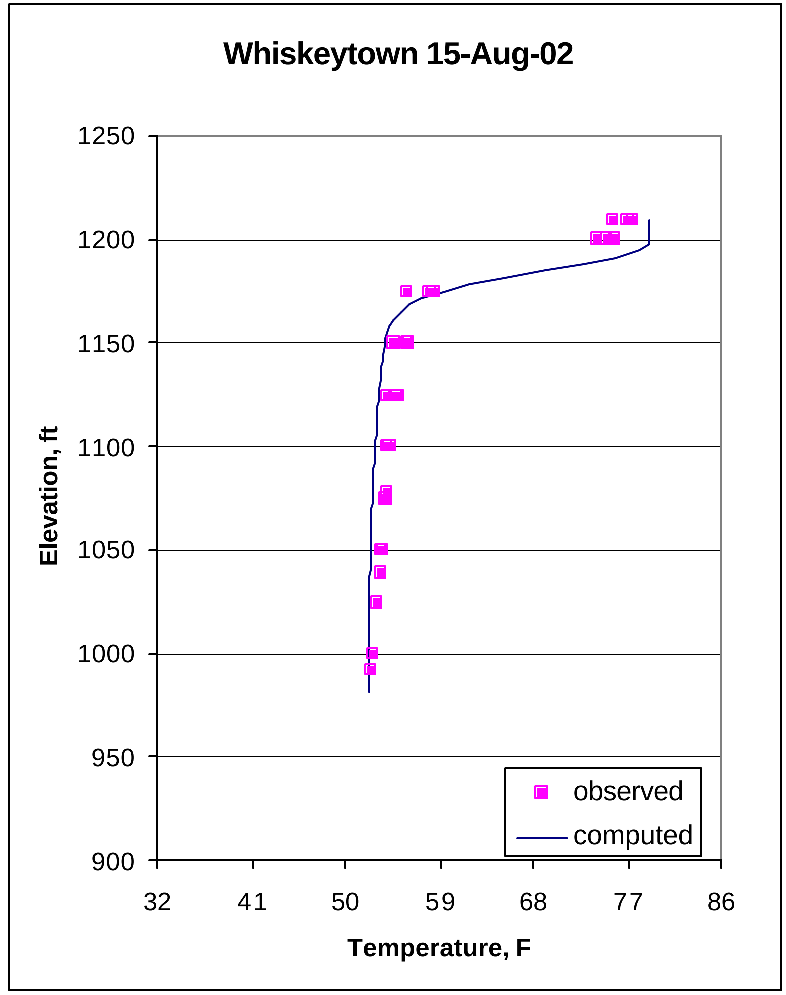


Figure 3-30 Computed and observed temperature profiles in Whiskeytown Reservoir on August 15, 2002.

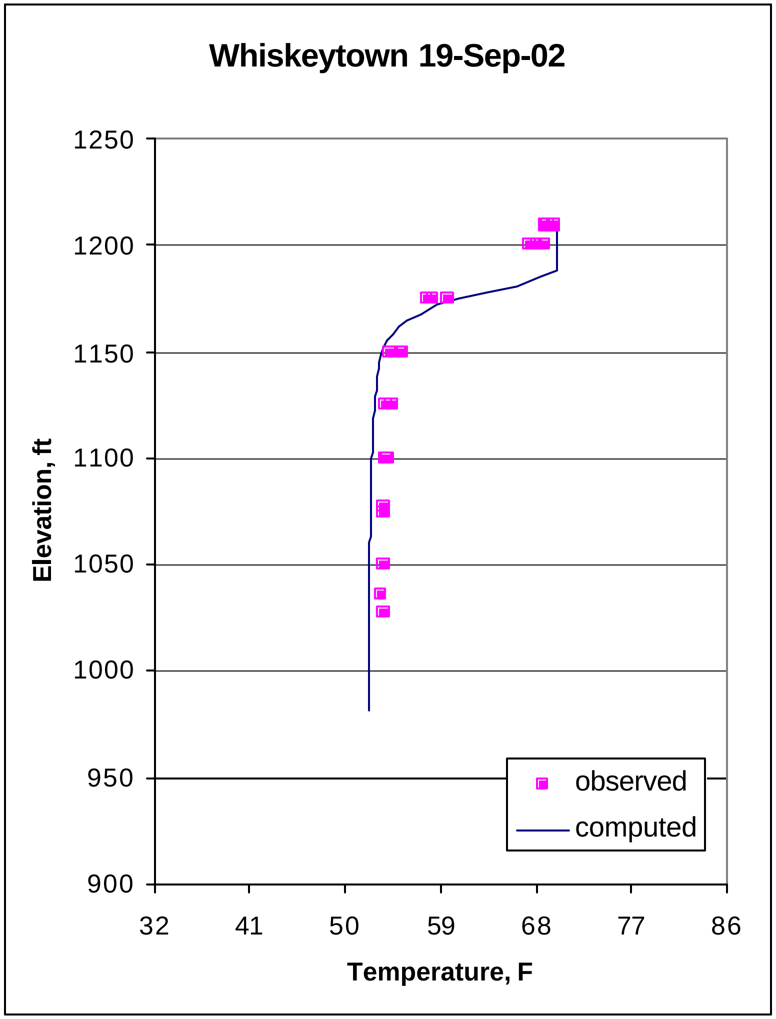


Figure 3-31 Computed and observed temperature profiles in Whiskeytown Reservoir on September 19, 2002.

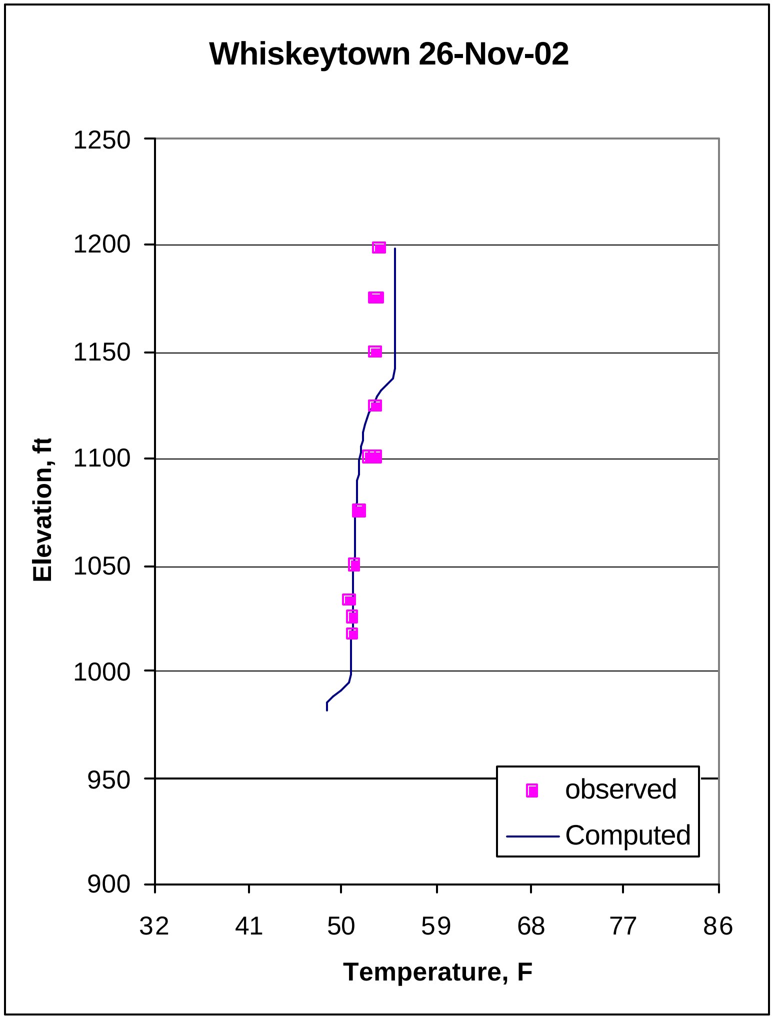


Figure 3-32 Computed and observed temperature profiles in Whiskeytown Reservoir on November 26, 2002.

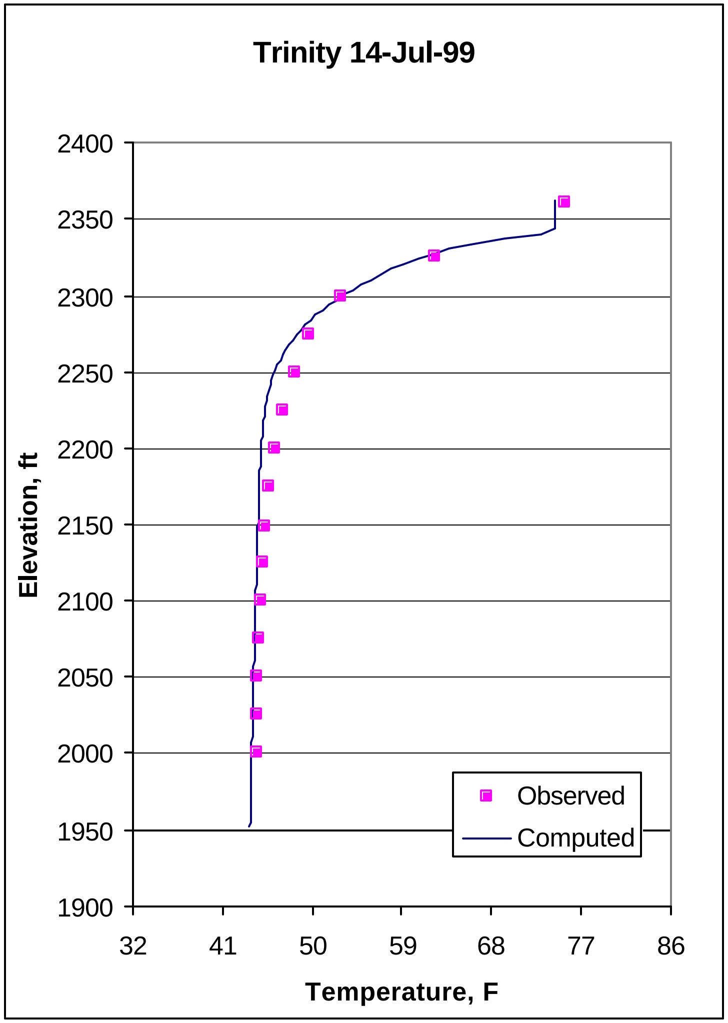


Figure 3-33 Computed and observed temperature profiles in Trinity Reservoir on July 14, 1999.

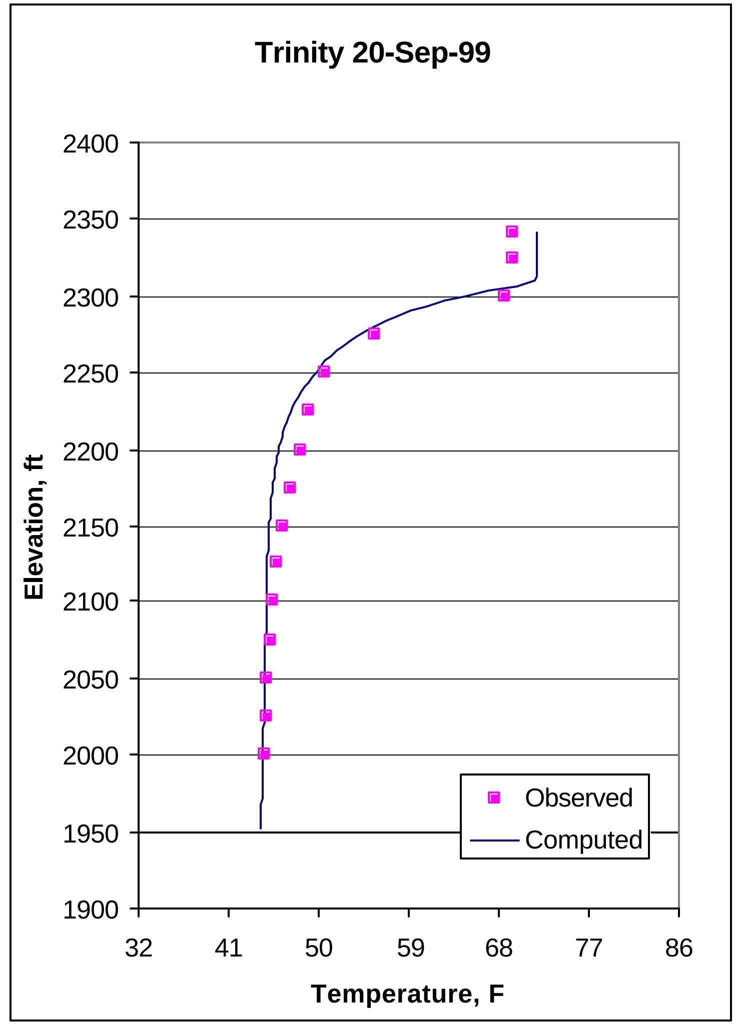


Figure 3-34 Computed and observed temperature profiles in Trinity Reservoir on September 20, 1999.

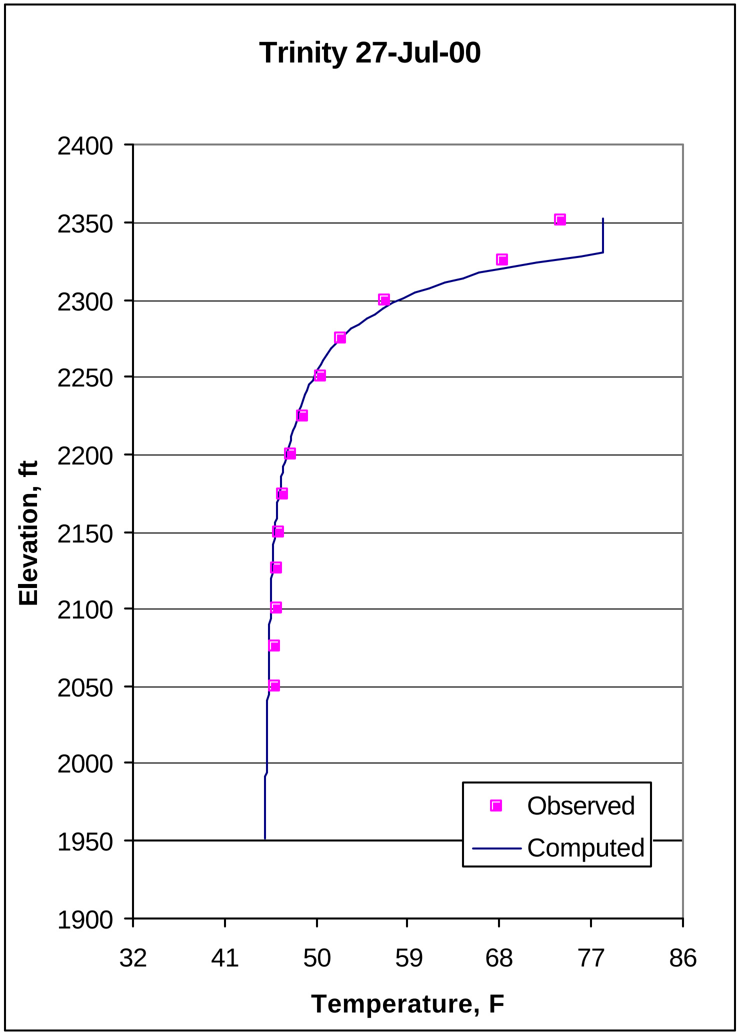


Figure 3-35 Computed and observed temperature profiles in Trinity Reservoir on July 27, 2000.

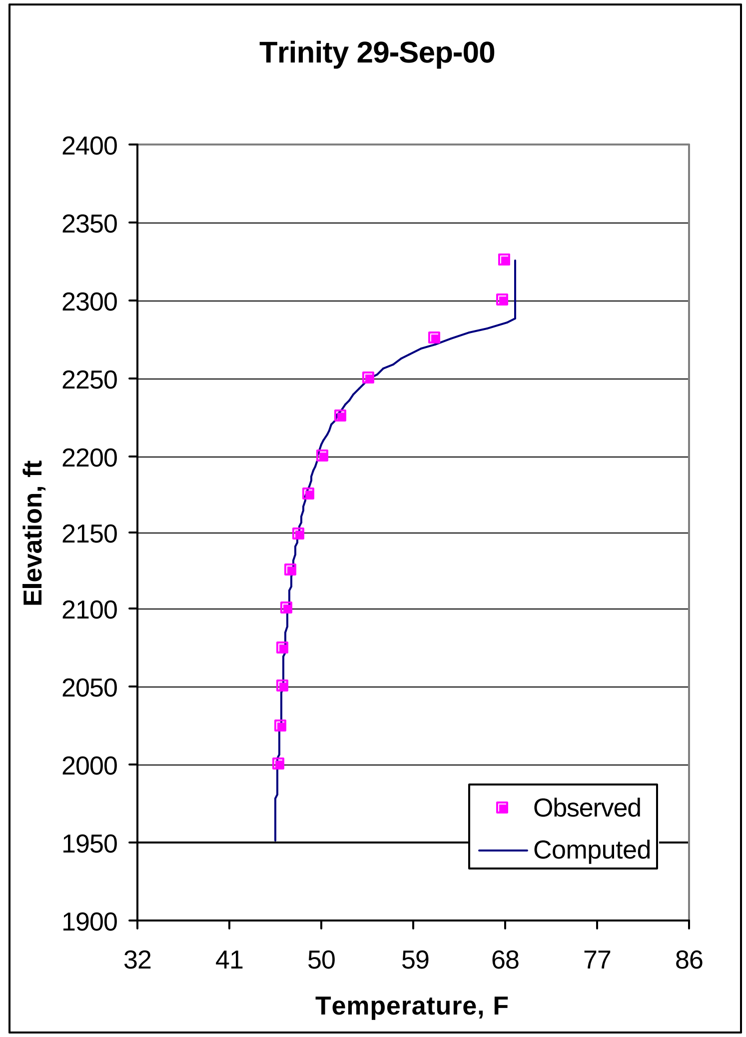
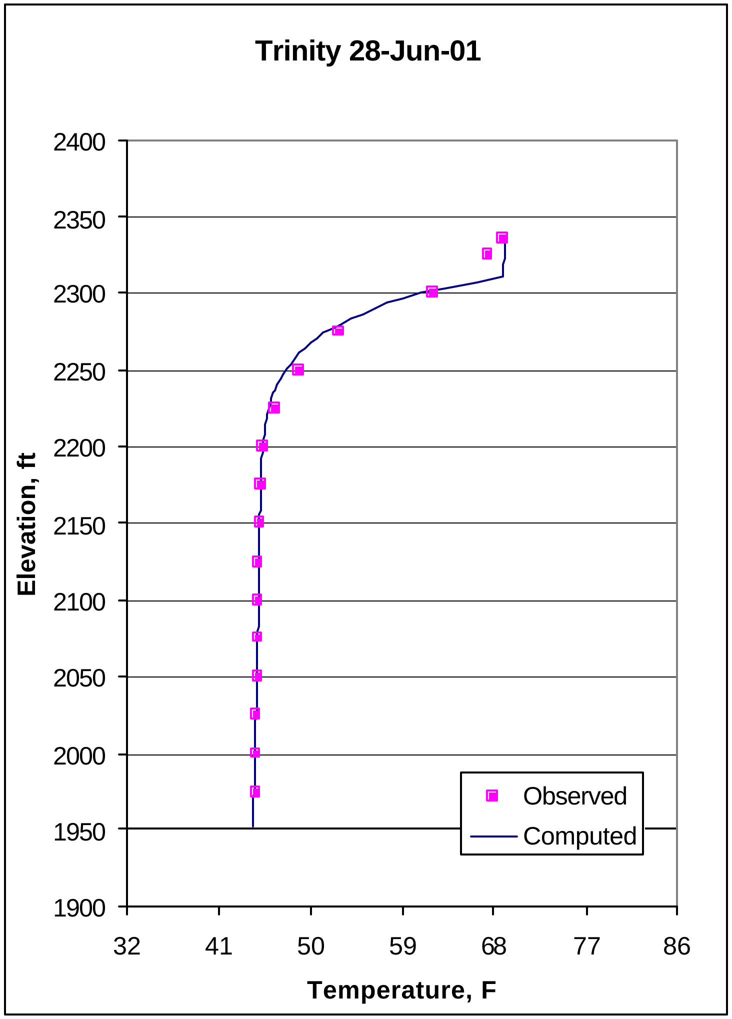


Figure 3-36 Computed and observed temperature profiles in Trinity Reservoir on September 29, 2000.



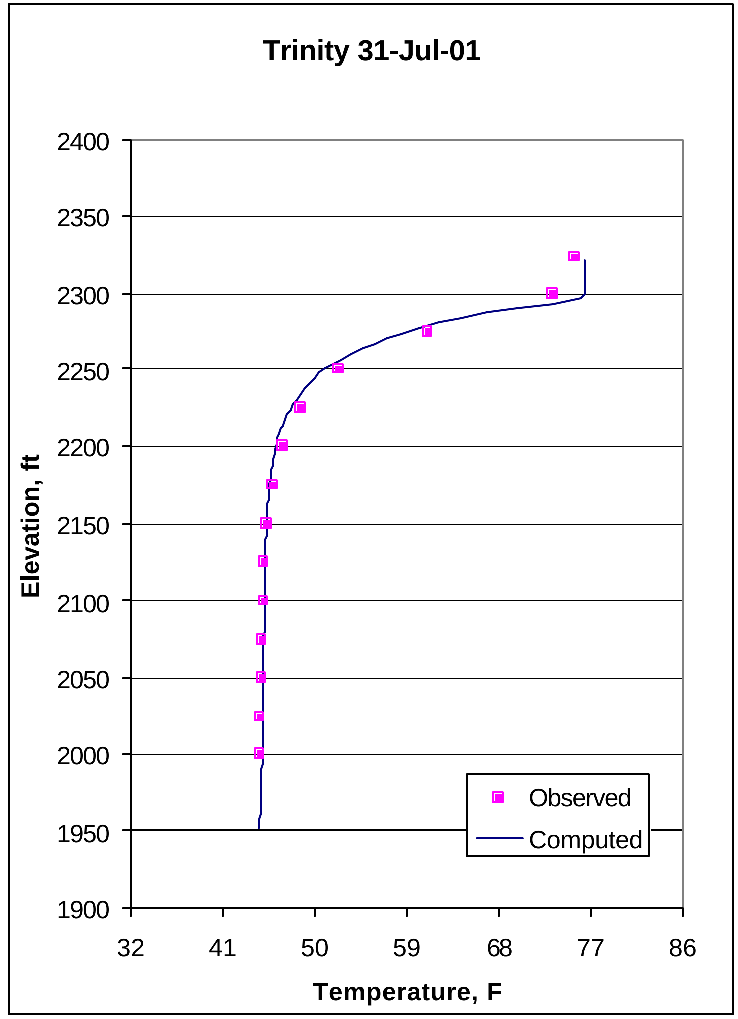


Figure 3-37 Computed and observed temperature profiles in Trinity Reservoir on June 28, 2001.

Figure 3-38 Computed and observed temperature profiles in Trinity Reservoir on July 31, 2001.

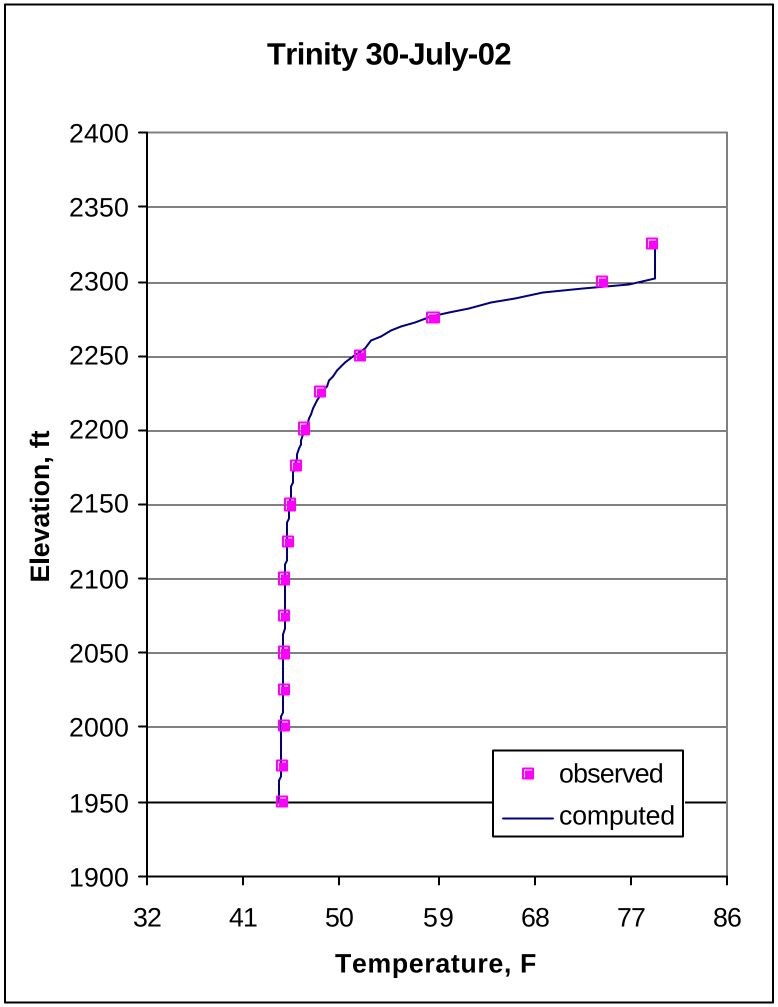


Figure 3-39 Computed and observed temperature profiles in Trinity Reservoir on July 30, 2002.

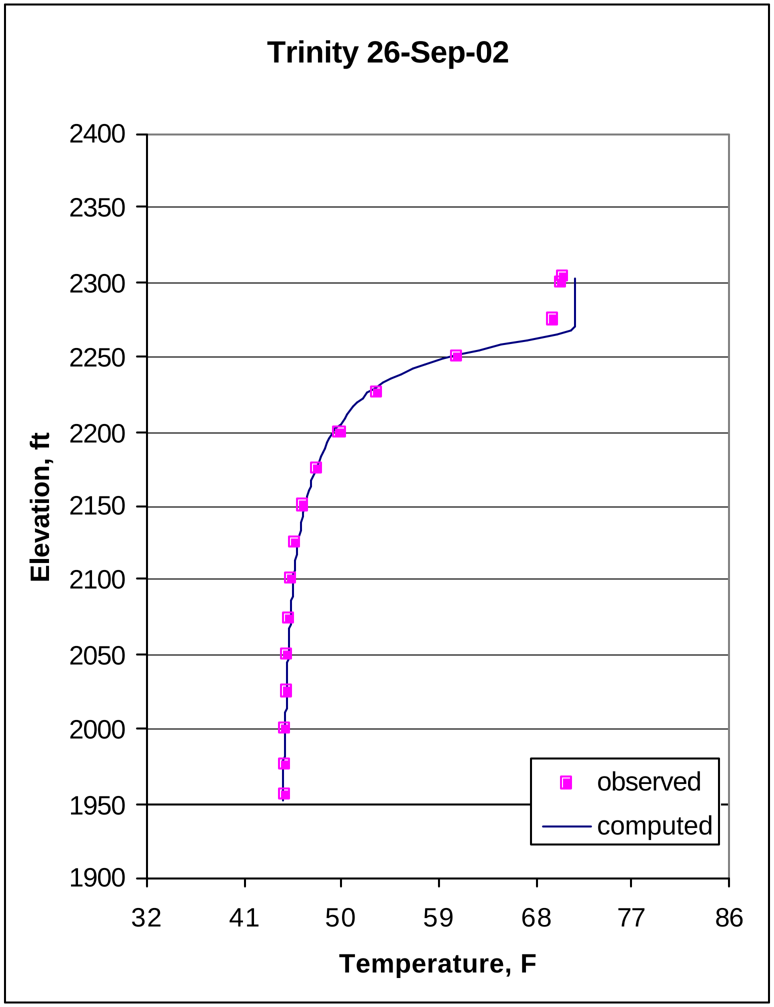


Figure 3-40 Computed and observed temperature profiles in Trinity Reservoir on September 26, 2002.

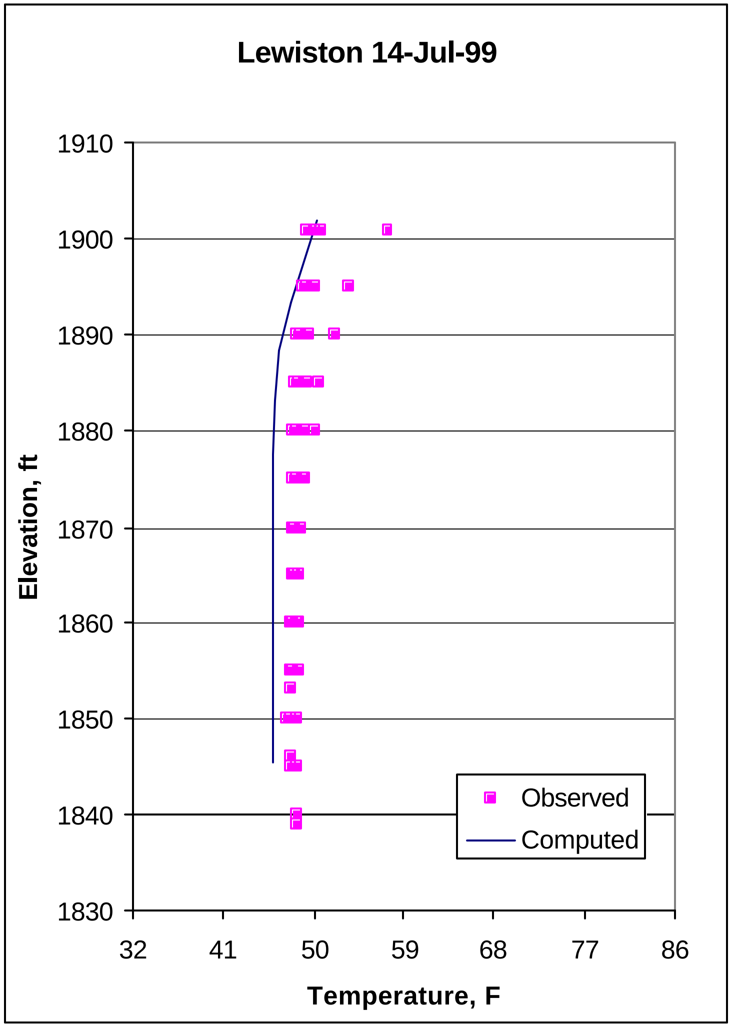


Figure 3-41 Computed and observed temperature profiles in Lewiston Reservoir on July 14, 1999.

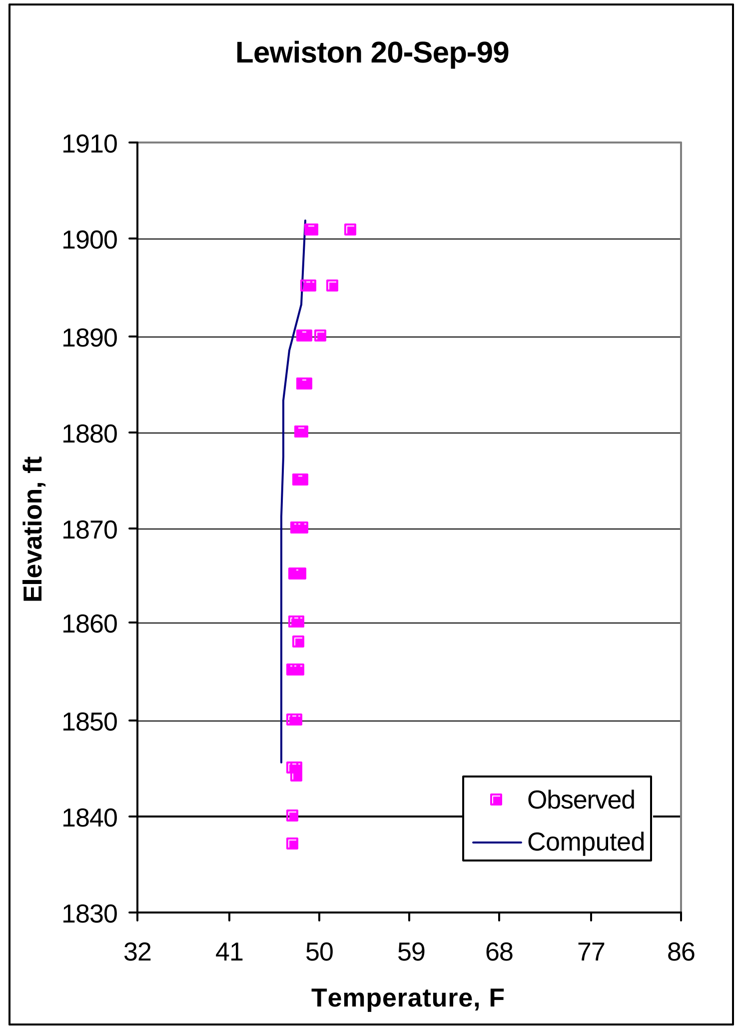


Figure 3-42 Computed and observed temperature profiles in Lewiston Reservoir on September 20, 1999.

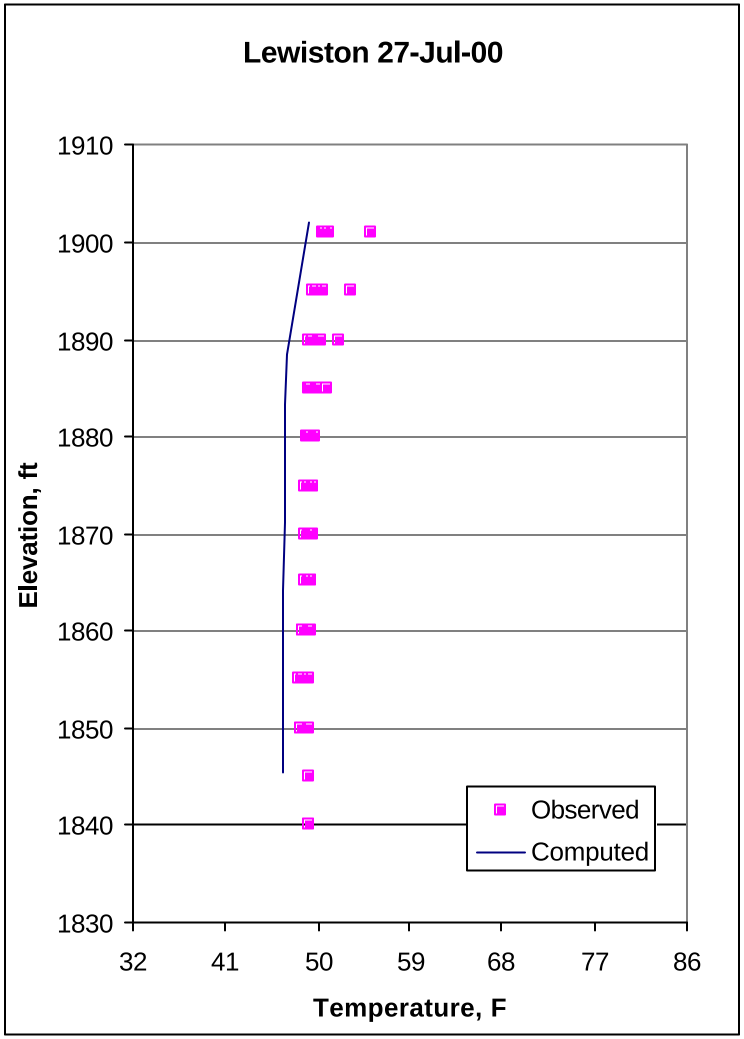


Figure 3-43 Computed and observed temperature profiles in Lewiston Reservoir on July 27, 2000.

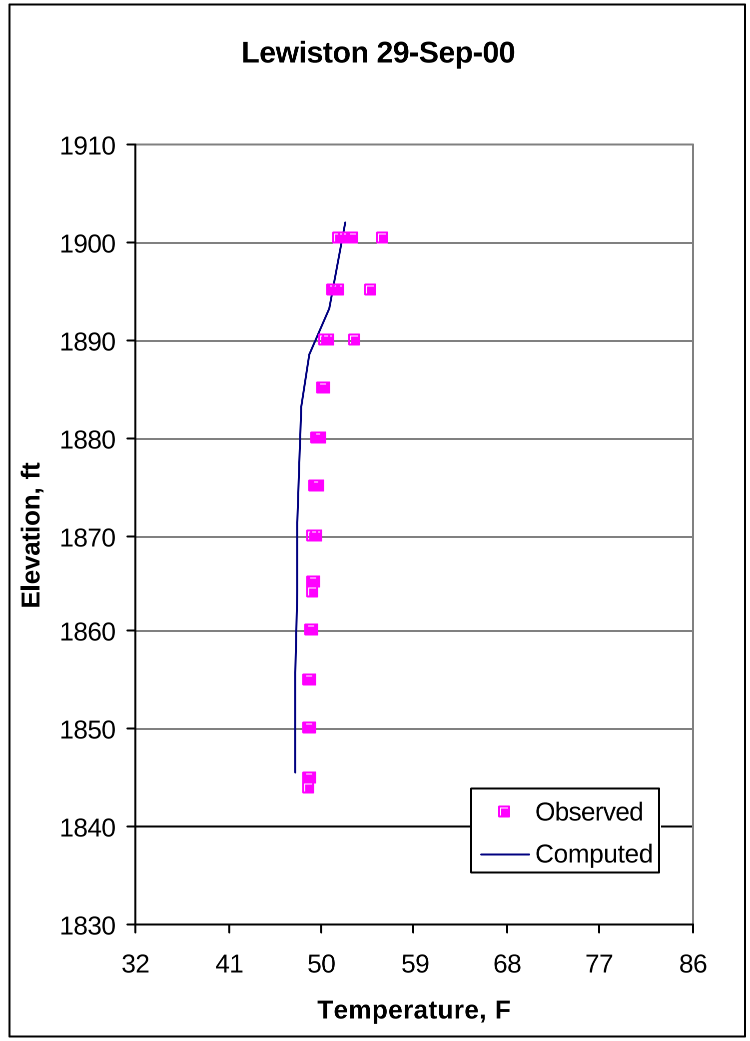


Figure 3-44 Computed and observed temperature profiles in Lewiston Reservoir on September 29, 2000.

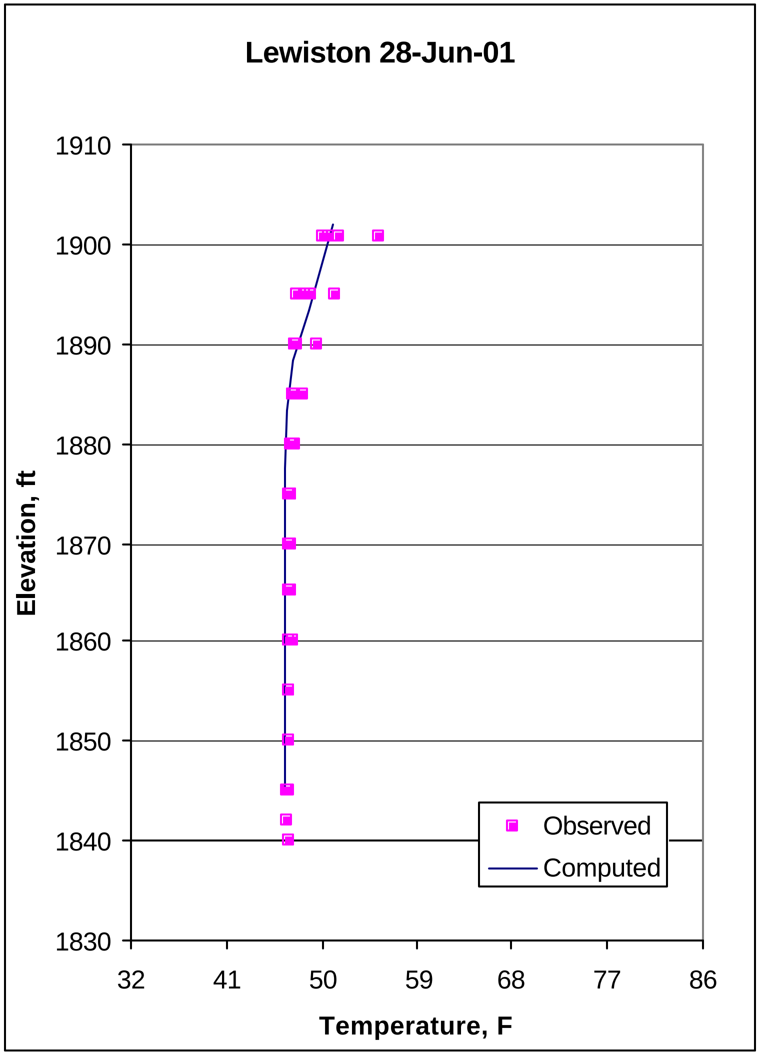


Figure 3-45 Computed and observed temperature profiles in Lewiston Reservoir on June 28, 2001.

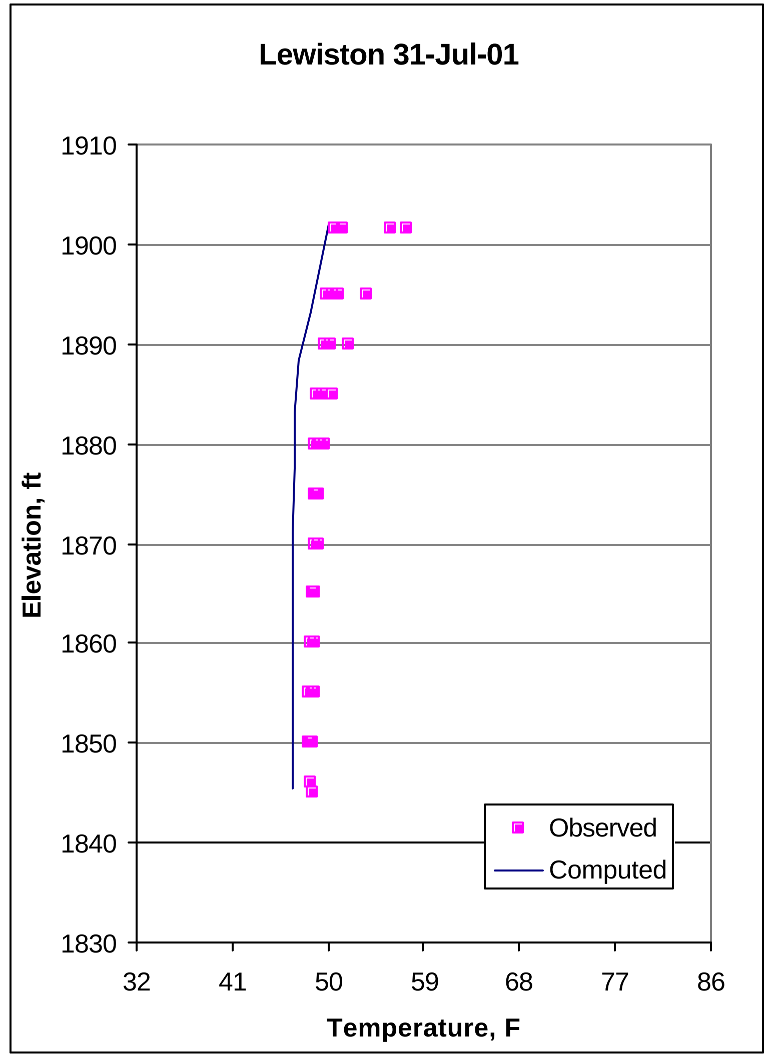


Figure 3-46 Computed and observed temperature profiles in Lewiston Reservoir on July 31, 2001.

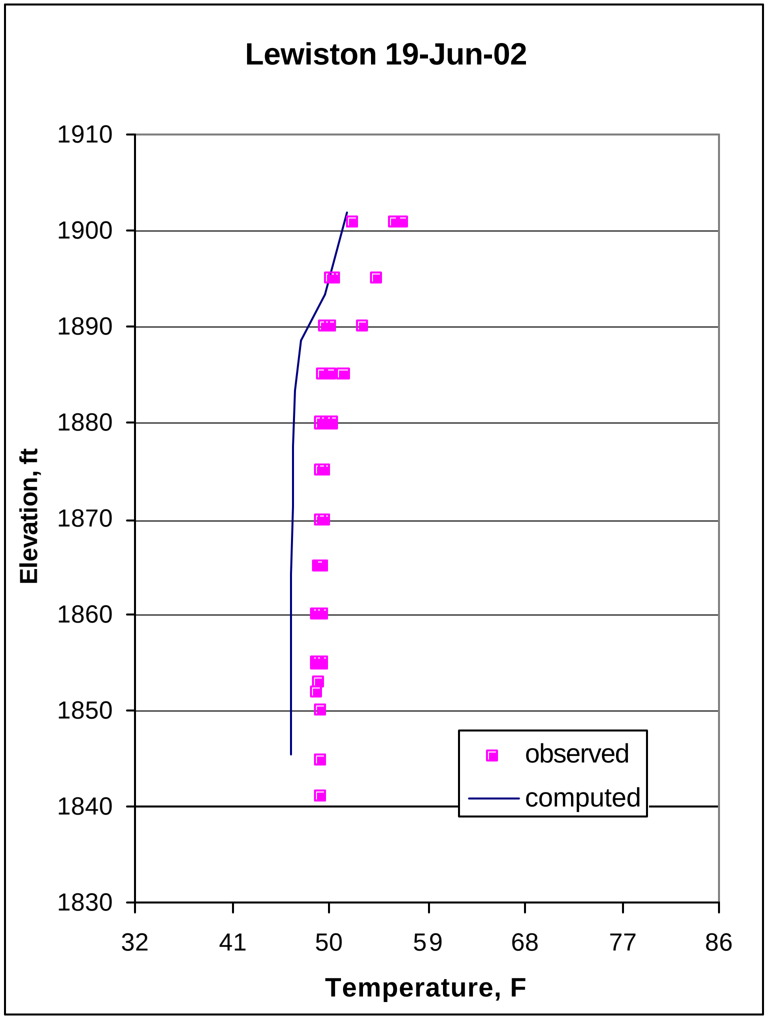


Figure 3-47 Computed and observed temperature profiles in Lewiston Reservoir on June 19, 2002.

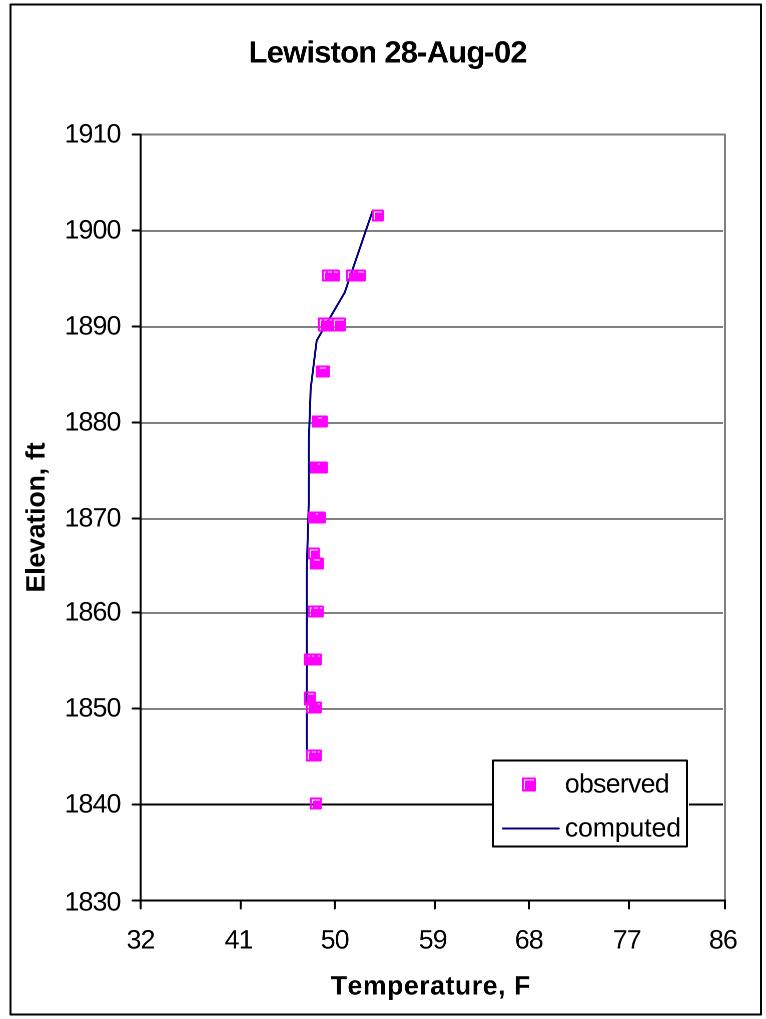


Figure 3-48 Computed and observed temperature profiles in Lewiston Reservoir on August 28, 2002.

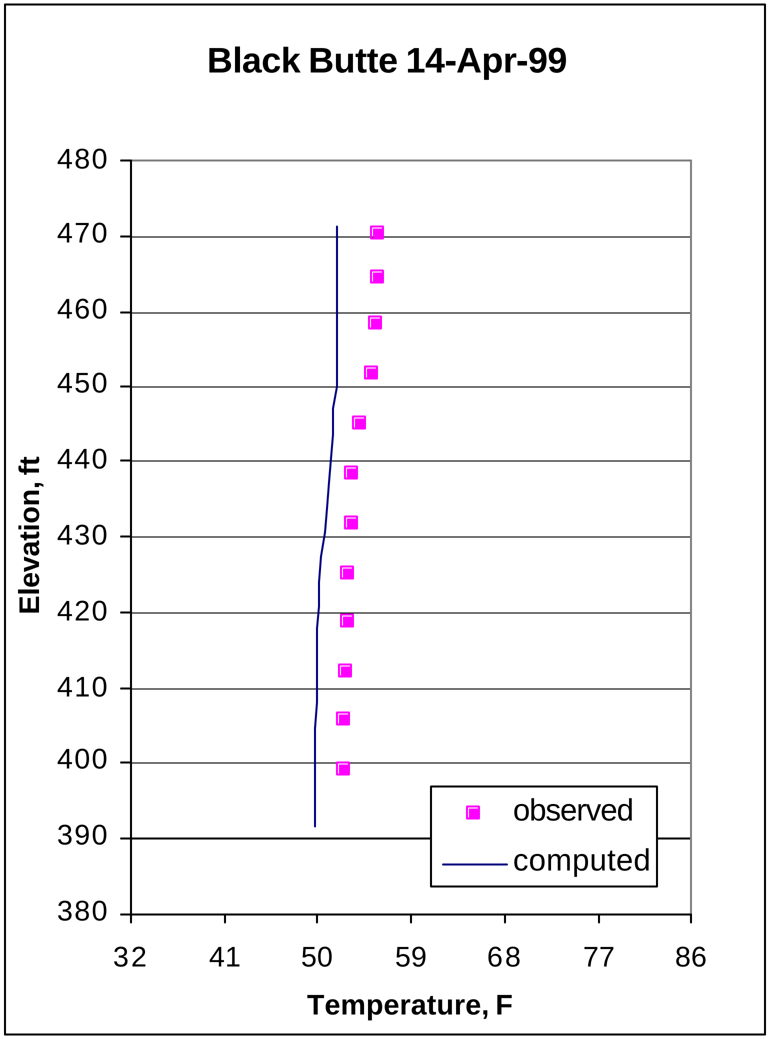


Figure 3-49 Computed and observed temperature profiles in Black Butte Reservoir on April 14, 1999.

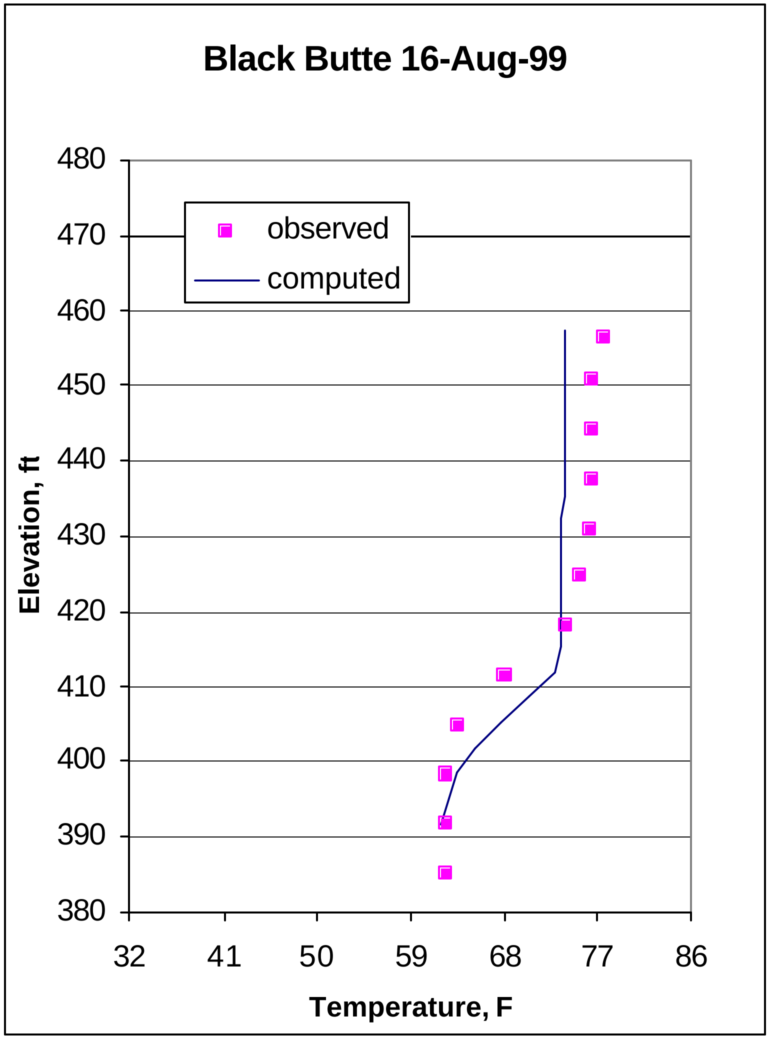


Figure 3-50 Computed and observed temperature profiles in Black Butte Reservoir on August 16, 1999.

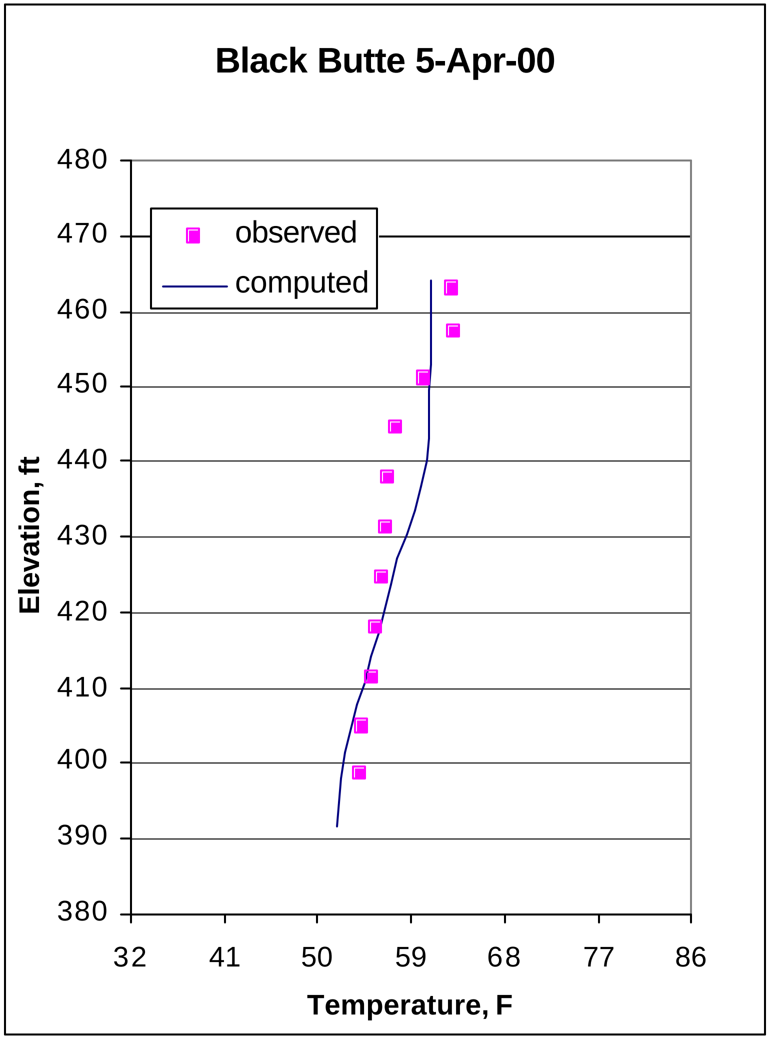


Figure 3-51 Computed and observed temperature profiles in Black Butte Reservoir on April 5, 2000.

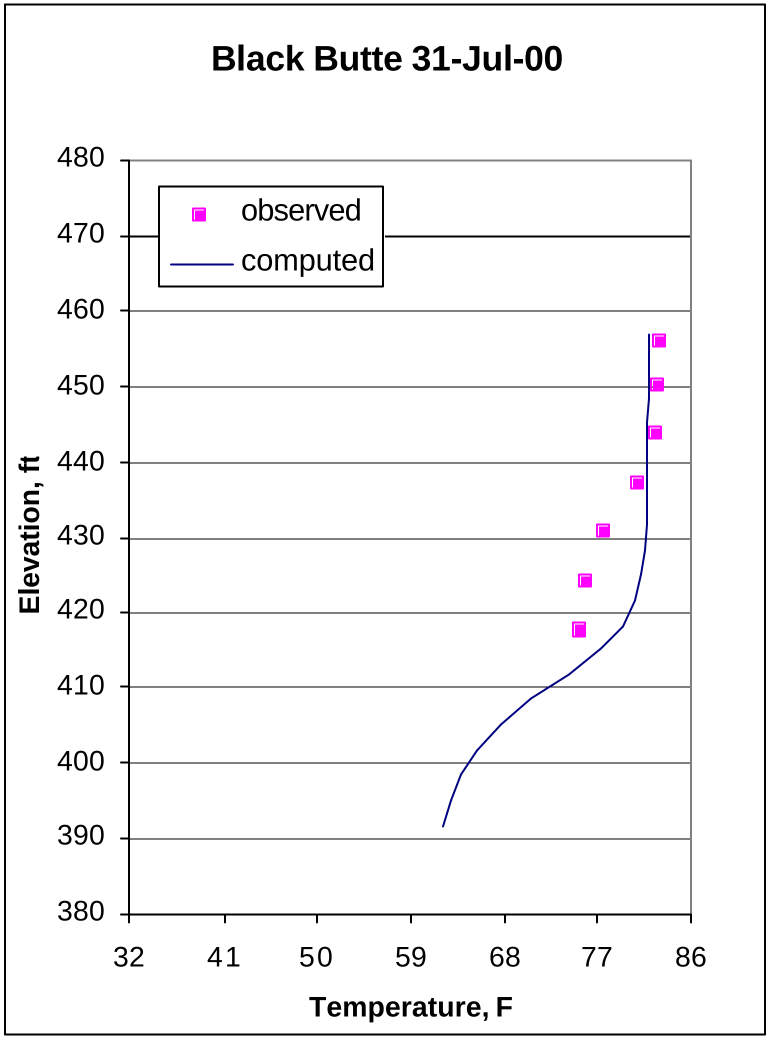


Figure 3-52 Computed and observed temperature profiles in Black Butte Reservoir on July 31, 2000.

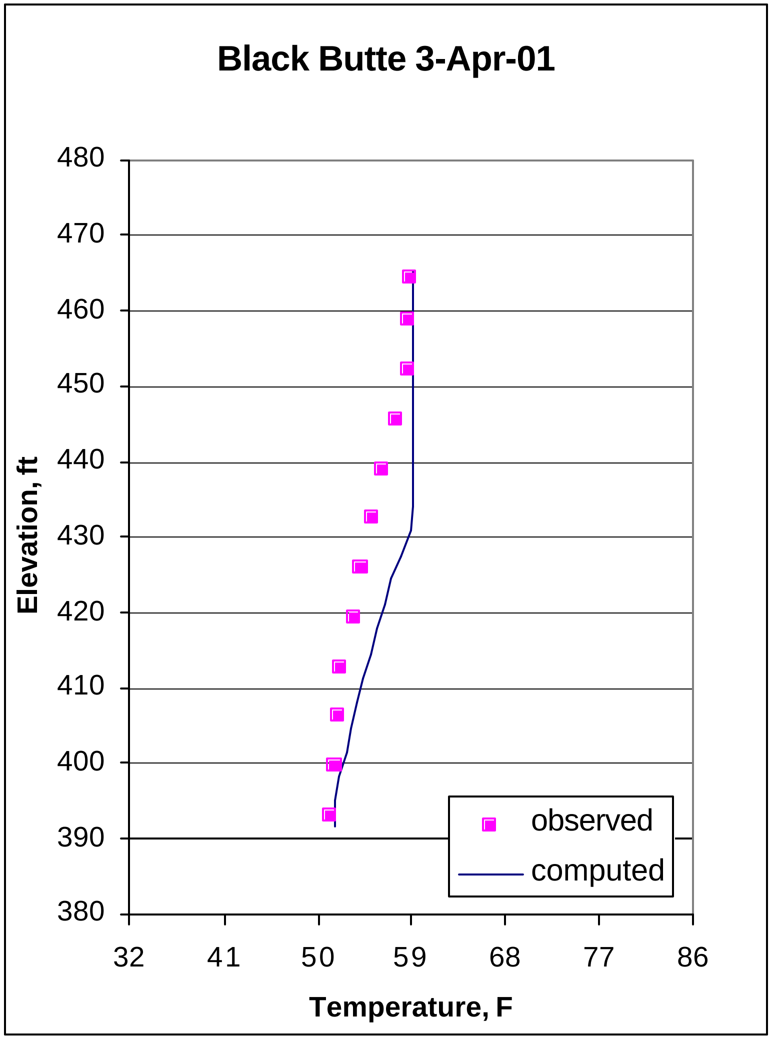


Figure 3-53 Computed and observed temperature profiles in Black Butte Reservoir on April 3, 2001.

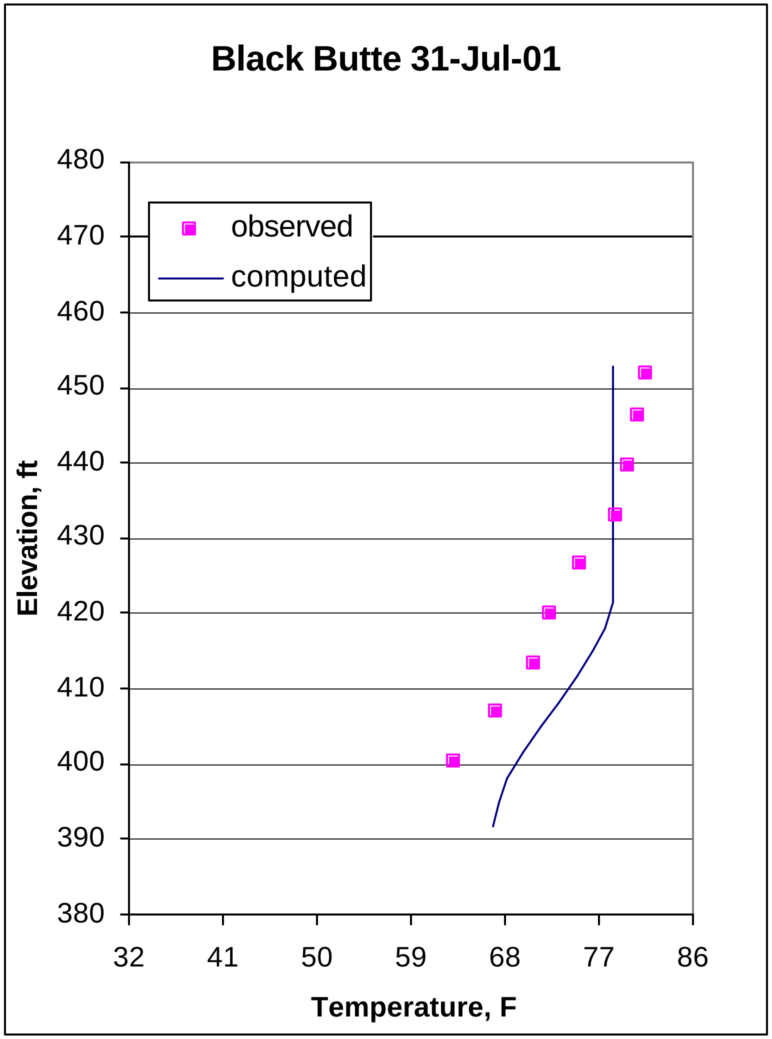


Figure 3-54 Computed and observed temperature profiles in Black Butte Reservoir on July 31, 2001.

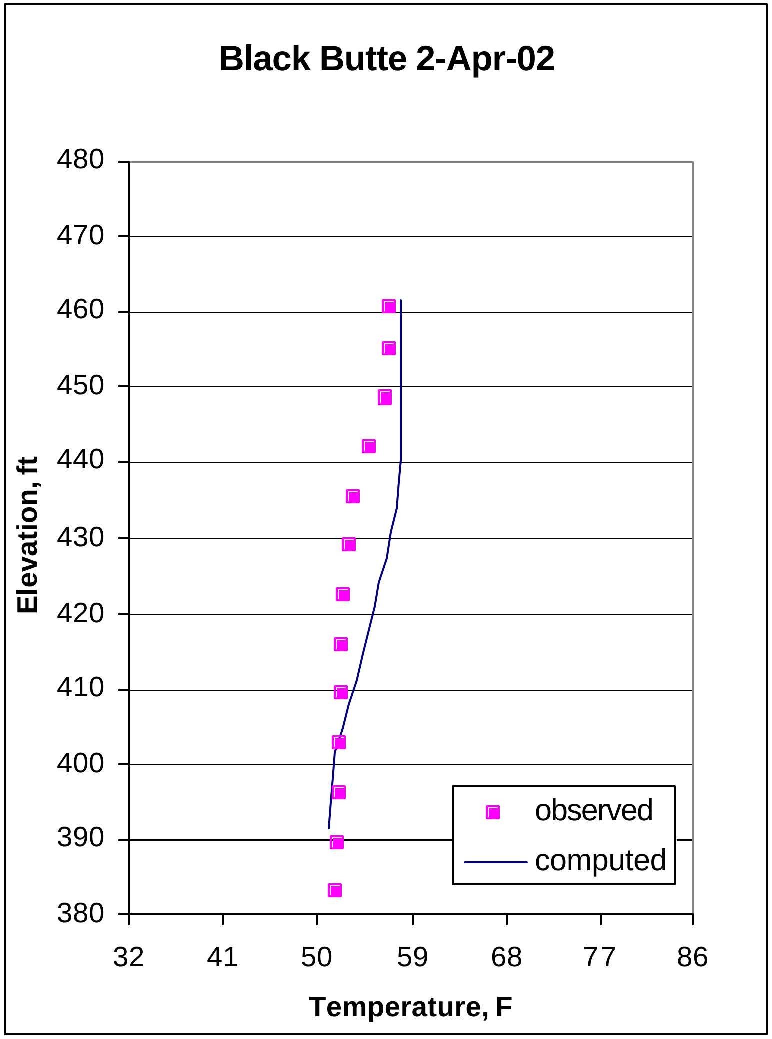


Figure 3-55 Computed and observed temperature profiles in Black Butte Reservoir on April 2, 2002.

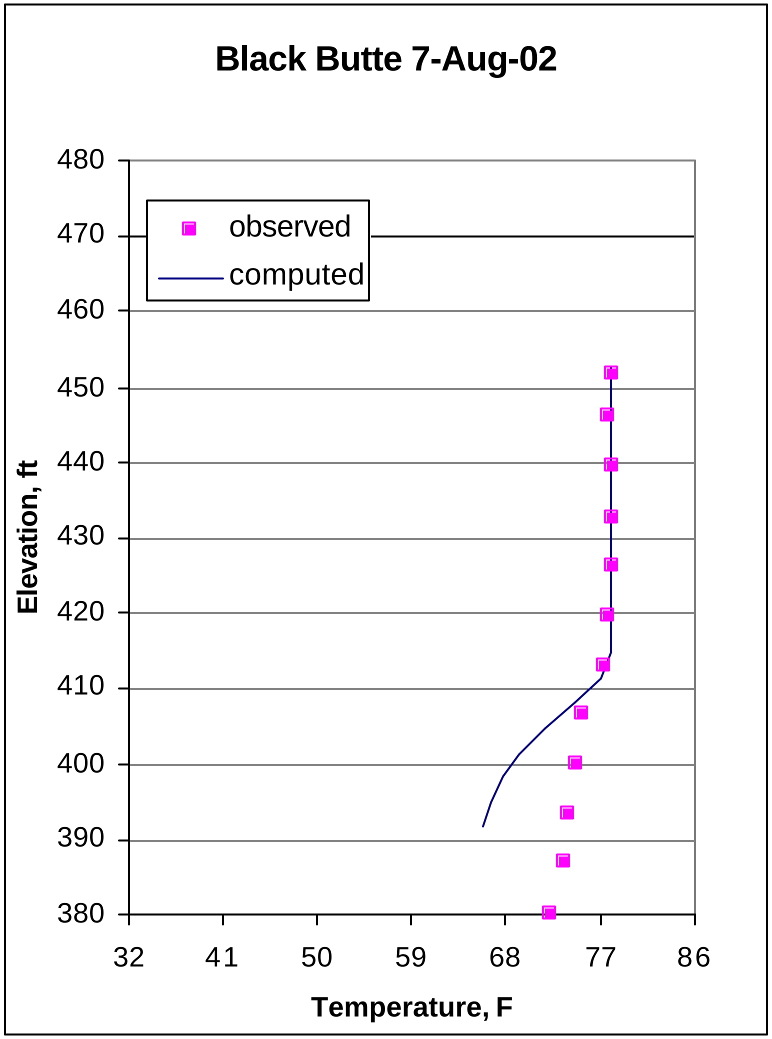


Figure 3-56 Computed and observed temperature profiles in Black Butte Reservoir on August 7, 2002.

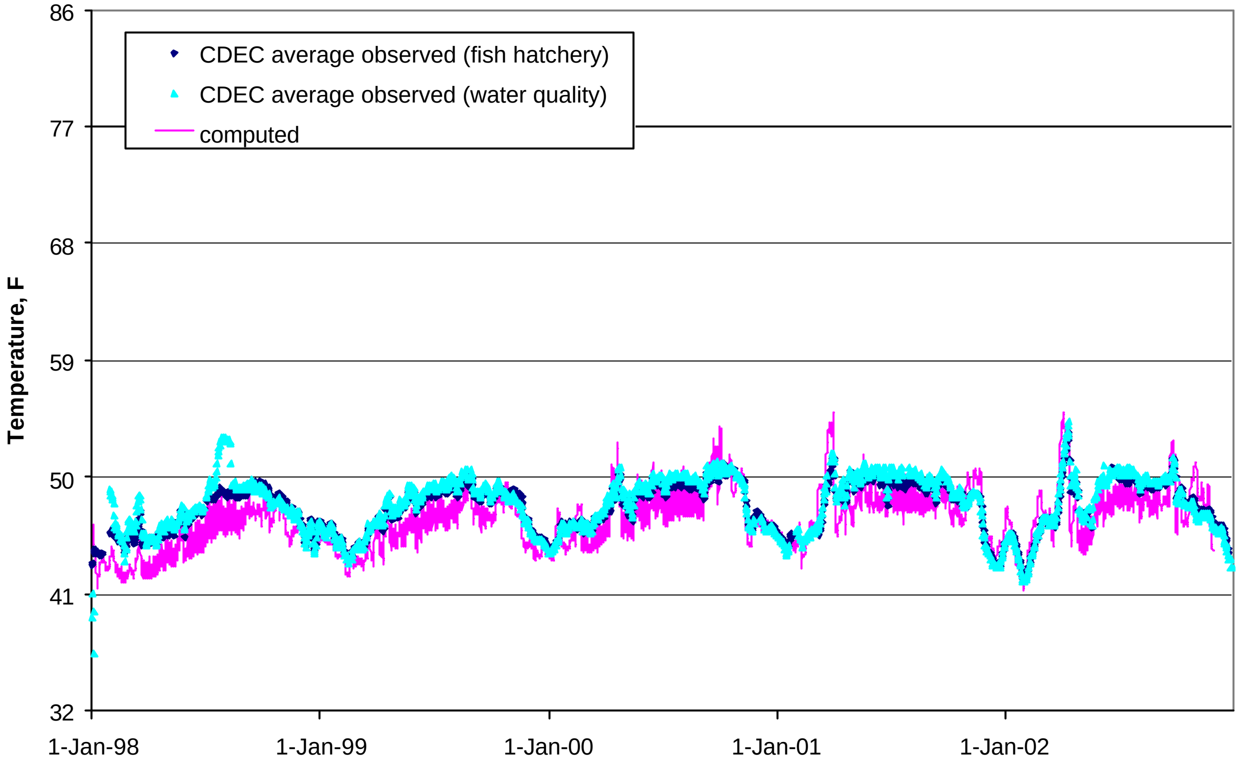


Figure 3-57 Computed and observed temperature time series at Lewiston Fish Hatchery.

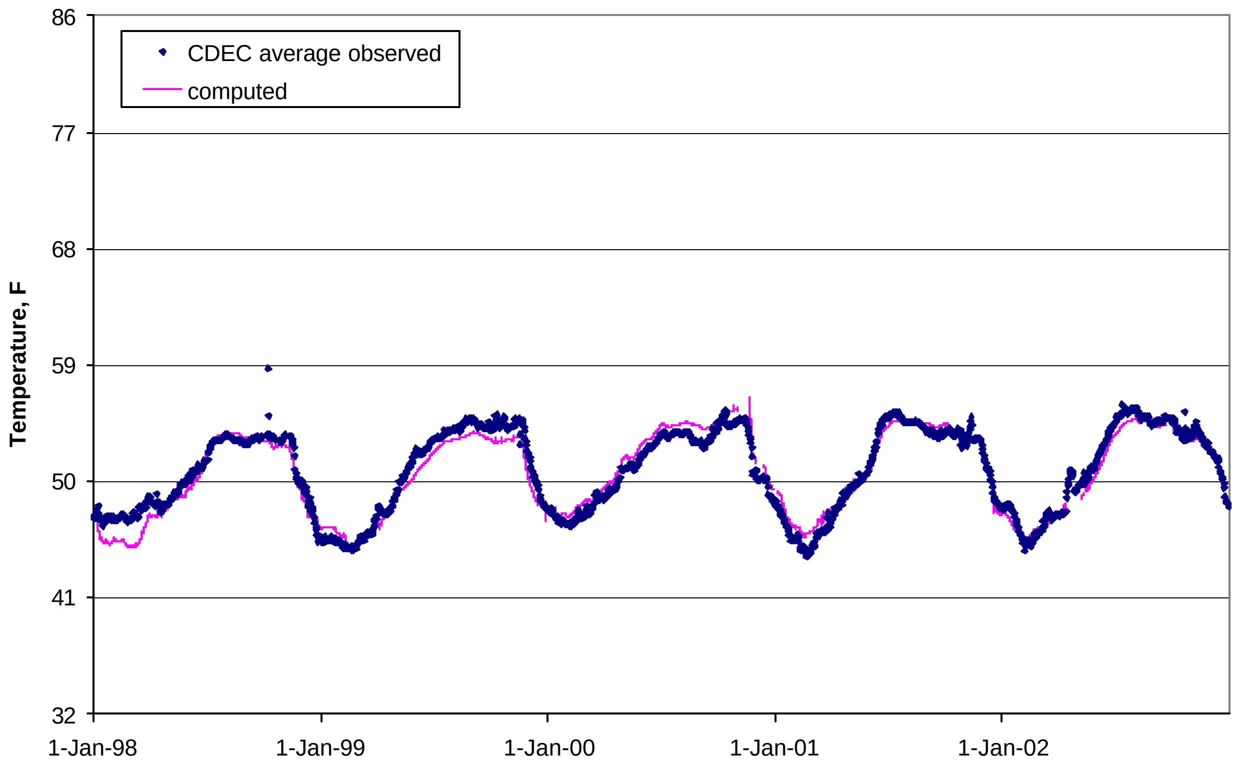


Figure 3-58 Computed and observed temperature time series at Spring Creek Powerhouse.

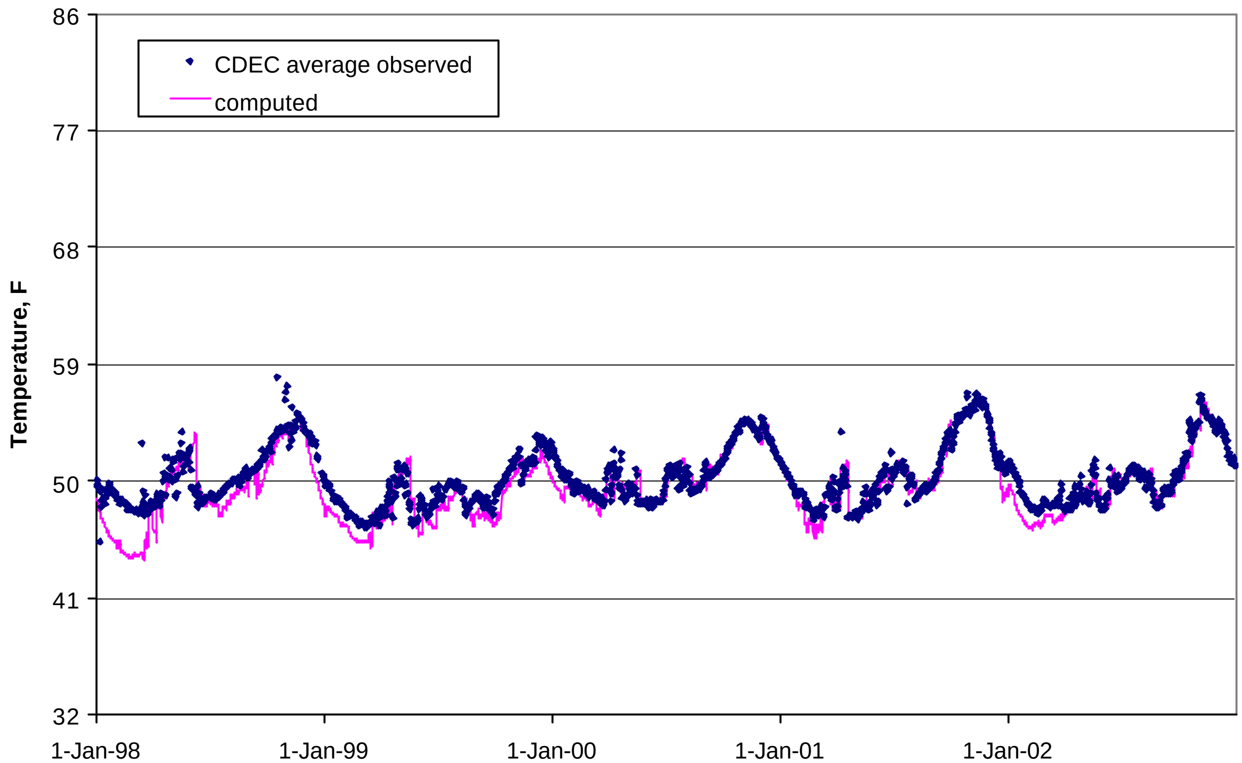


Figure 3-59 Computed and observed temperature time series in Sacramento River below Shasta Dam.

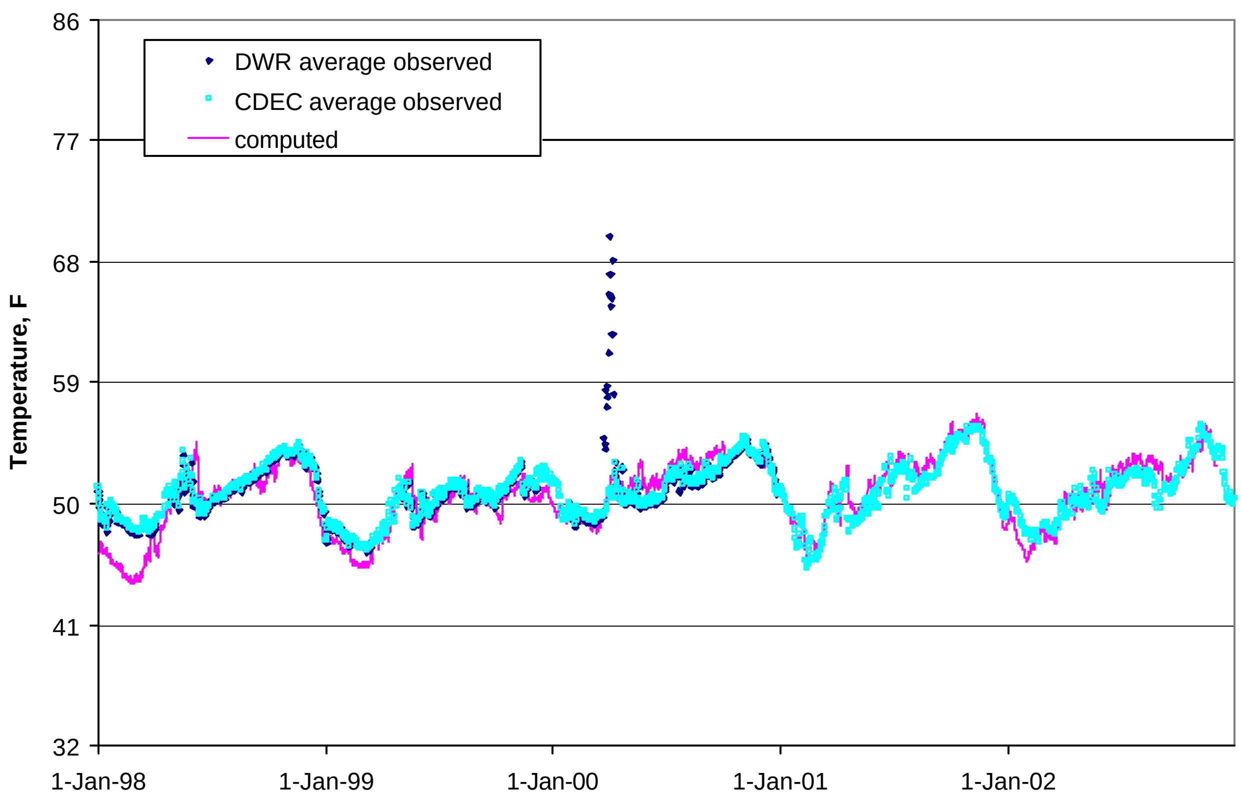


Figure 3-60 Computed and observed temperature time series in Sacramento River below Keswick Dam.

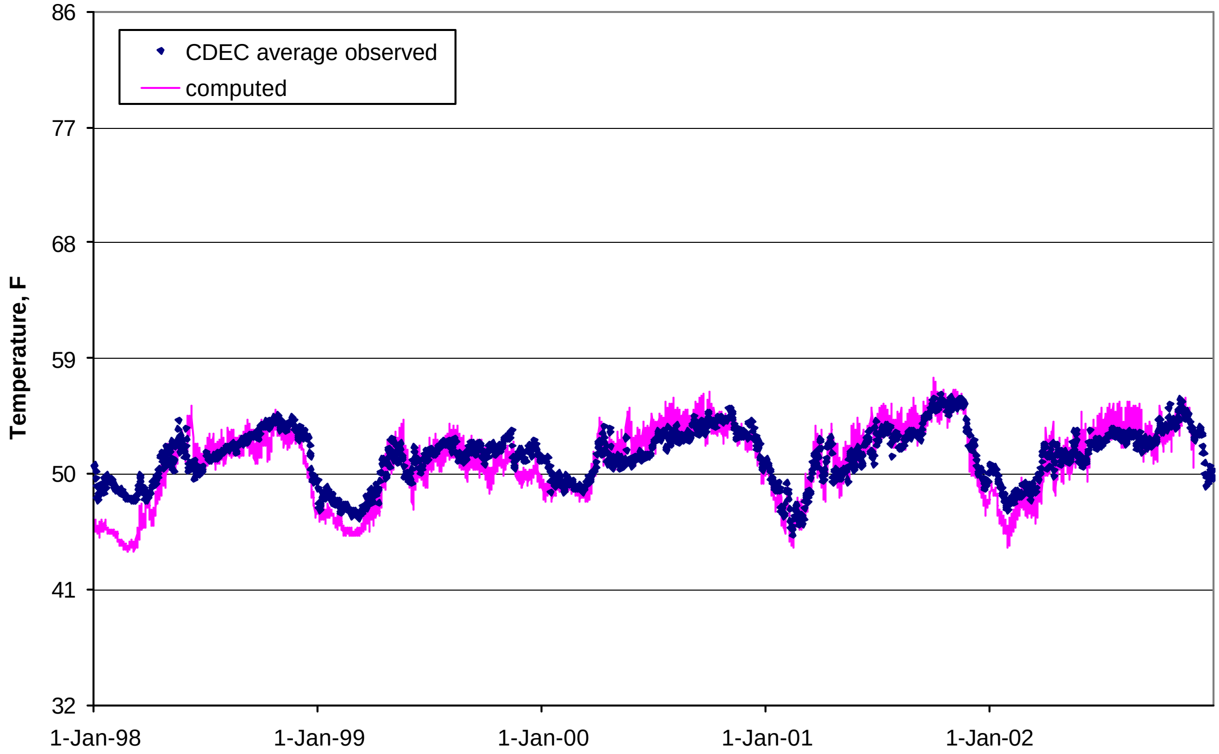


Figure 3-61 Computed and observed temperature time series in Sacramento River Clear Creek (Bonneview).

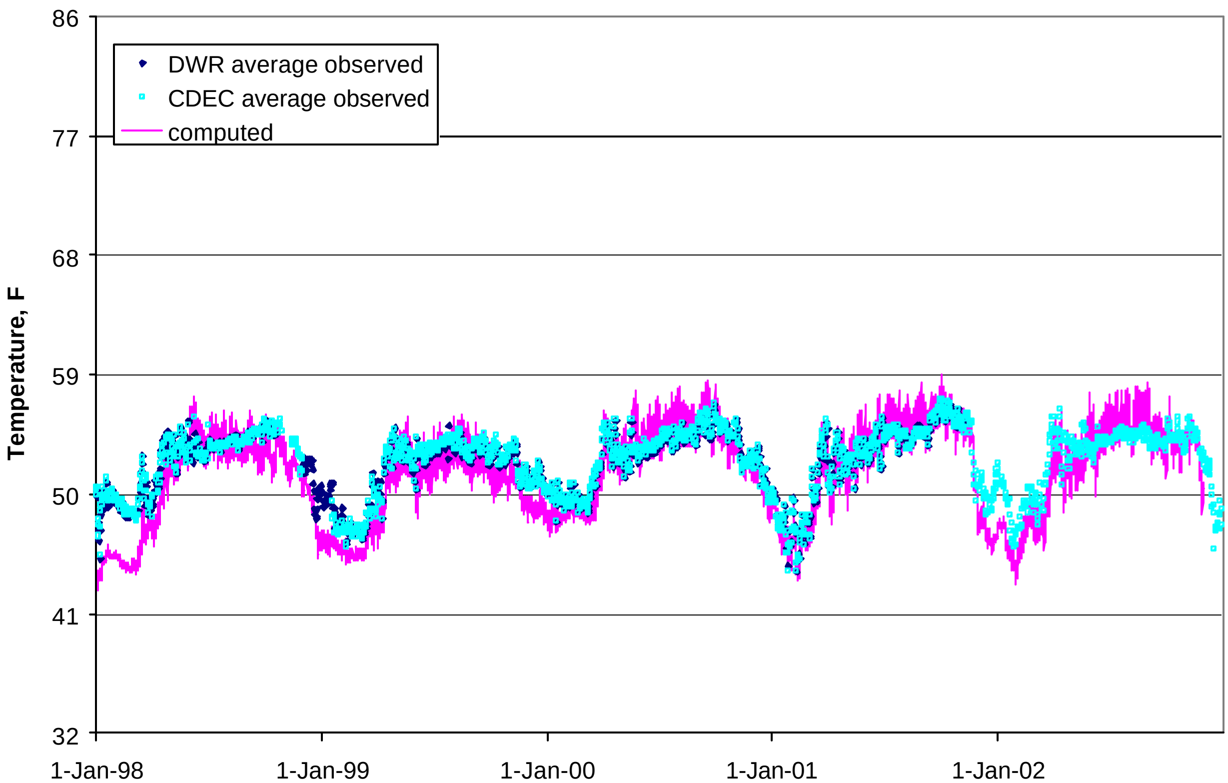


Figure 3-62 Computed and observed temperature time series in Sacramento River at Balls Ferry.

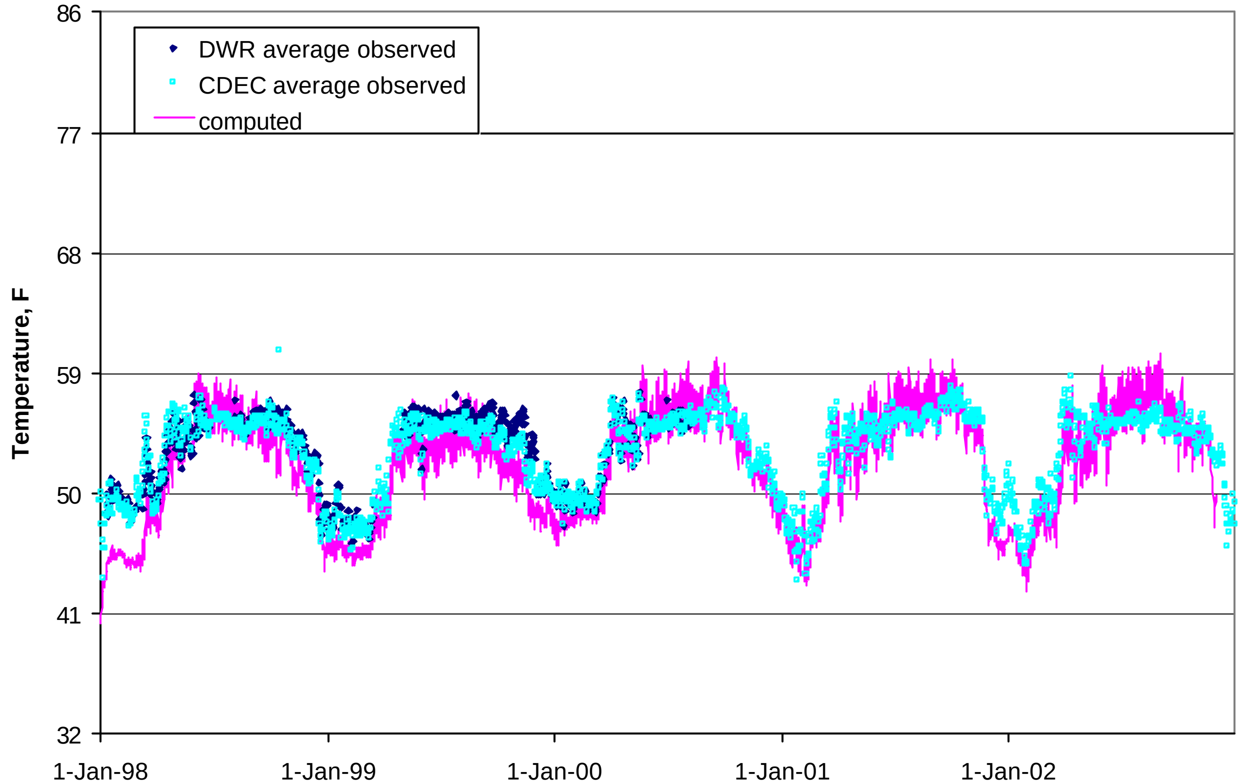


Figure 3-63 Computed and observed temperature time series in Sacramento River at Jellys Ferry.

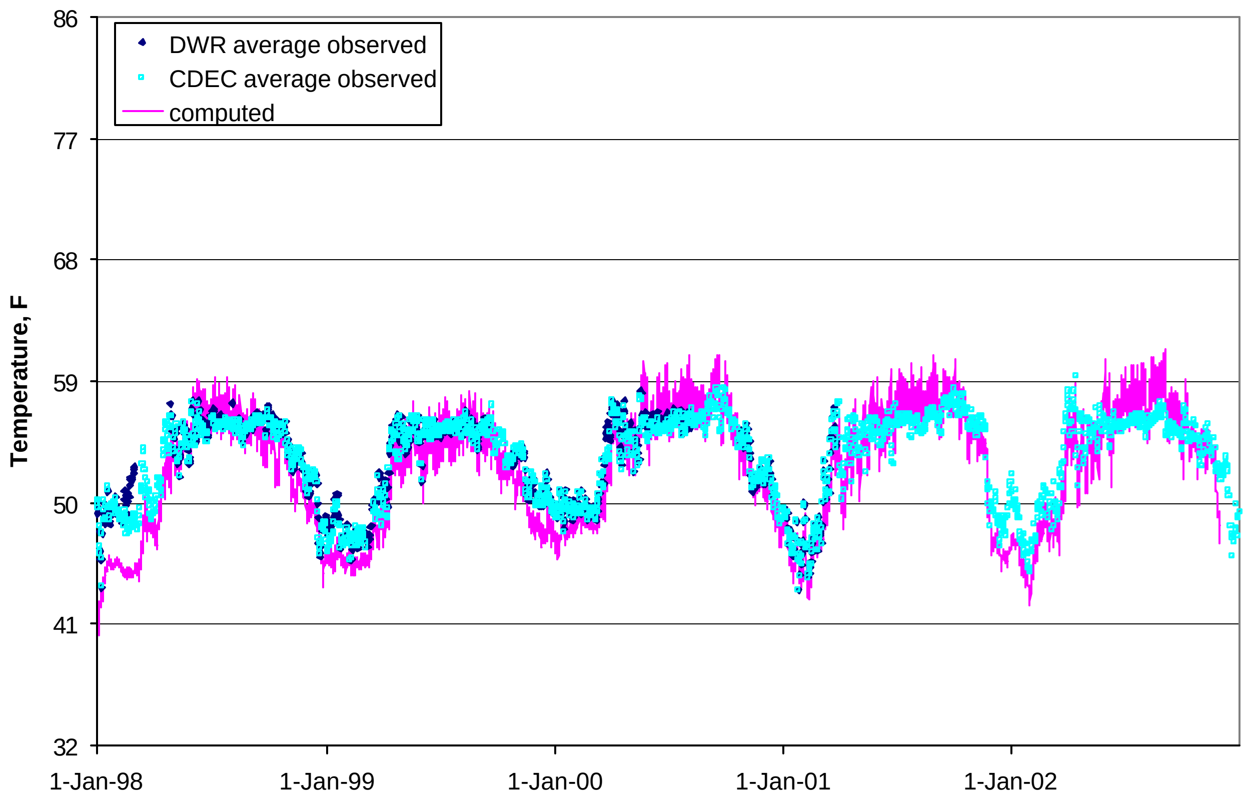


Figure 3-64 Computed and observed temperature time series in Sacramento River at Bend Bridge.

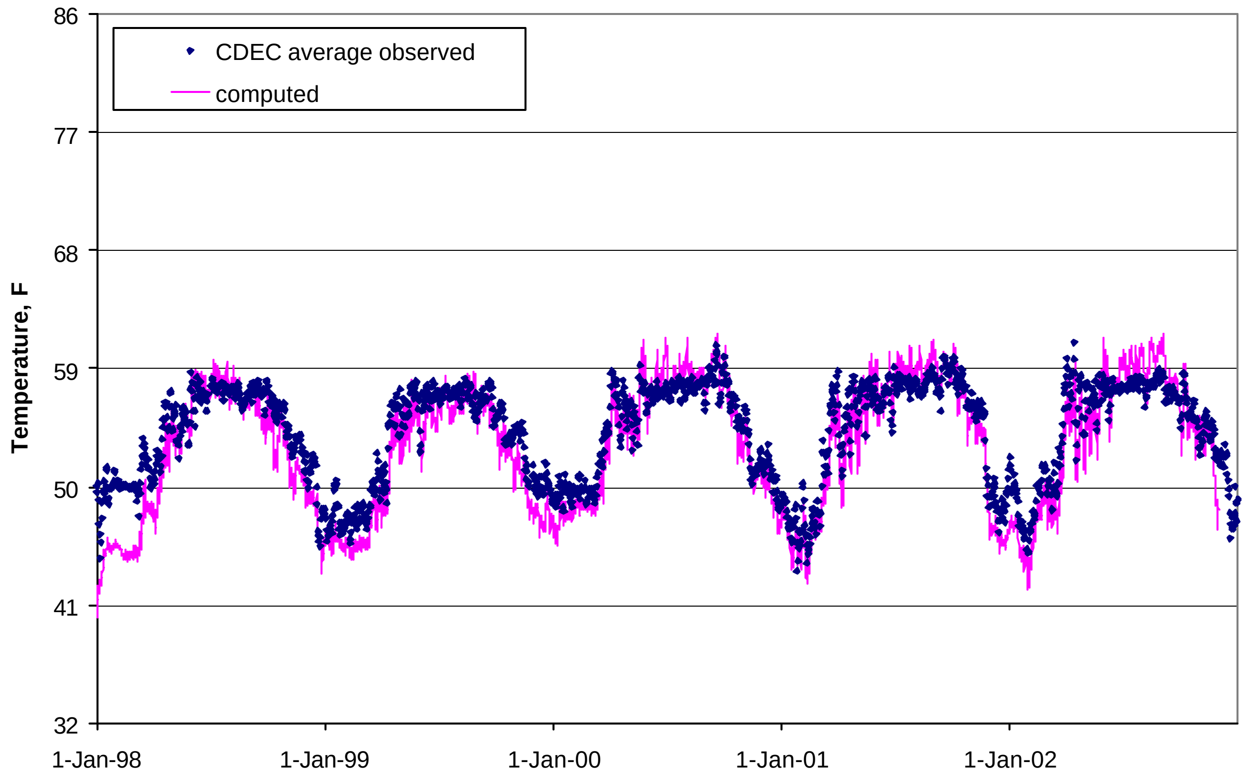


Figure 3-65 Computed and observed temperature time series in Sacramento River at Red Bluff Diversion Dam.

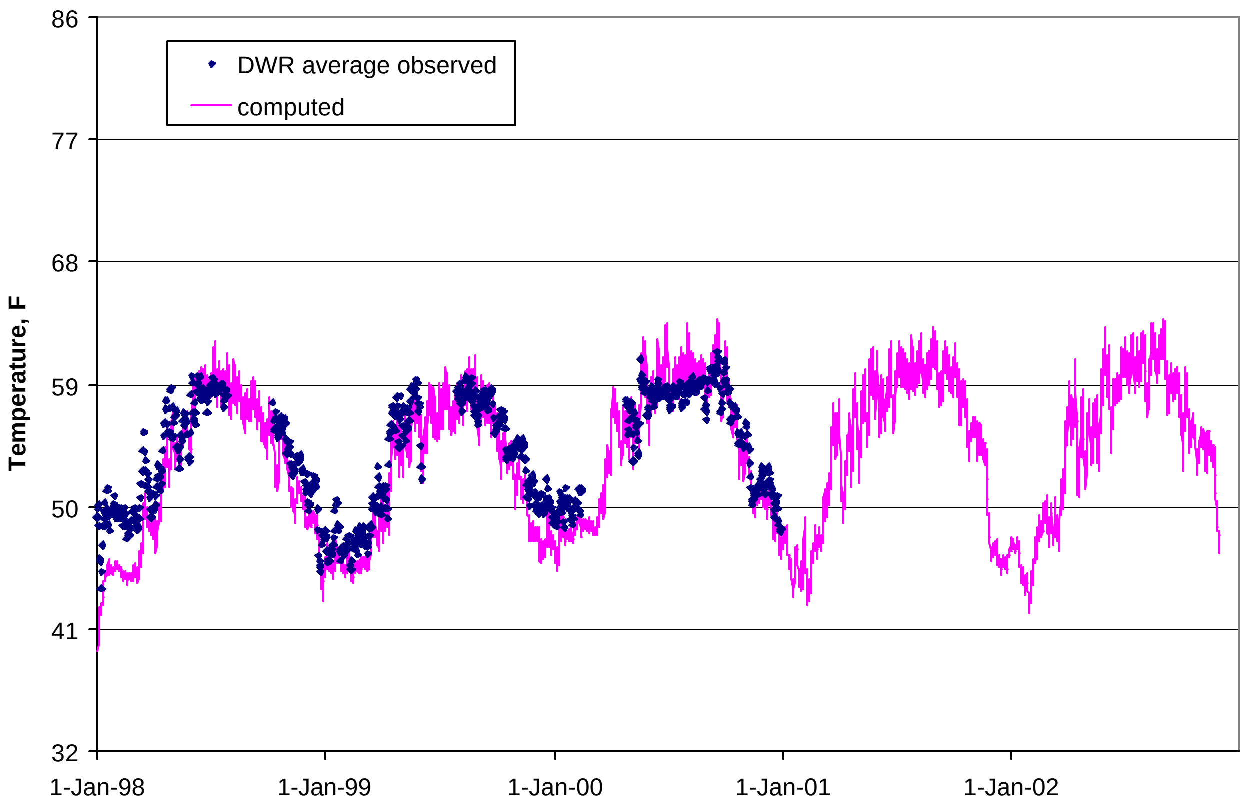


Figure 3-66 Computed and observed temperature time series in Sacramento River at Tehama.

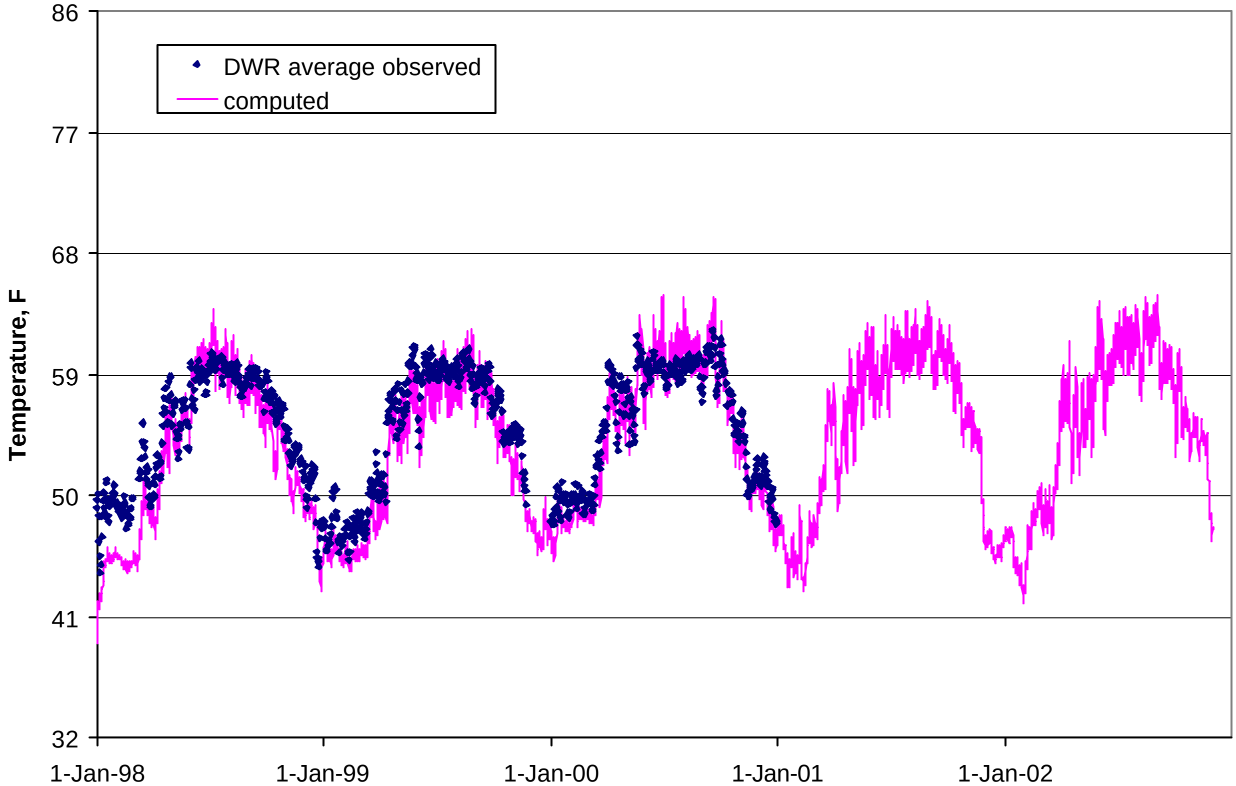


Figure 3-67 Computed and observed temperature time series in Sacramento River at Woodson Bridge.

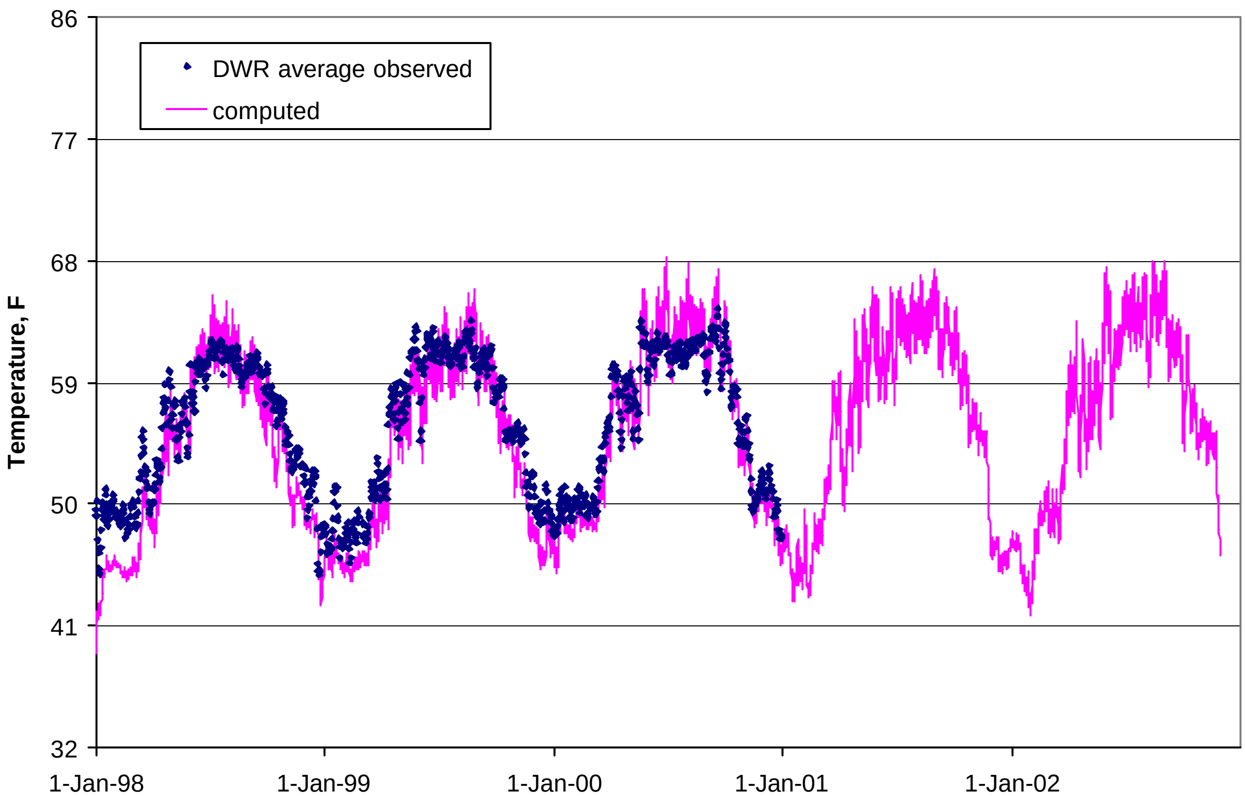


Figure 3-68 Computed and observed temperature time series in Sacramento River at Hamilton City.

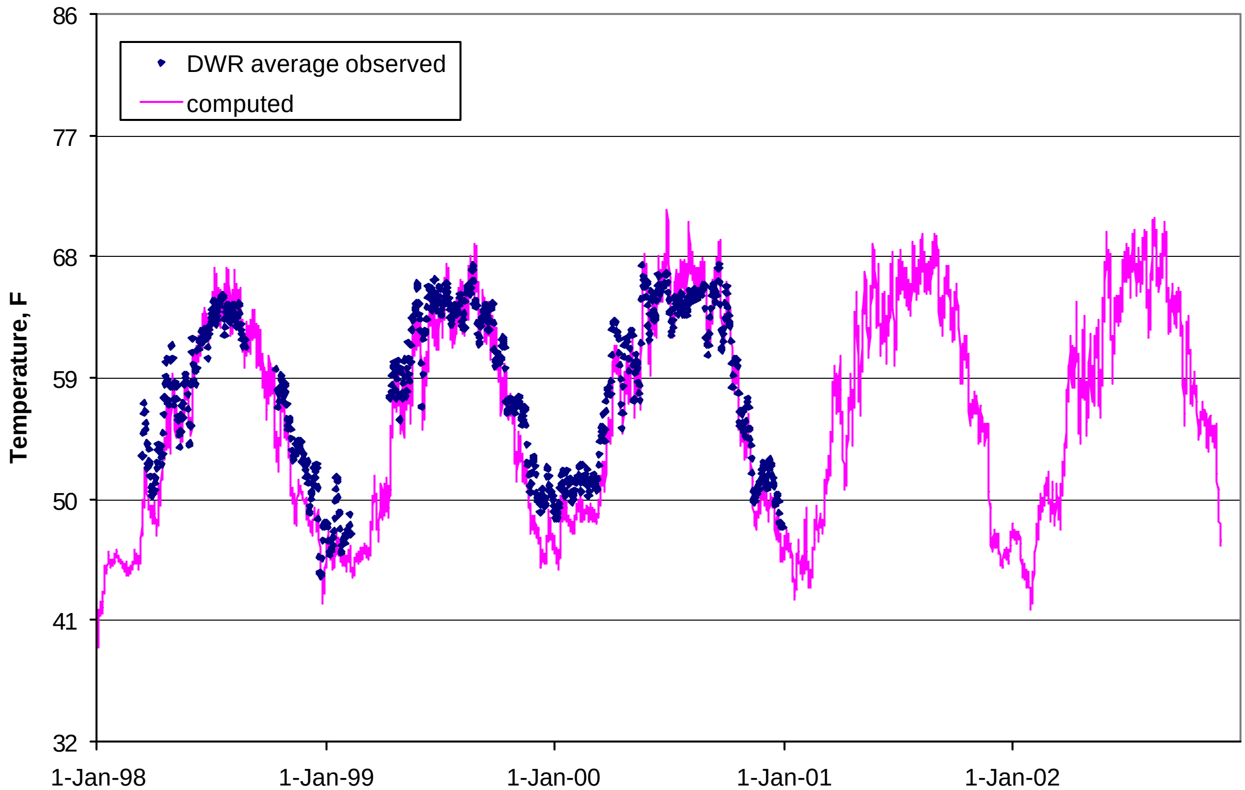


Figure 3-69 Computed and observed temperature time series in Sacramento River at Butte City.

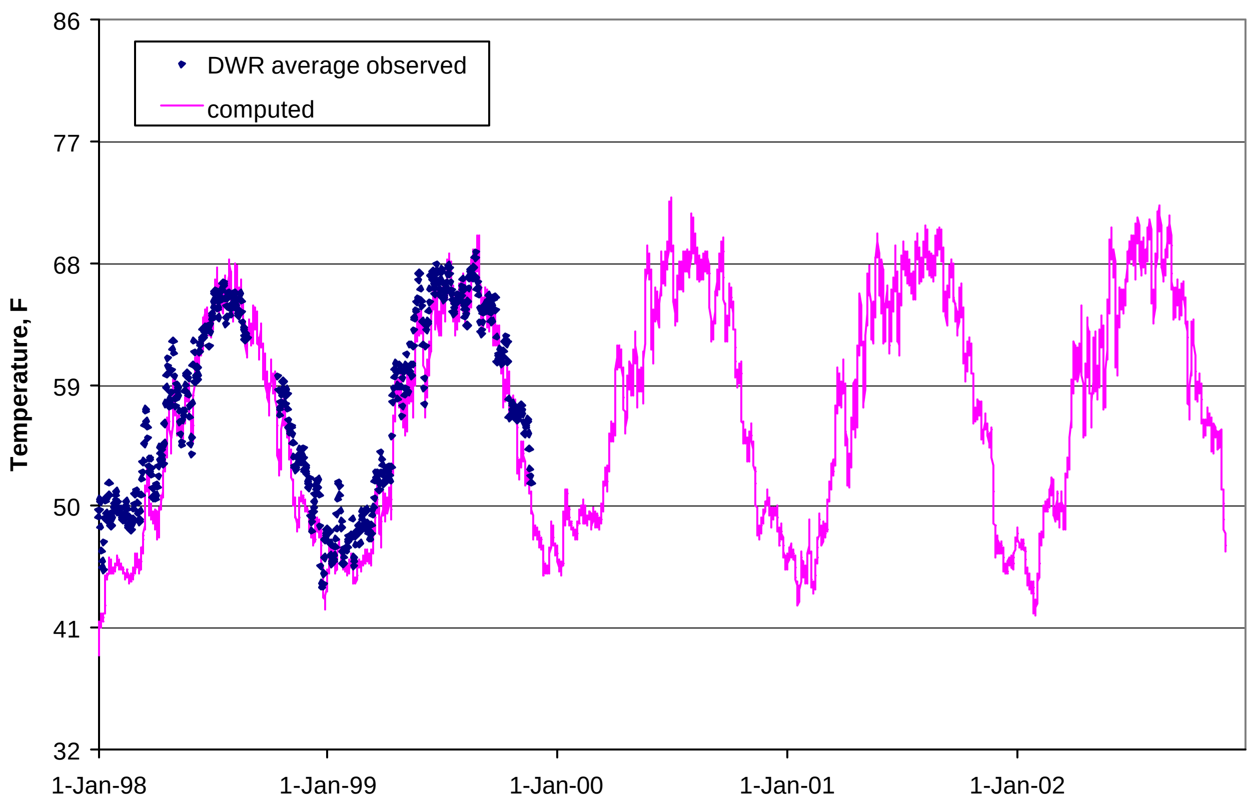


Figure 3-70 Computed and observed temperature time series in Sacramento River at Colusa.

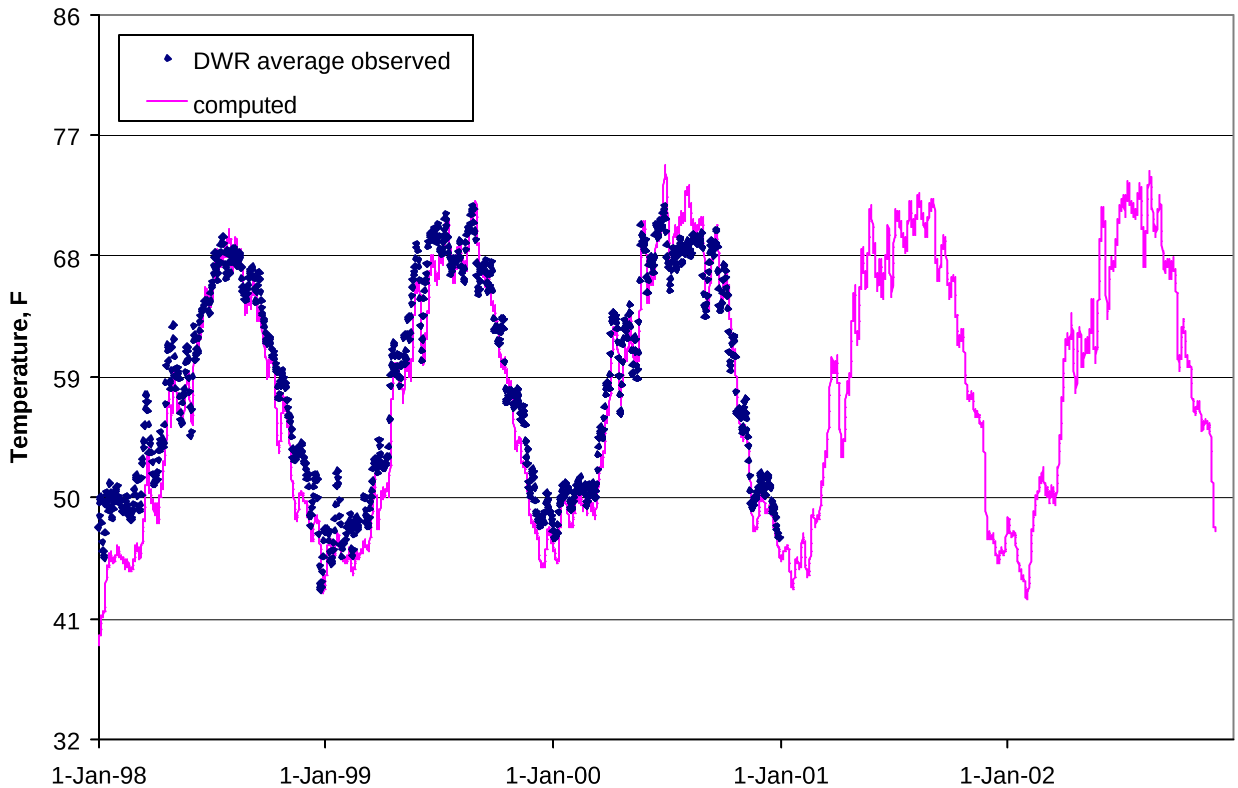


Figure 3-71 Computed and observed temperature time series in Sacramento River above Colusa Basin Drain.

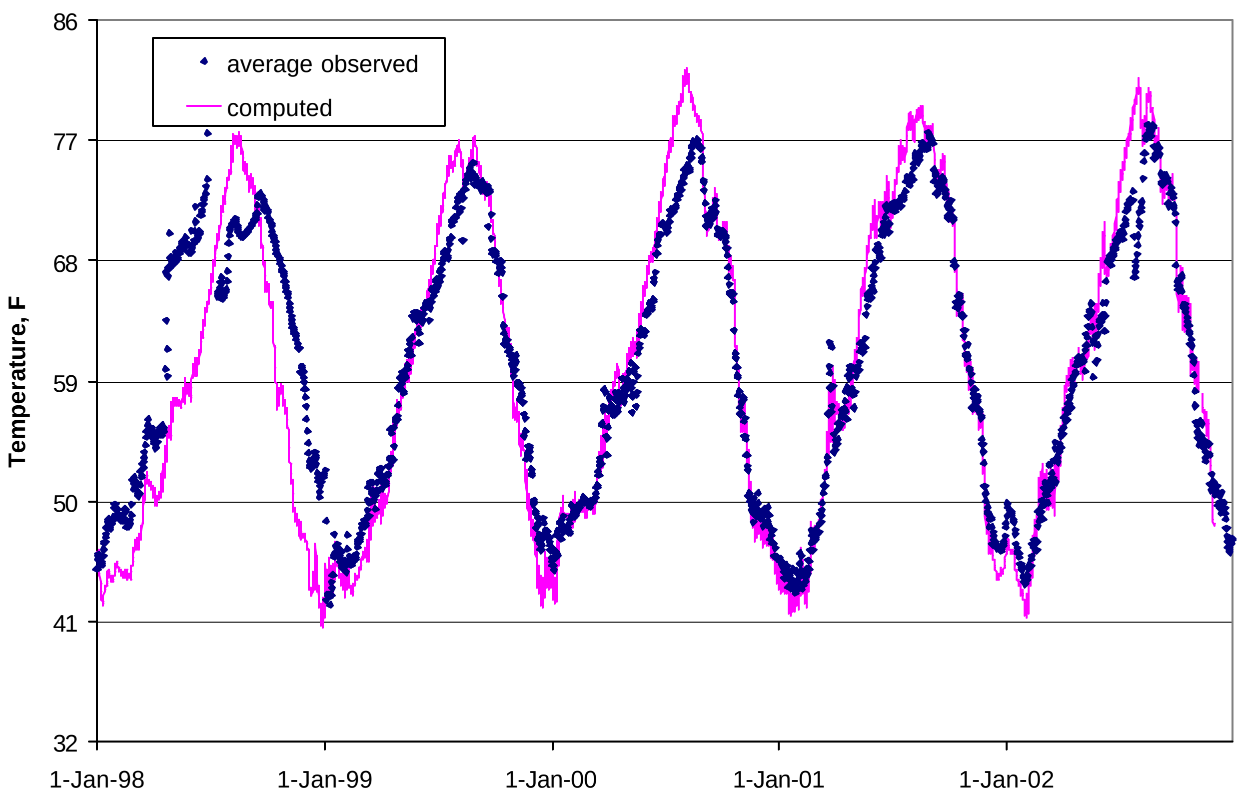


Figure 3-72 Computed and observed temperature time series in Stony Creek below Black Butte Dam.

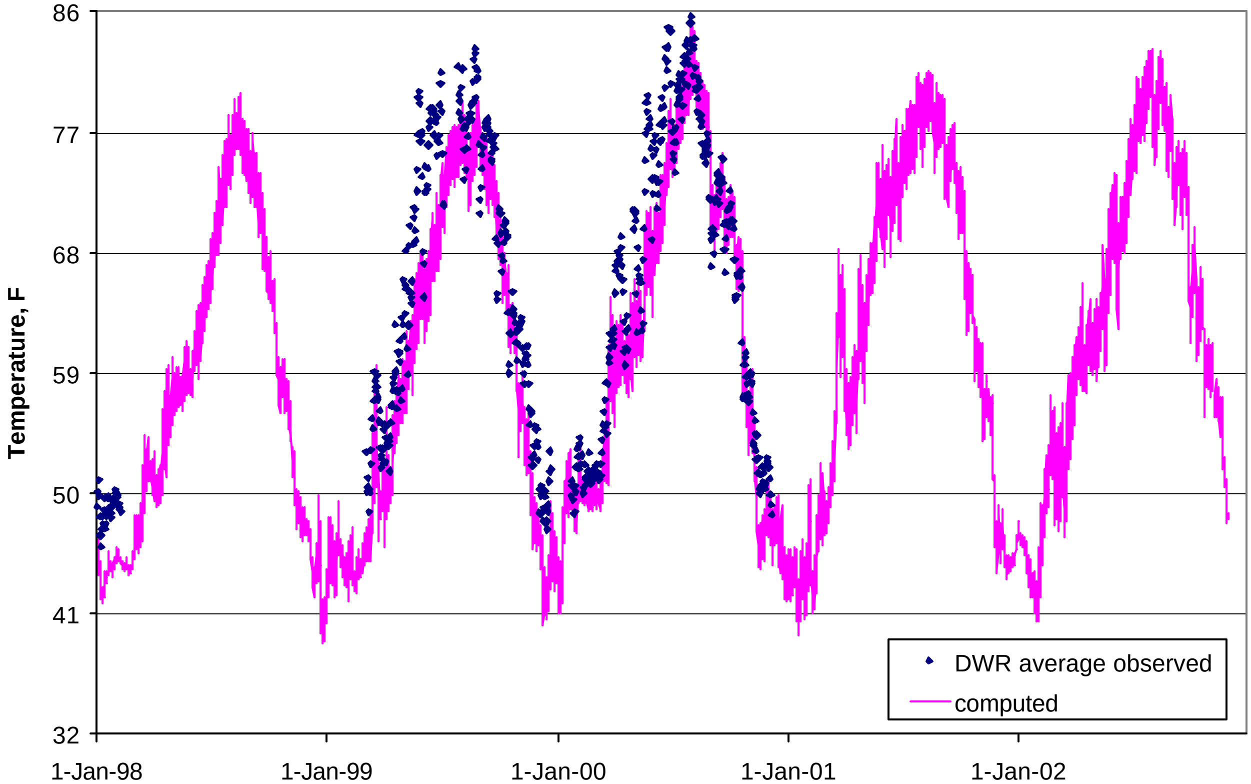


Figure 3-73 Computed and observed temperature time series in Stony Creek at Tehama Colusa Canal.

4 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 4-1. Model results were compared with temperature time series field observations at numerous locations in the Upper Sacramento River; tailwater temperature time series at Shasta, Lewiston and Keswick Dams; temperature time series at Spring Creek Powerhouse; and temperature profile observations in Lake Shasta. CDEC time series data, and Lake Shasta temperature profile data provided by USBR were utilized 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 1990's. Lake Shasta 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 described in Chapter 2 were assumed, with the exception that ambient water temperature data to develop tributary stream inflow temperatures were only available from CDEC.

The intent of the model validation exercise was to verify that the calibrated model adequately represents the 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 Lake Shasta temperature profiles.

4.1 HEC-5Q VALIDATION RESULTS

The following sections provide a brief discussion of the validation results.

4.1.1 Lake Shasta 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 4-2 through 4-17.

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. However, these deviations do not appear affect temperatures lower in the reservoir nor do they affect tailwater temperatures.

4.1.2 Stream Temperature Validation Results

Computed and observed temperature time series for selected locations throughout the Upper Sacramento River system are plotted in Figures 4-18 through 4-24. Computed values are plotted at 6-hour intervals at times 00:00, 06:00, 12:00 and 18:00. Observed data are plotted as daily average values.

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 the 1990 – 1992 relative to the 1993 – 1997 temperatures show that the model adequately represents ambient temperature conditions during wet and dry years. Validation results are summarized in Table 4.1.

Table 4.1 Summary of stream temperature calibration results.

Figure	Location	Description
4-18	Shasta Dam tailwater	Computed temperatures as much as 3° F lower than average observed data, with the greatest discrepancies occurring during the winter.
4-19	Trinity River at Lewiston	Computed temperatures are within 0 to 2° F of average observed data during the winters and within 0 to 3° F of average observed data during the summers.
4-20	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.
4-21	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.
4-22	Sac. R at Balls Ferry	Average computed temperatures are within 3° F or less of average observed throughout the calibration period, with the greatest discrepancies occurring during the winter.
4-23	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.
4-24	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.

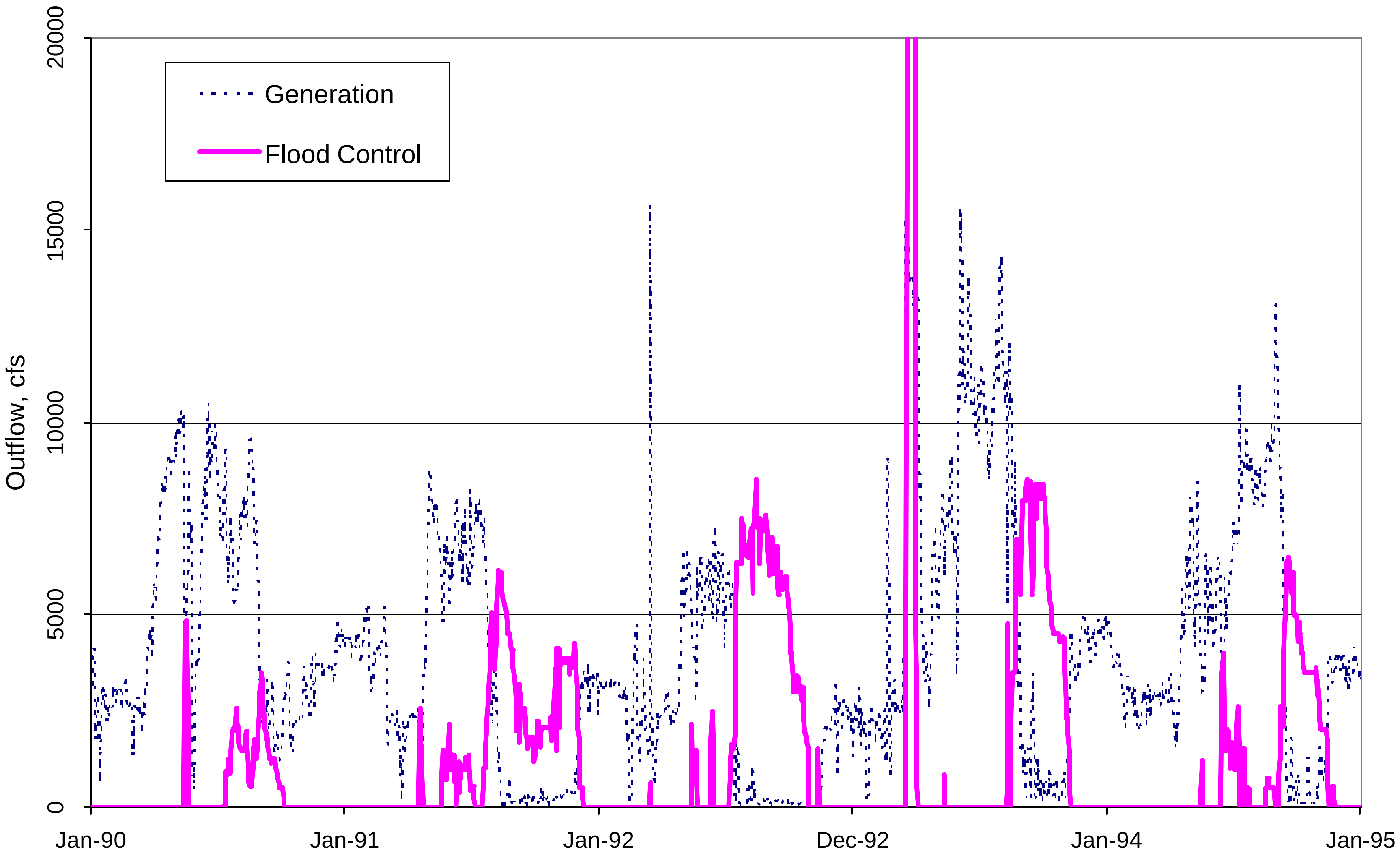


Figure 4-1 Shasta Dam penstock and flood control outlet flows during 1990—1995 Sacramento River temperature control operation.

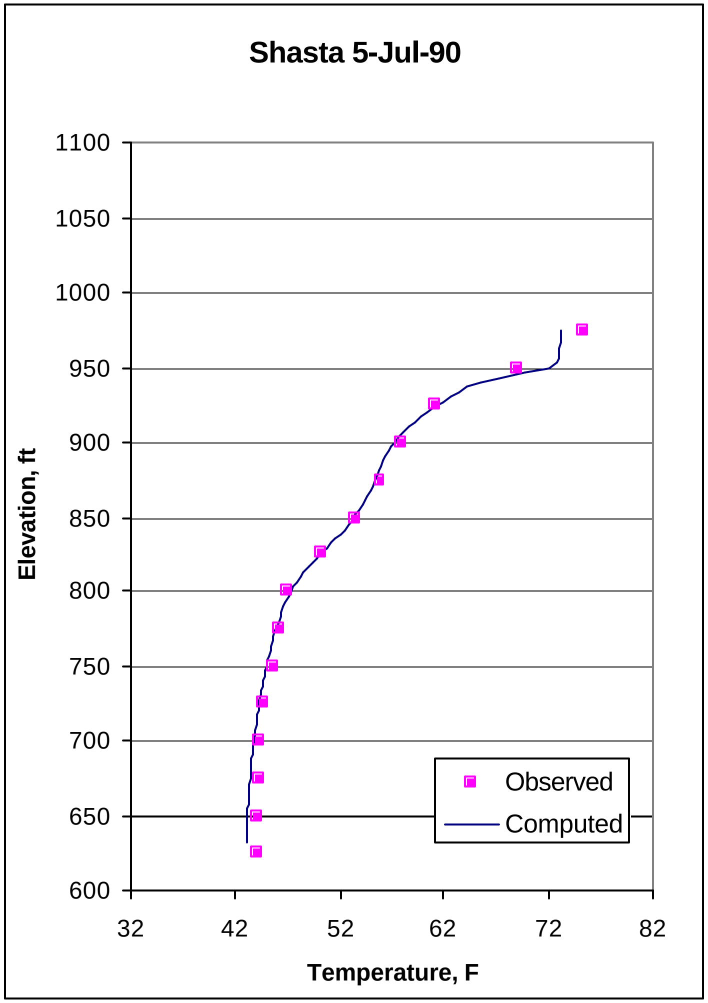


Figure 4-2 Computed and observed temperature profiles in Shasta Reservoir on July 5, 1990.

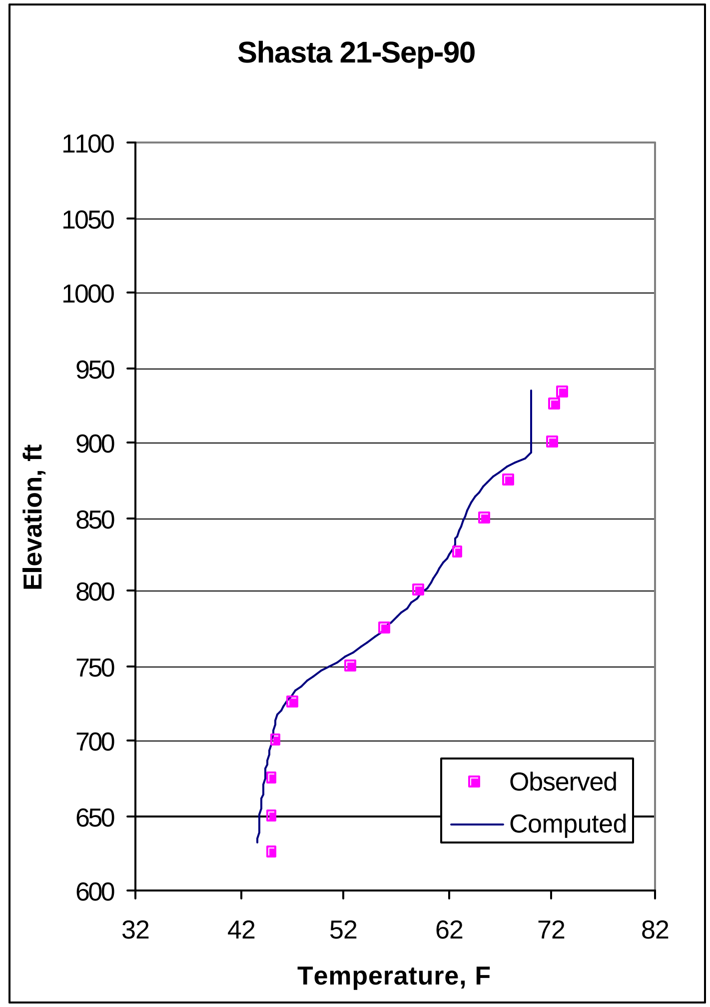


Figure 4-3 Computed and observed temperature profiles in Shasta Reservoir on September 21, 1990.

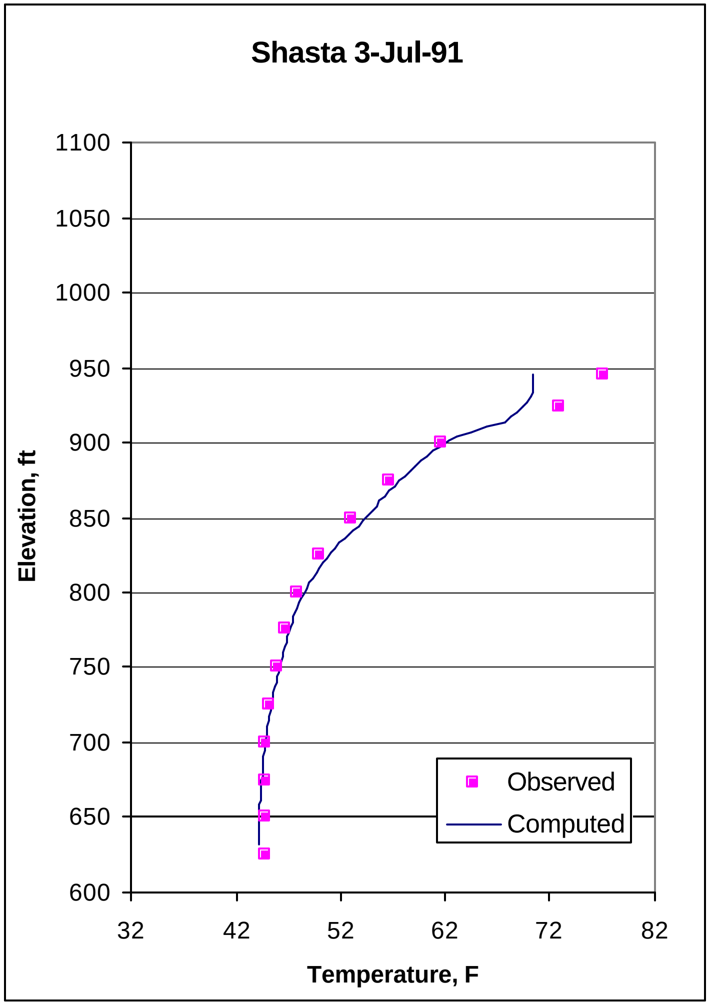


Figure 4-4 Computed and observed temperature profiles in Shasta Reservoir on July 3, 1991.

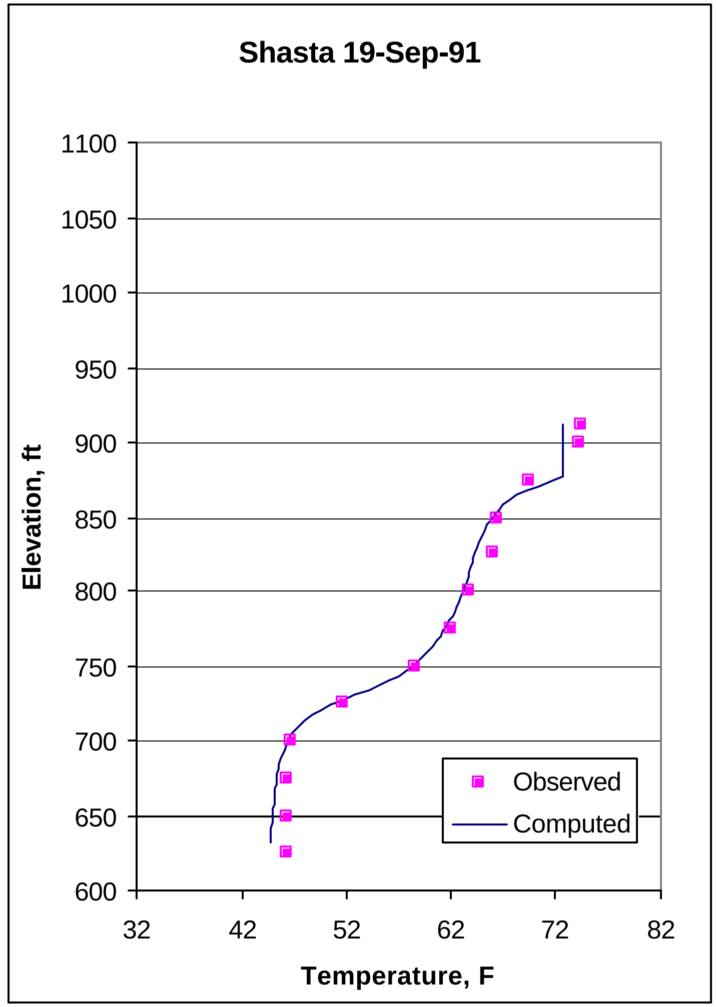


Figure 4-5 Computed and observed temperature profiles in Shasta Reservoir on September 19, 1991.

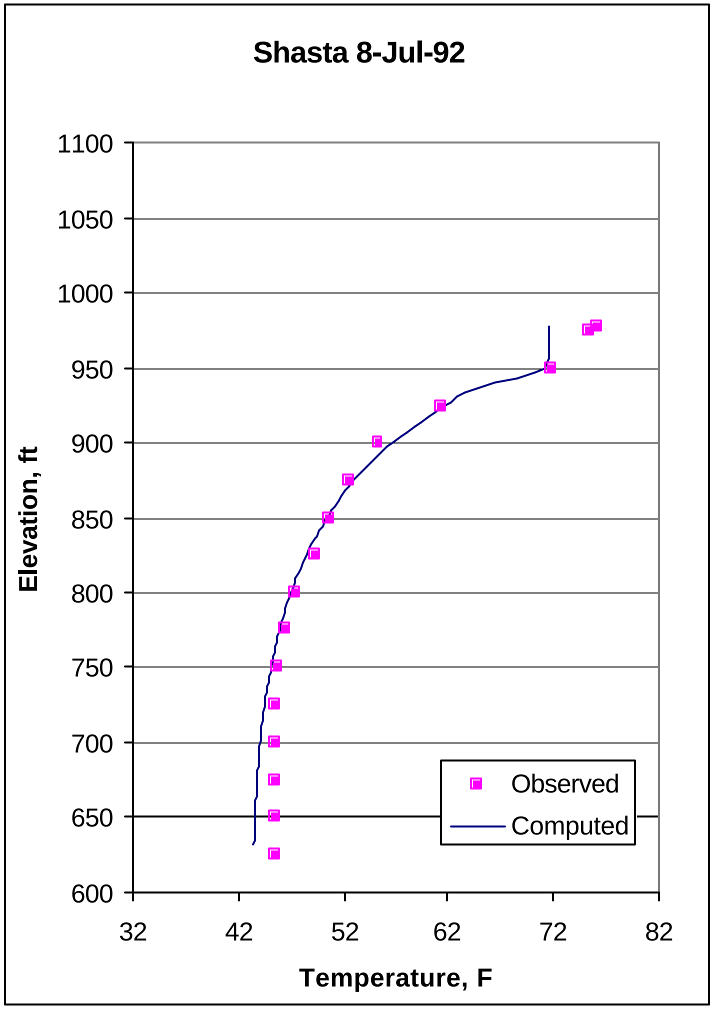


Figure 4-6 Computed and observed temperature profiles in Shasta Reservoir on July 8, 1992.

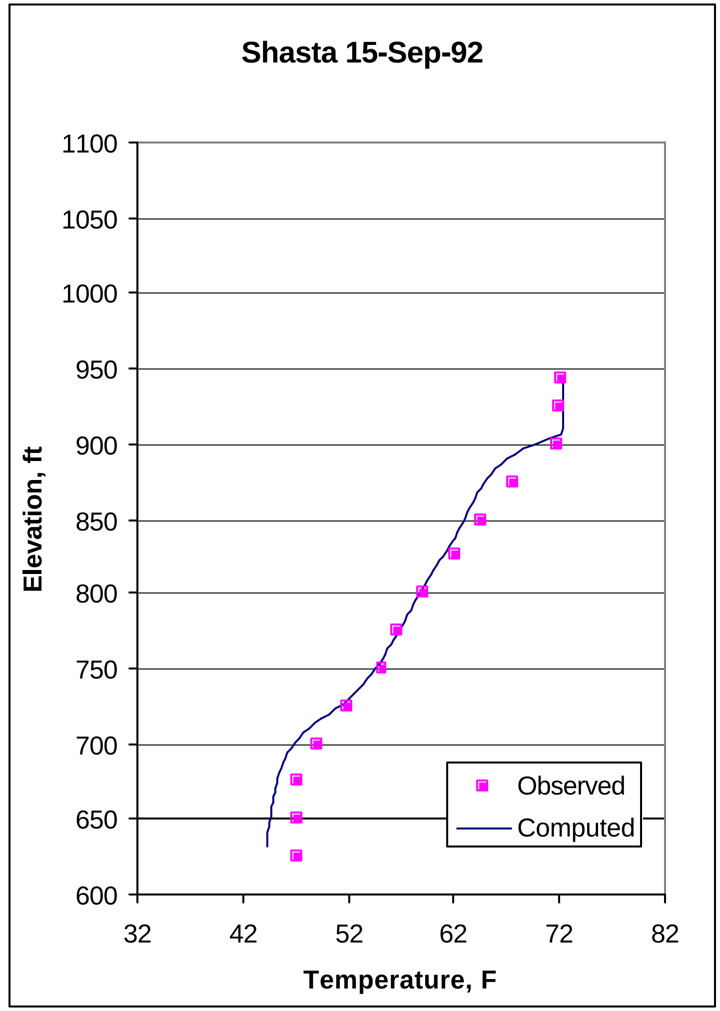


Figure 4-7 Computed and observed temperature profiles in Shasta Reservoir on September 15, 1992.

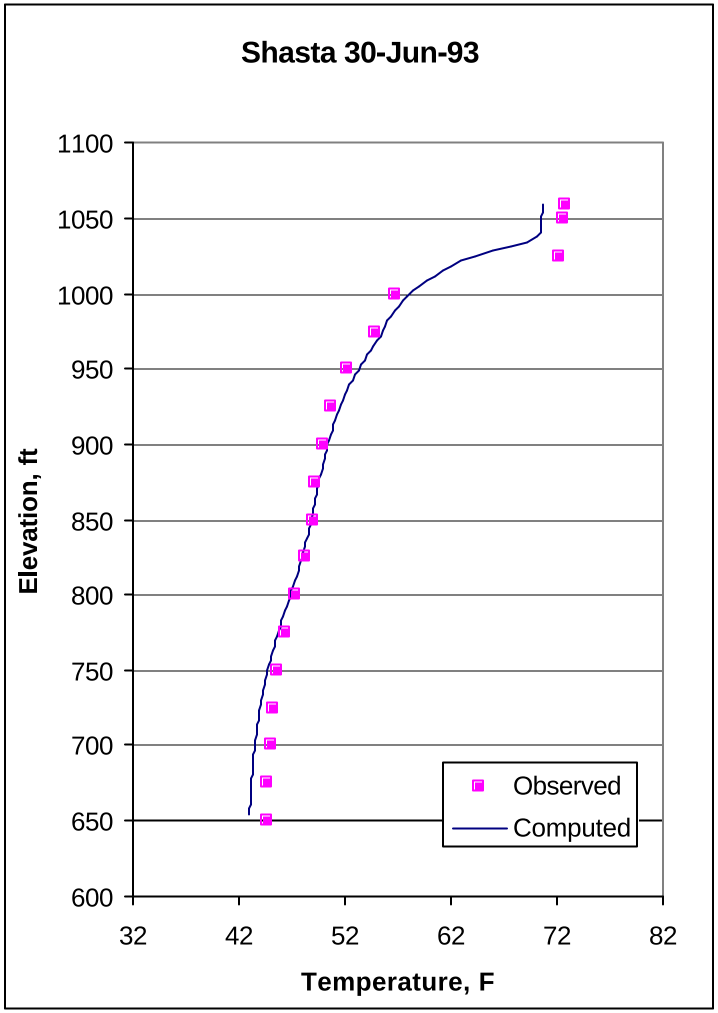


Figure 4-8 Computed and observed temperature profiles in Shasta Reservoir on June 30, 1993.

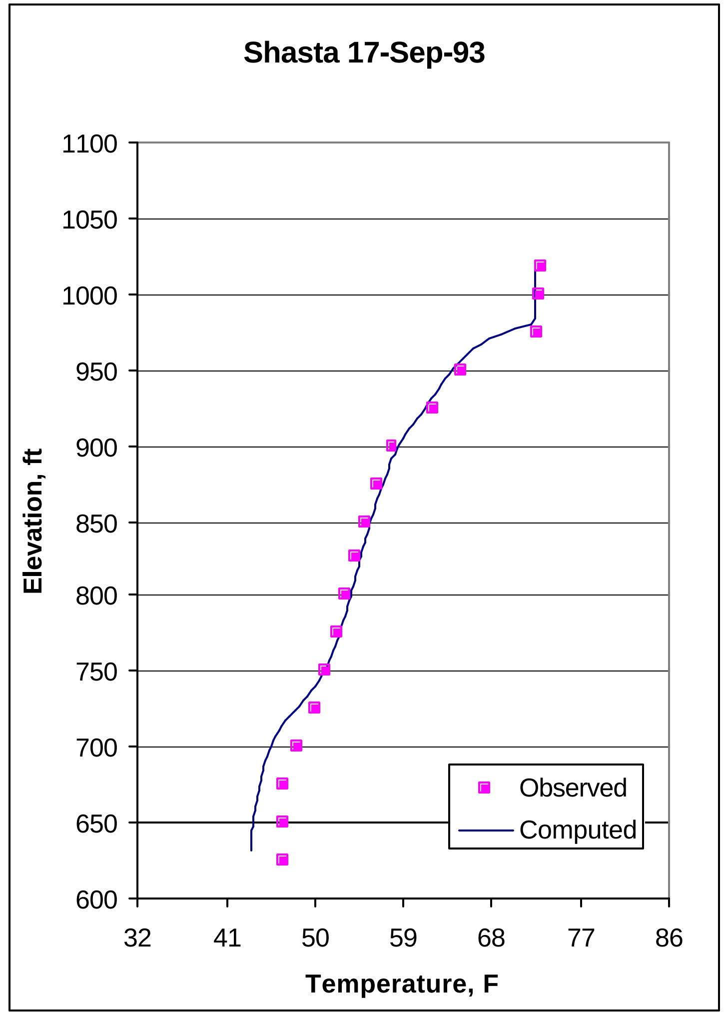


Figure 4-9 Computed and observed temperature profiles in Shasta Reservoir on September 17, 1993.

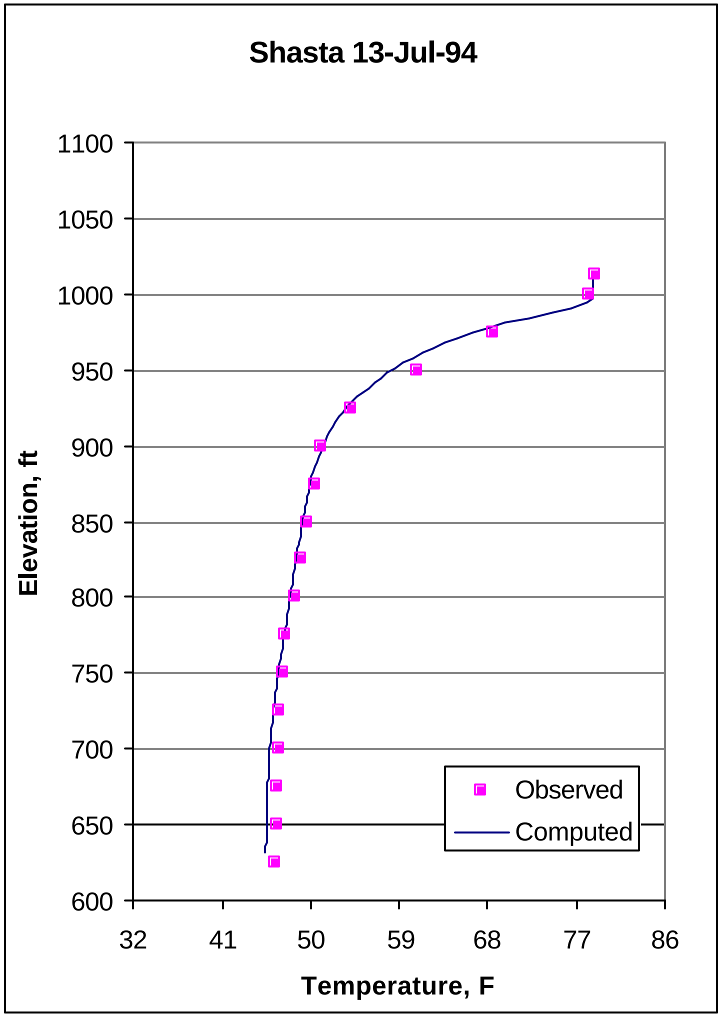


Figure 4-10 Computed and observed temperature profiles in Shasta Reservoir on July 13, 1994.

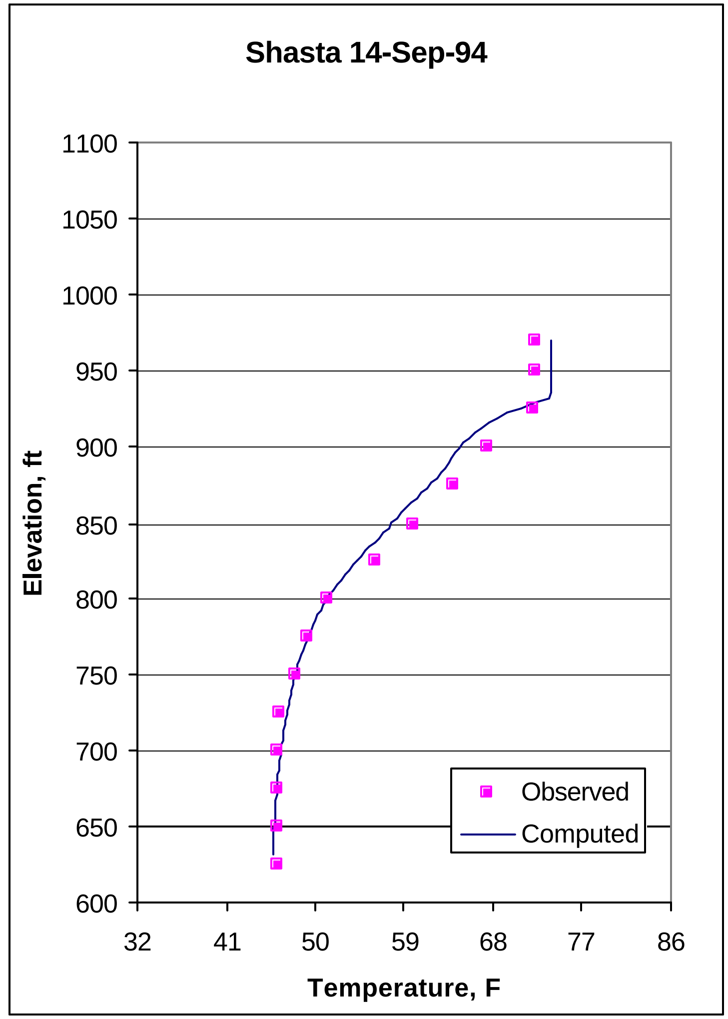


Figure 4-11 Computed and observed temperature profiles in Shasta Reservoir on September 14, 1994.

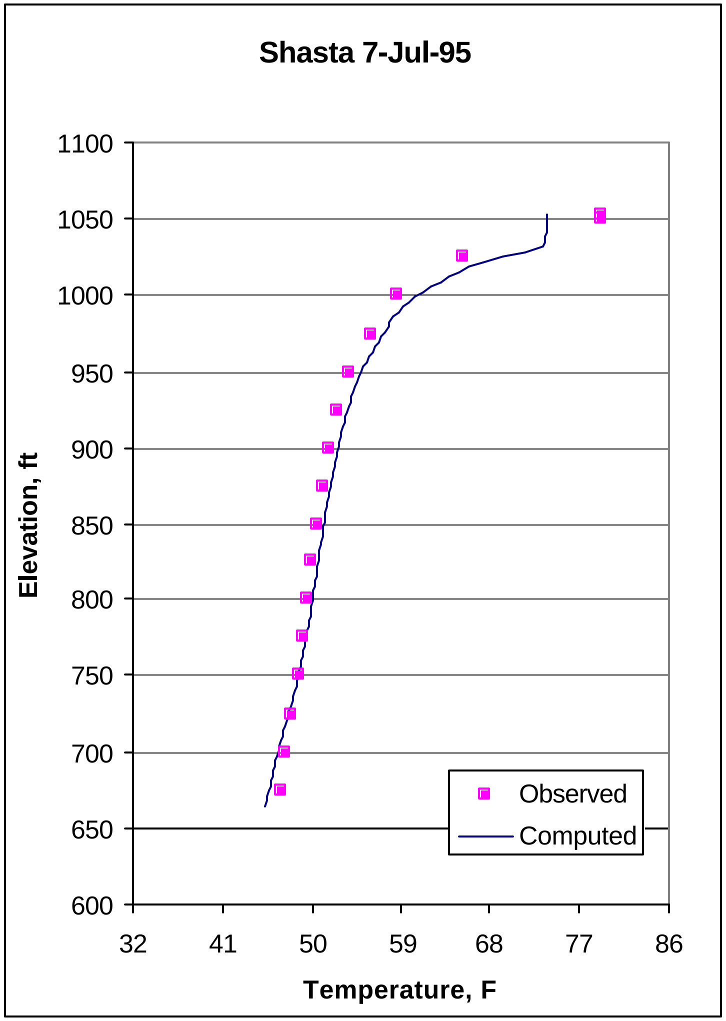


Figure 4-12 Computed and observed temperature profiles in Shasta Reservoir on July 7, 1995.

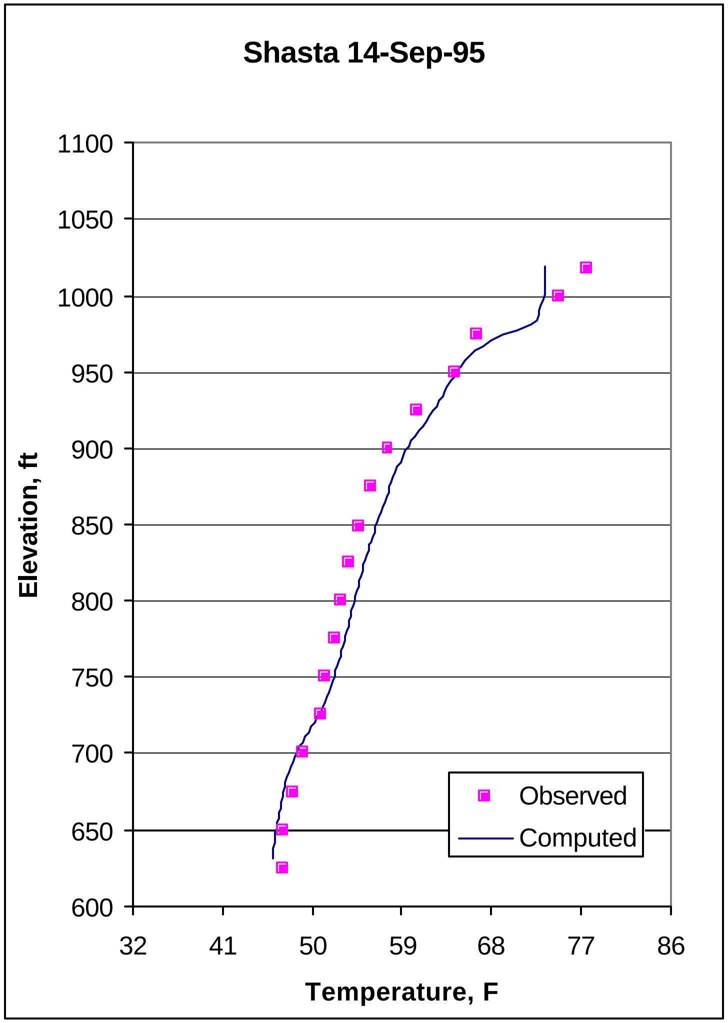


Figure 4-13 Computed and observed temperature profiles in Shasta Reservoir on September 14, 1995.

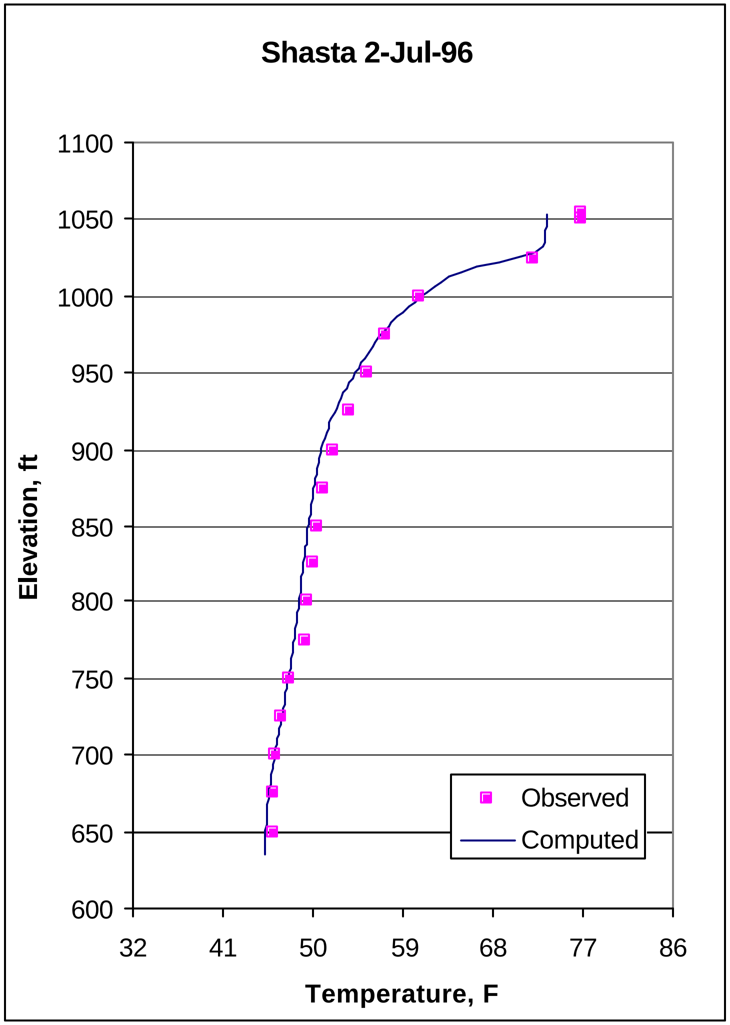


Figure 4-14 Computed and observed temperature profiles in Shasta Reservoir on July 2, 1996.

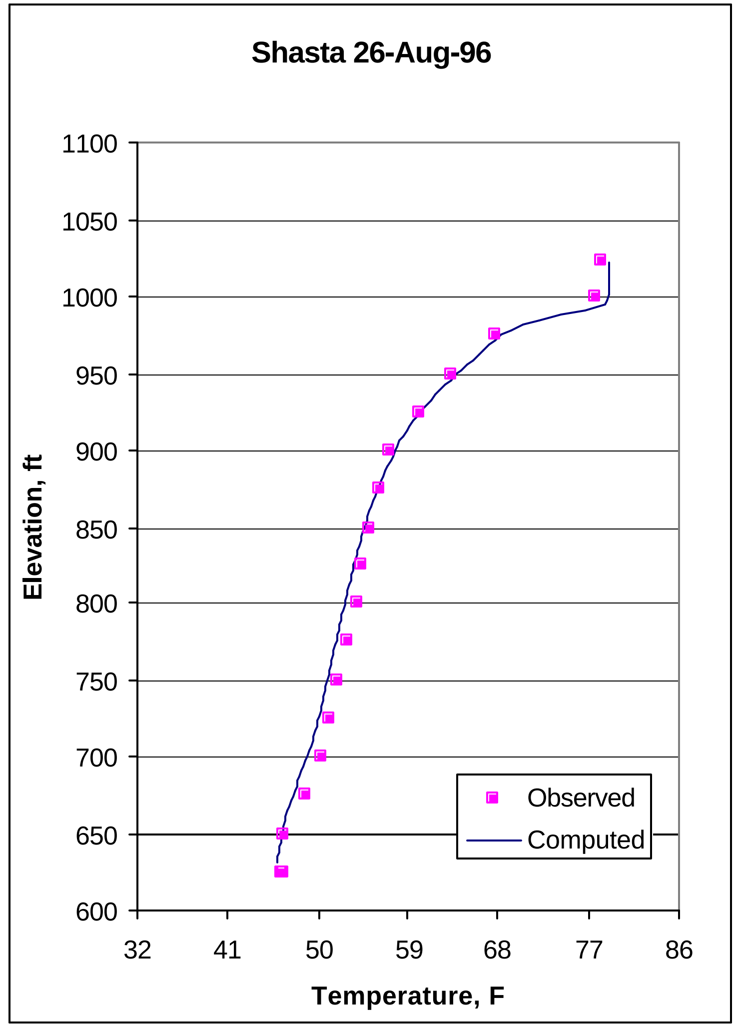


Figure 4-15 Computed and observed temperature profiles in Shasta Reservoir on August 26, 1996.

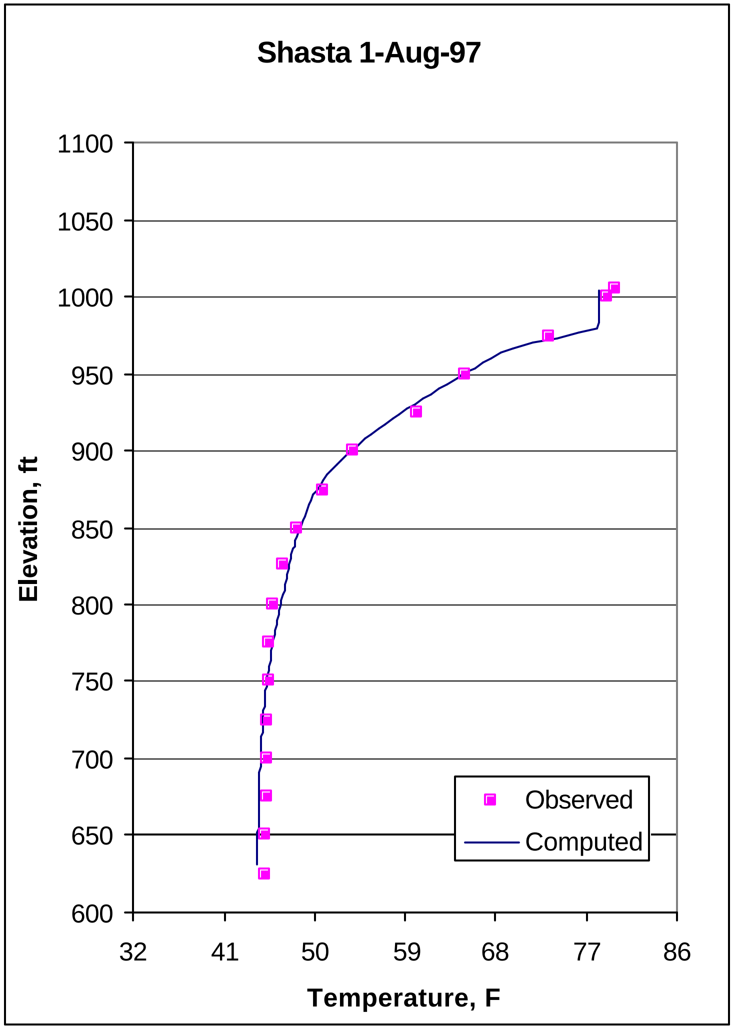


Figure 4-16 Computed and observed temperature profiles in Shasta Reservoir on August 1, 1997.

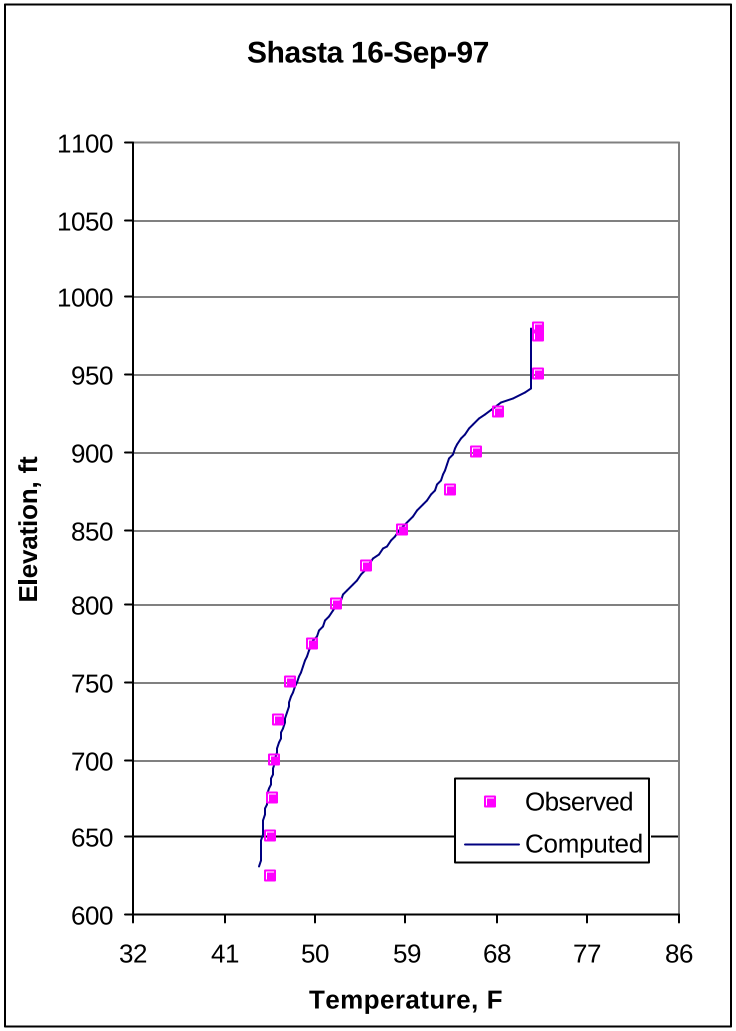


Figure 4-17 Computed and observed temperature profiles in Shasta Reservoir on September 16, 1997.

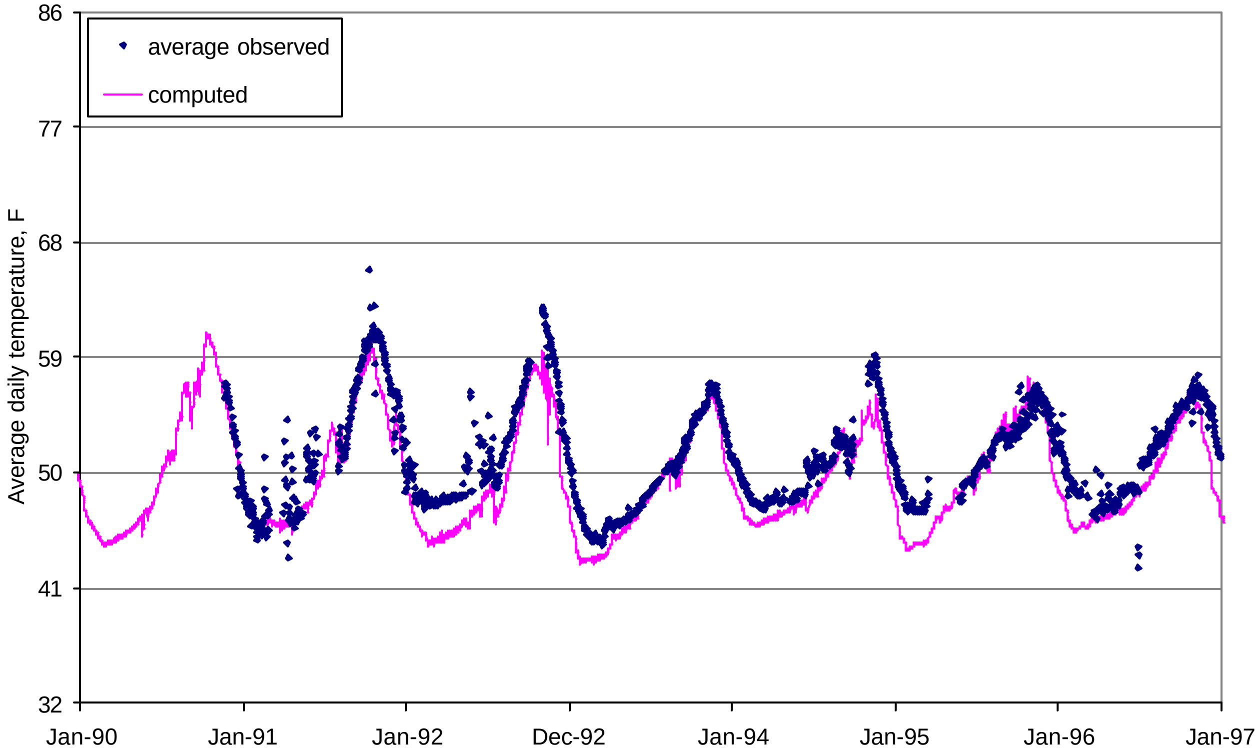


Figure 4-18 Computed and observed temperature time series in Sacramento River below Shasta Dam (with observed low level/penstock flow rates and no TCD).

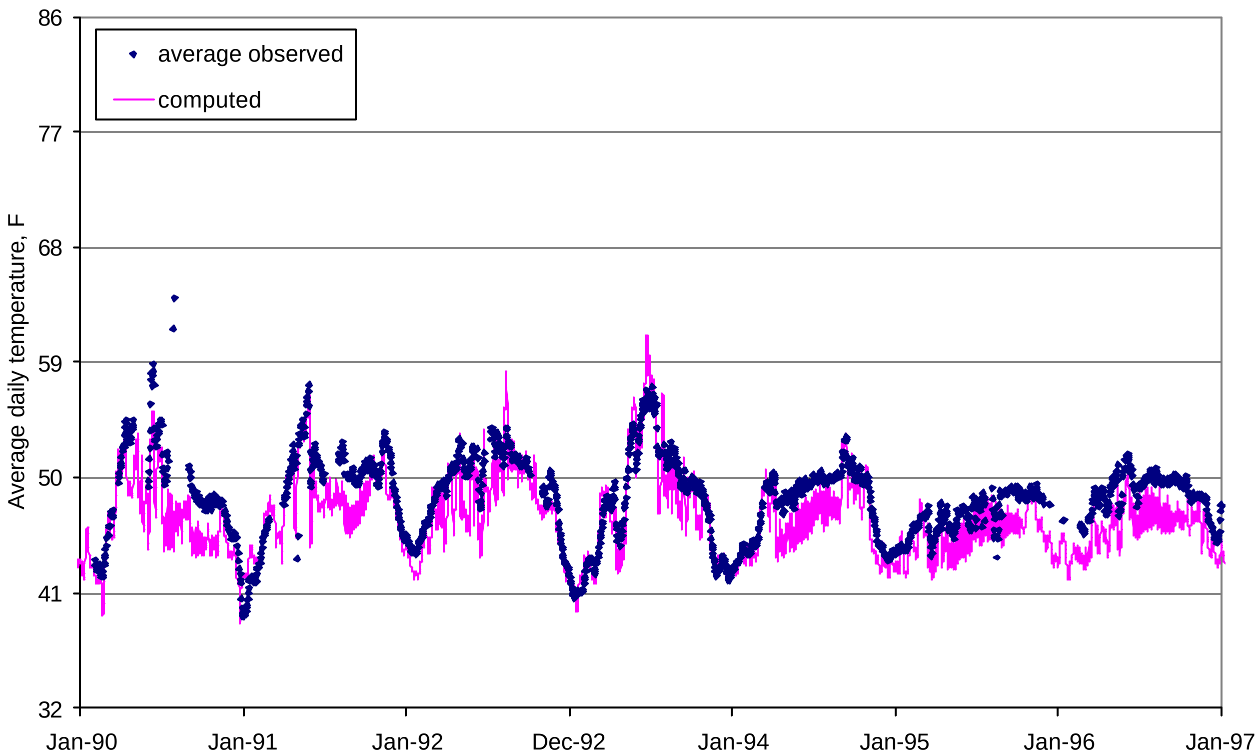


Figure 4-19 Computed and observed temperature time series in Trinity River at Lewiston.

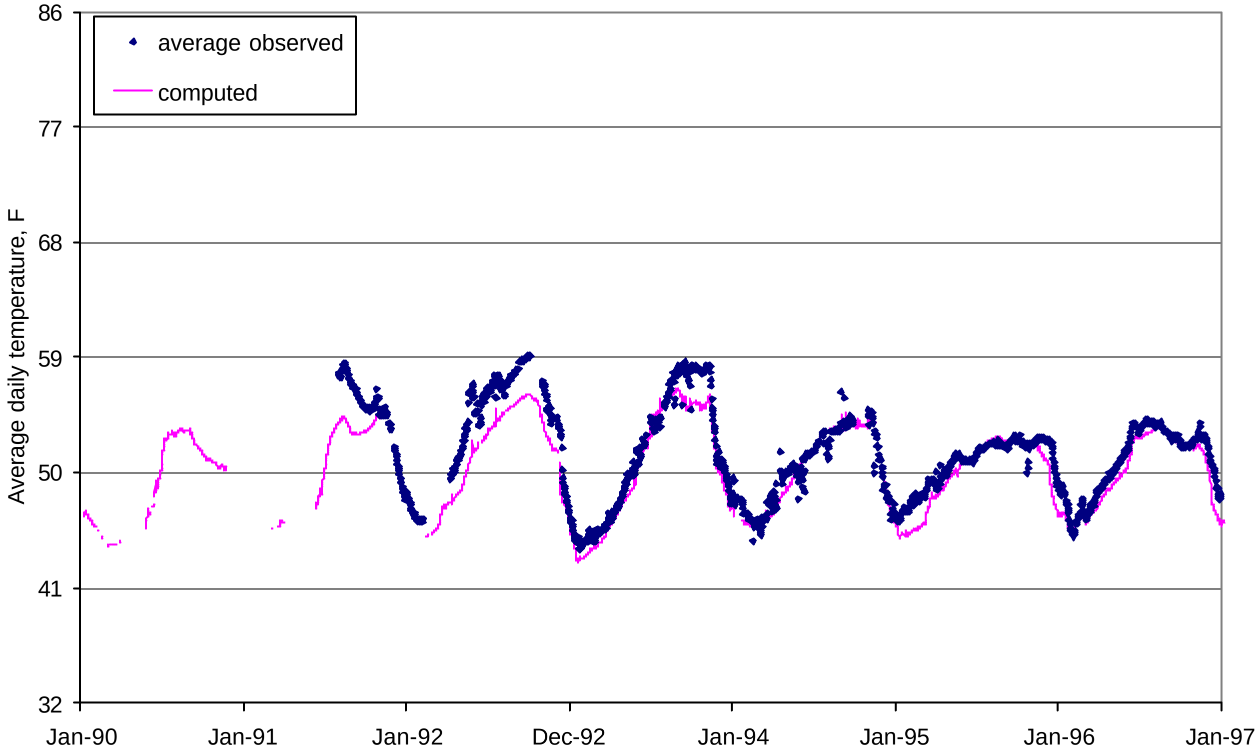


Figure 4-20 Computed and observed temperature time series in Spring Creek Powerhouse at Keswick.

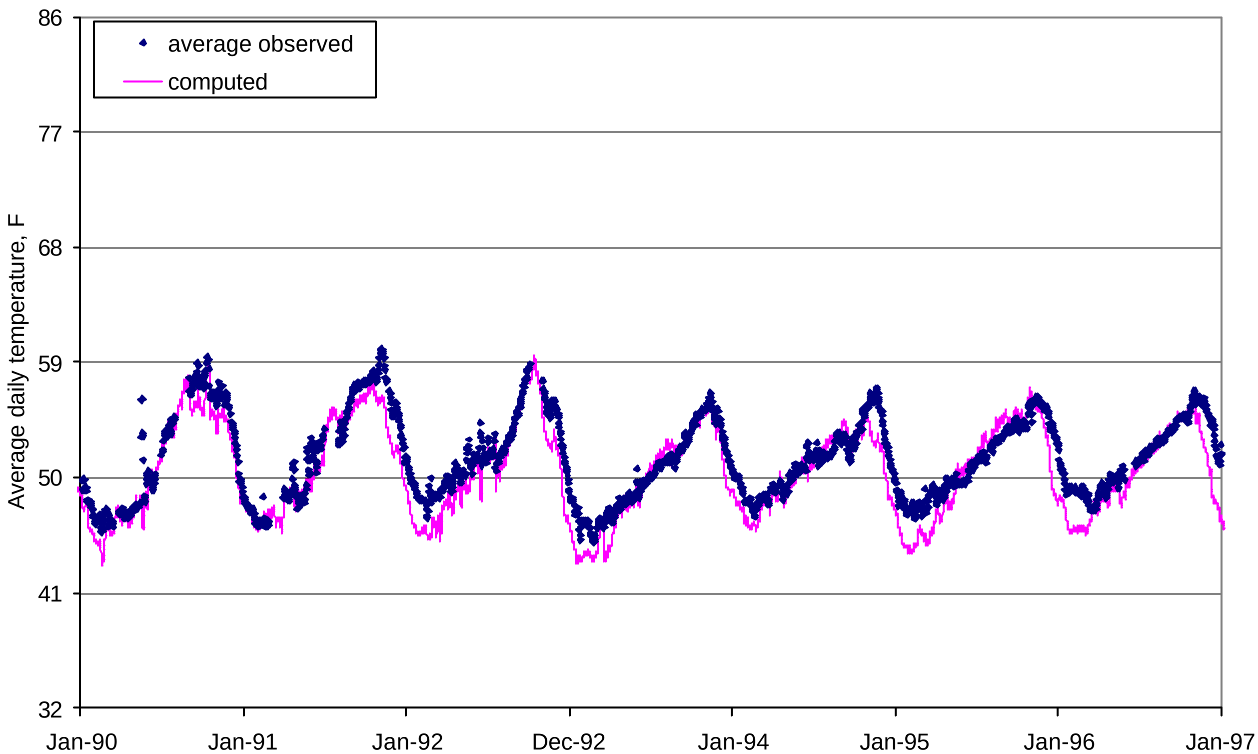


Figure 4-21 Computed and observed temperature time series in Sacramento River at Keswick.

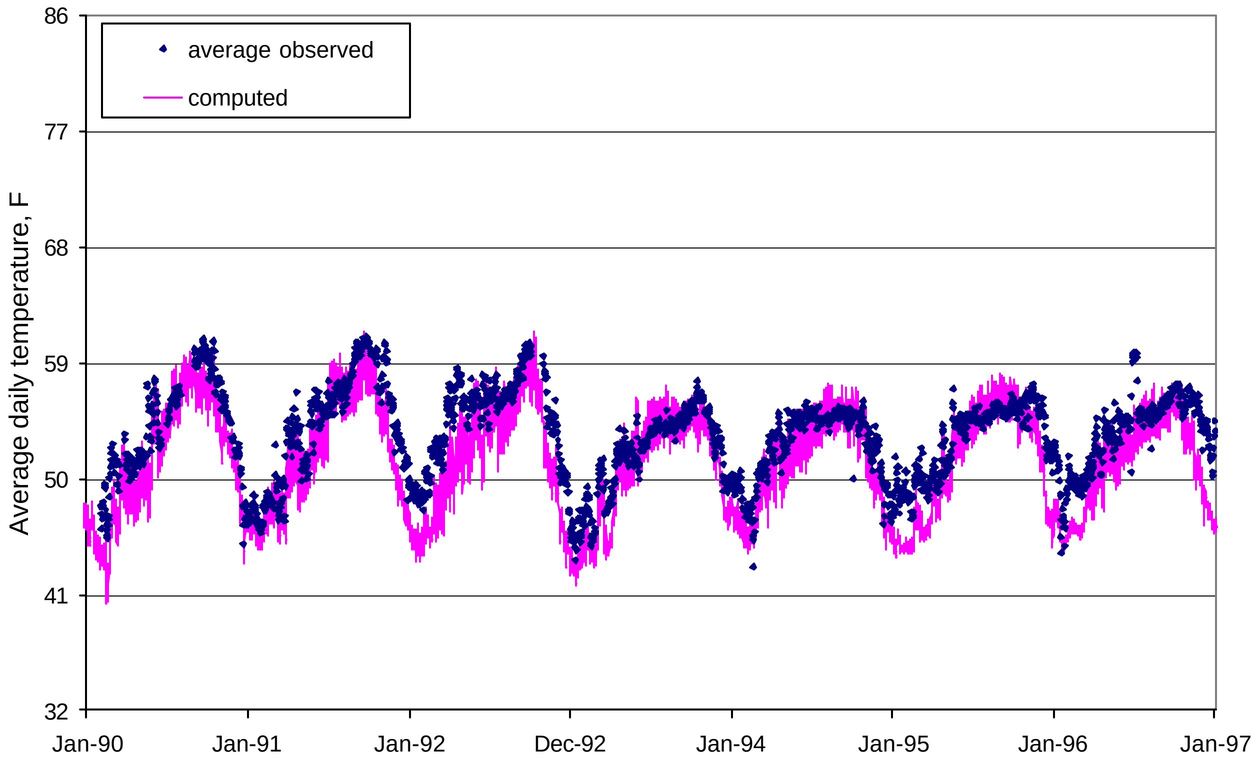


Figure 4-22 Computed and observed temperature time series in Sacramento River at Balls Ferry.

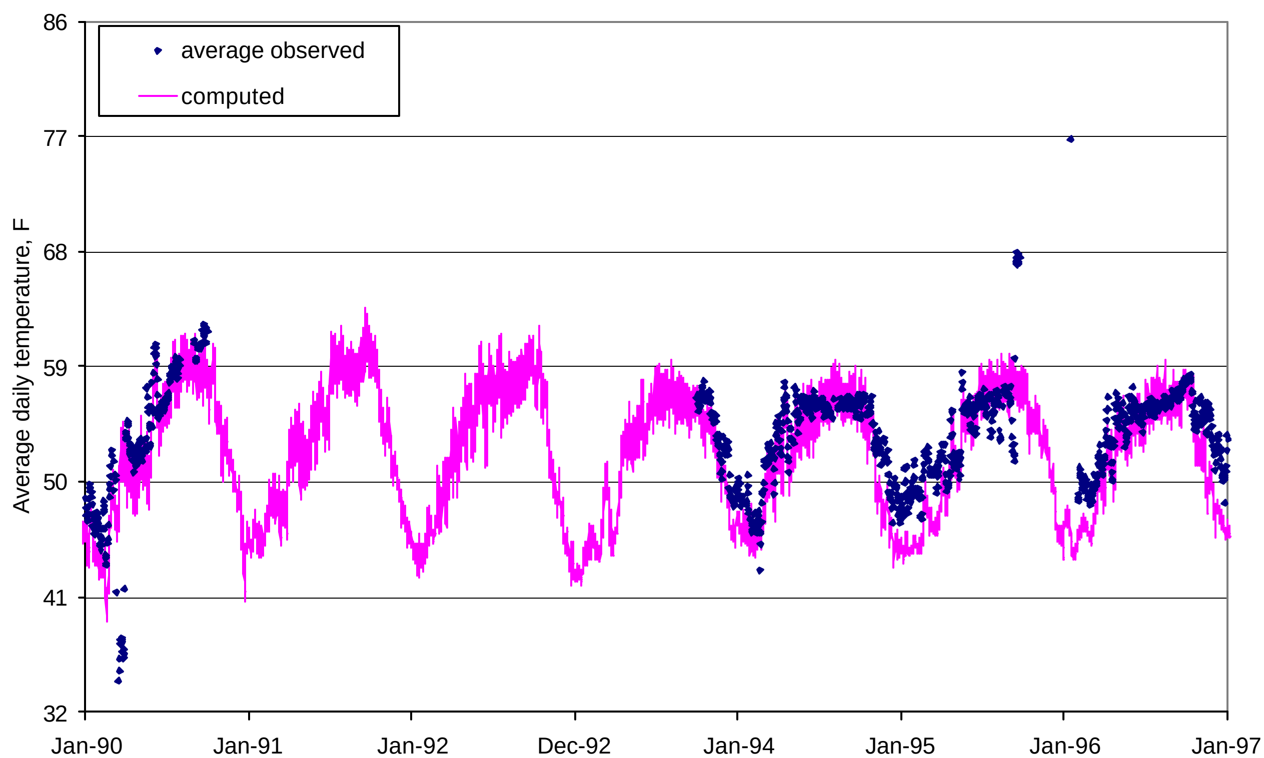


Figure 4-23 Computed and observed temperature time series in Sacramento River at Bend Bridge.

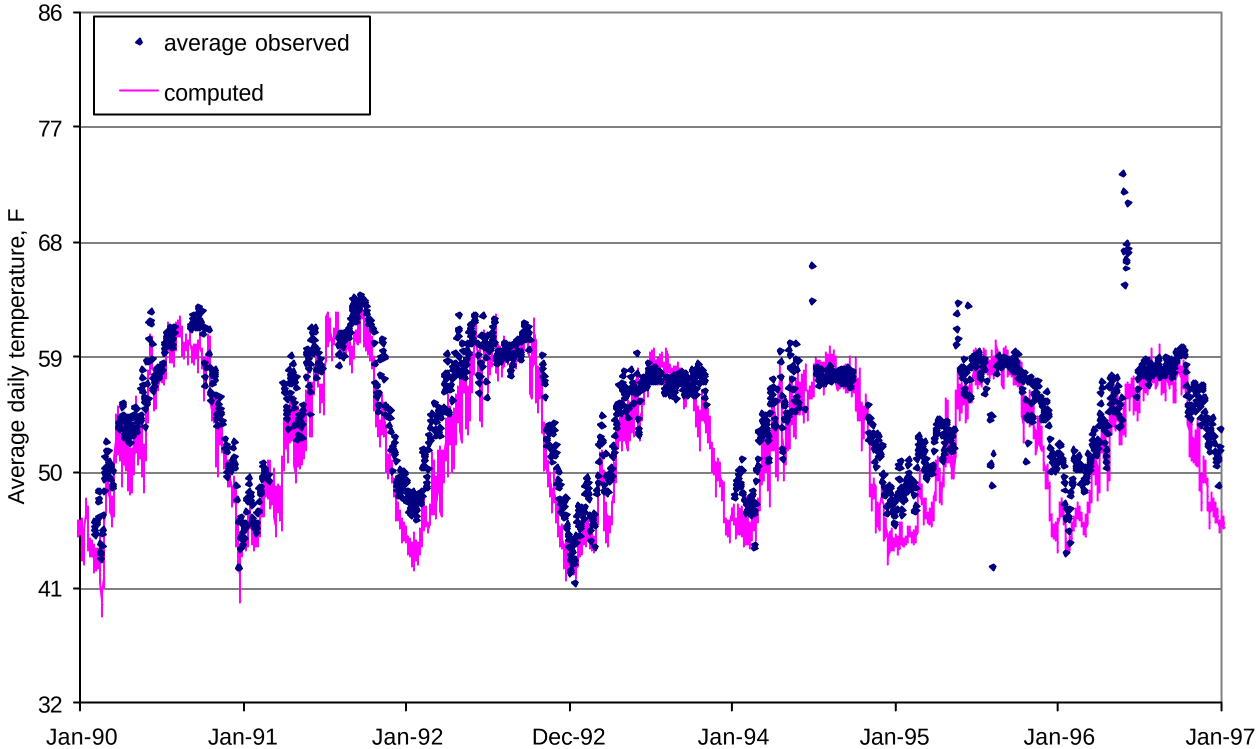


Figure 4-24 Computed and observed temperature time series in Sacramento River at Red Bluff Diversion Dam.

5 REFERENCES

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Hydrologic Engineering Center (HEC). 2000. “HEC-5, Simulation of Flood Control and Conservation Systems, Appendix on Water Quality Analysis”, Davis, CA.

Resource Management Associates (RMA), 1998. “HEC-5Q Simulation of Flood Control and Conservation Systems, Appendix on Water Quality Analysis,” Computer Program Manual, prepared for the Department of the Army, Corps of Engineers, Kansas City District, Kansas City, Missouri.

Resource Management Associates (RMA), 2002. “USBR-TMS Temperature Modeling System User’s Manual and Tutorial,” prepared for the U S Bureau of Reclamation, Sacramento, California.

U.S. Department of Interior, Bureau of Reclamation (USBR), 1999. “Shasta Temperature Control Device CFD Modeling Study”, Water Resources Research Laboratory, Denver, Colorado

6 APPENDICES

6.1 TEMPORAL DOWNSIZING OF CALSIM II FLOWS

For the Upper Sacramento River baseline and 18-foot enlarged Shasta scenarios, temporal downscaling was performed on the CALSIM II monthly average tributary flows to convert them to daily average flows for HEC5Q input. Monthly average flows are converted to daily tributary inflows based on 1921 through 1994 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 (Seven day trailing average for inflows below Butte City).

Each of the total monthly inflows specified by CALSIM II are scaled proportional to one of these three historical records.

Reservoir inflows were proportioned as defined above. Outflows and diversions are smoothed for a better transition at the end of the month without regard for reservoir volume constraints or downstream minimum flows. As flows are redistributed within the month, the minimum flow constraint at Keswick, Red Bluff and Knights Landing 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, Red Bluff and Knights Landing are satisfied by the following.

1) Redistribute TCC and GCC withdrawals up to the capacity of the conveyance facilities.
2) Reallocate Shasta outflows maintaining monthly outflow volume.
3) Increase Shasta release if 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).

Other flow considerations include the following.

1) Inflows (excluding returns) above Butte City are redistributed based on the Bend Bridge historical local flows.
2) Inflows below Butte City (valley streams) are redistributed based on the 7-day leading average of the Bend Bridge local inflow (attenuates the peaks to account for delayed runoff within the watershed).
3) Diversions to Sutter Bypass based on historical weir flows relative to river flows at Butte City.

A plot of Trinity and Shasta monthly average and daily average flows for October 1992 through September 1994 is shown in Figure 6-1.

6.1.1 CALSIM II Downscaling Utility

A utility program ("CALSIM25Q") has been developed to perform the conversion from CALSIM II monthly hydrology to daily inputs as required by HEC-5Q. The utility performs the following procedures.

1) Tabulate CALSIM II input and output data that reside in DSS files using standard DSS utility routines.
2) Extract pertinent DSS records.
3) Process data as described below and create an output file compatible with the DSS time series data entry utility (e.g., DSSTS IN=file.2ds).

The DSS records utilized for each reservoir are listed below.

Trinity Reservoir

Initial storage - /CALSIM/S1/STORAGE TAF

Surface Area - /CALSIM/A1/SURFACE-AREA ACRES

Evaporation ("/month) - /CALSIM/EVAP_S1/EVAPORATION-RATE IN

Evaporation (cfs) - /CALSIM/E1/EVAPORATION CFS

Inflow - /CALSIM/I1/FLOW-INFLOW TAF

Outflow - /CALSIM/C1/FLOW-CHANNEL CFS

Lewiston (constant storage)

Inflow - /CALSIM/I100/FLOW-INFLOW TAF

Outflow - /CALSIM/C100/FLOW-CHANNEL CFS

Diversion (Clear Cr. Tunnel) - /CALSIM/D100/FLOW-DELIVERY CFS

Whiskeytown

Initial Storage - /CALSIM/S3/STORAGE TAF

Surface area - /CALSIM/A3/SURFACE-AREA ACRES

Evaporation ("/month) - /CALSIM/EVAP_S3/EVAPORATION-RATE IN

Evaporation (cfs) - /CALSIM/E3/EVAPORATION CFS

Outflow - /CALSIM/C3/FLOW-CHANNEL CFS

Inflow - /CALSIM/I3/FLOW-INFLOW TAF

Diversion (Spring Cr. Tunnel) - /CALSIM/D100/FLOW-DELIVERY CFS

Diversion (Clear Cr. Tunnel) - /CALSIM/D3/FLOW-DELIVERY CFS

Shasta

Initial Storage - /CALSIM/S4/STORAGE TAF

Surface area - /CALSIM/A4/SURFACE-AREA ACRES

Evaporation ("/month) - /CALSIM/EVAP_S4/EVAPORATION-RATE IN

Evaporation (cfs) - /CALSIM/E4/EVAPORATION CFS

Outflow - /CALSIM/C4/FLOW-CHANNEL CFS

Inflow - /CALSIM/I4/FLOW-INFLOW TAF

Keswick *(constant storage)*

Diversion (inflow) - /CALSIM/D3/FLOW-DELIVERY CFS

Outflow - /CALSIM/C5/FLOW-CHANNEL CFS

Black Butte

Stony Creek at the Sacramento River - /CALSIM/I115/FLOW-INFLOW TAF

Black Butte Reservoir is not modeled in CALSIM II; therefore the following procedure is used to approximate reservoir operation. A typical annual volume distribution and minimum release pattern has been developed based on historical operation data. The CALSIM II Stony Creek at Sacramento River flow was assumed as inflow to the reservoir. After proportioning the monthly inflow to daily inflow, the outflow is computed as a function of the seasonal volume and minimum flow constraints.

6.1.2 Using CALSIM25Q

Prior to running the CALSIM25Q downscaling program, the HEC-DSS utility program "DSSUTL" is used to convert the CALSIM II DSS input and output to text format per the input requirements of CALSIM25Q.

Tabulate CALSIM II data using "**DSSUTL**"

Open the CALSIM II DSS input file – "**18ft_dsv.dss**"

Specify tabular format – "**fo (12f10.1)**"

Tabulate all monthly flows – "**ta.f a=calsim**" (assumes a common "a" part)

Name the output test file – "**18ft_dsv.txt**" (to be used as input in CALSIM25Q)

Exit DSSUTS utility program – "**fin**"

Repeat the process for the CALSIM II DSS output file

The following describes operation of the CALSIM25Q utility program that converts CALSIM II monthly flows to HEC5Q daily flows. Inputs and resulting output files for each combination of options are described. Bold values represent user input.

To pre-process DSS tabulated data for the enlarged Shasta scenario, the following example shows program prompts, user inputs and program output default file names:

```
Enter 1 for pre-processing DSS tabulated data or

       2 to create daily hydrology file for DSSTS

 ===>       1

 Enter 1 for enlarged Shasta or

       2 for baseline operation

       3 for other scenario

 ===>       1
```

Resulting output files are:

Default DSS input tab (12f10.1) file: 18ft_dsv.txt

Default DSS results tab (12f10.1) file: 18ft_ddv.txt

Table of all CALSIM II data (reference): 18ft.all

CALSIM II data used by the Upper Sac Model: 18ft_Rec.txt

Table of all DSS pathnames (reference): 18ft_index.I4

To create the daily hydrology file for the enlarged Shasta scenario:

```
 Enter 1 for pre-processing DSS tabulated data or

       2 to create daily hydrology file for DSSTS

 ===>       2

 Enter 1 for enlarged Shasta or

       2 for baseline operation

       3 for other scenario

 ===>       1

Project related CALSIM II data file:   18ft_rec.txt
```

Resulting output files is the DSSTS utility input file: DSSTS3.2ds (appended to 1920met.2ds)

Note: The meteorology data reside in the 1920met.2ds. For the default baseline condition [option 2] the DSSTS file is appended to DSSTS3.2ds to create DSSTS4.2ds. The DSSTS4.2ds file contains both sets of hydrology as well as the meteorological data.

To pre-process DSS tabulated data for other scenarios:

```
Enter 1 for pre-processing DSS tabulated data or
       2 to create daily hydrology file for DSSTS
 ===>      1
 Enter 1 for enlarged Shasta or
       2 for baseline operation
       3 for other scenario
 ===>      3
 DSS input tab (12f10.1) file:     18ft_dsv.txt
 DSS results tab (12f10.1) file:   18ft_ddv.txt
```

Resulting output files are:

Table of all CALSIM II data (reference): option3.all

CALSIM II data used by the Upper Sac Model: option3.txt

Table of all DSS pathnames (reference): option3.I4

To create the daily hydrology file for other scenarios:

```
 Enter 1 for pre-processing DSS tabulated data or
       2 to create daily hydrology file for DSSTS
 ===>      2
 Enter 1 for enlarged Shasta or
       2 for baseline operation
       3 for other scenario
```

```
===>        3

Project related CALSIM II data file: 18ft_rec.txt

DSS output file name: option3

"F" part for DSS path name: example
```

Resulting output file:

DSSTS utility input file, DSSTS5.2ds   (appended to 1920met.2ds)

The file “4tribs.dat” contains the historical tributary hydrographs and is utilized in all options.

The final step is to create the DSS input file for HEC-5 / 5Q by:

“**DSSTS in=dssts4.25Q**”

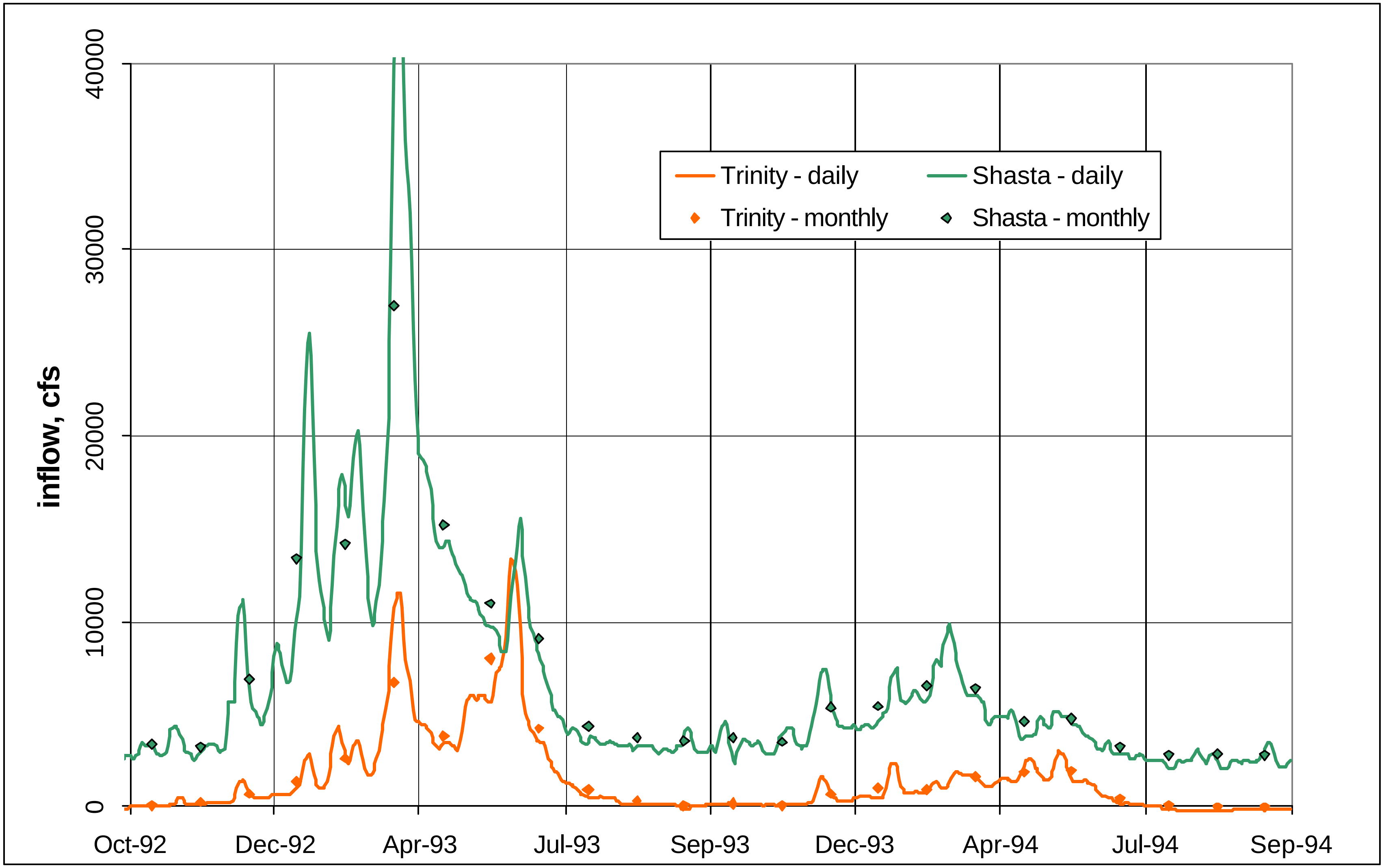

Figure 6-1 Trinity and Shasta CALSIM II monthly flows and downscaled daily flows.

6.2 POST-PROCESSOR

A post-processor is used to process HEC-5Q output and produce data that can be input to spreadsheets for plotting. Reservoir temperature profiles, seasonal time-series and accumulative temperature exceedance plots can be made. Following is a description of the post-processor options, inputs and outputs.

Option 1: A reservoir profile output file is created under the HEC-5Q LakeProFile option for multiple year output as described in Exhibit 3, section 2.9 of the HEC-5Q Users Manual. In the post-processor, Option 1 processes this output to summarize the minimum, 10%, median, 90% and maximum computed temperatures with depth at the four times during the year specified in the HEC-5Q data set. A semicolon separated text file (with an extension of *.amm) compatible with Excel is created. Example plots of this output are shown in Figure 6-2. Following is the post-processor input and output for this option. Note that user input values are shown in bold.

```
Enter 1 for reservoir profile option or
      2 for river time series option
=====>   1
HEC-5Q Reservoir profile output (LakeProFile option) file:
baseprof.2xl
```

Option 2: A river time series output file is created under the HEC-5Q EXCEL OUT option described in Exhibit 3, section 2.9 of the HEC-5Q Users Manual. The post-processor Option 2 is used to process this output to summarize the annual minimum, 10%, median, 90% and maximum computed temperatures for each output location. A comma separated text file (with an extension of *_TS.amm) compatible with Excel is created. Example plots of this output are shown in Figure 6-3.

A second optional feature allows the creation of a file that contains the accumulative temperature in excess of a user specified threshold at each of the river time series locations. A semicolon separated text file (with an extension of *_TS.exc) compatible with Excel is created. Example plots of this output are shown in Figure 6-4. Following is the post-processor input and output for Option 2 with user input values shown in bold.

```
Enter 1 for reservoir profile option or
      2 for river time series option
```

=====>   **2**

HEC-5Q stream time series output (EXCEL OUT option) file:

basets5.2xl

Temperature threshold for exceedance plots: **56.0**

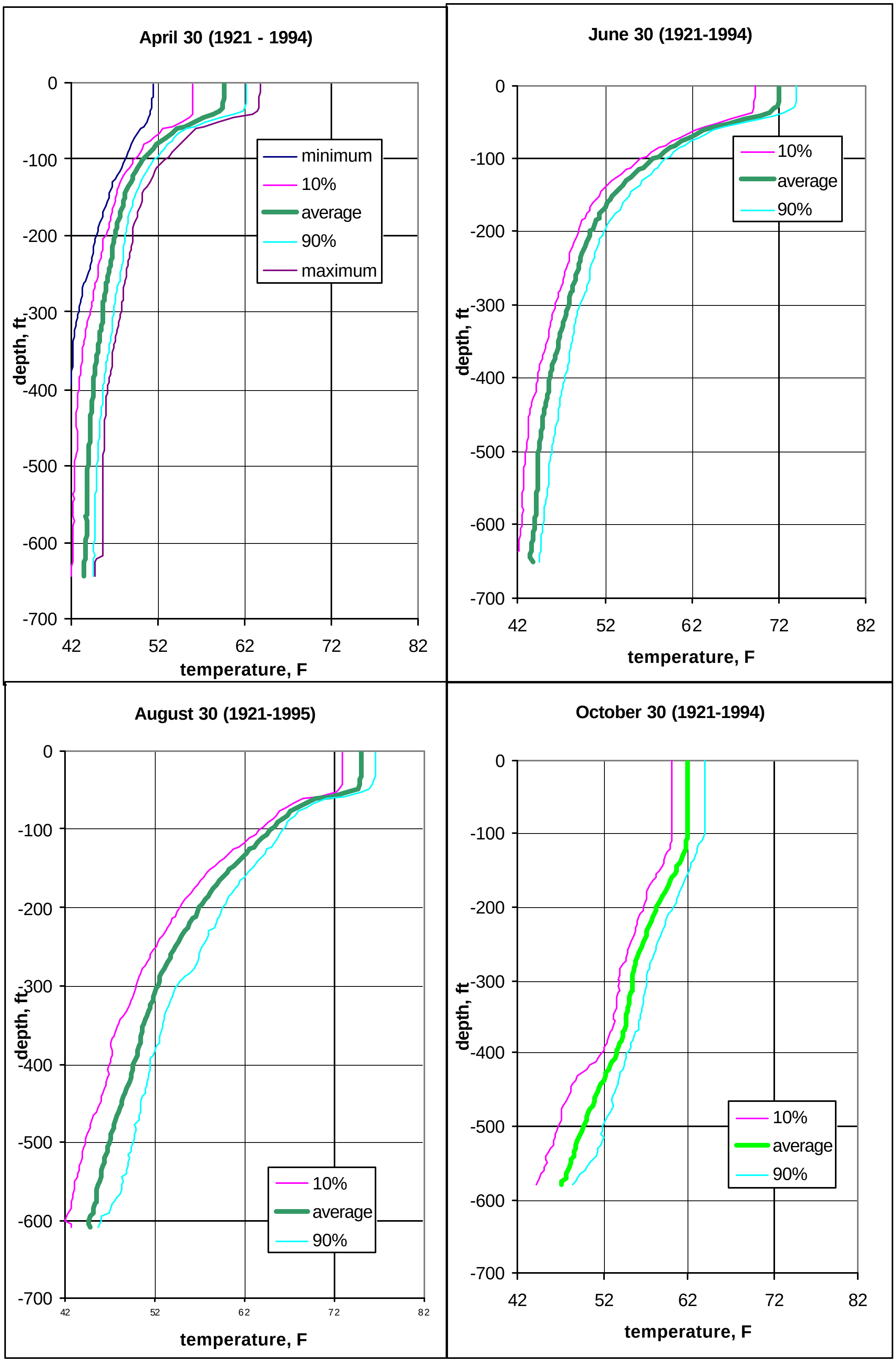

Figure 6-2 Example reservoir profile plots from post-processor Option 1.

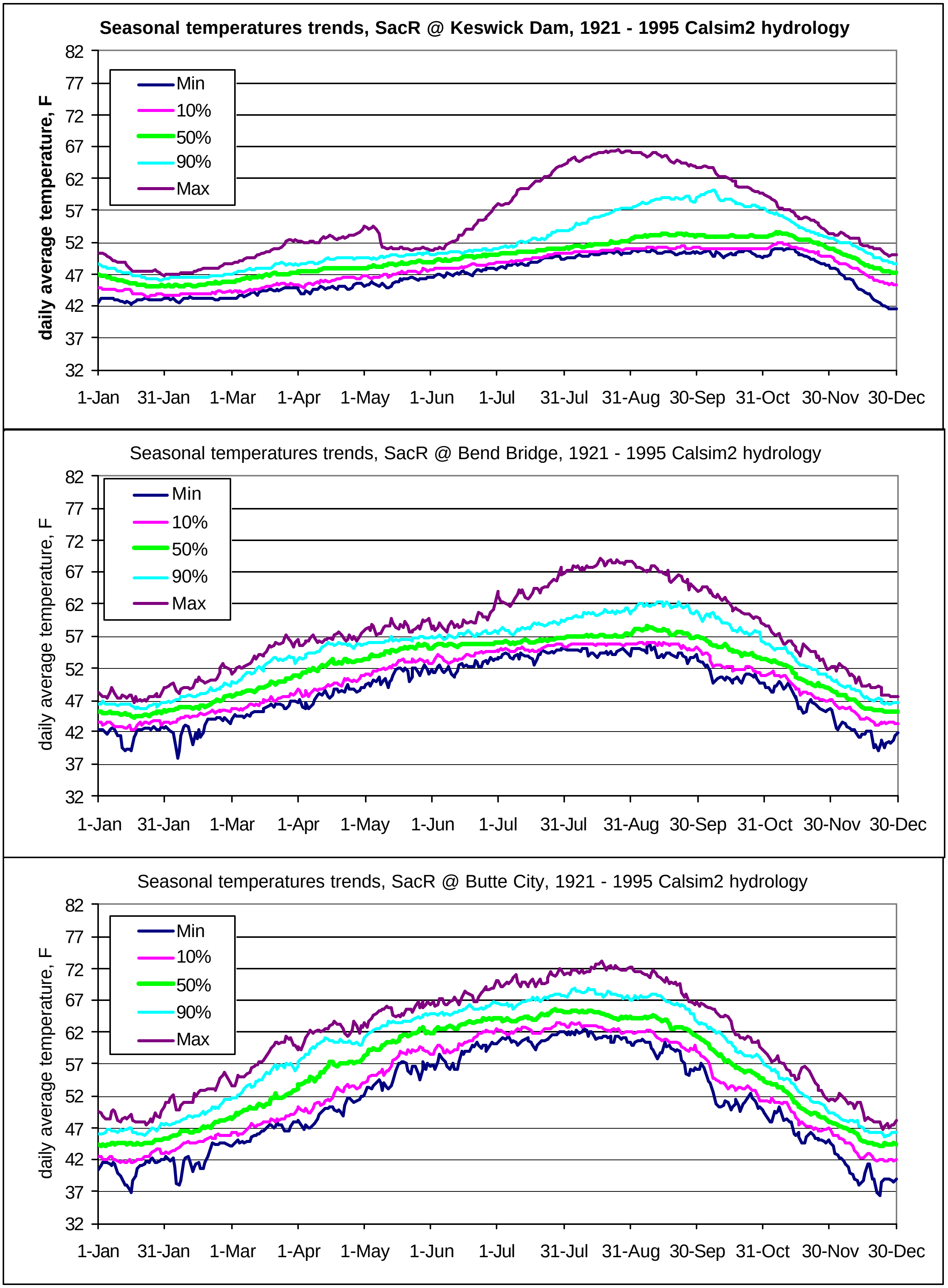

Figure 6-3 Example time series plots from post-processor Option 2.

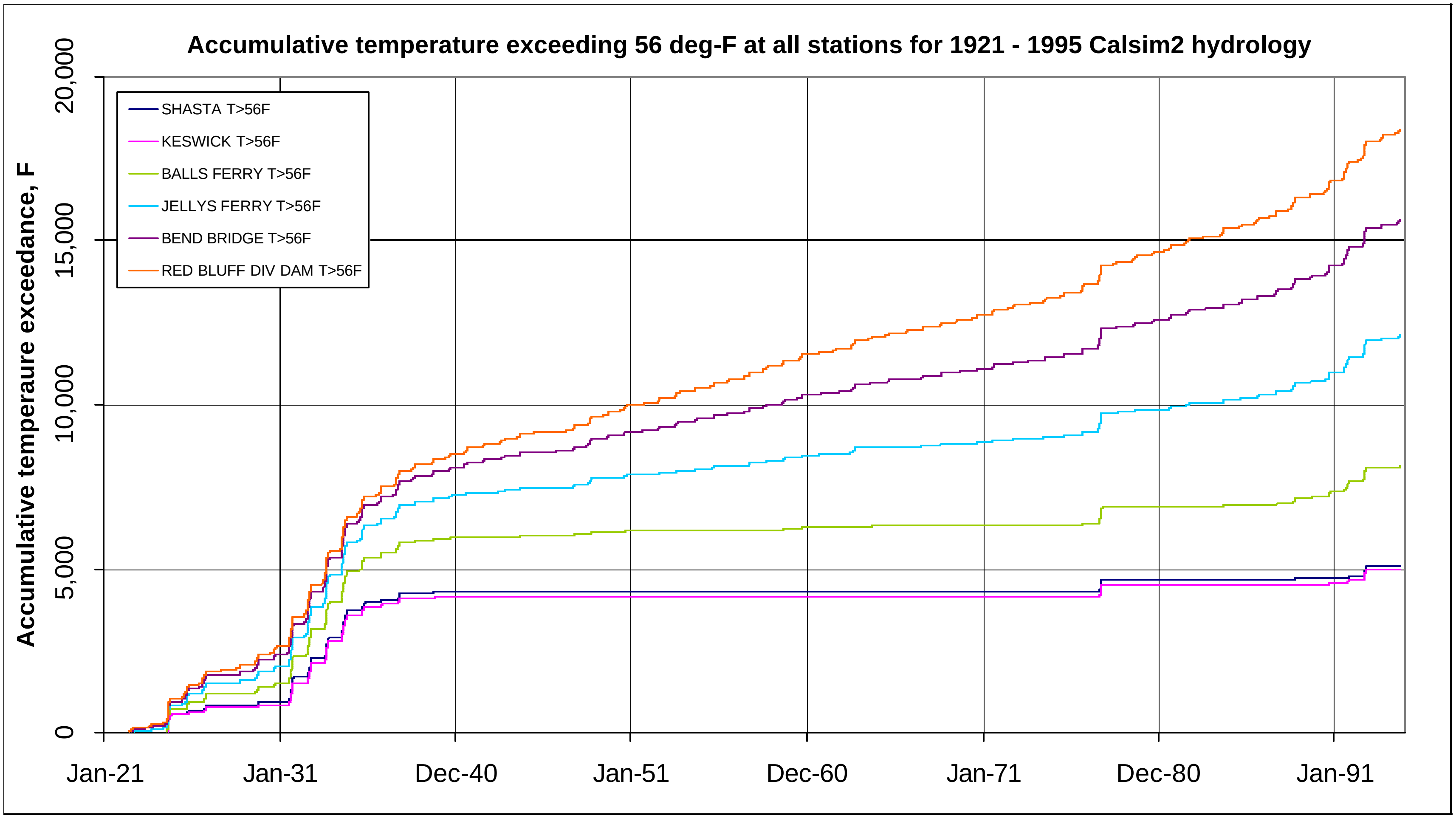

Figure 6-4 Example accumulative temperature time series plot from post-processor Option 2.

6.3 SHASTA DAM TEMPERATURE CONTROL DEVICE (TCD) OUTPUT

Project specific output is produced for the Shasta Dam TCD. A summary of the TCD operation is contained in two output files. The output is written for each time step. The user specified file (example: "Shasta Dam TCD opp file **base_TCD.out**") lists the flows in the first line and temperatures in the second line. The following describes the output by section. The numbers heading each table refer to the column numbers within the output table. The columns on the left in each table are inserted for description only and are not part of the output table.

The second row in the following table identifies the output option and the simulation date and time. Columns 1 through 6 list the date, water surface elevation (feet) and the number of gates that are open at each of the four gate levels. The second line lists the tailwater temperature objective (^oF) for TCD operation. The other fields are blank since the gate temperature is listed with the gate flow.

	1	2	3	4	5	6
	USBR Sacramento River specific: Run date and time: 13JAN04 - 10:50:51					
	date	elevation			gates open	
		target	top	middle	penstock	lower
flow	1-Oct-21	996.3	0	1	2	0
temperature		53.6				
flow	2-Oct-21	996.3	0	0	0	1
temperature		48.2				
flow	3-Oct-21	996.3	0	0	0	1
temperature		48.2				

Columns 7 through 11 list the flow (cfs) through each of the four gates, the total power generation flow (note that the total power generation flow includes TCD leakage) and the corresponding water temperature on the following line. Temperatures represent the water temperature through the open gates or the lake temperature at the gate centerline elevation when gates are closed.

	1	7	8	9	10	11
	date			gate flows		total
		top	middle	penstock	lower	power
flow	1-Oct-21	0	122	2626	0	4016
temperature		73.2	66.5	52.7	46.4	53.6
flow	2-Oct-21	0	0	0	2749	4016
temperature		73.2	66.8	52.7	46.4	48.2
flow	3-Oct-21	0	0	0	2749	4016
temperature		73.2	66.7	52.8	46.5	48.2

Columns 12 through 18 list the flow rate and corresponding temperature for each of the leakage zones considered by the TCD operation algorithm. The column labeled "over" (leakage from above the structure) has no flow since the water surface is below the top of the TCD. Column 17 includes flow from beneath the main TCD and accounts for well over half of the total leakage. Column 18 is the leakage through the low-level intake extension on the easterly side of the structure.

	1	12	13	14	15	16	17	18
	date				leakage			
		over	1000-945	945-900	900-831	831-804	804-780	780-750
flow	1-Oct-21	0	175	26	113	27	880	43
temperature			73.1	66.2	55.5	51.6	49.8	48.3
flow	2-Oct-21	0	175	26	113	27	880	43
temperature			72.8	66.2	55.4	51.5	49.7	48.3
flow	3-Oct-21	0	175	26	113	27	880	43
temperature			72.8	66.2	55.5	51.6	49.8	48.4

Columns 19 through 21 list the flow rate and corresponding temperature for the three flood control outlets and the gated spillway. These flows and are not associated with the TCD structure, however, temperature objectives are adjusted to account for downstream effects on tailwater temperature before operating the TCD. Note that the temperature fields are left blank if the flow is zero.

	1	19	20	21	22
	date		FC		spill
		top	middle	lower	
flow	1-Oct-21	0	0	0	0
temperature					
flow	2-Oct-21	0	0	0	0
temperature					
flow	3-Oct-21	0	0	0	0
temperature					

A second semicolon separated file, with the extension of "*.ssf", contains the same information on a single line to facilitate plotting in Excel.

The files are written in the "Shasta_TCD.for" routine that is specific to the TCD design. A summary of the TCD modeling approach and assumptions is provided in Section 2.3 of this report.