Temperature Modeling of Folsom Lake, Lake Natoma, and the Lower American River

Special Report
Sacramento County, California

U.S. Department of the Interior
Bureau of Reclamation
Mid-Pacific Region
Sacramento, California

U.S. Department of the Interior
U.S. Fish and Wildlife Service
Sacramento, California

Sacramento Water Forum
Sacramento, California

April 2007

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Temperature Modeling of Folsom Lake, Lake Natoma, and the Lower American River

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prepared by

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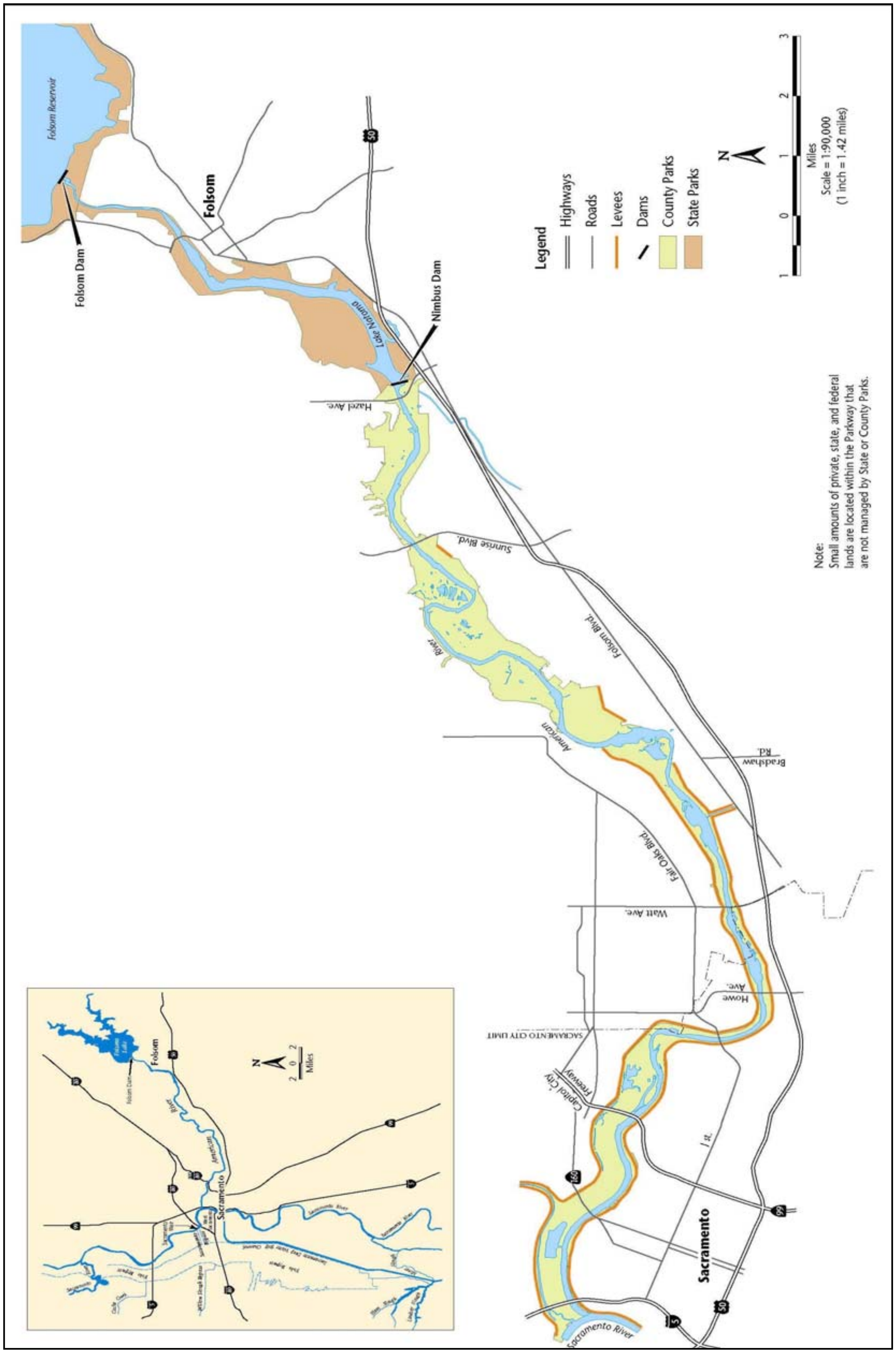

Figure 1.—Location map of the lower American River.

Abstract

The purpose of this study was to model and evaluate five identified actions that may improve transport of cold water through Lake Natoma and reduce the temperature of the lower American River. The five identified actions were a Nimbus Dam curtain, a Lake Natoma plunge zone curtain, Nimbus powerplant debris wall removal, dredging Lake Natoma, and modifying Folsom Powerplant peak loading operation. Folsom Lake and Lake Natoma were modeled with hourly data to investigate seasonal, daily, and hourly thermal variations. Observations for additional actions beyond the five identified actions are based on limited information and incomplete investigation and may require more modeling.

Four models were used in this study. Calibrated CE-QUAL-W2 two-dimensional mathematical flow and temperature models were assembled for both Folsom Lake and Lake Natoma. Near-field hydrodynamic effects for ½ kilometer (1/3 mile) of Lake Natoma just upstream from Nimbus Dam (Nimbus Dam forebay) were modeled with a three-dimensional (FLOW-3D) computational fluid dynamics (CFD) model, using a quasi-steady-state assumption. A one-dimensional ADYN/RQUAL unsteady flow and temperature model representing major riffles and pools was assembled for the tailwater reach from Nimbus Dam to the Sacramento River.

Modeling of Folsom Lake indicated that changing operations from existing peak-loading operations to more continuous base-loading operations results in undesirable warmer releases from Folsom Dam.

Modeling of Lake Natoma indicated that construction of a curtain near Nimbus Dam or alteration to the debris wall could slightly reduce the temperature of releases from Nimbus Dam. Modeling indicated that a dam curtain provides more temperature reduction than debris wall alteration. Dredging of Lake Natoma may provide a slight reduction in Nimbus Dam release temperature. A plunge zone curtain would undesirably increase release temperatures due to more mixing.

A calibrated one-dimensional flow and temperature model was used to determine sensitivity of meteorology, release temperature, and release rate on tailwater temperatures from Nimbus Dam to just past Watt Avenue Bridge, a 21.7 kilometer (13.5 mile) reach. Of these three variables, Nimbus Dam release temperature had the most significant impact on tailwater temperature.

Improvements in the transport of cold water through Lake Natoma could be made with a temperature curtain at Nimbus Dam, modification of the debris wall, and dredging Lake Natoma. Construction of a removable L-shaped Nimbus Dam forebay curtain, acting as a skimmer wall, around the powerplant penstock intakes should be optimized to reduce vorticity and debris removal concerns and designed for optimal safety. A physical modeling study of the forebay is recommended.

Acknowledgments

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The TSC primary modeling team members that contributed substantially to the success of this project included Merlynn Bender, Joe Kubitschek, Tracy Vermeyen, James Higgs, Annette Turney, and Jason Wagner. Merlynn Bender acted as the TSC team lead, served as primary author, and was responsible for one-dimensional and two-dimensional modeling. Joe Kubitschek was responsible for the three-dimensional modeling, served as co-author, and provided partial internal peer review.

Overall internal TSC peer review was done by Tracy Vermeyen who also participated significantly in the early stages of the project and served as co-author. Tracy's initiative and extra efforts were instrumental in developing the foundation for the project.

Independent external peer review was done by Rod Hall. Rod Hall provided coordination and oversight for the Water Forum. Rod's project knowledge, guidance, and coordination were critical to project success.

Reclamation peer review of the final report was done by Jim Yahnke, a senior physical scientist and water quality specialist.

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Tables

Acronyms and Abbreviations

1-D	one-dimensional (fully mixed riverine models)
2-D	two-dimensional (laterally averaged reservoir models)
3-D	three-dimensional (models)
ABS	absolute error
ADYN/RQUAL	flow and temperature one-dimensional river model
AFD	American River below Folsom Dam (CDEC station name)
AFRP	Anadromous Fish Restoration Program
AMSL	above mean sea level
AGPM	Animator and Graphics Portfolio Manager
AROG	American River Operations Work Group
ARP	South Fork American River near Pilot Hill (CDEC station name)
BO	Biological opinion
BOD	Biochemical oxygen demand
CDFG	California Department of Fish and Game
CE-QUAL-W2	COE 2-D mathematical flow and water quality model
CDEC	California Data Exchange Center
CFD	Computational fluid dynamics (model)
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
CALFED	California Federal Bay-Delta Program
CCOMWP	Sacramento City-County Office of Metropolitan Water Planning (Sacramento Water Forum)
cfs	cubic feet per second
CIMIS	California Irrigation Management Information System
COE	U.S. Army Corps of Engineers
°C	degree Celsius
°F	degree Fahrenheit
DO	dissolved oxygen
EID	El Dorado Irrigation District
EMS-I	Environmental Management System, Inc.
ERP	Ecosystem Restoration Program
ESA	Endangered Species Act
ESU	Evolutionary Significant Unit
FAVOR	Fractional Area/Volume method
FA study	Lower American River Temperature Improvement Study Function Analysis Report study
ft/s	feet per second
FLOW-3D	Three dimensional model, using computational fluid dynamics
km	kilometer
LAR	lower American River
LARM	lower American River mile from mouth

m	meter
m/s	meter per second
mg/L	milligram per liter
M&I	municipal and industrial
MP	Mid-Pacific (regional office of Reclamation)
NFA	North Fork American River at Auburn dam (CDEC station name)
NOD	nitrogenous oxygen demand
NMFS	National Marine Fisheries Service (NOAA Fisheries)
NOAA	National Oceanic Atmospheric Administration
OCAP	Operations, Criteria, and Plan
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
RMS	root mean square error
RMS4	River Modeling System 4
SCUBA	Self-contained underwater breathing apparatus
SWP	State Water Project
TCD	temperature control device
TIN	triangular irregular network
TSC	Reclamation's Technical Service Center (Denver)
USGS	U.S. Geological Survey
WMS	Watershed Modeling System
Work Group	American River Operations Work Group
WSC	wind sheltering coefficient

Helpful metric and English unit conversion factors

Flow:
1,000 cfs = 28.32 m^3/s
0.0283 m^3/s = 1 cfs

Temperature conversion equations:
°C = (°F -32.0)*(5/9)
°F = °C * (9/5) + 32.0

Distance:
0.3048 m = 1 ft
1 m = 3.281 ft
1 mile = 1.609 km
1 km = 0.621 miles

Summary

Folsom Lake, the deep storage reservoir located just upstream of Lake Natoma, has strong thermal stratification, Folsom Dam peaking power, and is used to provide cool water for the lower American River. Lake Natoma, a small re-regulation reservoir with run-of-the-river flows, has weak thermal stratification with significant natural heating during summer flow operating conditions (Water Forum, FISH Plan, 2001, page 6-17). Cold water released from Folsom Dam warms as it passes through Lake Natoma during the warmer seasons. Aquatic biological resources, primarily anadromous salmonid fish (fall-run Chinook salmon and steelhead), can be adversely affected by warm temperatures in the lower American River downstream from Nimbus Dam in Sacramento County, California. Several structural and operational modifications at Lake Natoma and Folsom Dam were identified to potentially improve the efficiency of transporting cold water though Lake Natoma for release through Nimbus Dam into the lower American River. This modeling study was conducted to evaluate the effectiveness of five suggested structural and operational modifications at Lake Natoma and Folsom Dam, hereafter referred to as the “identified actions.”

Identified Actions

The following structural and operational actions were identified as likely to reduce temperatures in the lower American River downstream from Nimbus Dam (CCOMWP-USBR Agreement, 2003):

- Install a temperature control curtain immediately upstream of Nimbus Dam.
- Install a mid-reservoir temperature control curtain downstream from Lake Natoma’s plunge point — the location where Folsom’s cool inflow plunges beneath Lake Natoma’s warm surface water.
- Remove the submerged debris (barrier) wall in front of Nimbus Dam powerplant intakes.
- Modify the old river channel in Lake Natoma by dredging.
- Modify Folsom Dam powerplant’s peak loading operation.

Each of and combinations of these identified actions were modeled with hourly flow, temperature, and meteorological inputs and are presented in this report.

Flow and Temperature Dynamics

Lower American River ecology and water quality are dependent on Nimbus Dam release temperatures, Folsom Dam peaking power operations, and draining or filling of Folsom Lake. The dynamics of mixing and interflows (momentum driven layers of different temperature and density) between the branches of Folsom Lake, seiching (sloshing) in Lake Natoma, and diel (day and night) meteorological variations produce dynamic responses that change the Nimbus Dam tailwater temperatures hourly. Field data and modeling indicate that warm summer temperatures and large summer releases could deplete the cold water volume in Folsom Lake before autumn. Furthermore, wind mixing and convective mixing caused by large flows moving through the relatively shallow Lake Natoma increases Nimbus Dam release temperatures. However, efforts are being made to minimize the warm release temperatures in the summer and autumn by selectively withdrawing cool mid-level waters from Folsom Lake in the spring and early summer to preserve cold water in storage for use during autumn.

Models

Two separate two-dimensional CE-QUAL-W2 reservoir models, a three-dimensional computational fluid dynamics (CFD) FLOW-3D model for the Nimbus Dam forebay, and a one-dimensional ADYN/RQUAL tailwater model were assembled and calibrated for flow and temperature to better understand the effects of interflows and reservoir operations on Folsom Lake, Lake Natoma, and the lower American River downstream from Nimbus Dam to the confluence with the Sacramento River. These state-of-the-art fully-hydrodynamic unsteady-flow models were used for sensitivity analyses and for simulations of the five identified actions.

CE-QUAL-W2 Reservoir Modeling

Two CE-QUAL-W2 models were developed, one for Folsom Lake and one for Lake Natoma. Folsom Lake and Lake Natoma seasonal thermal stratification patterns were simulated from January 1, 2001, to December 31, 2003, using hourly model input data. The Folsom Lake and Lake Natoma models were calibrated with data for calendar years 2001, 2002, and 2003 to cover a range of hydrologic conditions. Calendar year 2001 was a low inflow year; 2002 was below average inflow; and the high spring flow events of 2003 produced near-average annual inflow. Operations have been improved since 2003. Therefore some of the conclusions of this report have been implemented.

Using a two-dimensional array of longitudinal and vertical elements, the hydrodynamic CE-QUAL-W2 model calculates flow exchange and heat budget. The model simulates the warm surface layer (epilimnion) floating over the denser cold bottom water (hypolimnion). Currently, a small amount of cold hypolimnetic water is trapped temporarily upstream of the Nimbus Powerplant's intake barrier structure which was designed to prevent bedload material from passing through the penstocks and turbines. This barrier structure is herein referred to as the debris wall. The debris wall is part of the upstream dam apron. A larger amount of cold water is stored for months upstream in the hypolimnion of Folsom Lake. Peaking power releases from Folsom Dam and continuous baseload releases withdrawn over the debris wall at Nimbus Dam causes sloshing which mixes Lake Natoma. The hourly diel heat budget includes drybulb and dewpoint temperatures, solar radiation, wind mixing, convective cooling, and inflow density distribution.

The CE-QUAL-W2 model of Folsom Lake (1-meter layers and 35 active longitudinal segments in two branches) was developed to investigate existing selective withdrawal and proposed operational alternatives at Folsom Dam. The only identified action simulated and analyzed for Folsom Lake was the shifting from peaking hydropower operations to a continuous baseload hydropower operation.

The separate CE-QUAL-W2 model of Lake Natoma (1/2-meter layers and 19 active longitudinal segments in one branch) was used to model the temperature changes due to proposed structural or channel changes upstream of Nimbus Dam or in Lake Natoma. Changes at Nimbus Dam were investigated more thoroughly since much has been done or is proposed at Folsom Dam to reduce release temperatures to the lower American River for salmonids and may require future investigations. The remaining four identified actions were modeled with the Lake Natoma CE-QUAL-W2 model individually, and combinations or variations of the four identified actions were also simulated to investigate cumulative benefits.

Complete removal of the debris wall to trashrack centerline elevation 26.46 meters (m) (86.81 feet above mean sea level [AMSL]) was investigated using the Lake Natoma W2 model. A Nimbus Dam curtain installation with a curtain bottom elevation at 30.37 m (99.64 feet AMSL) was investigated with the W2 model. A shallow plunge zone curtain 3.79 kilometer (km) (2.35 miles) upstream of Nimbus Dam and with a curtain bottom elevation at 32.37 m (106.2 feet AMSL) was investigated with the W2 model. A shallow curtain was modeled mid-reservoir with the W2 model to limit horizontal velocities to less than 0.15 meter per second (0.5 ft/s) under most typical peaking power release conditions. Dredging 382,277 cubic meters (500,000 cubic yards) from the bottom of Lake Natoma was modeled using the Lake Natoma W2 model.

CE-QUAL-W2 Results

When compared to the Lake Natoma model simulations, the Folsom Lake model simulations indicated that peaking power operations and selective withdrawal at Folsom Dam reduced heating of the lower American River more than changes at

Nimbus Dam. The Folsom continuous baseload hydropower simulation, when compared to the historical peaking hydropower condition, indicated that setting the temperature shutters at different levels on each unit and then varying the percentage of time that each unit is operated showed the most temperature reduction of lower American River temperatures downstream from Folsom Dam. This is currently being done as part of normal operations. Comparing the model output of intermittent peak-load operations relative to more continuous base-load operations indicates that changing to base-load operations would result in the undesirable increase of Folsom Dam release temperatures. Interflows flushing cold water through Folsom Lake increased with continuous baseload releases and decreased with intermittent peaking releases. In addition, baseload operations minimized diurnal (daily cycling) stratification and mixed Folsom Lake warm surface and cool bottom waters, which resulted in warmer Folsom Dam release temperatures throughout the summer and fall months

The Lake Natoma W2 model was used to investigate seasonal stratification, proposed structural alternatives, and dredging. The W2 model simulated wide versus narrow Nimbus Dam curtains, deep versus shallow curtain bottom elevation, dredging 382,277 cubic meters (500,000 cubic yards) of sediment, partial versus complete removal of the debris wall, and other combinations.

W2 modeling indicated that dam curtain installation at Nimbus Dam would reduce the two-week moving average of the noon and midnight release temperatures by about 0.2 degree Celsius (°C) (0.36 degree Fahrenheit [°F]) during the summer of a dry year. A curtain located just upstream around the powerplant intakes and one that extended the full width of the dam produced nearly identical reduction of Nimbus Dam release temperatures.

Additional mixing generated by substantial flow velocity under a mid-Lake Natoma plunge zone curtain in this relatively shallow reservoir increased mixing of the reservoir and slightly, but undesirably, increased Nimbus Dam release temperatures. A mid-reservoir curtain would also obstruct boating and other recreational activity.

W2 modeling indicated that removing the top 8.5 meters (27.9 feet) of the debris wall would decrease two-week moving average release temperatures by about 0.15 °C (0.27 °F) during the summer and autumn of a dry year and less during wetter conditions.

Modeling indicated that dredging about 382,277 cubic meters (one-half million cubic yards) of sediment from Nimbus Dam to a point 3.9-km (2.4-mile) upstream appeared to minimally decrease the two-week moving average release temperatures by about 0.1 °C (0.18 °F) during the summer and autumn of a dry year and less during wetter conditions. Such a large amount of dredging would increase the volume of Lake Natoma by about 4 percent of full pool. A small amount of forebay sediment near and upstream of Nimbus Dam hydropower penstock intakes may need to be dredged to remove sediment or channel obstructions for optimization of potential structural alternatives.

Typically, average summer releases would be reduced by about 0.5 °C (0.9 °F) if a combination of a Nimbus Dam curtain, an undesirable plunge zone curtain, removal of the debris wall, and dredging 382,277 cubic meters (500,000 cubic yards) occurred (not including Folsom Dam operational changes).

Based on the Lake Natoma CE-QUAL-W2 results for alternatives showing temperature reduction potential, the concepts were refined using the three-dimensional FLOW-3D CFD model of the Nimbus Dam forebay.

FLOW-3D Modeling and Results

To augment the CE-QUAL-W2 model, the three-dimensional CFD model (FLOW-3D) of the Nimbus Dam forebay was used to investigate near-field and smaller scale effects of the debris wall and an intake curtain located just upstream of the debris wall with a fine grid of 1.5 meters (5-foot grid). For this computationally intensive CFD model, the forebay, including about a half kilometer (a third of a mile) upstream from Nimbus Dam, was modeled. The CFD model indicated that either installing a deep curtain near the Nimbus Powerplant intakes or removing the debris wall would decrease Nimbus Dam release temperatures during periods of strong stratification in Lake Natoma. The combination of both a curtain and debris wall removal did not further reduce release temperatures since the curtain effectively controlled the withdrawal zone and negated the effect of the debris wall.

A Nimbus Dam curtain, acting to hold warm surface water upstream, is expected to reduce Nimbus Dam release temperatures by a maximum of 1.2 °C (2.2 °F) under conditions of strongest stratification in Lake Natoma. During less stratified conditions, expect less than 1.2 °C (2.2 °F) release temperature reduction with a curtain in Nimbus Dam forebay. Debris wall removal is expected to reduce Nimbus Dam release temperatures a maximum of 1.0 °C (1.8 °F) under conditions of strongest stratification in Lake Natoma. As thermal stratification breaks down, the benefits will decrease.

These results represent the greatest temperature reductions that can likely be achieved with the modeled dam curtain and debris wall removal options since the benefit of these modifications decreased with the strength of stratification in Lake Natoma. Partial debris wall removal was also considered and the effect was almost indistinguishable from complete debris wall removal. However, this result is likely a function of the debris wall top elevation such that the temperature reduction will range from that for the existing condition to that for the partial debris wall removal considered.

Presently, surface vortex formation located upstream of the Nimbus Powerplant intakes exists and may be considered undesirable from both air and warm surface water entrainment standpoints. Debris wall removal or installation of an intake curtain may increase or decrease vortex strength depending on the near-field approach flow and water surface elevation conditions. A better understanding of the issues associated with vortex formation and strength will require further investigation and is best achieved via laboratory physical modeling which incorporates varying flow and water surface elevation conditions to eliminate many of the assumptions required for a three-dimensional mathematical CFD model.

ADYN/RQUAL 1-D Modeling and Results

A one-dimensional (1-D) flow and temperature model was used to investigate the longitudinal variation in lower American River (LAR) temperatures downstream from Nimbus Dam. Detailed geometry was developed from about 160 channel cross-sections ranging from the Nimbus Dam tailwater to the confluence of the LAR and the Sacramento River. The July through August 2001 period was used for 1-D model calibration and this period includes a decrease in dam release rate from 2,100 cubic feet per second (cfs) to 1,500 cfs.

Modeled water travel time from Nimbus Dam to Watt Avenue Bridge at 2,000 cfs is about 16 hours. Cool afternoon releases from Folsom Dam heat up through Lake Natoma during the warm sunny portions of the day. If cool water could be released from Folsom Dam early evening and cooler water could be released at midnight from Nimbus Dam, afternoon temperatures in the lower American River reach just upstream of Watt Avenue Bridge might be reduced. However, such scenarios were outside the scope of this report and may require more study.

1-D modeling showed that Nimbus Dam release temperature had more effect on temperature reduction than typical Nimbus Dam release rates or warm meteorology, which suggested that alternatives to reduce release temperature at Folsom Dam, may reduce Lake Natoma temperatures, and have temperature reduction potential for the Nimbus Dam releases.

Summary Conclusions and Recommendations for Identified Actions

Following are conclusions and recommendations for each of the five identified actions.

- Install a temperature control curtain immediately upstream of Nimbus Dam

Of the identified actions investigated for Lake Natoma, installing a temperature control curtain just upstream of the powerplant and debris wall (i.e., immediately upstream of Nimbus Dam) provided the greatest temperature reduction. Alternatives in Nimbus Dam forebay, such as a temperature curtain, are more effective for reducing Nimbus Dam release temperatures than dredging or a mid-reservoir plunge zone curtain in Lake Natoma. On the basis of a combination of 2-D and 3-D modeling, as well as engineering experience, the maximum relative difference in temperature between a dam curtain and the existing condition may be 1.2 °C (2.2 °F) for an hour or more, depending on hydrodynamic conditions. W2 modeling indicated that installing a curtain just upstream of Nimbus powerplant and debris wall may temporarily reduce or increase Nimbus Dam release temperatures, depending on hydrodynamic and thermal conditions. However, with a Nimbus Dam curtain, overall there are more periods of temperature reduction during warm meteorological conditions. Based on W2 modeling and a two week moving average, release temperature reduction with a dam curtain were about 0.2 °C (0.36 °F) during warm months. Also, a dam curtain may reduce vortex formation and may facilitate trash removal.

If this curtain is selected for further investigation and design, a laboratory physical modeling study of Nimbus Dam forebay may be necessary to optimize the design and positioning and to reduce vortex formation and trash removal concerns.

- Install a mid-reservoir temperature control curtain downstream from Lake Natoma's plunge point — the location where Folsom's cool inflow plunges beneath Lake Natoma's warm surface water.

A plunge zone curtain is not recommended because of increased reservoir mixing, which resulted in higher Nimbus Dam release temperatures. In addition to its undesirability from a temperature reduction perspective, a plunge zone curtain also would result in mid-reservoir restrictions on recreation and boat travel. Installing a plunge zone curtain in combination with other actions reduced the effectiveness of the other actions.

- Remove the submerged debris (barrier) wall in front of Nimbus Dam powerplant intakes

Based on 3-D CFD modeling, debris wall removal is expected to reduce Nimbus Dam release temperatures a maximum of 1.0 °C (1.8 °F) under conditions of strongest stratification in Lake Natoma. Based on W2 modeling, removing the submerged debris wall reduced Nimbus Dam release temperatures by about 0.15 °C (0.27 °F) on a summer two-week moving average and was less effective at reducing temperatures than a Nimbus Dam forebay curtain. Partial removal or port cutting (to provide continued protection of the Nimbus Dam powerplant intakes from debris during catastrophic floods) of the debris wall to potentially minimize vortex formation, to enhance temperature reduction, and to prevent protrusive effects due to a curtain could be less costly than dam curtain installation and maintenance, and it may provide power generation benefits. However, any structural modifications to Nimbus Dam and associated benefits would need to be thoroughly investigated before such a recommendation could be made.

- Modify the old river channel in Lake Natoma by dredging

Based on W2 modeling with the debris wall already removed, additionally dredging 382,277 cubic meters (500,000 cubic yards), a relatively large amount of sediment, reduced Nimbus Dam release temperatures by about 0.10 °C (0.18 °F) on a summer two-week moving average and was less effective at reducing temperatures than solely a Nimbus Dam forebay curtain or solely debris wall removal. Straightening and deepening a large portion of the channel by dredging 382,277 cubic meters (500,000 cubic yards) of sediment from just upstream of the island located 2.4 river miles (3.9 kilometers) upstream of Nimbus Dam through the boating race course and upstream of Nimbus Dam to the debris wall could provide a deeper and straighter conduit for cold water to be carried more quickly downstream. The sloshing of water due to headwater and flow reversals forces warm water to travel back upstream and then back downstream quickly. That mixing in the middle of Lake Natoma reduced the quantity of cold water reaching Nimbus Dam. Narrow spots in Lake Natoma could be dredged or a large swath dredged to deepen the channel. Total removal or partial removal of the top portion of the debris wall, as well as dredging the underwater hill in the forebay, would allow cool water to pass less restricted through Lake Natoma during critical warm periods of the year. However, localized dredging of small areas was not modeled because of the small cooling potential.

- Modify Folsom Dam powerplant’s peak loading operation

W2 modeling of Folsom Lake indicated that operational or structural alternatives to provide lower release temperatures from Folsom Lake may generate larger lower American River temperature reductions than temperature reductions generated by the identified actions for the shallow Nimbus Dam and Lake Natoma system. Timing of peaking power releases from Folsom Dam affects Nimbus Dam release temperatures; however, this was not studied in detail. Based on modeling continuous flows versus peaking power flows, potential temperature reduction alternatives at Folsom Lake and Dam are likely more effective at cooling Nimbus Dam tailwater that those at Nimbus Dam and Lake Natoma.

I. Introduction

Cool water temperatures are needed during warm seasons in the lower American River to protect steelhead trout (*Oncorhynchus mykiss*) and fall-run Chinook salmon (*Oncorhynchus tshawytscha*). The purpose of this Folsom Lake, Lake Natoma, and the lower American River temperature modeling study is to develop predictive flow and temperature models for evaluating the effectiveness of potential physical and operational alternatives for more efficient transport of cold water through Lake Natoma. This mathematical modeling assessment provides information on the potential temperature benefits of constructing temperature curtains, dredging the channel in Lake Natoma, modifying or removing the debris wall at Nimbus Dam, and changing Folsom Dam powerplant operations. The alternatives considered were selected based on their conceptual potential to benefit the management of available cold water from Folsom Reservoir to maintain adequate temperatures in the lower American River for steelhead and fall-run Chinook salmon.

In recent years, it has became apparent that on an annual basis there is a limited amount of cold water in Folsom Lake to provide adequate temperatures for both steelhead trout and fall-run Chinook salmon in the lower American River. Steelhead trout in the lower American River are listed as threatened pursuant to the federal Endangered Species Act. The water in Folsom Lake that is less than 15.56 °C (60 °F) is known as the “cold water pool” and is selectively managed to maintain target temperatures in the lower American River. As cold water releases from Folsom Dam flow through Lake Natoma, they are warmed by meteorological conditions during the spring, summer and early fall. To maintain target temperatures in the lower American River, it is necessary to release water from Folsom Lake that is colder than the target temperature to compensate for the warming in Lake Natoma and the lower American River.

Releases of cold water from Folsom Lake are managed using the temperature control device (TCD) on Folsom Dam’s turbine penstocks. By manipulating the shutters on the TCD and selectively operating the units, release temperatures can be controlled. Cold water at the bottom of Folsom Lake that cannot be released through the turbine penstocks can be released through the river outlets. However, this requires by-passing the turbines and results in lost hydrogeneration. A TCD located on the M&I intake at Folsom Dam has been operating since May 2004.

Prior to 2000, Reclamation’s operation to control water temperature in the LAR was primarily to meet temperature requirements for spawning salmon during the fall. Subsequent to the listing of steelhead as threatened, Reclamation released cold water from Folsom Lake to meet the needs of over-summering juvenile steelhead. Meeting the needs of both salmon and steelhead greatly taxes the availability of cold water in Folsom Lake (Water Forum, 2005, page 28), and it became apparent that innovative operational and structural measures would be required to protect both species.

In January 2001, Reclamation conducted a functional analysis temperature improvement study for the LAR (Bureau of Reclamation, 2001). During the warm part of the year, releases from Folsom Dam increase in temperature passing through Lake Natoma, which is a relatively shallow reservoir. The results of the study identified operational and structural proposals to improve water temperatures in the LAR by improving the efficiency of moving cold water through Lake Natoma. The following five structural and operational actions were identified as likely to reduce temperatures in the lower American River, and are referred to as the "Identified Actions."

- Install a temperature control curtain immediately upstream of Nimbus Dam
- Install a mid-reservoir temperature control curtain at Lake Natoma's plunge point
- Remove the debris wall in front of Nimbus Dam powerplant intakes
- Modify the channel in Lake Natoma
- Modify Folsom Dam powerplant's peak loading operation

Before implementing any of these proposals, it was decided to determine their effectiveness for water temperature reduction, which required the development and use of 1-, 2-, and 3-dimensional mathematical models. This modeling study uses and builds on data collected and analyzed for the report entitled, "Lake Natoma Temperature Curtain and Channel Modification Study, 2001-2002," (Vermeyen, 2005).

The most significant stressor affecting steelhead in the LAR appears to be high summer water temperatures. Starting in 2000, Reclamation began releasing colder water from Folsom Lake during the summer to provide more suitable cool temperatures for steelhead. During spring 2003, the temperature control device (TCD) for the water supply intake at Folsom Dam began operation.

II. Site Description

Folsom Dam is located on the American River about 31 miles upstream of its confluence with the Sacramento River in Sacramento County, California and forms Folsom Lake (see figure 1, the frontispiece map). Nimbus Dam is located about 23 miles upstream of the confluence and forms Lake Natoma which is operated as an afterbay for Folsom Dam. The authorized purposes of Folsom and Nimbus Dams, which are operated by Reclamation, are to provide flood control, water supply for agricultural, municipal, and industrial use, water quality, recreation, fish and wildlife, and power generation. Peak-loading power operations at Folsom Dam are absorbed by Lake Natoma and constant releases are made from Nimbus Dam to the lower American River.

Folsom Dam, one of the principal features of the American River Division of the Central Valley project (CVP), is about 40.2 kilometers (25 miles) northeast of Sacramento, California and about 3.7 kilometers (2.3 miles) northeast of Folsom (Ferrari, 1995). The historic submerged confluence of the North and South Forks of the American River is less than a mile (1.6 kilometers) upstream of Folsom Dam. The American River drains into the Sacramento River, and the Sacramento River drains into the Sacramento-San Joaquin Delta. Chili Bar Reservoir is located upstream of Folsom Lake on the South Fork of the American River. French Meadows Reservoir, on the Middle Fork American River, and Hell Hole Reservoir, on the Rubicon River, are on the North Fork arm of the American River. The tailwater of Folsom Dam is the headwater of Lake Natoma.

III. Model Descriptions

The CE-QUAL-W2 model version 3.1 (Cole and Wells, 2002), which is well-suited for two-dimensional reservoir temperature modeling in stratified environments, was used for Folsom Lake and Lake Natoma hydrodynamic temperature modeling. The FLOW-3D version 8.2 (Flow Science, Inc., 2003) was used for modeling the 3-D velocities and temperatures in the forebay area (about 0.5 kilometer (one-third mile)) upstream of the Nimbus Dam powerplant intakes to provide greater detail than the 2-D model. The ADYN/RQUAL model, River Modeling System version 4 (RMS4), which is well suited for one-dimensional completely mixed longitudinal dynamic riverine flow and temperature modeling, was used for the LAR downstream from Lake Natoma.

Both W2 and RMS4 use a version of the Animator and Graphics Portfolio Manager (AGPM) to facilitate model input and output development. CE-QUAL-W2 outputs results in metric units and some results were converted to English units during post-processing. ADYN/RQUAL and FLOW-3D outputs results in English units or mixed metric and English units.

Discussions of model calibrations, results, and conclusions and recommendations are presented individually for CE-QUAL-W2, FLOW-3D, and ADYN/RQUAL in sections V, VI, and VII, respectively.

CE-QUAL-W2

The CE-QUAL-W2 model is a two-dimensional, laterally averaged, hydrodynamic water quality multiple branch model that allows long-term simulation of both riverine and reservoir flow exchange, heat budget, and dissolved oxygen (DO) conditions. DO concentrations were not modeled for this study. The model represents boundary geometry with longitudinal segments (figure 2) and vertical layers. Model elements are laterally averaged from bank to bank of the water body. The CE-QUAL-W2 model simulates water quality constituents as a function of longitudinal and vertical location and time for transient hydraulic, meteorological, and inflow temperature conditions. CE-QUAL-W2 was developed by the Army Corps of Engineers (COE) (Vicksburg, Mississippi) and is public domain software (Cole and Wells, 2002).

CE-QUAL-W2 has been used successfully for a variety of applications and investigations, including:

- Minimal pools for fish refuge volume
- Seasonal thermal, nutrient, and organic loading reductions

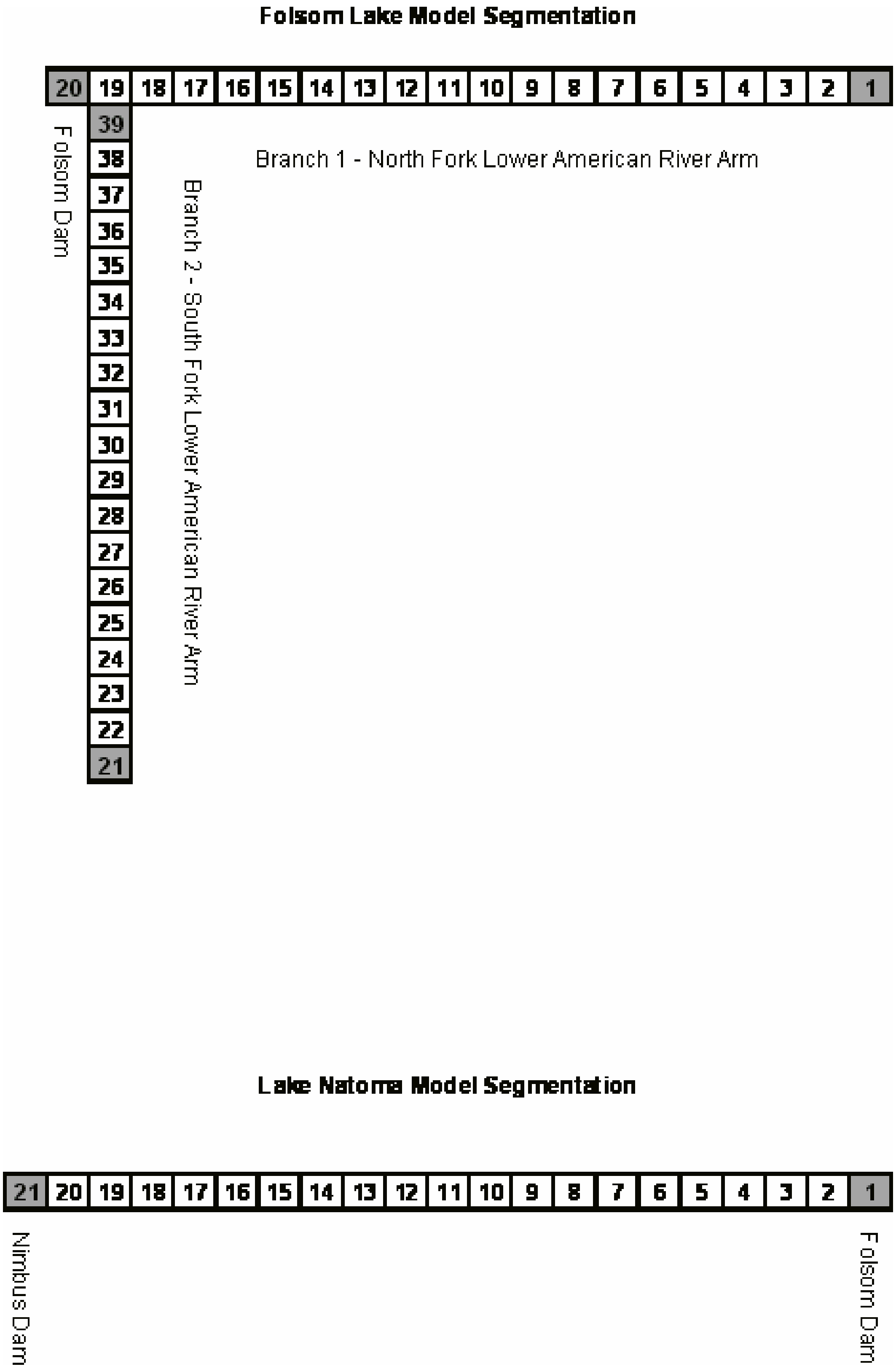


Figure 2.—Folsom Lake and Lake Natoma CE-QUAL-W2 Model longitudinal segments.

- Alternatives to flush reservoirs with poor water quality
- Estimating the effects of operational, structural, and remediation measures on flow and water quality, including thermal stratification and longitudinal variation of temperature

The selective withdrawal algorithms in the model can calculate the vertical extent of the withdrawal zone based on multiple outlet geometry, outflow, and water density. The version of CE-QUAL-W2 used for this study allows linking of multiple water bodies, such as rivers and reservoirs, in series with steeply sloping riverine sections between reservoirs. Vertical grid spacing can vary in thickness between water bodies. An internal weir algorithm for submerged or skimmer weirs, vertical turbulence algorithms more appropriate for rivers, and numerical algorithms for pipe, weir, and pump flow are included.

Using hourly-input data and an hourly time step to capture the effects of hydropower operations, both the Folsom Lake and Lake Natoma W2 models simulated the seasonal warm surface layer (epilimnion) and cold bottom layer (hypolimnion). The heat budget input data included drybulb and dewpoint temperature, solar radiation, directional wind mixing, convective heat exchange, and inflow density distribution.

The CE-QUAL-W2 model simulated three distinct mixing mechanisms that induce vertical mixing between layers:

- Convective mixing due to surface cooling and sinking of dense water
- Mixing due to wind shear at the surface
- Turbulent mixing between layer flows driven by differing water velocities

Wind mixing of near-surface layers was simulated using both wind speed and direction in an energy balance approach that increased the mixing depth until the potential energy required to mix stratified layers equaled the kinetic energy transferred from the wind.

Reservoir temperatures depend on the rate and temperature of inflow and outflow and heat transfer across the air/water interface. Incoming solar radiation is absorbed as heat, starting at the surface, with lower layers absorbing heat according to an exponentially decreasing light extinction formulation. The formulation is a function of light absorption properties of pure water, inorganic suspended sediment, and suspended organic matter.

An advantage of using the W2 model for Folsom Lake and Lake Natoma is the potential to create a future multi-water body CE-QUAL-W2 model, which could link Folsom Lake, Lake Natoma, and the riverine tailwater downstream from

Nimbus Dam. However, this approach would require additional time and funding and has the following limitation. CE-QUAL-W2 is essentially a 2-D model that is designed for multiple-layer longitudinal systems. It cannot represent trapezoidal channel geometry unless at least a two-layer configuration is used. Using a two-layer configuration from Nimbus Dam to the confluence with the Sacramento River may cause instability issues because of steep slopes and may not adequately represent the riffle-pool water travel time caused by the many hydraulic controls which pool or slow water transport. Assembling the input data and simulating the lower American River downstream of Nimbus Dam for a continuous 3-year period was beyond the scope of this study.

FLOW-3D

The three-dimension computational fluid dynamics (CFD) model, FLOW-3D version 8.2 by Flow Science Inc., was used to model near-field hydrodynamics of the Nimbus Dam forebay for comparison of the temperature reduction effect of modifying the debris wall and constructing a Nimbus Dam curtain. FLOW-3D is a finite difference/volume, free surface, transient flow modeling system that solves continuity, the Navier-Stokes equations, and conservation of thermal energy in three spatial dimensions. The finite difference equations are based on an Eulerian mesh of non-uniform hexahedral control volumes using the Fractional Area/Volume (FAVOR) method. FLOW-3D uses an orthogonal coordinate system as opposed to body-fitted or unstructured grid systems (Flow Sciences, Inc., 2003).

ADYN/RQUAL

The ADYN/RQUAL model that is embedded within the River Modeling System version 4 (Hauser, 2003) is a one-dimensional flow and water quality model and was used for modeling the lower American River tailwater downstream from Nimbus Dam to its confluence with the Sacramento River (figure 3). The fish hatchery weir located just downstream of Nimbus Dam was modeled as an internal boundary condition within ADYN. A 2-week end-of-July to early August warm weather period was modeled. Figure 3 shows the modeled riffle pool geometry downstream from Nimbus Dam with the modeled corresponding water surface profile at 1,500 cfs with the pickets installed at the fish hatchery weir. Reclamation (1971) indicated that the reach-average gradient downstream from Nimbus Dam is approximately 3 feet per mile. The lower 8 kilometers (5 miles) or more of the river is influenced by tidal action and backwater effects from the Sacramento River. These latter effects, under higher flows, extend a few miles above the H Street Bridge. To avoid modeling instabilities, the backwater and tidal influences of the Sacramento River were modeled with an assumed constant 3.0 meter (10 foot) water surface elevation, which was higher than observed during July and August 2001, the period used for modeling the lower American

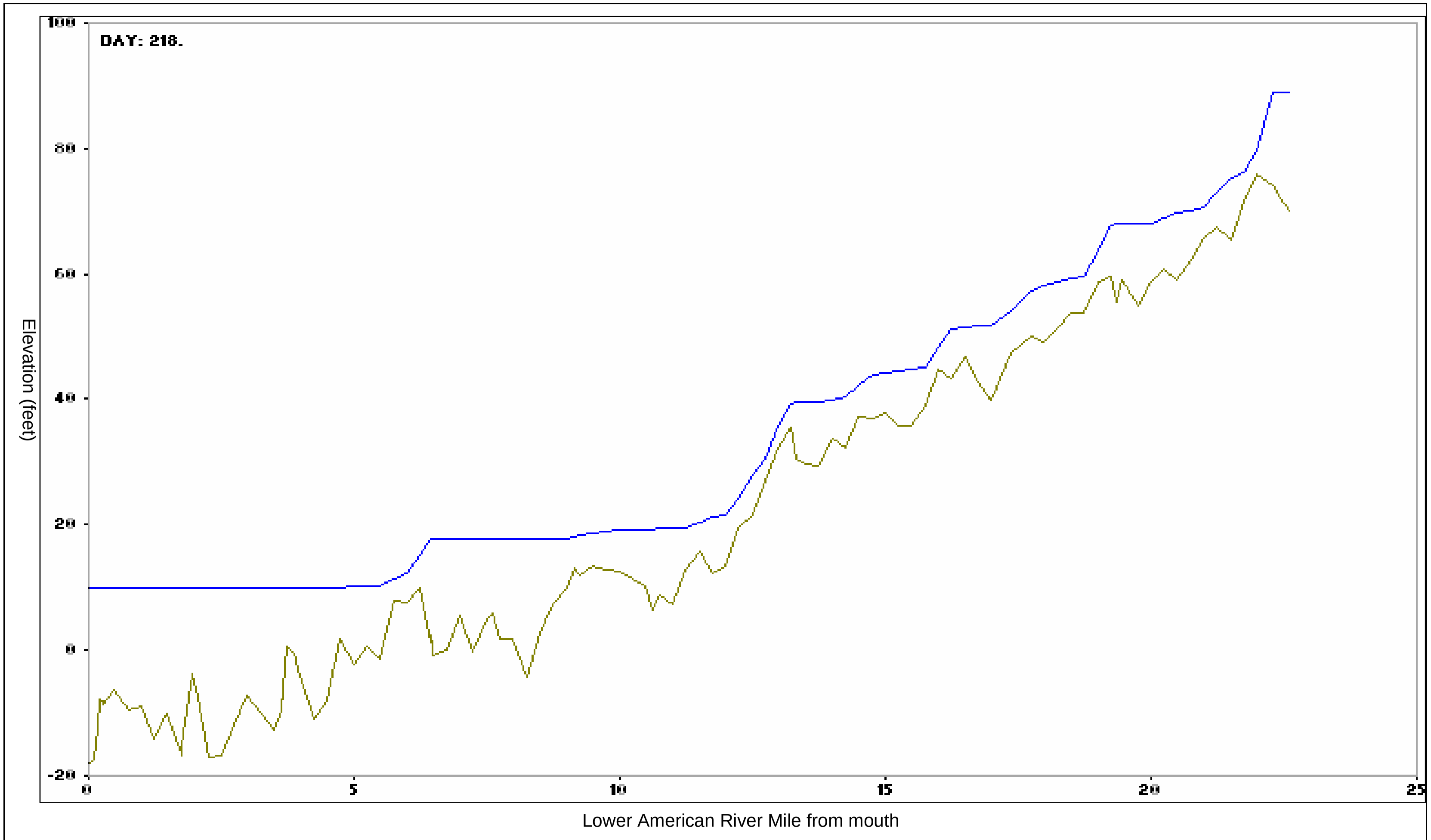


Figure 3.—Modeled water surface (at 1500 cfs) and channel bottom profiles for Nimbus Dam tailwater.

River tailwater. During non-flood control season for this temperature modeling study, the effects of modeled backwater from the Sacramento River did not extend upstream of the Watt Avenue Bridge.

ADYN is a hydrodynamic model that solves the one-dimensional equations for conservation of mass and momentum known as the St. Venant equations, also known as the shallow water equations. ADYN outputs hydraulic parameters such as discharge, water surface elevation, horizontal velocity, depth, water travel time, and wetted area over time. It is well suited for simulating changes in travel time and water temperature associated with riffles and pools in a riverine environment. Output from ADYN drives RQUAL, a water quality model, which solves the advection-diffusion equation to determine the change in temperature and transport of heat and other water quality constituents.

RQUAL is a water quality model decoupled yet used in conjunction with ADYN to study water temperature, nitrogenous oxygen demand (NOD) and carbonaceous biochemical oxygen demand (BOD), and dissolved oxygen (DO) in rivers where the one-dimensional longitudinal flow assumption (completely mixed bank-to-bank) is appropriate. For this study, only temperature was modeled with RQUAL. RQUAL uses a full heat budget that includes atmospheric heat exchange, channel shading by trees and barriers, channel bottom heat exchange, heated discharges to the river, and other factors.

IV. Model Inputs and Methodology

Three consecutive years (2001, 2002, and 2003) were simulated with the W2 models because of the complexity of developing initial conditions and water mass balances for each individual year. Historical flow, water temperature, and meteorological data were used as inputs for both calibration and simulations of Folsom Lake and Lake Natoma for consistent comparison of results. The geometry for the models was developed from aerial, bathymetric, existing topographic maps, and surveyed channel geometry.

Reservoir Geometry

Geometry for the Folsom Lake and Lake Natoma W2 models was developed from existing geospatial data in AutoCAD format. The bathymetric surveys were conducted and reported by Ferrari (1995). Mid-Pacific (MP) regional staff provided partial AutoCAD files for Lake Natoma and a complete AutoCAD file for Folsom Lake. Due to missing data for Lake Natoma, a topographic quadrangle labeled “Folsom California” was imported into AutoCAD and the contours were digitized up to elevation 39.6 meters (130 feet) AMSL. Environmental Management System, Inc., (EMS-I) software was then used to process the data into a format that was used by the Folsom Lake and Lake Natoma W2 models.

The processed W2 reservoir geometry consisted of longitudinal segments with vertical layers in each segment. One-meter layers were used in Folsom Lake, and half-meter layers were used in Lake Natoma. During simulation, a floating layer scheme was used so that all layers remained at specified depths from the surface. The floating layer scheme preserved near-surface gradients and allowed direct comparison with field surveys at fixed depths.

For Folsom Lake, the following were modeled: two reservoir branches, distributed local inflows for each branch, selective withdrawal for penstock and the M&I intake temperature control devices, upper and lower river outlet works, and the spillway at Folsom Dam. A small amount of dam leakage and the El Dorado Irrigation District water intake were modeled as separate withdrawals. Distributed local inflows for the South Fork American River and the North Fork American River were calculated from a water mass balance and apportioned according to drainage area. A similar mass balance process was calculated for the single branch of Lake Natoma to derive the local drainage. A modeled Lake Natoma tributary at Willow Creek was added to minimize water mass balance error, increase model stability, and provide a means to add thermal, nutrient, and organic loading for potential future water quality studies which are outside the scope of this study.

Geometry for the Folsom Lake W2 model was derived from 1990 aerial coverage collected by airplane and 1991 reservoir bathymetric soundings collected by boat. These data were collected to update the area-capacity curve that has been used for reservoir operations since 1993. The merged spatial data sets provided an updated bathymetric map and a storage-elevation relationship. Merged into one coverage were the above-water reservoir area measured from aerial photography and the bathymetric survey measured from sonic depth recording equipment interfaced with an automated survey system, consisting of a line-of-sight microwave positioning unit combined in a geographic information system. Contours for elevations were computed using a triangular irregular network (TIN) surface modeling package within ARC/INFO. The TIN was clipped at the water edge, formatted in an AutoCAD file, and the model geometry and segmentation was developed using the Watershed Modeling System (WMS) module of the EMS-I software package. The geometry was calibrated to the 1991 Folsom Lake area-capacity curve. Each Folsom Lake longitudinal segment has 1-meter layers, referred to as cells. Model geometry consisted of cell thickness, cell width, and cell length. Thirty-five active reservoir longitudinal segments plus an upstream and downstream inactive inflow and exit mixing cell for each branch were developed.

The Folsom Lake W2 model contains (1) 35 active longitudinal segments in two dynamic branches with four inactive segments at branch ends, (2) selective withdrawal at 18 elevations, (3) the Eldorado Irrigation District withdrawal on the South Fork arm of Folsom Lake, (4) one dam outlet withdrawal for leakage, and (5) distributed tributary inflows representing local inflow to the surface layer. Turbine leakage through Folsom Dam penstock shutters was incorporated into the development of the spreadsheet analysis of the selective withdrawal by relating to hourly generation data. Most of Folsom Dam releases were through the turbines during 2001 through 2003. Simulations of alternatives used the same municipal and industrial (M&I) withdrawals, leakage, and spills estimated during 2001-2003. Differences in flow were accounted for by changes to the turbine releases. The M&I temperature control device was modeled using 10-foot increments (3 meters). Leakage through the gates of the M&I TCD was not estimated or included because the leakage and TCD flows were minimal in comparison to Folsom Dam powerplant releases.

The complicated set of penstock shutters on Folsom Dam resulted in extensive derivation of W2 model inputs for this selective withdrawal structure. Eighteen outlet levels were used for deriving the Folsom Dam W2 model inputs for the spillways, for the penstock intake shutters which serve as the primary temperature control device (TCD), for the M&I intake TCD, and for the upper and lower river outlets. The configuration of the Folsom Dam penstock selective withdrawal levels, including the spillway, were modeled as horizontal line sinks which act as horizontal slits in the water column. Likewise, each level of shutter withdrawal (lower, middle, upper, and all) was modeled as a horizontal line sink. Selective withdrawal through the lower and upper tier of river outlet works valves and the

M&I TCD, which are closer to the bottom, were modeled as point sinks. For Lake Natoma, a combination of underwater surveys, flown aerial data, and topographic quadrangle contours provided a mix of geospatial information which was calibrated to an area-capacity curve dated 1950. At Nimbus Dam, all outlets were modeled as horizontal line sinks, except the fish hatchery withdrawal, which was modeled as a point sink.

River Geometry

About 160 cross sections either surveyed one-quarter mile apart or spaced more closely near bridges were used to develop detailed river geometry capturing the major riffle-pool sequence in the lower American River from Nimbus Dam to the confluence with the Sacramento River. Some cross sections near bridges were removed from the geometric data set to minimize numerical instability resulting in 131 modeled cross sections. An internal boundary condition was used for the fish hatchery weir. A rating curve was derived from measured data and theory for a condition with and without racks and pickets on the weir structure.

Initial Conditions

Both Folsom Lake and Lake Natoma CE-QUAL-W2 reservoir model simulations were started on January 1, 2001, using observed temperature profiles recorded on January 17, 2001, and run continuously for years 2001, 2002, and through 2003.

ADYN/RQUAL riverine model simulations for the LAR downstream from Nimbus Dam were started with a warm weather low flow scenario for sensitivity analyses to flow, meteorology, and release temperature; inputs were repeated for 4 days to dampen unknown initial conditions; and the last day of the simulation analyzed. The warm, low flow, late summer day chosen to be repeated was August 8, 2001, during a dry period with minimal local tributary drainage. The cool, low flow, summer day chosen to be repeated was July 27, 2001.

Flow

Known major branch and tributary inflows, outflows, and change in reservoir storage from the California Data Exchange Center (CDEC) and U.S. Geological Survey (USGS) data were used to derive unknown local inflow. The unknown local inflow was derived by adding known inflows, subtracting known outflows derived from power generation records, calculating the change in reservoir volume, and comparing that to a reservoir volume based on known water surface elevation. The unknown local inflow could be negative due to evaporation, bank storage, groundwater inflow/outflow, and reservoir water surface elevation gage errors.

Negative local inflow could be large, depending on water surface elevation in relation to groundwater table fluctuation and reservoir water surface elevation gage error. All three years had typical runoff patterns with large spring and fall inflow periods. Calendar year 2001 was a below-average inflow year, 2002 was slightly below average, and 2003 was a near average inflow year.

Any flow errors were incorporated into distributed drainage for Folsom Lake and distributed drainage and Willow Creek inflow for Lake Natoma. Release data from Folsom and Nimbus Dams included penstock releases, spillway releases, river outlet works data, TCD releases, Nimbus fish hatchery release data, and the Folsom South Canal deliveries for calendar years 2001, 2002, and 2003. Flow and temperature data collected from acoustic flowmeters on the Folsom and Nimbus penstocks did not always match the flows and temperatures derived from other gages, so they were not used to develop model input data.

Inflow Temperature

Temperature of inflows greatly affects model calibration. Cool inflows plunge below the warm surface layer. Unfortunately, minimal inflow temperature data were collected just upstream of Folsom Lake backwater during some periods. Inflow temperatures collected every 15 minutes at North Fork American River at the Auburn Dam site (site NFA) were used to develop hourly inputs for Branch 1 of the Folsom Lake Model. USGS 15-minute data and daily average data for the South Fork American River at Pilot Hill (site ARP) were used for Branch 2 of the Folsom Lake Model. To fill in missing temperature data at Pilot Hill on the South Fork American River, the water temperature data for North Fork American River at Auburn were increased slightly and used for the South Fork. Fifteen-minute combined release temperature data just below Folsom Dam (site AFD) were used to compare modeled release temperatures. Interpolation between known values or data from a nearby site was used to fill data gaps. Rapidly changing weather conditions, uncertainties in solar radiation due to cloud cover differences at different locations, and large inflows during periods of missing inflow temperature data increased the uncertainty of obtaining an accurate reservoir heat balance.

Hazel Avenue Bridge water temperature data was not available from January 1, 2001, to June 29, 2001, so data from the American River at Fair Oaks (AF) gage (located about 0.6 kilometers (0.4 miles) downstream) were used for that period. Fair Oaks data on average are about 0.7 °C (1.3 °F) warmer due to being located in a backwater eddy; therefore, whenever Fair Oaks data were used, it was adjusted cooler. Data outside the period of significant missing data were used for one-dimensional model calibration. The period July 27, 2001, through August 12, 2001, provided an adequate and complete data set for calibration and selection of representative data for sensitivity analyses.

Meteorology

Hourly average drybulb temperature, dewpoint temperature, windspeed, wind direction, and solar radiation data were used for the CE-QUAL-W2 models. Hourly weather data for drybulb temperatures, dewpoint temperatures, and windspeeds were assembled from the California Irrigation Management Information System (CIMIS) Fair Oaks gage 15 minute event data collected near Nimbus Dam tailwater. Average hourly measured solar radiation from the Fair Oaks CIMIS station was used instead of cloud cover. The meteorological data significantly affected Folsom Lake and Lake Natoma calibrations.

The Fair Oaks CIMIS station is in a sheltered urban site and indicates moderate wind speeds. Folsom Lake has a long fetch, which greatly affects wind mixing characteristics. The W2 model automatically adjusts wind speed to an elevation 2 meters (6.56 feet) above the water surface by using the one-seventh power law. Additionally, Folsom W2 model coefficients were adjusted during calibration to accommodate these differences.

Water Mass Balance Check

Modeled water mass inputs and outputs were balanced closely by incorporation into the distributed tributary flows on both Lake Natoma and Folsom Lake. The cumulative average flow over the 3-year period was corrected to within about -0.2 cfs for Lake Natoma and to less than -3 cfs for Folsom Lake. This resulted in a close match between daily observed and modeled water surface elevations. A total or global water mass balance of Folsom Lake and Lake Natoma was accomplished by using Folsom Dam releases that were corrected for estimated leakage using generation data and penstock shutter gate opening data. The corrected Folsom Dam release data were used as a starting point for both the Folsom Lake and Lake Natoma W2 model water mass balances.

V. CE-QUAL-W2 Reservoir Model Calibrations and Analysis of Management Alternatives

Because models are mathematical representations, in most cases approximating complex physical processes, the results must be compared to field data to provide confidence in the model output. Model calibration is based on the understanding of existing model algorithms and intuition and experience regarding the many processes occurring in nature.

Figure 4 shows the average annual flows plotted through time from 1905 through 2004 for the lower American River downstream from Nimbus Dam, including system storage effects. Calendar years 2001, 2002, and 2003 were selected for model calibration to include operational and structural changes through 2003. During 2003, the TCD on the Folsom Dam M&I water supply intake was operational, which was partially responsible for a larger end of warm season cold water pool than was present during 2001 and 2002. Efforts concentrated on calibrating the reservoir models to 2001, a slightly dry year in which the Folsom cold water pool was depleted. Both 2002, the slightly below average inflow year, and 2003, the near average inflow year, had larger cold water pools during spring.

To calibrate the model to a range of hydrologic and meteorological conditions, model calibration coefficients were based on a combination of the closeness-of-fit to the three years of data. Appendix A for Folsom Lake and Appendix B for Lake Natoma provide comparisons between observed field data and model results for 2001, 2002, and 2003. Closeness-of-fit statistics (defined in Appendix A) between the measured and modeled reservoir temperature profiles provide a better overall indication of model calibration than comparison of observed and modeled release temperatures.

Folsom Lake and Lake Natoma Temperature Model Calibrations

Overall, the Folsom Lake (FC21: Folsom Calibration version 21) and the Lake Natoma (NC8: Natoma Calibration version 8) final temperature calibration simulations matched observed profiles for 2001, 2002, and 2003 to within about 1.0 °C (1.8 °F) based on absolute error closeness-of-fit statistics. To more accurately calibrate the bottom of Folsom Lake and more closely match cool bottom release temperatures, a large light extinction coefficient, which traps more heat in the surface layers, was used in the Folsom Lake W2 model to more closely

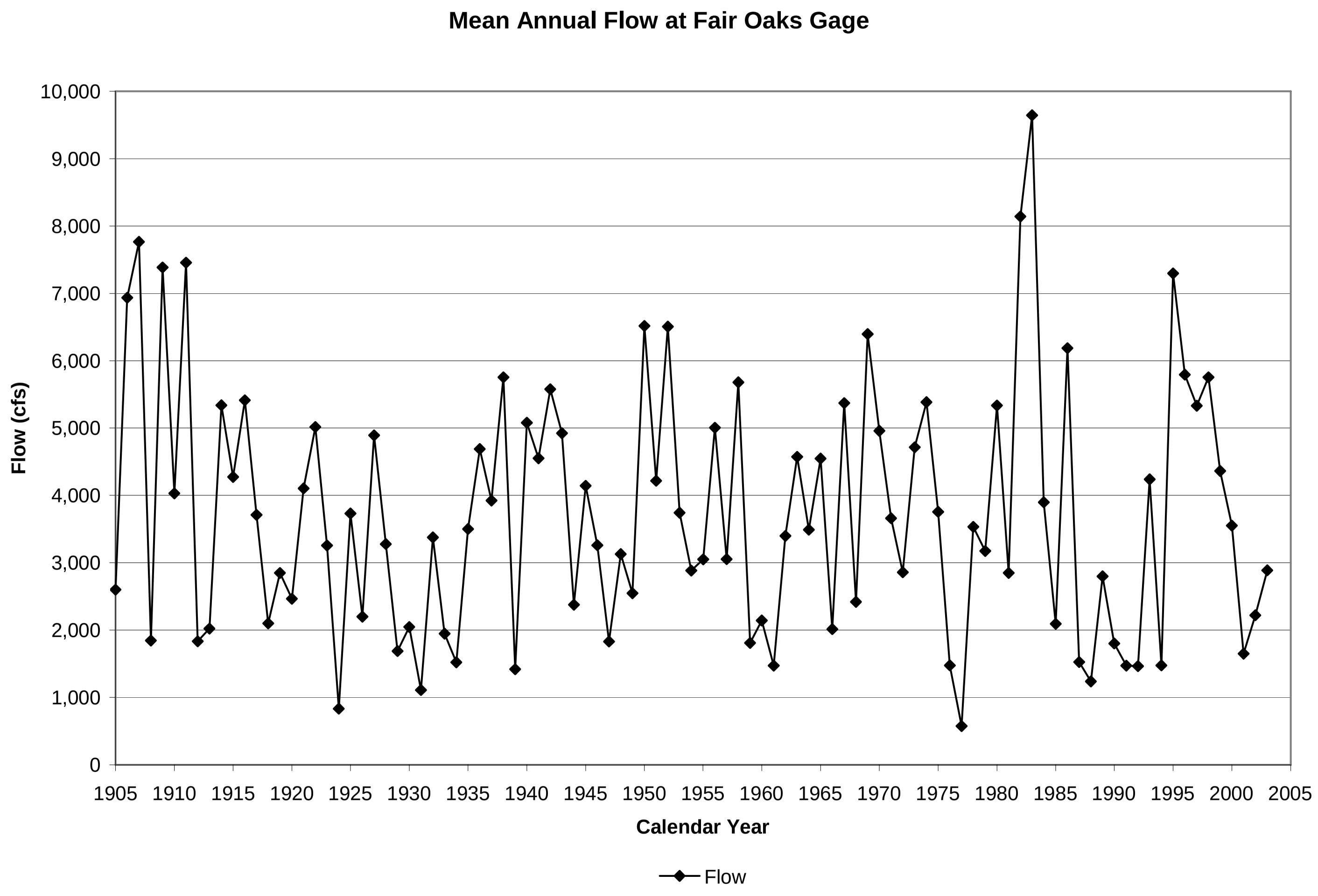


Figure 4.—Average annual flow of the lower American River downstream from Nimbus Dam (1905-2003).

match model release temperatures during the spring and summer with observed data. Additional heat in the surface layer of Folsom Lake caused warmer than observed releases during autumn drawdown. Lake Natoma passes flow continuously and stratifies and destratifies each day because of peaking power operations at Folsom Dam. Temperature calibrations indicated that the Fair Oaks solar radiation appeared more intense than indicated by comparing observed and modeled surface temperatures for both Lake Natoma and Folsom Lake. No corrections were made to the Fair Oaks solar radiation during model calibration due to lack of understanding the data.

One of the most influential factors affecting reservoir and reservoir release temperatures is the degree of wind mixing. Due to reduced wind speeds recorded at the Fair Oaks weather station located in a sheltered urban area, significant simulated vertical mixing was required to calibrate the models to observed reservoir temperatures.

A constant wind sheltering coefficient (WSC) of 1.0 was used for Lake Natoma. A constant WSC of 1.2 was used for Folsom Lake, which means 20 percent more wind mixing was required for the Folsom Lake calibration. Fang and Stefan's (1994) technique to compute fetch effects on wind was also used on Folsom Lake to improve the bottom profile temperature calibration. A term-by-term accounting scheme was used for surface heat exchange. The Folsom Lake and Lake Natoma models were conservatively calibrated to slightly warmer than observed conditions. One hundred percent of the incident short-wave solar radiation impinging on the channel bottom was re-radiated as heat to the water column by the models, resulting in no loss of solar radiation from the large, deep Folsom Lake. The more quickly moving waters in Lake Natoma are affected less by solar heating.

Cool inflows plunge to the various outlet levels, creating interflows and internal seiching within both the hypolimnion and epilimnion of Folsom Lake. This effect is less in Lake Natoma because it is relatively shallow. Temperature interflows from the South Fork American River affect Folsom Lake stratification and Folsom Dam release temperatures. North Fork American River interflows slowly propagate upstream into the South Fork American River, which allows mixing between branches of Folsom Lake. Strong stratification of Folsom Lake occurs during warm conditions. Lake Natoma has weak stratification due to small storage volume and short residence time compared to Folsom Lake. Fall drawdown, accompanied by wind and atmospheric cooling, can influence when fall destratification occurs in Folsom Lake.

Bottom dam forebay temperatures calibrated well during average release flows for both Folsom Lake and Lake Natoma. However, during autumn at low Folsom Lake levels, the model produced greater withdrawal of warm surface water than observed in the field.

During above-average spring flow conditions, flows from the combined North and Middle Forks of the American River dominate reservoir stratification and water quality. During low flow summer and autumn conditions, flows are controlled by releases from upstream dams. Thermal interflows caused by peaking power at Folsom Dam greatly influence reservoir stratification patterns in both Folsom Lake and Lake Natoma.

Following a finite volume of water through the system during a warm summer day provides an introduction to understanding the thermal dynamics of the Lower American River system from Folsom Lake inflows to Watt Avenue Bridge. Figure 5 is a modeled sideview slice of Folsom Lake temperatures from Folsom Dam modeled kilometer 0.0 (mile 0.0) to the inflow backwater areas on the North and South Forks of the American River modeled inflow points on July 31, 2001 (day 212). Figure 5 shows the strong summer thermal stratification in Folsom Lake for both main branches. The dashed outline on figure 5 is the cold water volume less than 15.56 °C (60 °F). During noon of July 31, 2001 (day 212.5), inflow to Folsom Lake was about 18.5 °C (65.3 °F). Modeled Folsom Dam noon average release temperature from all outlets (including those not discharging to the river) was about 17.1 °C (62.8 °F). Modeled Nimbus Dam midnight release temperature for July 31, 2001 (beginning of day 213), was about 17.9 °C (64.2 °F), as shown in figure 6. Modeling indicated that Folsom releases can increase in temperature as much as 3 °C (5.4 °F) while passing through Lake Natoma depending on the season, daily meteorology, flows, and Lake Natoma pool level. Observed release temperatures just below Nimbus Dam at Hazel Avenue Bridge are also shown in figure 6 and indicate an adequate release temperature calibration.

Figure 5 shows the outline of the cold water pool (zone) volumes for July 31, 2001 (day 212), for a plot of Folsom Lake North Fork American River temperature (top) and South Fork American River temperature (bottom). Due to the large length-to-depth aspect ratio of this plot, results should be interpreted with caution. The reservoir is kilometers long in comparison to meters deep. Surface area is much greater than the bottom area of the reservoir. Most of the cold water volume less than 15.56 °C (60.0 °F) exists in the upper layers of the outline of the zone of cold water on figure 5.

The modeled and observed release temperatures at Folsom Dam (AFD site) located about 0.5 kilometer (0.3 mile) downstream from Folsom Dam for years 2001, 2002, and 2003 (dry, below average, and average years) calibrated well overall. However, variations of as much as 3 °C (5.4 °F) between Folsom modeled release temperature and AFD site temperature measurements were noted because of peaking flow, seiching, and the observed water temperature probe being in a pool downstream from Folsom Dam. The modeled hourly diurnal temperature swings were greater than those observed at the AFD site.

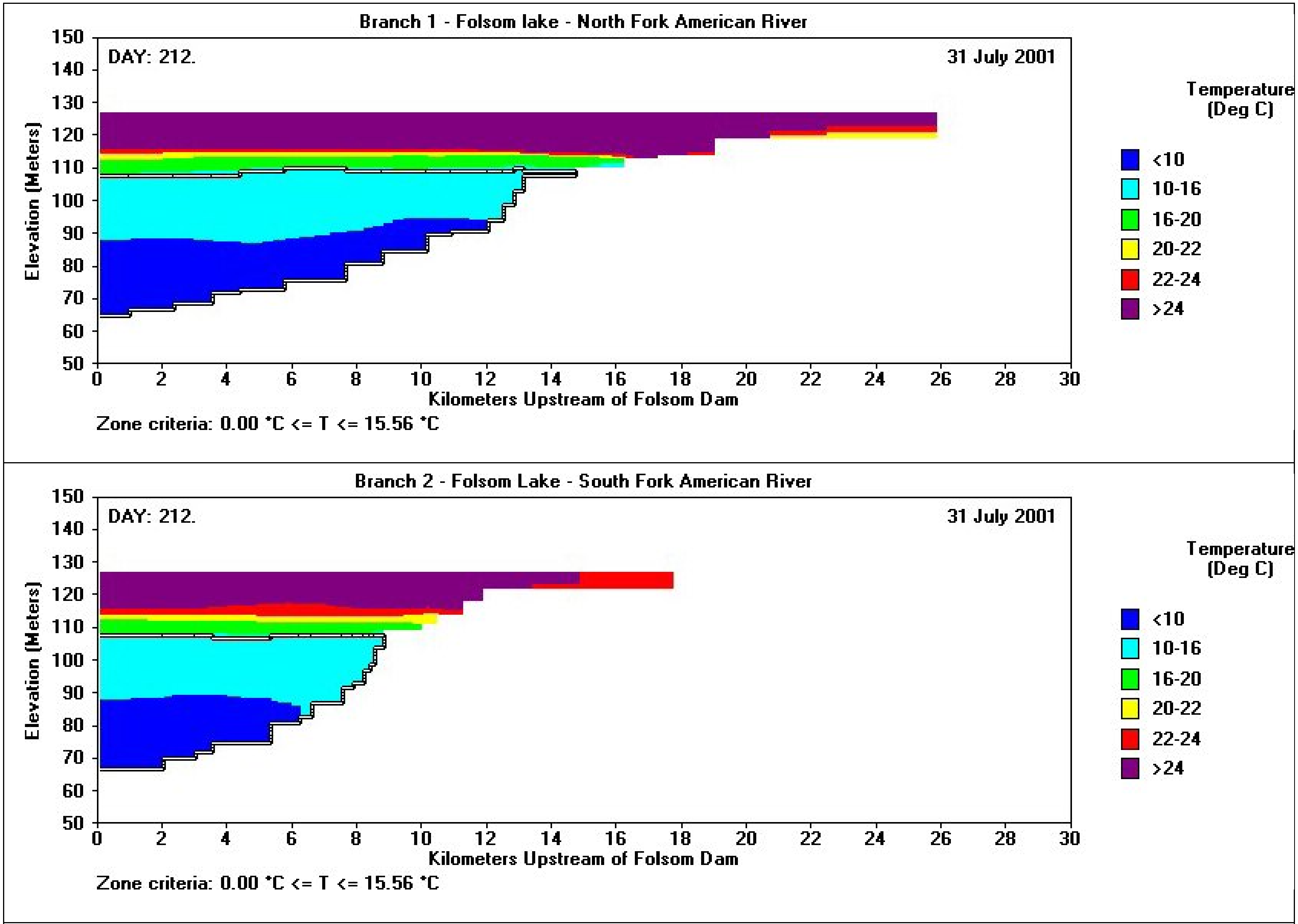


Figure 5.—Modeled temperature contours for midnight of July 31, 2001 (day 212), for the North (top) and South (bottom) Forks of the American River (elevation versus kilometers from Folsom Dam).

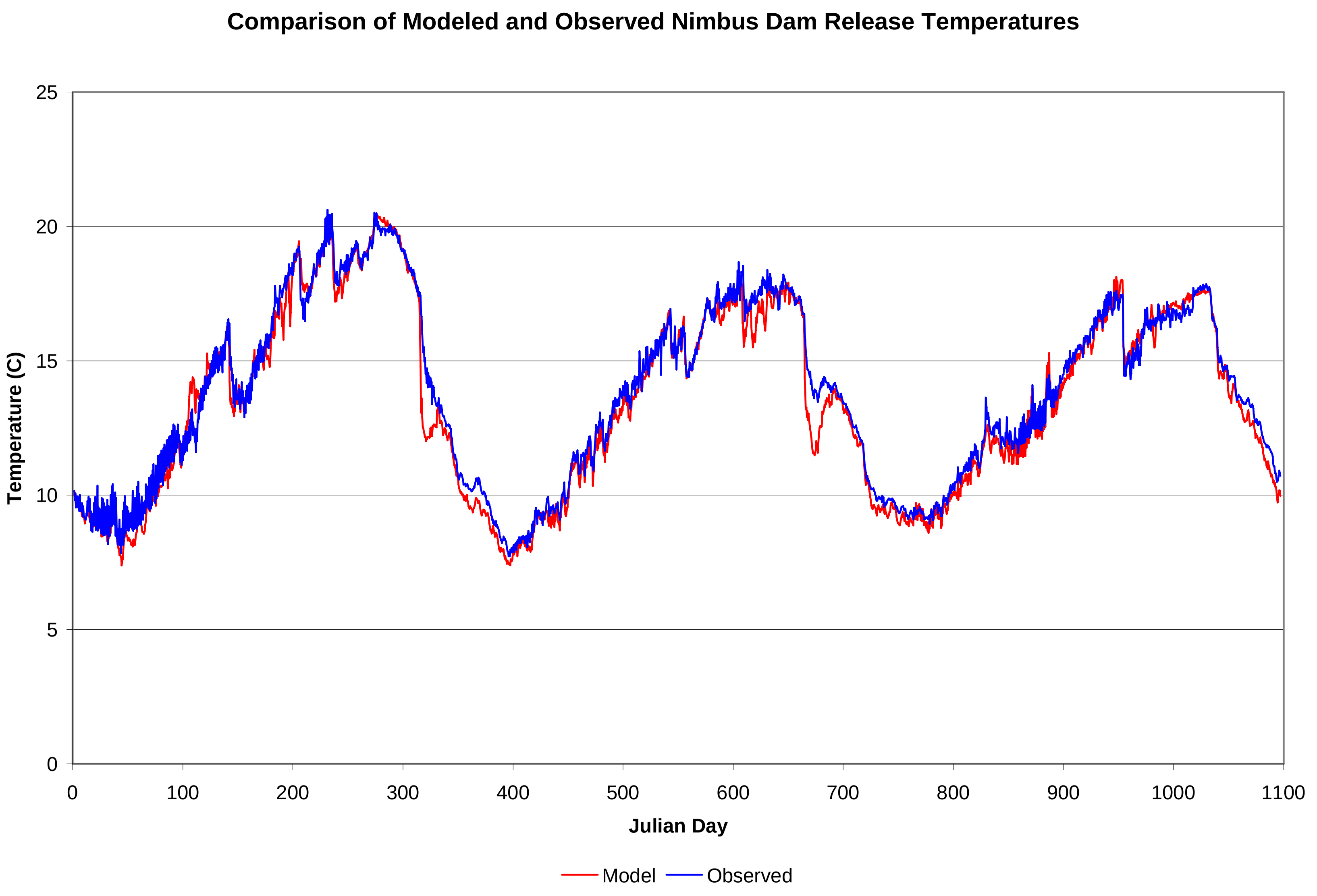


Figure 6.—Modeled and observed Nimbus Dam release temperature versus time during 2001, 2002, and 2003.

Folsom Lake inflows can be more than 5 °C (9 °F) cooler than outflows during spring. The filling of Folsom Lake with cool winter and spring inflows is an important factor for maintaining an adequate supply of cool lower American River flows to Watt Avenue Bridge.

Figure 7 shows 2001 through 2003 modeled daily temperature data in the Folsom Dam forebay. Vertical contours or band boundaries near the surface indicate periods of vertical mixing such as during fall destratification. When there are no horizontal bands, the reservoir is fully mixed. When there are many color bands on a particular day, horizontal contours indicate periods of thermal stratification during warm weather. Figure 7 shows the dramatic seasonal change in water surface elevation (more than 20 meters (66 ft)) for this large storage reservoir. Corresponding to a wetter reservoir inflow condition during 2003, with a higher water surface elevation, more cold water is in Folsom Lake.

Figure 8 compares the total Folsom Lake volume to the cold water volume less than 15.56 °C (60 °F) for calibration calendar years 2001, 2002, and 2003. During late autumn of 2001, cold water volume was nearly depleted. During 2002, a minimal amount of cold water was available during autumn. During 2003, the cold water pool was not depleted and cold water was carried over into 2004.

Overall, the Folsom Lake calibration reflects long-term seasonal storage and was more difficult to calibrate than Lake Natoma. The Lake Natoma temperature calibration reflects run-of-the-river and nearly steady-state conditions, which tends to flush input or numerical errors within days. Lake Natoma has steady outflow but unsteady inflows and water surface elevations caused by powerplant peaking power operations at Folsom Dam.

Analysis of Management Alternatives Using CE-QUAL-W2 Reservoir Models

During the period of 2001 through 2003, operations were modified to improve cold water pool management. The recent 2001, 2002, and 2003 operational conditions were used as a baseline for comparison of simulations and incorporated into the modeling. The greatest recent changes to Folsom Lake are the spring 2003 initiation of operation of the M&I TCD, operational changes to accommodate cold water fisheries, and associated changes in selective withdrawal through the Folsom penstocks and M&I TCD to provide for release of cool water to the river during autumn.

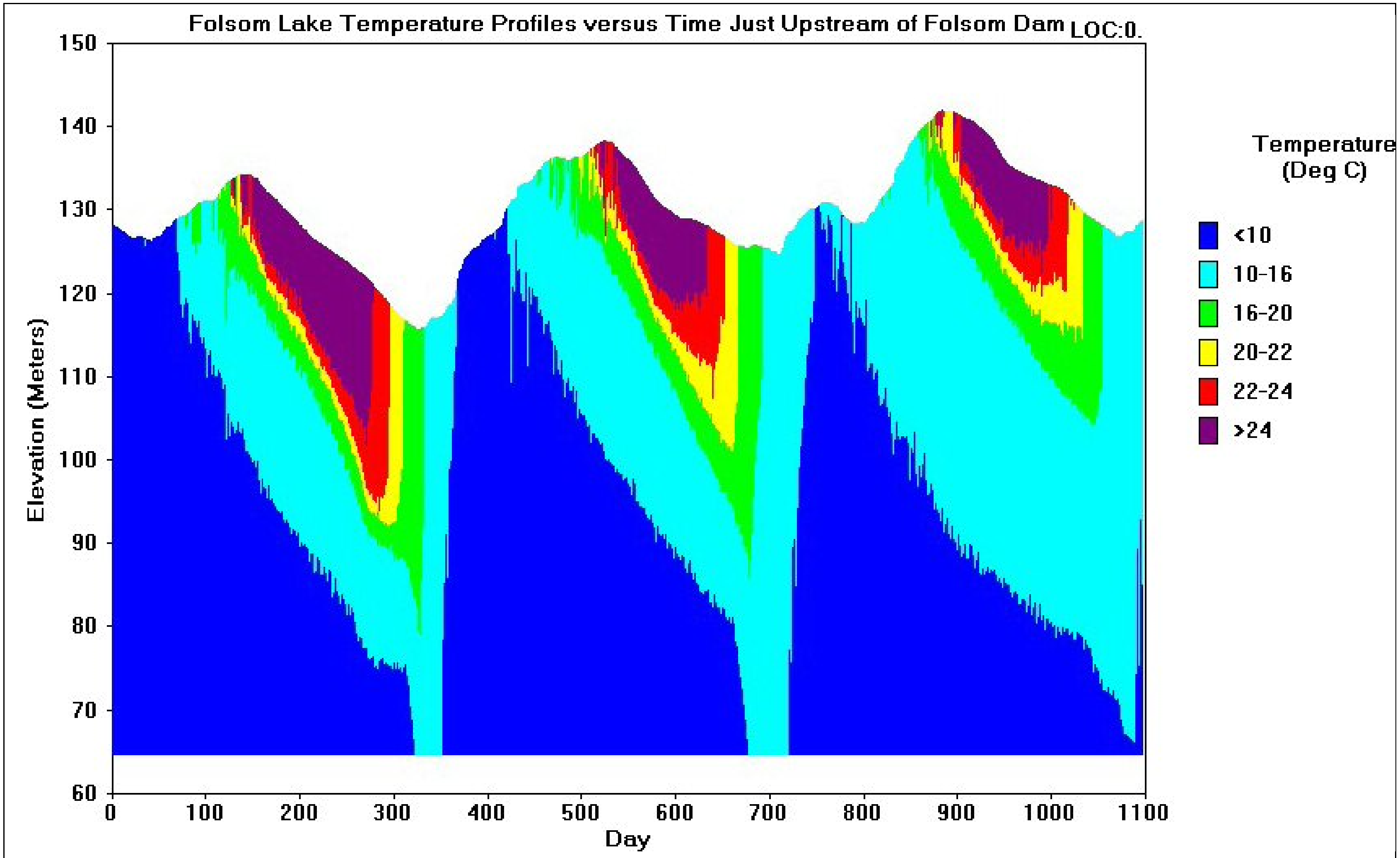


Figure 7.—Modeled temperature contours in Folsom Dam forebay during 2001, 2002, and 2003.

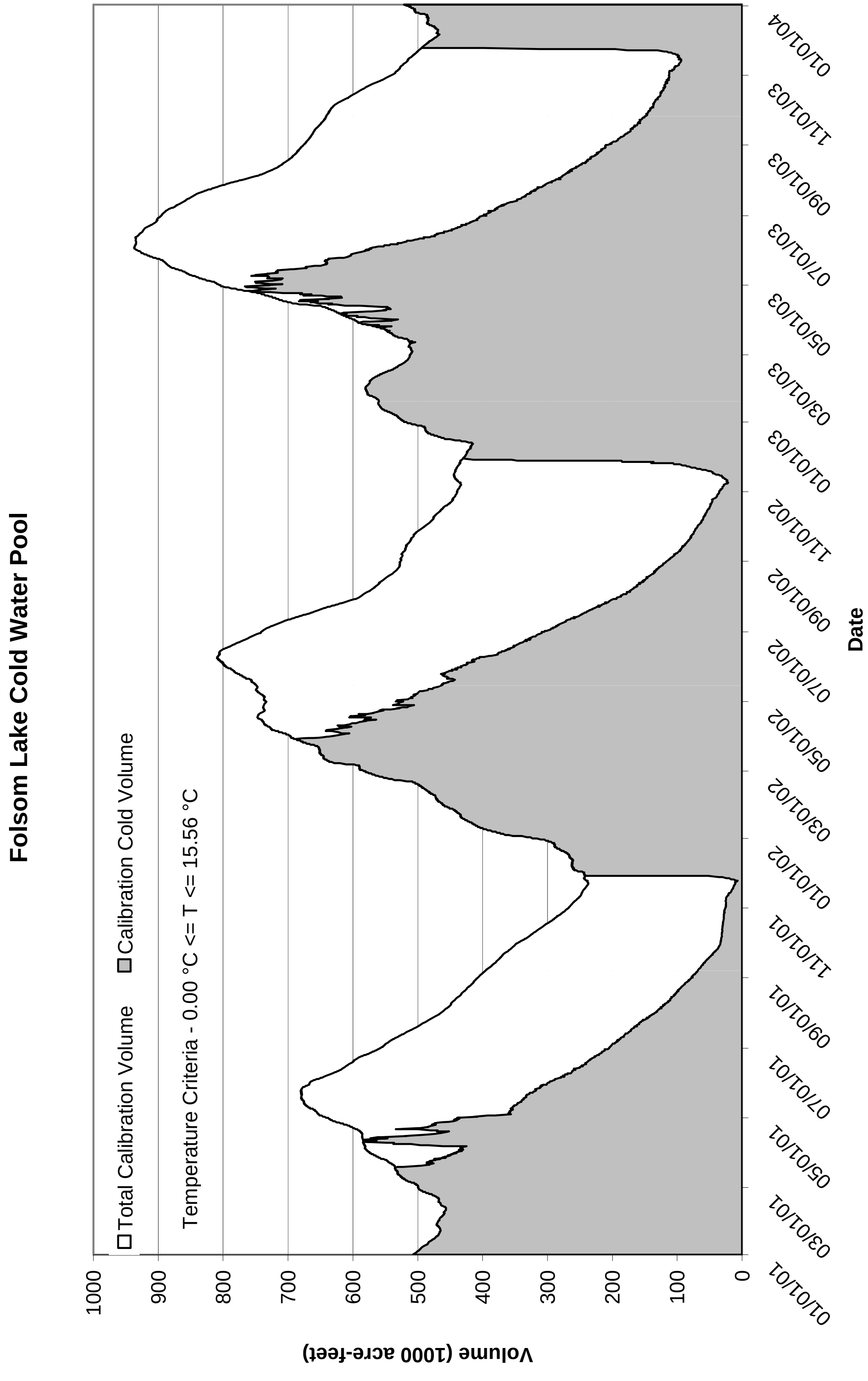


Figure 8.—Modeled total Folsom Lake volume versus cold water volume for calibration calendar years 2001, 2002, and 2003.

All identified actions and some selected combinations of the five actions were compared with the conditions that existed during 2001, 2002, and 2003 when possible. However, for some simulations, the debris wall at the Nimbus powerplant intakes was removed in the model to show more temperature reduction of releases.

The model results of the simulations for each identified action and selected combinations of identified actions were compared with the existing conditions which were simulated by a continuous calibration run for the period January 1, 2001 through December 31, 2003. Due to the large amount of data produced by hourly output, the differences in water temperature between two corresponding data values per day (noon and midnight) for each simulation were output, plotted, and compared. Model output moving averages for noon and midnight data points per day compared well with model output moving averages for 24 output data points per day.

Folsom Lake CE-QUAL-W2 Sensitivity Scenarios

To bracket and evaluate the downstream temperature benefits of modifying the peak load operation of the Folsom Dam powerplant (identified action No. 5), the results of the following two model simulations were compared:

- Calibration Run FC23 – calibration to existing 2001, 2002, and 2003 conditions for Folsom Dam and Lake.

- Run F1 – Simulating the changing of the peak load operation at Folsom Dam to a baseload operation by modeling the Folsom Dam powerplant releases with the nearly continuous historical Nimbus Dam re-regulation baseload releases without changing the historical operation of selective withdrawal shutters at Folsom Dam or any other model inputs used in run FC21.

Folsom Lake Sensitivity Scenario Findings

Changing Folsom Dam powerplant peak load operations to baseload operations resulted in the warming of Folsom Dam releases (figure 9). Net increases of several degrees in release temperatures from Folsom Dam were seen under a base-load operation with continuous flows (figure 10). Modeling indicated that the net warming during continuous releases appeared to be attributable to an increase in continuous mixing of the colder and warmer water in Folsom Lake and the elimination of periods of time to restratify the lake. Conversely, it can be concluded that peaking operations are favorable for cooling downstream from Folsom Dam largely due to less time of mixing in Folsom Lake, reduced erosion of the Folsom Lake cold water pool during non-continuous mid-depth interflows, and more time to re-stratify Folsom Lake during off peak periods. Factors

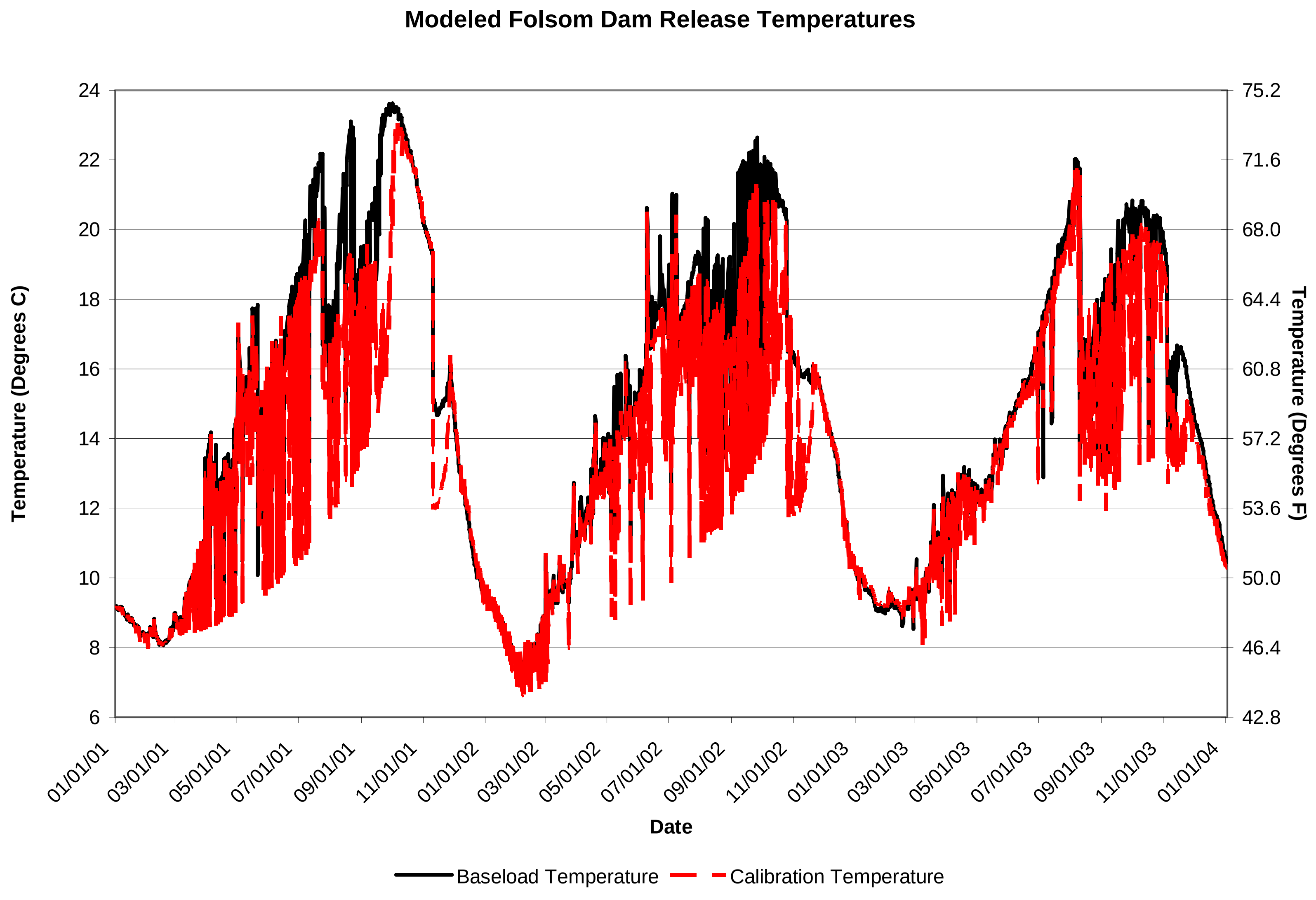


Figure 9.—Modeled Folsom Dam release temperature versus time for historical calibration peaking power operations and simulated baseload operations for 2001, 2002, and 2003.

minimizing continuous mixing in Folsom Lake tended to override the effect of a larger withdrawal zone caused by the relatively large peaking power releases when compared to smaller, more continuous, baseload releases.

Subtracting base-load simulation release temperatures from modeled historical calibration peaking release temperatures shows the temperature differences between runs. Figure 10 shows modeled increases in Folsom Dam release temperatures due to modeled base-load operation of Folsom Dam, relative to a peak-load operation for 2001, 2002, and 2003. A 14-day moving average is shown on Figure 10 and on following similar temperature difference figures as a blue line. More warming occurred during below average inflow years such as 2001 and 2002. Warmer Folsom Dam releases would cause warmer releases from Nimbus Dam and warmer water in the lower American River.

Lake Natoma CE-QUAL-W2 Sensitivity Scenarios

To evaluate the downstream temperature benefits of the four identified actions for Lake Natoma (which are the installing of a temperature curtain upstream of Nimbus Dam, installing a mid-reservoir temperature control curtain in Lake Natoma, removing the debris wall in from of Nimbus Dam powerplant intakes, and modifying the old river channel in Lake Natoma by dredging) the results of the following ten model simulations for Lake Natoma were compared:

- Calibration Run NC8 – calibration to existing 2001, 2002, and 2003 conditions for Nimbus Dam and Lake Natoma.
- Run N1 – Removal of the debris wall.
- Run N2 – Removal of the debris wall and installation of a deep dam curtain hanging down to elevation 100 feet AMSL and enclosing only the penstock intakes.
- Run N3 – Removal of the debris wall and installation of a plunge zone curtain.
- Run N4 – Removal of the debris wall and dredging of 500,000 cubic yards from the reach 3.9 kilometers (2.4 miles) upstream of Nimbus Dam.
- Run N5 – Combined effects of removal of the debris wall, installation of a deep dam curtain hanging down to elevation 100 feet, installation of a plunge zone curtain, and dredging of 500,000 cubic yards. This simulation showed combined effects of all four Lake Natoma identified actions.

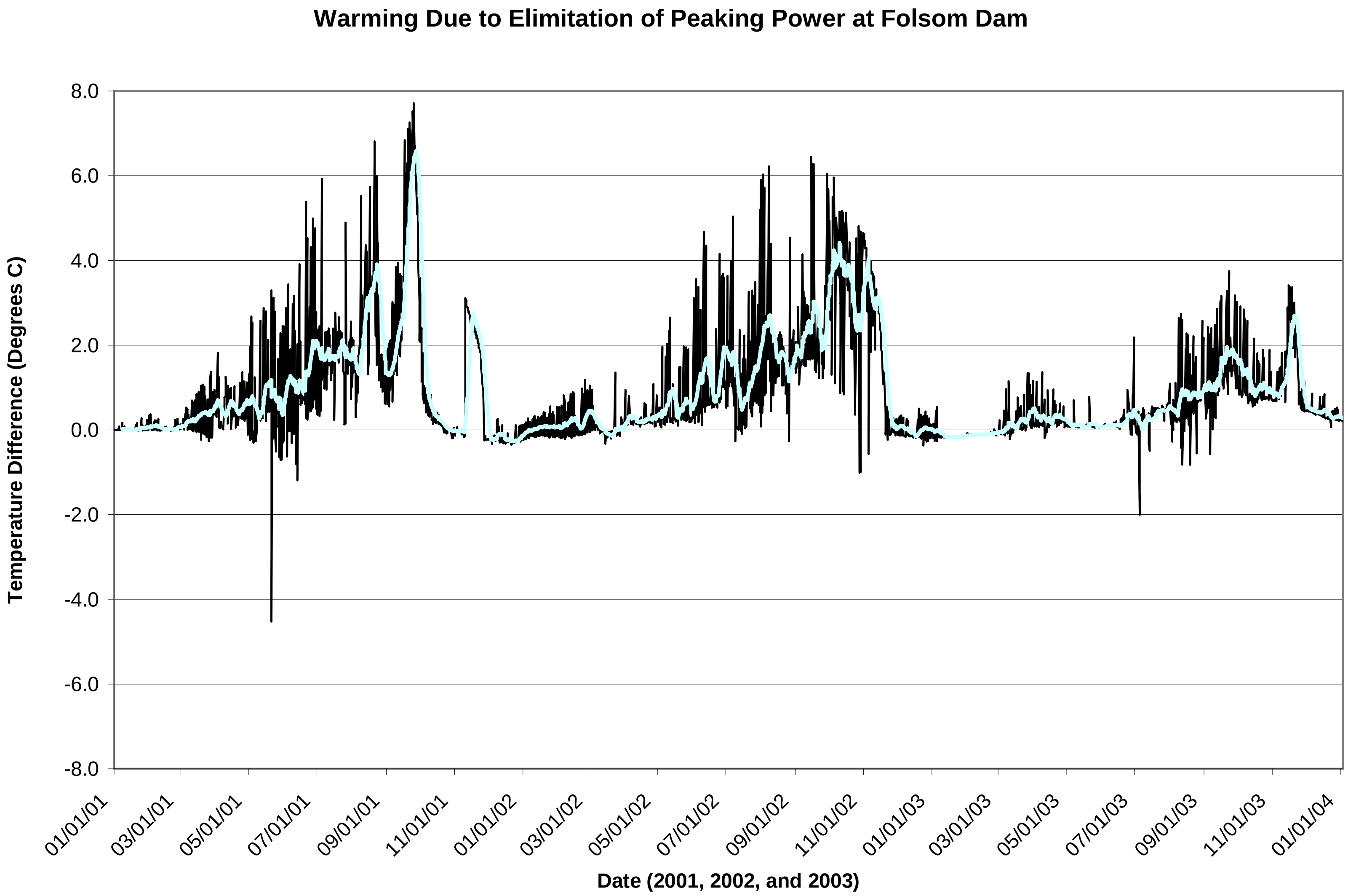


Figure 10.—Modeled Folsom Dam release temperature differences versus time showing warming due to elimination of Folsom Dam peaking power operations for 2001, 2002, and 2003.

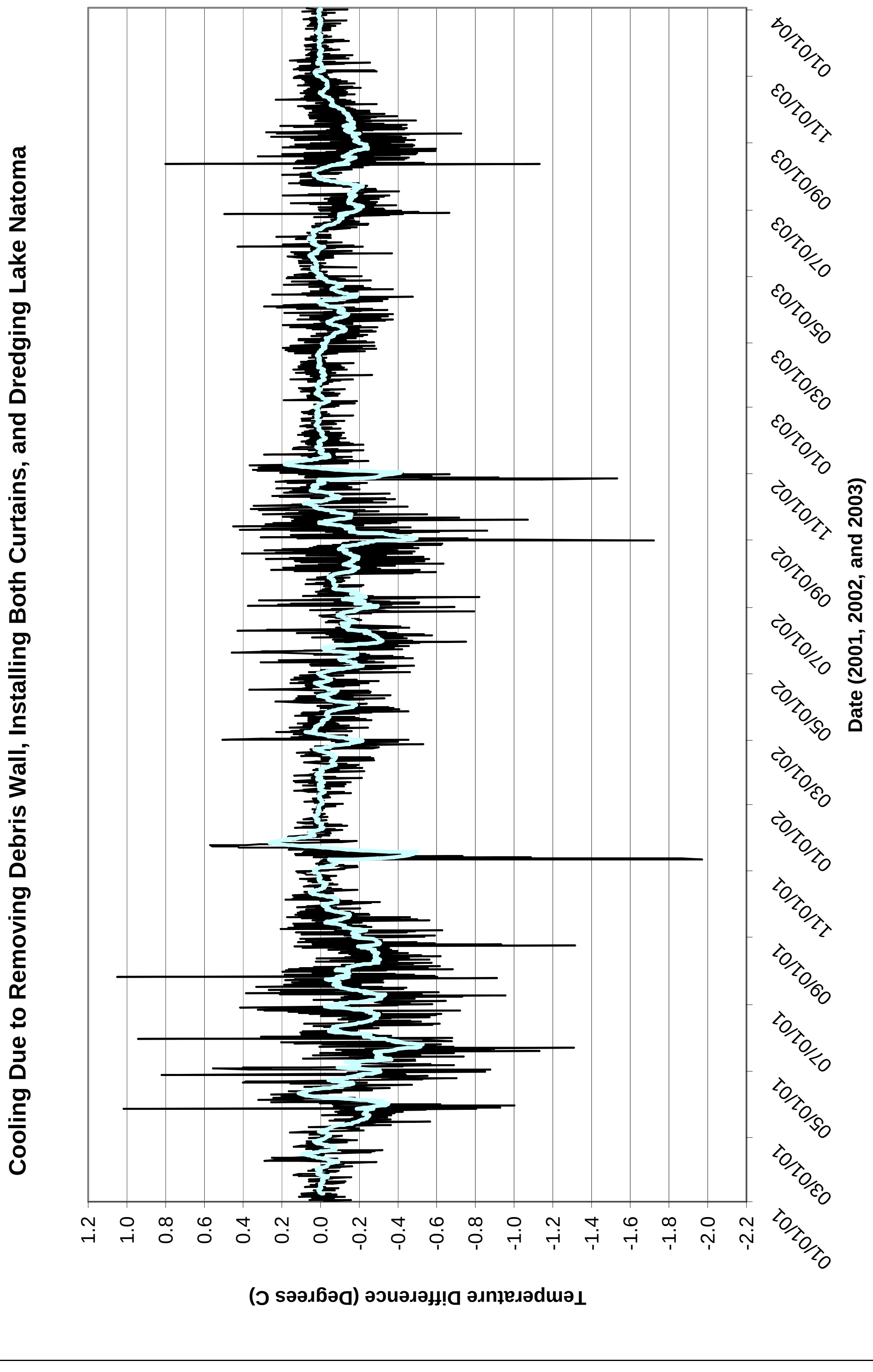


Figure 11.—Modeled Nimbus Dam release temperature differences showing temperature variations due to removing the debris wall, installing plunge zone and dam curtains, and dredging 382,277 cubic meters (500,000 cubic yards).

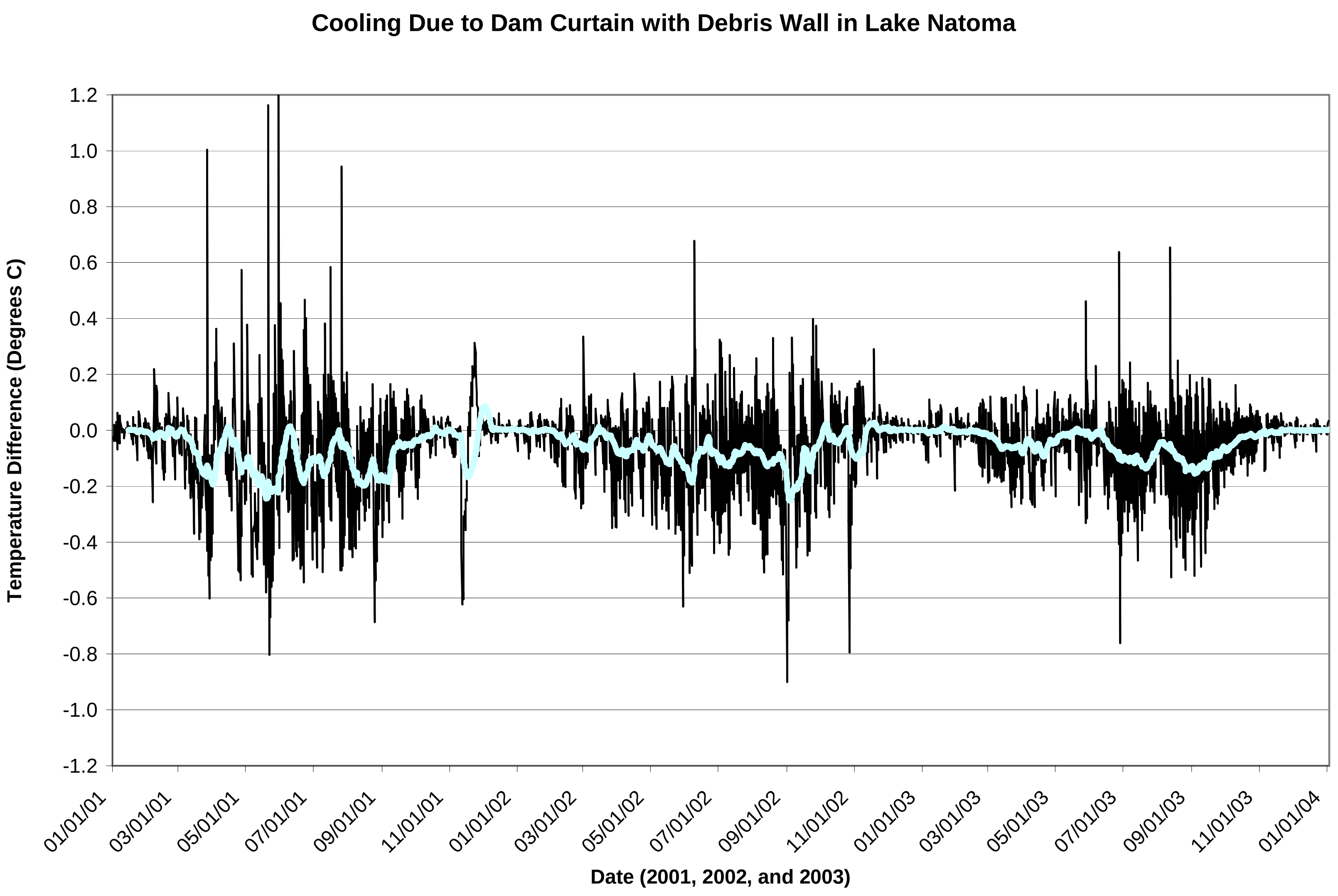


Figure 12.—Modeled Nimbus Dam release temperature differences showing temperature variations due to installation of a dam curtain around the debris wall.

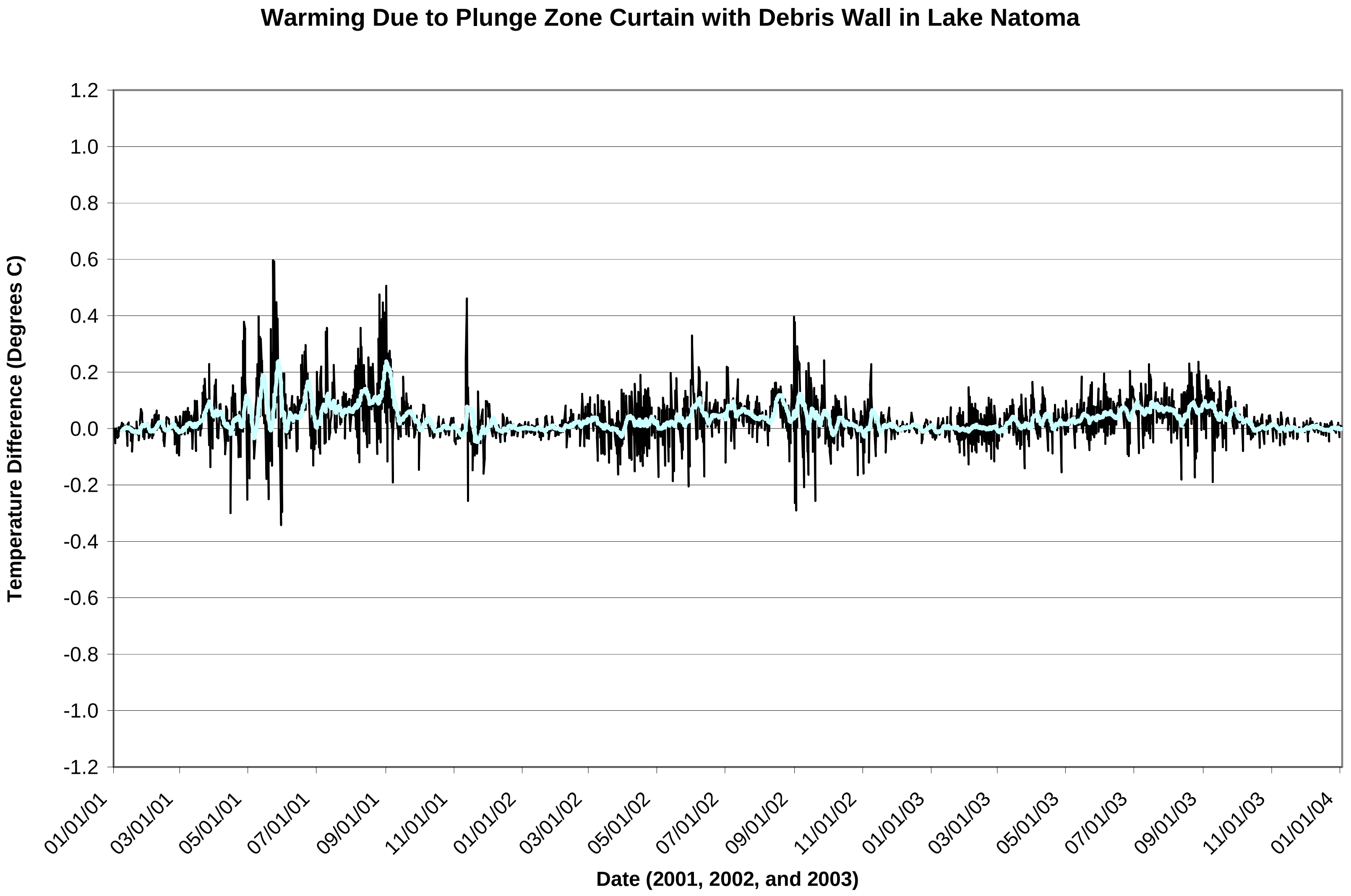


Figure 13.—Modeled Nimbus Dam release temperature differences showing temperature variations due to installation of a plunge zone curtain.

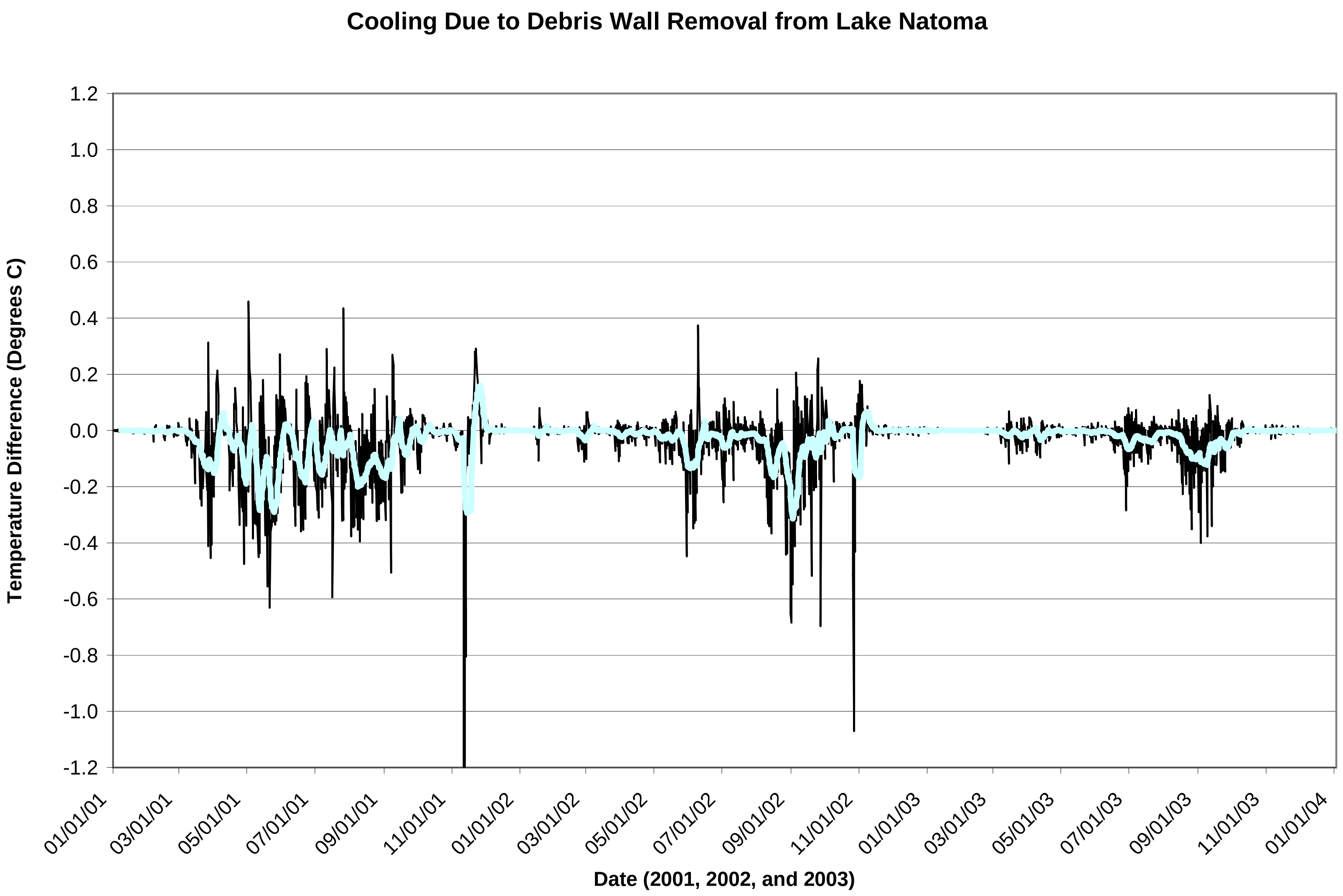


Figure 14.—Modeled Nimbus Dam release temperature differences showing temperature variations due to debris wall removal.

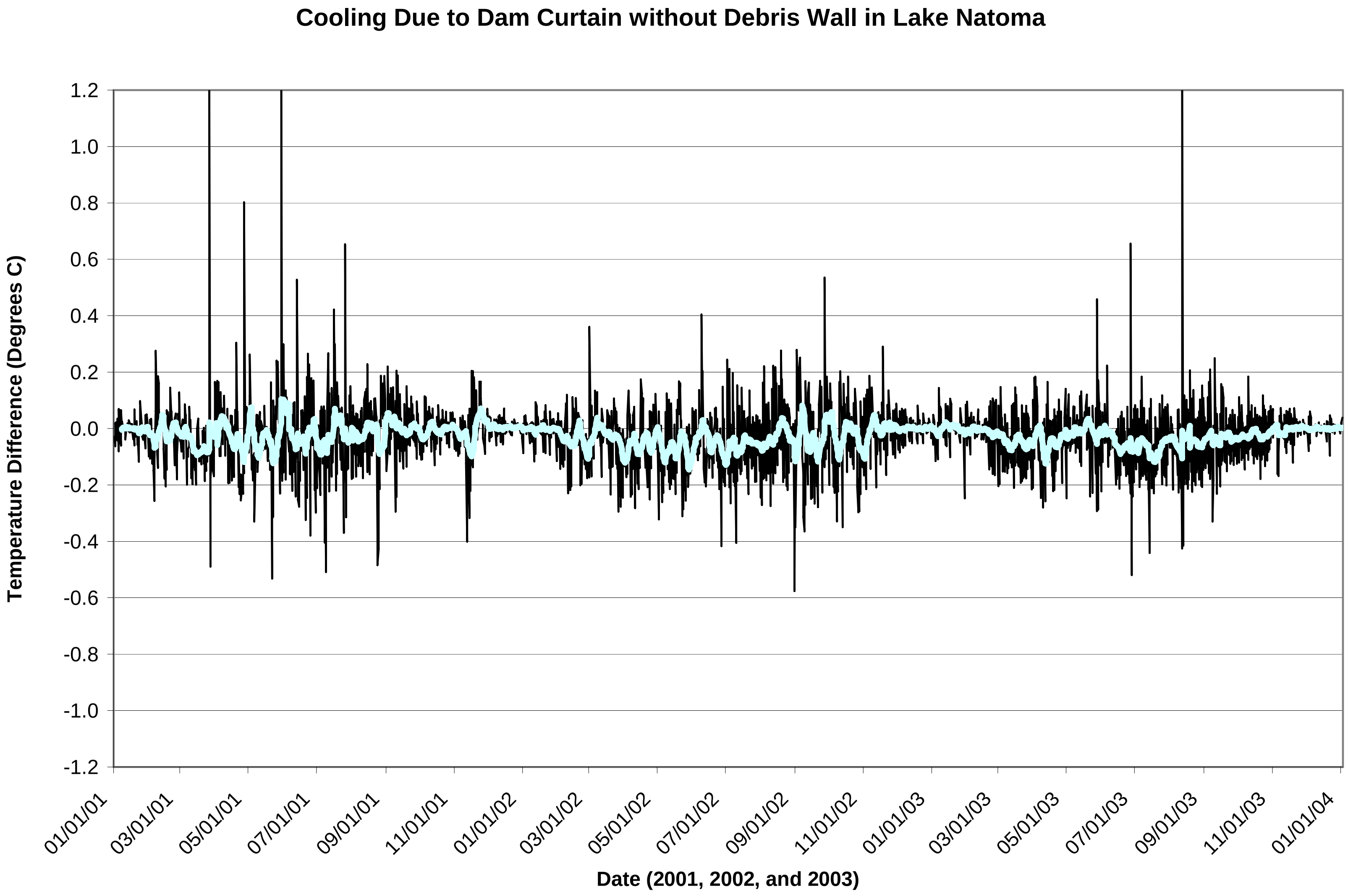


Figure 15.—Modeled Nimbus Dam release temperature differences showing temperature variations due to a dam curtain with removal of the debris wall.

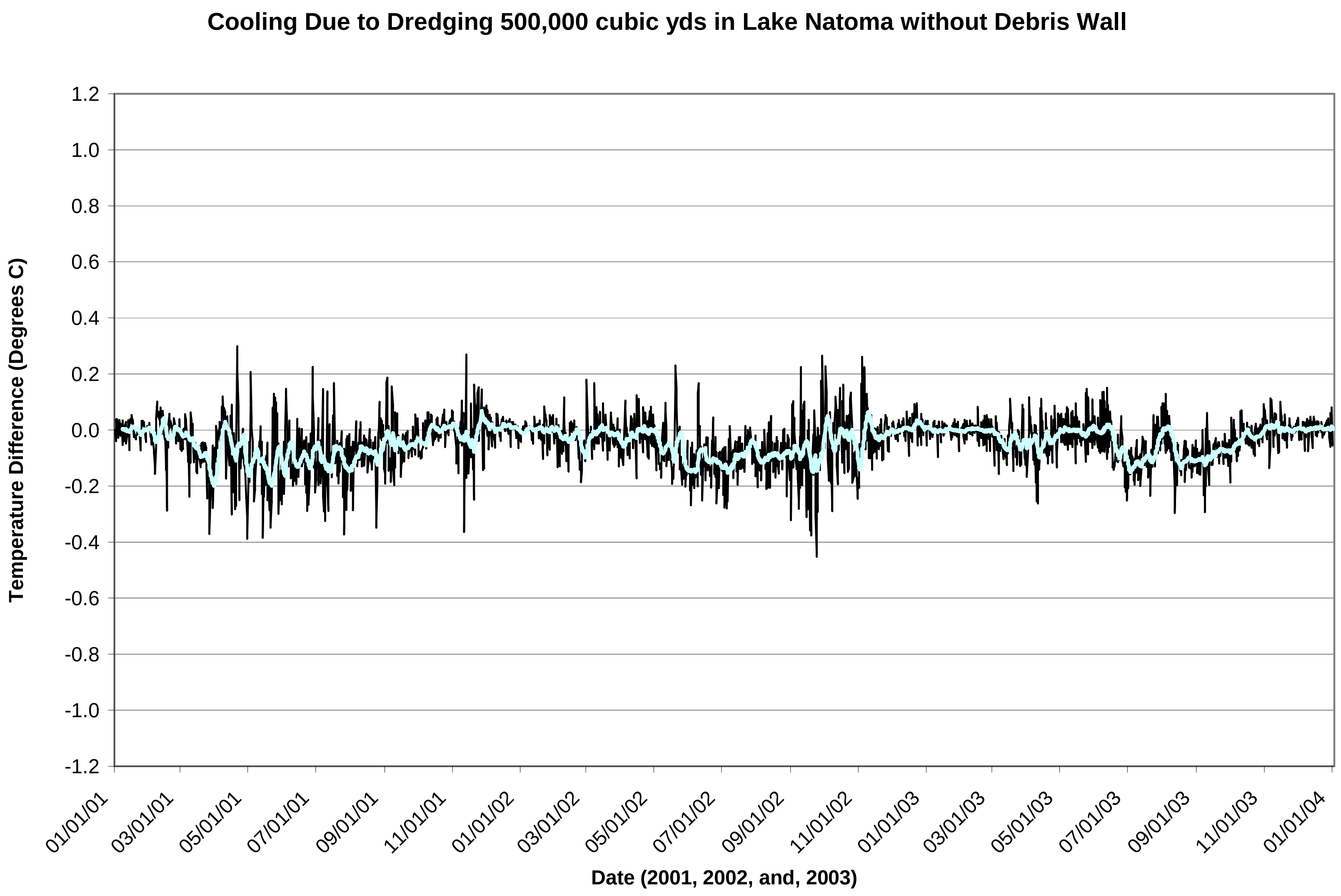


Figure 16.—Modeled Nimbus Dam release temperature differences showing temperature variations due to dredging 382,277 cubic meters (500,000 cubic yards) of sediment and debris wall removal.

- Run N6 – Installation of a deep dam curtain with debris wall left in place. A deep dam curtain with bottom elevation at 30.5 meters (100 feet) AMSL affecting only the Nimbus penstock withdrawals and not affecting the spillways was modeled with the 2-D model.

- Run N7 – Installation of a shallow plunge zone curtain with debris wall left in place.

- Run N8 – Installation of both a deep dam curtain and a plunge zone curtain with debris wall left in place.

- Run N9 – Installation of a deep dam curtain all the way across the spillways with debris wall left in place.

Lake Natoma Sensitivity Scenario Findings

Combinations of the four identified actions within Lake Natoma were investigated. The differences in Nimbus Dam release temperatures between the existing condition (Run NC8) and the combined four Lake Natoma Actions (Run N5) are shown in figure 11. Model results are plotted for noon and midnight of each day for the three year period from 2001 through 2003. A 14-day moving average is shown on figure 11. The moving average on figure 11 at times shows 0.4 °C (0.7 °F) temperature improvement during summer 2001 to 0.2 °C (0.4 °F) during summer 2003, with some noon and midnight temperature reduction over 1.2 °C (2.2 °F). Differences were positive or negative, depending on internal seiching (sloshing due to differences in momentum and density of the layers), hydraulics, and other modeled factors. Peaking power operations at Folsom Dam and therefore varying release rates from Folsom Dam cause water surface elevations of Lake Natoma to fluctuate over the day. The fluctuations in Folsom Dam releases as well as increases in internal seiching increases mixing in Lake Natoma and may intermittently warm Nimbus Dam release temperatures.

The differences in Nimbus Dam release temperatures between the existing condition (Run NC8) and an L-shaped Nimbus Dam curtain only around the power penstocks (Run N6) are shown in figure 12. Figure 12 shows that installing a Nimbus Dam curtain accounts for about half of the total temperature reduction associated with all the identified actions shown in figure 11. Figure 12 shows the results for the existing debris wall condition with a dam curtain added. A Nimbus Dam curtain enclosing only the penstocks produces similar temperature reduction benefits as those of a curtain that extends along the entire face of the dam and the spillway bays.

The differences in Nimbus Dam release temperatures between the existing condition (Run NC8) and a plunge zone curtain (Run N7) are shown in figure 13. No improvement is attributed to the addition of the plunge zone curtain. Figure 13 indicates that the plunge zone curtain does not improve thermal conditions in Lake Natoma and actually increases Nimbus Dam release temperatures slightly because of additional mixing. Modeling also indicated that installing both the dam curtain and a plunge zone curtain would provide less temperature reduction than installing only the dam curtain.

The previous figures compared results to existing conditions which included no modifications to the debris wall. If the debris wall were removed, minimal additional temperature reduction attributed to a dam curtain would be gained.

The differences in Nimbus Dam release temperatures between the existing condition (Run NC8) and removing the debris wall (Run N1) are shown in figure 14. Figure 14 shows that removal of the debris wall decreases release temperatures by about 0.15 °C (0.27 °F).

The differences in Nimbus Dam release temperatures between removing the debris wall (Run N1) and the combination of completely removing the debris wall and installing an L-shaped Nimbus Dam curtain around the debris wall (Run N2) are shown in figure 15. If the dam curtain were installed in combination with debris wall removal, the effect of the additional dam curtain installation would provide minimal overall additional temperature reduction. This result was confirmed using FLOW-3D modeling.

The differences in Nimbus Dam release temperatures between removing the debris wall (Run N1) and removing the debris wall as well as dredging 382,277 cubic meters (500,000 cubic yards) of material from the channel of Lake Natoma (Run N4) are shown in figure 16. If the debris wall was removed, dredging a large amount of material would deepen Lake Natoma and provide some minimal additional temperature reduction of about 0.1 °C (0.2 °F). Dredging without debris wall removal is less effective at temperature reduction than similar dredging with debris wall removal.

CE-QUAL-W2 Reservoir Model Conclusions and Recommendations

An examination of the CE-QUAL-W2 two-dimensional reservoir model results in the following conclusions and recommendations.

1. Based on modeling continuous Folsom Dam powerplant releases rather than peak load operation, Folsom Dam operations should continue to be a peak-load operation. It appears that concentrating on operational or structural modifications at Folsom Dam and their effects on Lake Natoma might have the greatest impact on reducing Nimbus Dam tailwater temperatures. The timing of peaking releases at Folsom

Dam may be optimized to cool afternoon warming down to Watt Avenue Bridge. However such investigation is outside the scope of this study.

2. A powerplant curtain at Nimbus Dam reduces summertime release temperatures by about 0.2 °C (0.36 °F) which is greater than any other of the individual identified actions for Lake Natoma.

3. A Nimbus Dam curtain around the powerplant intake is preferred over a curtain across the entire forebay. Extending the Nimbus Dam curtain across the forebay to prevent spilling from the warm surface water through either the power penstock or a portion of the spillways is not recommended because it provides little improvement in release temperatures. Releases typically pass through the powerplant. Furthermore, such a configuration will pool more warm epilimnetic water which could increase release temperatures during surface spills. Due to the extra expense of a longer curtain and interference with spillway operations and recreation, a curtain enclosing the penstock intakes such as an L-shaped skimmer wall is recommended over a full-length curtain.

4. A plunge zone curtain is not recommended because of increased reservoir mixing which results in higher Nimbus Dam release temperatures. The plunge zone curtain is an undesirable option from a temperature reduction perspective and it would restrict boat travel in Lake Natoma.

5. Installing a plunge zone curtain in combination with other actions reduces the effectiveness of the other actions.

6. With any Nimbus Dam curtain, releases over the spillways should be minimized during the warm seasons.

7. Debris wall removal reduces Nimbus Dam summer release temperatures by about 0.15 °C (0.27 °F).

8. Dredging just upstream of the dam would allow for a deeper curtain.

9. Dredging 382,277 cubic meters (500,000 cubic yards) over a 3.9 km (2.4 mile) reach upstream of Nimbus Dam with the debris wall removed provides a summer temperature reduction of about 0.1 °C (0.18 °F); which is smaller than other identified actions for Lake Natoma. The existing row boat race course on Lake Natoma does not fully meet Olympic standards because a portion of it is too shallow. Localized dredging in the boat course is desirable for improving boat draft depths, which can affect boats racing at opposite sides of the boat

> course differently. Depending on design, dredging the channel might have the ancillary benefit of enabling the race course to meet Olympic standards.

Structural improvements at Nimbus Dam, such as installation of a Nimbus Dam curtain or debris wall removal is only recommended after the operational and structural fine tuning of releases from the cold water pool at Folsom Dam and Lake are exhausted or considered in combination with those at Nimbus Dam.

Although model results indicated that changing Folsom Dam power generation from peak load to baseload operations increased Nimbus Dam release temperatures and there may be temperature benefits associated with shifting the timing of peak load generation, analysis of peak load shifting is outside the scope of this study. Minimum pools, raising Folsom Dam, and raising Nimbus Dam, and other options that involve operational changes were not simulated because these options were also beyond the scope of work. For these scenarios, an operational study would be needed to develop flows and water surface elevations which correspond to operational regulations. Only releases from Folsom Lake were changed to match Nimbus Dam baseload flows. A peaking power operational study coupled with a temperature modeling study may provide additional information on timing of flows for downstream cooling. However, such an operational study was outside the scope for this modeling study.

Partial removal or port cutting (to provide continued protection of the Nimbus Dam powerplant intakes from debris during catastrophic floods) of the debris wall to potentially minimize vortex formation, to enhance temperature reduction, and to prevent protrusive effects due to a curtain could be a less costly action than dam curtain installation and maintenance, and it may provide power generation benefits. However, any structural modifications to Nimbus Dam and associated benefits would need to be thoroughly investigated before such a recommendation could be made.

A Nimbus Dam curtain around the power penstocks would increase surface water temperatures upstream of the curtain including those in front of the spillways. Therefore, if a dam curtain around the penstocks is constructed, releases over the spillway are not recommended during periods when cool water management for fisheries was necessary. A dam curtain may also interfere with recreational activities near the boat docks at the dam and has the potential to affect vortex formation, size, and location. However, physical modeling of vortex formation near the penstock intake was beyond the scope of this study.

Vortices, especially those with air entrainment, have several disadvantages in hydraulic design. Air entrainment can affect hydraulic machinery or hydropneumatics. Pressure surges, increased head loss, reduction in efficiency in hydraulic machinery, increased cavitation and vibration, entrainment of floating material, and reduced longevity of mechanical parts are potential detrimental effects. At low submergence, a withdrawal structure can be more prone to vortices.

VI. FLOW-3D Modeling

The FLOW-3D Model—a computational fluid dynamics (CFD) model—of the Nimbus Dam forebay compared selected identified actions with existing conditions to determine the relative effect of such actions in reducing Nimbus Dam powerplant release intake temperatures on a short-term basis. The two dimensional, laterally averaged CE-QUAL-W2 model is not capable of resolving three dimensional mixing processes on a spatial scale representative of the powerplant intakes. Such a small scale is important for comparing the relative effectiveness of the selected actions because performance involves entrainment and mixing. Thus, three dimensional modeling with a much smaller grid than that of the CE-QUAL-W2 model was deemed necessary to capture these smaller scale processes attributable to the selected actions in the vicinity of the Nimbus Dam Powerplant intakes. As shown in figure 17, the Nimbus Dam forebay was modeled to include the width of Lake Natoma extending 1,500 feet (457 meters) upstream of Nimbus Dam. Flow through the powerplant and powerplant internal details were not modeled. However, powerplant intake temperatures are expected to be representative of Nimbus Dam release temperature for this comparative analysis.

Although FLOW-3D has the capability of modeling unsteady hydro-thermodynamics, modifications to the source code to include transient thermal processes were considered too costly and computationally intensive making it impractical for the model grid that contains small cells (i.e., 1.5 m (5-ft) grid) within a large spatial extent such as the Nimbus Dam forebay. The CFD modeling was accomplished using a quasi-steady-state approach that assumes no seiching (sloshing) and that assumes changes in Lake Natoma thermal stratification occur over a time scale that is longer than the CFD model convergence to steady state. That being the case, one can compare the effect of different alternatives for specified “point-in-time” conditions.

To assess the physical meaning and adequacy of the quasi steady-state assumption, the convergence time of the CFD model was compared with the time scale for typical field-measured changes in Nimbus Dam forebay thermal stratification. Figure 18 shows time-varying temperature profiles in the Nimbus Dam forebay during a one day period of August 2001 for conditions of strong stratification and demonstrates that the time scale for significant changes in stratification is typically longer than eight hours. The CFD model required four hours in real-time to reach steady-state convergence. Thus, the quasi-steady-state assumption is reasonable in consideration of time-varying field-measured temperature profiles in the Nimbus forebay. However, the results should only be interpreted as a snapshot in time, and the intake temperature reduction exhibited by the selected actions that were modeled should only be viewed as persisting for a short period of time during which the stratification conditions exists. The

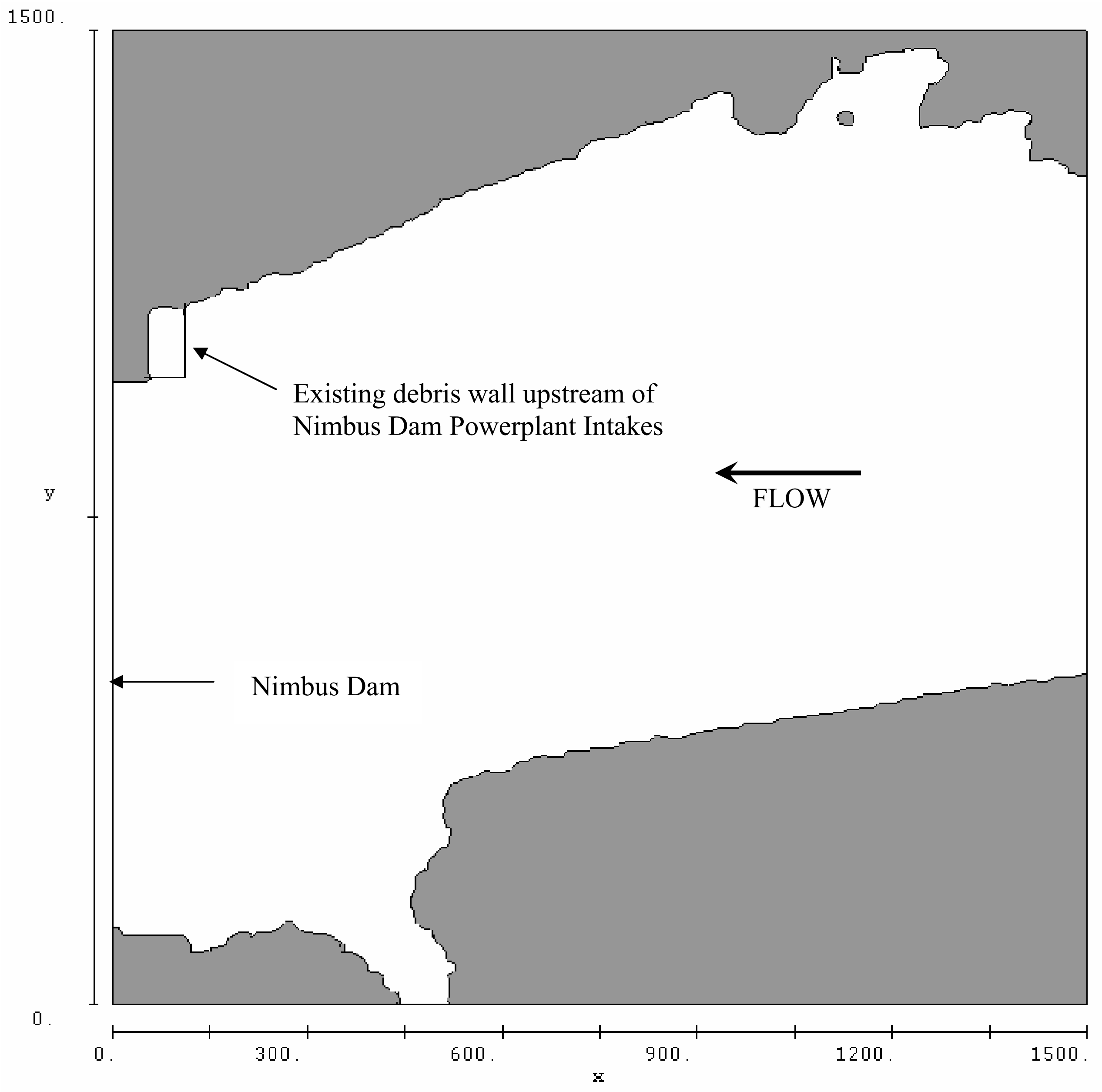


Figure 17.—Plan view of Nimbus Dam forebay modeled using FLOW-3D® CFD model.

limitation of this approach is that the CFD model results cannot be used to predict long-time scale effects due to seasonal changes in cold water storage volumes. However, since Lake Natoma has a relatively small storage volume, the capability for storing large volumes of cold water on a seasonal time scale is minimal and all of the selected alternatives will likely only reduce the degree of warming by keeping the cold water releases from Folsom as deep as possible as they flow through Lake Natoma. This provides the potential for reducing Nimbus Dam

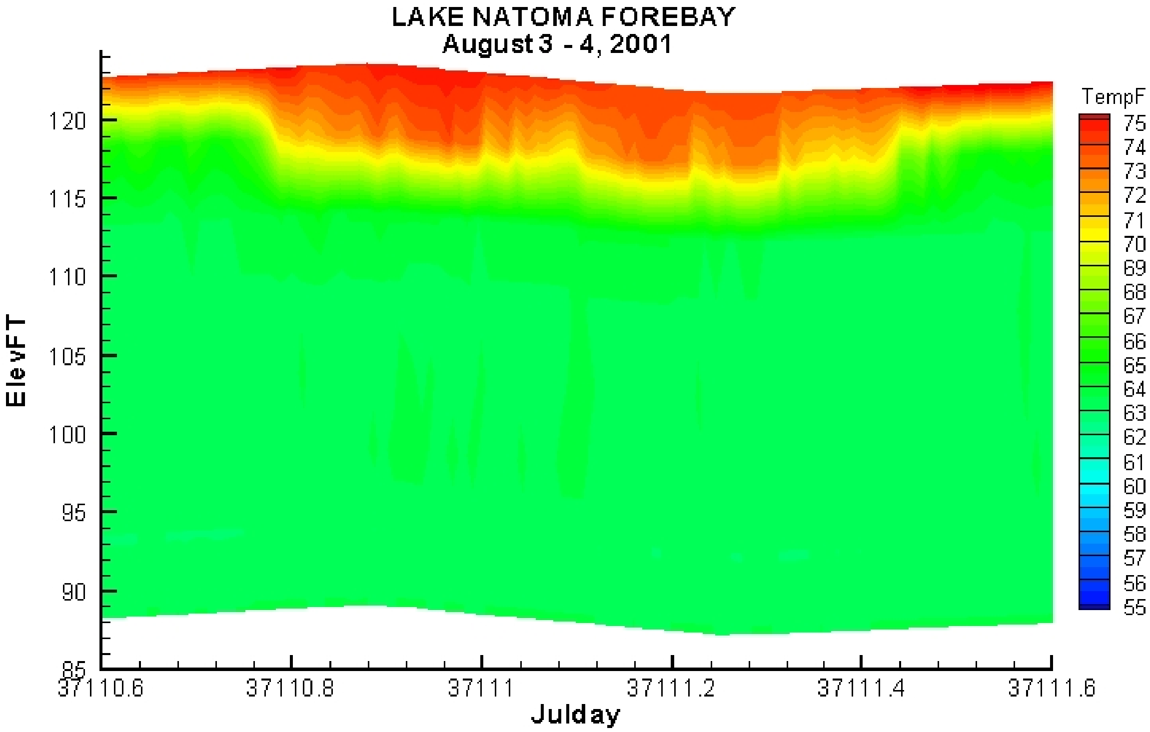


Figure 18.—Field measured temperature profiles for Lake Natoma forebay showing characteristic time scale for changes in stratification.

Powerplant intake temperatures as well as release temperatures on a short time scale (i.e., reducing the daily peak temperatures entering the powerplant). The question then becomes how much reduction in the daily maximum intake temperature is possible and which selected action has the most potential for such reduction. Thus, conditions representative of the largest degree of stratification in Lake Natoma were selected for comparative modeling of identified actions and are expected to be indicative of the best that can be achieved from a Nimbus Powerplant intake temperature reduction standpoint.

The configurations under the identified actions that were modeled as described using FLOW-3D include:

- Existing Nimbus Dam forebay and powerplant intakes (baseline for comparison)
- Partial debris wall removal
- Entire debris wall removal

- Installation of a powerplant intake curtain with existing debris wall
- Installation of a powerplant intake curtain with debris wall removed

The powerplant intake temperatures were computed for each of these configurations and compared to determine the reduction in temperatures during the specified Lake Natoma water surface elevations and Nimbus Powerplant discharges representative of the largest degree of stratification. Field measured-temperature profiles were reviewed and indicated that a period of strong stratification occurred during August 3 - 4, 2001; as a result, the forebay temperature profiles and operating conditions during this period were selected for configuration performance comparisons.

Model Boundary Conditions

The Nimbus Dam forebay bathymetry was used to generate a stereolithography file that represents geometric boundary conditions in FLOW-3D. The measured August 3, 2001, temperature profile and uniform horizontal velocity profiles were used as the upstream temperature and velocity initial conditions. Figure 19 shows the modeled profile compared with the measured profile. The temperature profile was fixed in time and a density-dependent hydrostatic pressure condition was used to represent the upstream temperature and hydrodynamic boundary conditions. The effects of temperature-density relationships were modeled according to the Boussinesq approximation that assumes a linear variation of density with temperature. External heat transfer across boundaries was not modeled since it can be considered negligible for this quasi-steady-state comparative analysis.

Model Results

The model results are presented as plan and profile views (in dimensions of feet) of flow field velocity overlaying color contours of temperature. The plan views in the vicinity of the powerplant intakes were taken at an elevation of 31.2 m AMSL (102.5 ft) to show stream-wise and lateral distributions in velocity and temperature. The elevation views were taken at the centerline of the intakes to show the streamwise and vertical distributions in velocity and temperature. The temperature scales differ between plan and profile plots because the highest temperatures are located near the surface and will be captured in the profile view, but not in the plan view which represents a slice of the flow field at depth.

Existing Nimbus Dam Forebay and Powerplant Intakes

The existing Nimbus Dam forebay configuration was modeled first to provide the baseline for comparison. The results indicate that for the specified thermal

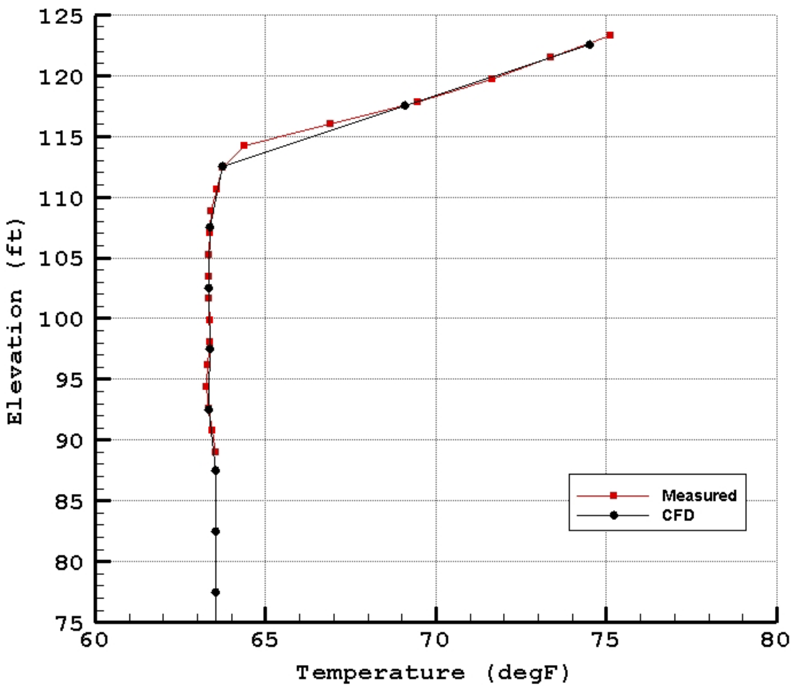
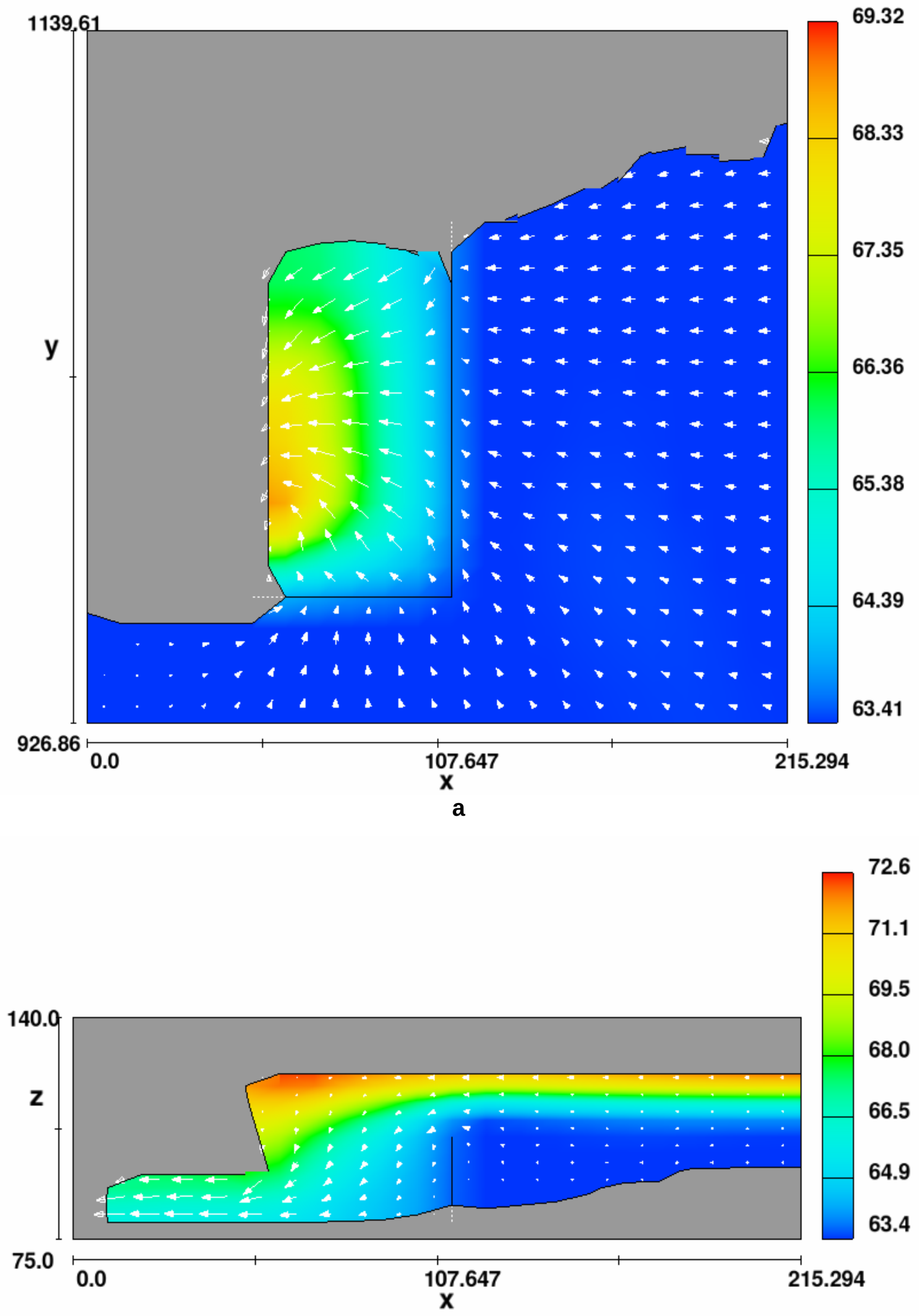


Figure 19.—Comparison of measured temperature profile (August 4, 2001) with that used as upstream boundary conditions for FLOW-3D® CFD model.

stratification and operating conditions, the computed powerplant intake temperature was 19 °C (66.2 °F). Figures 20a and 20b show the plan view (distance units in feet) sliced at elevation 31.2 m AMSL (102.5 ft), and profile views including velocity vectors overlayed on temperature contours (in degrees Fahrenheit) to provide an indication of the withdrawal zone characteristics. It can be seen that the effect of the debris wall (top elevation 32.0 m AMSL (105.0 ft)) is to withdraw warmer epilimnetic water from Lake Natoma. The model grid comprised of 1.52 meter cells (5-foot cells) was able to resolve large-scale flow rotation (see figure 20a). However, such a grid resolution is not considered sufficient to accurately represent vortex formation.

Debris Wall Partially Removed

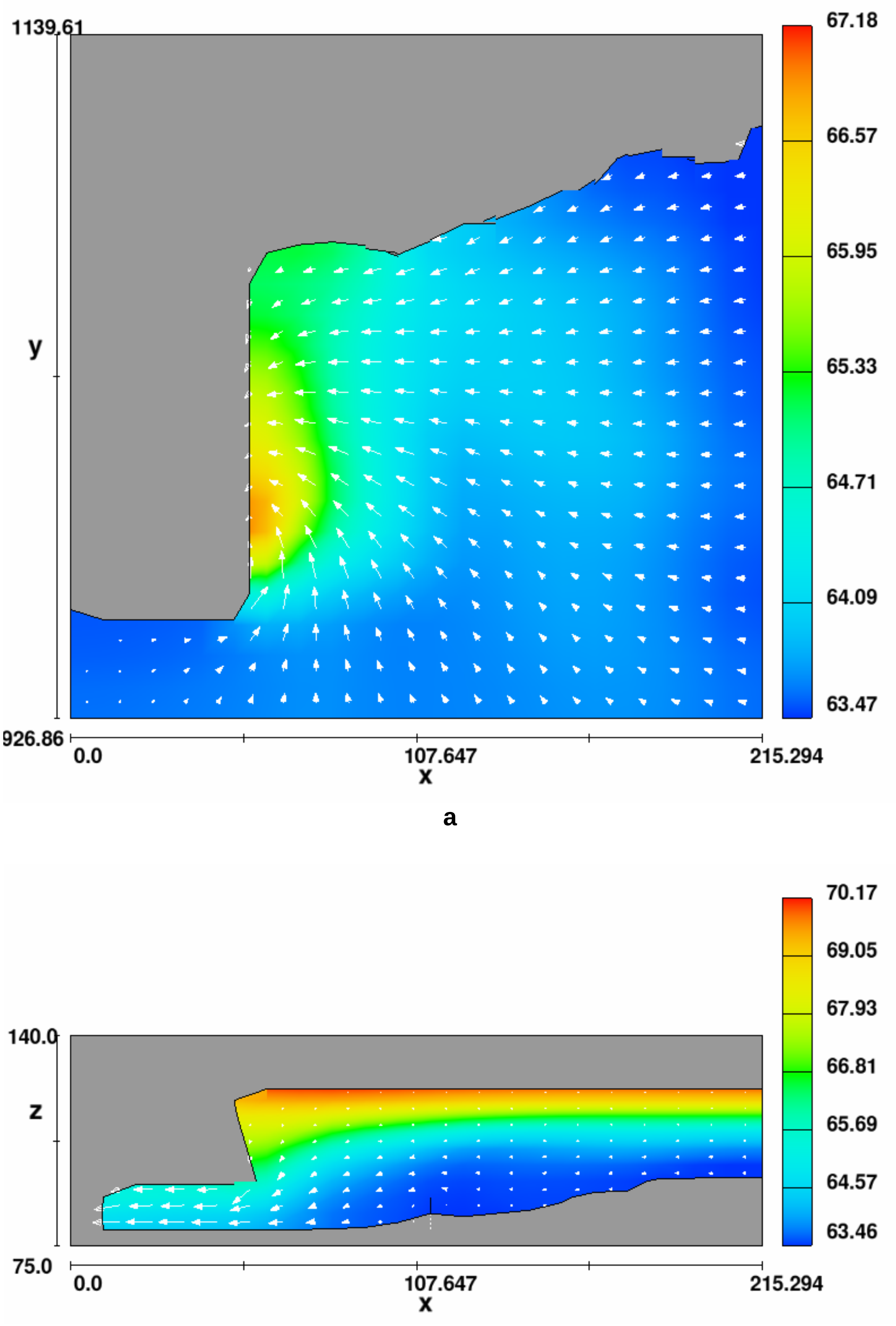
The debris wall top elevation was reduced to 27.4 meters (90 feet) and powerplant intake temperatures were computed as 18.1 °C (64.6 °F). Figures 21a and 21b show the effect of partial debris wall removal in modifying the withdrawal zone compared with the existing configuration (figure 20). It can be seen that some warmer epilimnetic water is still withdrawn with this alternative. However, the results show a reduction in intake temperature of -0.9 °C (-1.6 °F) when compared with existing conditions.



a

b

Figure 20.—Baseline existing configuration plan at elevation 31.2 meter (102.5 feet) (a) and profile (b) CFD model results in near-field of Nimbus Powerplant intakes showing effect of debris wall. The color contours represent temperature (°F), x and z distances are in feet, and vectors represent resultant velocities.



a

b

Figure 21.—Partial debris wall removal configuration plan at elevation 31.2 meters (102.5 feet) (a) and profile (b) CFD model results in near-field of Nimbus Powerplant intakes. The color contours represent temperature (°F), x and z distances are in feet, and vectors represent resultant velocities.

Debris Wall Fully Removed

Entire removal of the debris wall produces computed powerplant intake temperatures of 18.0 °C (64.4 °F). Figures 22a and 22b indicate that entire removal of the debris wall only has a small, virtually indistinguishable, additional effect on the withdrawal zone from Lake Natoma as compared with partial debris wall removal. It can be seen that warm epilimnetic water is also still withdrawn for this alternative as compared with existing conditions. Although partial and complete removal of the debris wall shows no significant relative difference in powerplant intake temperatures, complete removal of the debris wall likely has an additional positive effect on vortex formation and strength near the Nimbus Powerplant intakes and likely negative effect on preventing sediment and debris from entering the penstock; however, demonstration of either of these effects would require further investigation via laboratory physical modeling.

Intake Curtain Installed with Debris Wall

Model results indicated that installation of an intake curtain with the existing debris wall produces a computed intake temperature of 17.8 °C (64.0 °F). Figures 23a and 23b show the improved effects of the intake curtain in modifying the withdrawal zone to one of dominant hypolimnetic withdrawal, thereby producing reduced powerplant intake temperatures compared with existing conditions. Comparing figure 23 with figures 20, 21, and 22 shows an improvement in the withdrawal conditions producing the largest temperature reduction with an intake curtain in which case the curtain acts as a barrier to withdrawal of warmer epilimnetic water. Furthermore, it appears that the flow rotation near the sidewall for baseline conditions gives way to a large corner eddy with an intake curtain with the existing debris wall (see figure 23a).

Intake Curtain Installed with Debris Wall Removed

Installation of an intake curtain with the debris wall removed also produces a computed intake temperature of 17.8 °C (64.0 °F). Figures 24a and 24b show the resulting velocity and temperature distributions for this configuration. It is important to note that there appears to be no additional benefit from removing the debris wall when the intake curtain is installed. Under quasi-steady state conditions, the intake curtain effectively becomes the control point for the Lake Natoma withdrawal zone and produces hypolimnetic withdrawal regardless of whether the debris wall is left in place or removed. It appears that with the intake curtain installed and the existing debris wall removed, two larger eddies on both sides of the intakes develop (see figure 24a). Installation of a curtain with the existing debris wall in place or removed may affect vortex location and strength near the Nimbus Powerplant intakes (by increasing the vortex size and pushing the vortex into the corner of the powerplant intakes); however, this effect would require further investigation via laboratory physical modeling.

Figures 25-27 of Nimbus Dam forebay illustrate the effect of each identified action in altering the withdrawal from Lake Natoma. Comparisons of figure 27

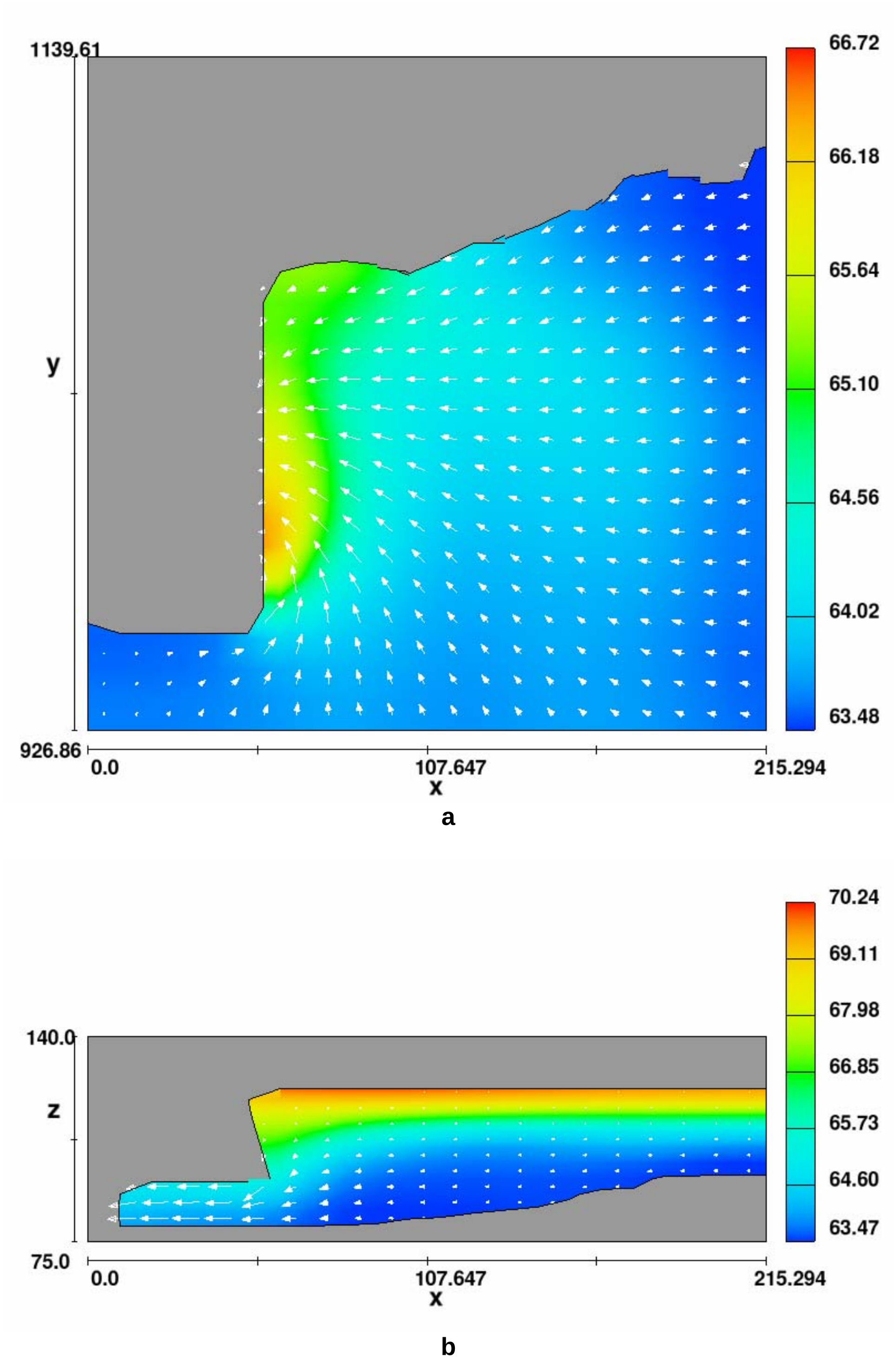


Figure 22.—Fully removed debris wall configuration plan at elevation 31.2 meters (102.5 feet) (a) and profile (b) CFD model results in near-field of Nimbus Powerplant intakes. The color contours represent temperature (°F), x and z distances are in feet, and vectors represent resultant velocities.

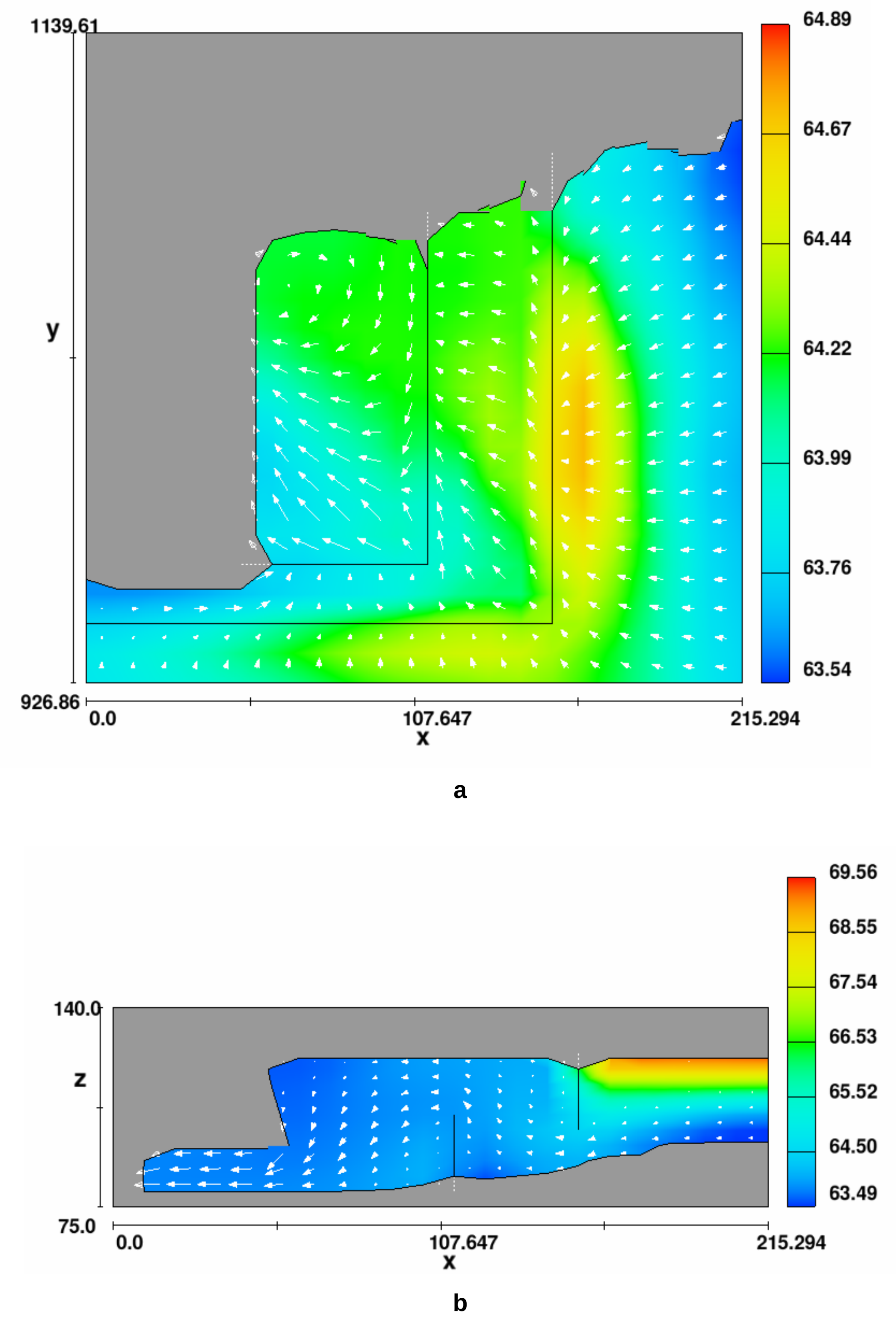
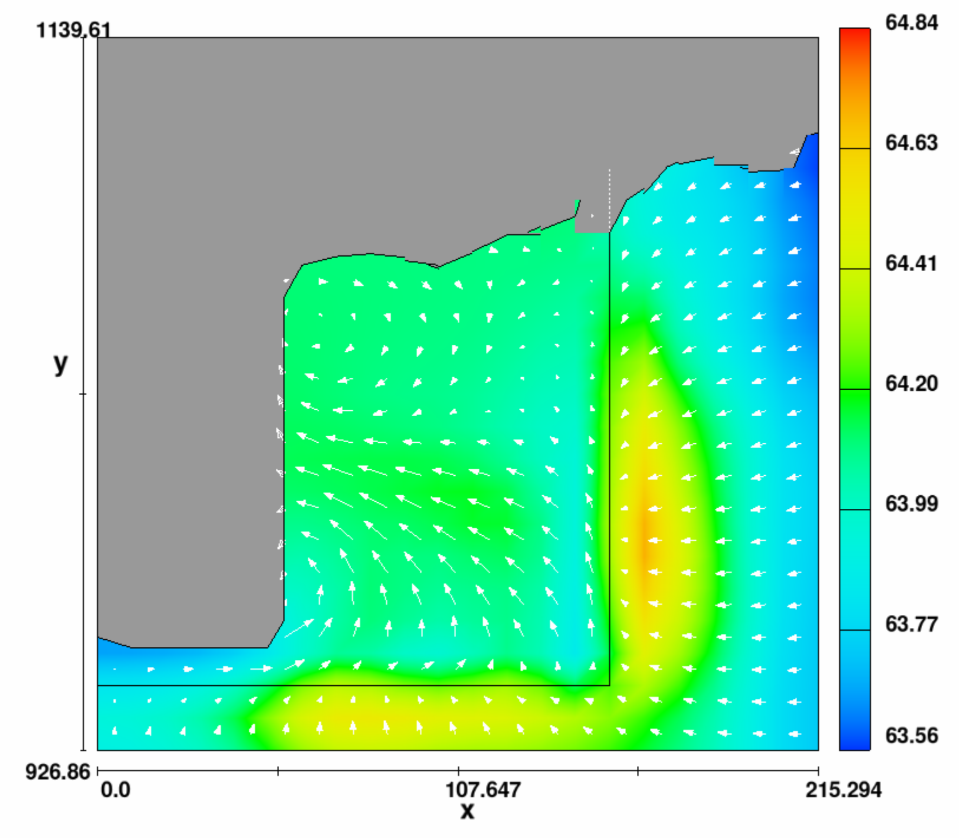
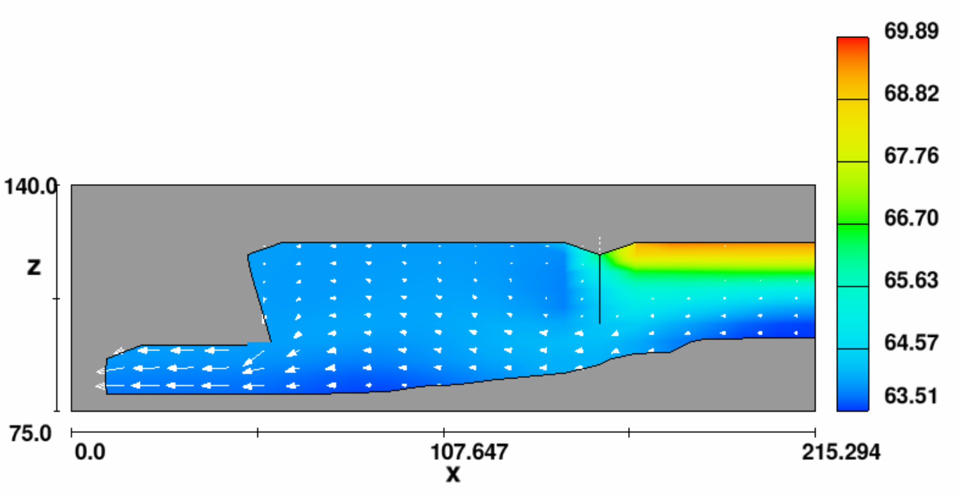


Figure 23.—Intake curtain with existing debris wall configuration plan at elevation 31.2 meters (102.5 feet) (a) and profile (b) CFD model results in near-field of Nimbus Powerplant intakes showing combined effect of debris wall and intake curtain. Note that the curtain effectively excludes warm water from the penstock intakes. The color contours represent temperature (°F), x and z distances are in feet, and vectors represent resultant velocities.



a



b

Figure 24.—Intake curtain with debris wall removed configuration plan at elevation 31.2 meters (102.5 feet) (a) and profile (b) CFD model results in near-field of Nimbus Powerplant intakes showing effect of the intake curtain. Note that the curtain effectively excludes warm water from the penstock intakes. The color contours represent temperature (°F), x and z distances are in feet, and vectors represent resultant velocities.

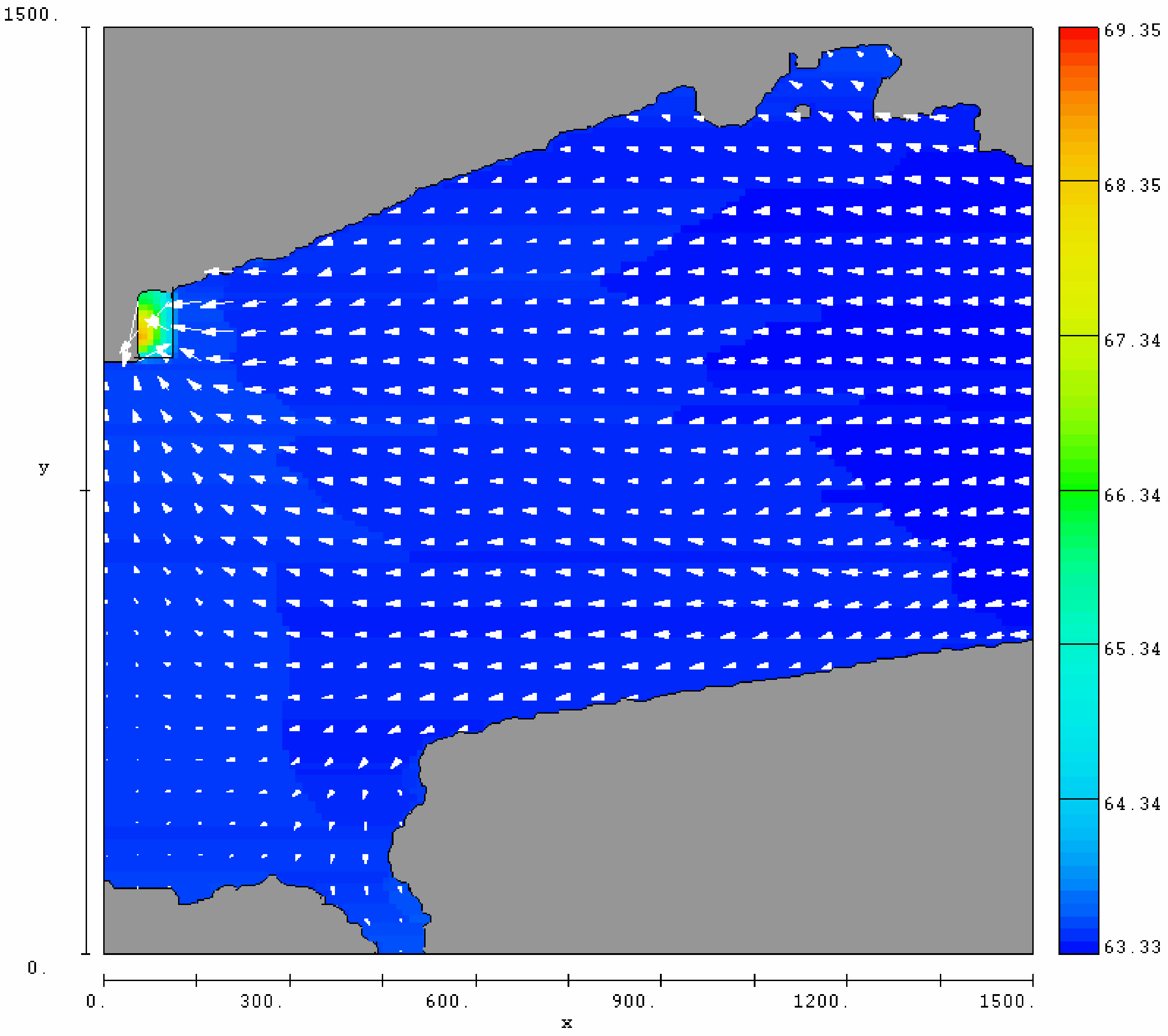


Figure 25.—Flow field and temperature contours plan view of Nimbus Dam forebay for existing condition (baseline) at elevation 31.2 meters (102.5 feet). The color contours represent temperature (°F), x and y distances are in feet, and vectors represent resultant velocities.

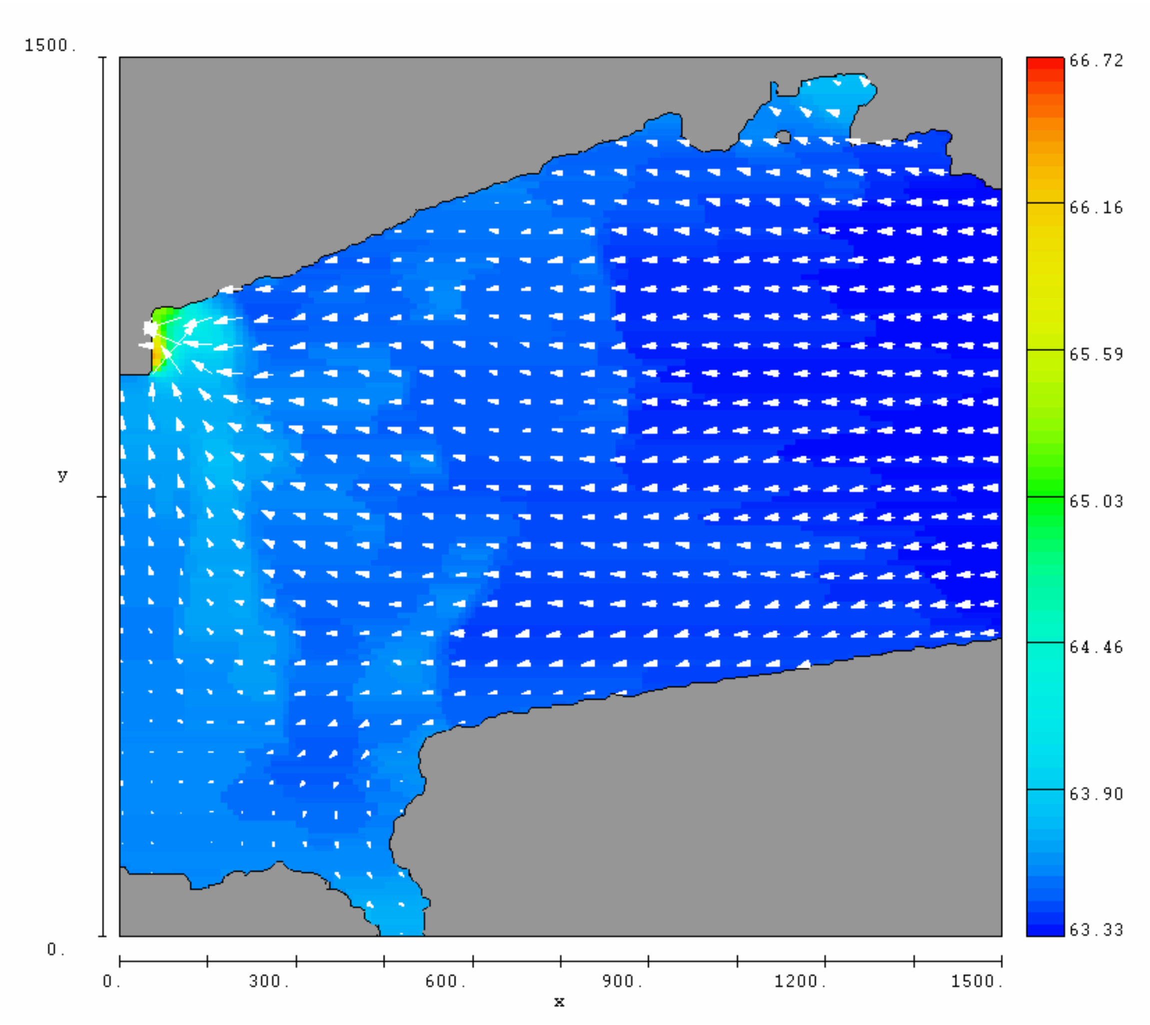


Figure 26.—Flow field and temperature contours plan view of Nimbus Dam forebay at elevation 31.2 meters (102.5) feet for debris wall removed configuration. The color contours represent temperature (°F), x and y distances are in feet, and vectors represent resultant velocities.

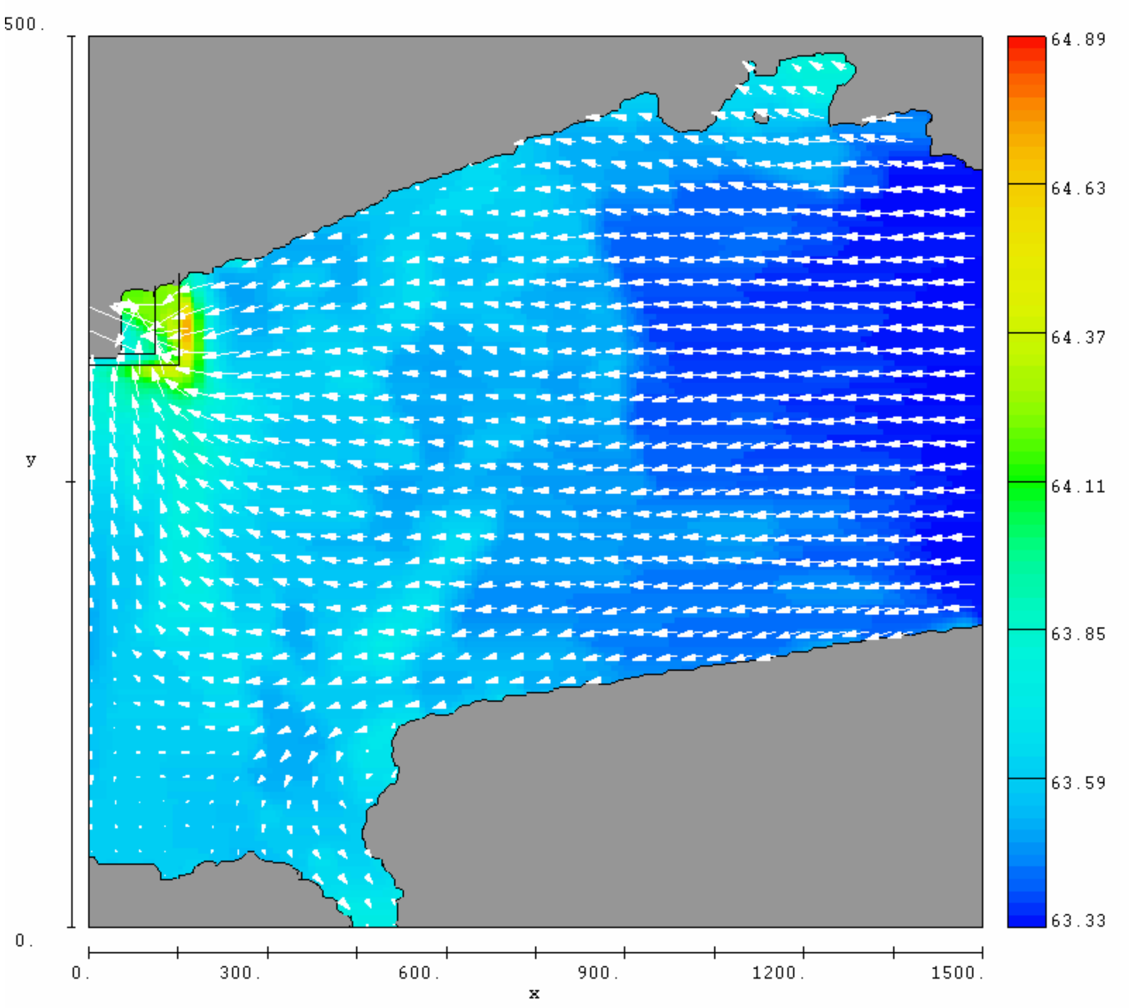


Figure 27.—Flow field and temperature contours plan view of Nimbus Dam forebay at elevation 31.2 meters (102.5 feet) for intake curtain with existing debris wall configuration. The color contours represent temperature (°F), x and y distances are in feet, and vectors represent resultant velocities.

with figure 25 reveal that the warmer epilimnetic water in Lake Natoma is retained by installing an intake curtain, and colder hypolimnetic water is withdrawn instead. This is evidenced by the increased temperature contours at the elevation shown. Table 1 compares intake temperatures of the modeled configurations and highlights the effect of each action in producing a short term reduction in Lake Natoma release temperatures compared with the existing configuration.

Table 1.—Comparison of Nimbus Powerplant intake temperatures for identified actions modeled

Configuration	Computed intake temperature	Reduction of intake temperature from existing configuration
Existing	19.0 °C (66.2 °F)	--
Partial debris wall	18.1 °C (64.6 °F)	-0.9 °C (-1.6 °F)
No debris wall	18.0 °C (64.4 °F)	-1.0 °C (-1.8 °F)
Intake curtain with debris wall	17.8 °C (64.0 °F)	-1.2 °C (-2.2 °F)
Intake curtain without debris wall	17.8 °C (64.0 °F)	-1.2 °C (-2.2 °F)

This comparative analysis provides an indication of the powerplant intake temperatures reduction that that are expected by modifying the existing conditions accordingly. The effect of reducing the intake temperatures reflected here is due to modification of the withdrawal zone inherent to each configuration. Installing an intake curtain with a bottom elevation of 30.5 meters (100 feet) appears to produce the largest reduction in powerplant intake temperatures. This reduction is independent of the debris wall removal, because the intake curtain is located upstream of the debris wall and becomes the withdrawal zone control point; thereby, negating the effect of the debris wall.

Based on table 1, the effects of partial debris wall removal and full debris wall removal are similar. This result indicates that partial debris wall removal is possible and would have a beneficial effect in reducing peak powerplant intake temperatures while retaining some of the benefit of the debris wall for protecting the powerplant from entrainment of large debris. However, installation of an intake curtain while keeping most of the height of the debris wall in place would appear to be the best action to retain all of the original benefit of the debris wall while producing the maximum reduction in peak powerplant intake temperatures.

These results represent the best that can likely be achieved (a 1.2 °C [2.2 °F] reduction in release temperatures) because the conditions modeled consisted of the strongest degree of stratification occurring during the field-measured temperature profile period of record used in this study. Conditions of weaker stratification will reduce the relative effectiveness of each configuration modeled.

3-D Modeling Conclusions and Recommendations

Based on the findings of this analysis, it is recommended that an intake curtain with a bottom elevation of 30.5 meters (100 feet), located approximately (15.2 meters (50 feet) upstream and to the sides of the existing debris wall, be considered to provide the most effective reduction in powerplant intake temperatures during the periods of strongest stratification. However, the cost of this installation should be weighed against the value of providing a 1.2 °C (2.2 °F) release temperature reduction for the brief time periods when Lake Natoma is strongly stratified and the effectiveness of or desire for managing temperature on a short term basis (i.e., daily) . The frequency with which relatively strong stratification occurs on a seasonal time scale can be obtained from “Lake Natoma Temperature Curtain and Channel Modification Study, 2001-2002” (Vermeyen, Tracy B., August 2005).

VII. ADYN/RQUAL Nimbus Dam Tailwater 1-D Model Calibration

The flow model, ADYN, was calibrated initially for flow, water mass balance, channel friction, and water travel time. The temperature model, RQUAL, was then calibrated to the ramp-down flow conditions seen during the July 27, 2001, through August 12, 2001 warm summer period which covers a near worst-case warm-weather and low-flow condition. Appendix C provides details for the one-dimensional (1-D) model temperature calibration.

The lower American River temperatures are managed to protect over-summering steelhead trout and spawning fall-run Chinook salmon in accordance with the 2004 biological opinion which establishes a 20.0 °C (68.0 °F) target (herein referred to as an operational threshold) at Watt Avenue Bridge with a preferred operational target of 18.33 °C (65 °F). The 2004 biological opinion is presently being revised. See appendix D for a further discussion of steelhead and salmon temperature and flow criteria.

Flow and Travel Time

Near worst-case warm temperature conditions during 2001 were selected for both calibrating the temperature model and for deriving input data for simulation of the lower American River. Conditions during 2001 are indicative of low flows and warm releases from Folsom Dam at a time when the releases from Nimbus Dam dropped below 1,500 cfs and resulted in warm temperatures at Watt Avenue Bridge during late summer.

Following a short period in which the Nimbus Dam spillway gates were exercised with high river flows, the flows during 2001 were dropped from 2,100 cfs to 1,500 cfs during the last day in July. These historic events provided the opportunity to calibrate the model to a range of flow from a relatively full channel condition ramped down to relatively low steady-flow conditions with less modeling instability.

Model travel time was sensitive to channel friction (represented using Manning's "n" values). Modeled water particle travel time is greater than raft travel time due to stagnant water at the sides of the main flow path which the raft does not experience. After calibration, water particle travel times patterns appeared to roughly match float travel time patterns (see appendix table C-1). However, a more convincing calibration factor is reflected in the diel variations of temperature that showed strong agreement both in terms of amplitude (peaks and troughs) and timing of the peaks. Diel temperature variations and timing agreed closely at both William B. Pond Park (lower American River mile [LARM] 13.0) and at the Watt Avenue Bridge (LARM 9.10); the latter of which is the temperature management target location.

The Nimbus Dam tailwater flow and temperature model calibrates to Watt Avenue Bridge to about 0.5 °C (1.0 °F). Late July and early August 2001 warm weather cases were used for model calibration. Figure 28 shows that during this period, flows were dropped from 2,100 cfs to about 1,500 cfs on July 31, 2001 (day 212). Figure 28 was derived by combining outflows from Nimbus Dam and subtracting the Folsom South Canal deliveries. During the summer 2001 calibration period, observed Fair Oaks river discharges were roughly 5 percent less than releases calculated by system water mass balance at Nimbus Dam. The tailwater model downstream from Watt Avenue Bridge is influenced by the Sacramento River backwater. Due to factors such as insufficient stage, stratification, and temperature data at the mouth of the American River, diurnal peaks in water temperature of the lower American River downstream from Watt Avenue Bridge are not sufficiently represented with the one-dimensional flow model boundary conditions or calibrated to short term fluctuations. However, the trends downstream of Watt Avenue Bridge did match warming or cooling trends seen in observed data. Figure C8 (see Appendix C) shows that diurnal peaks do not match at Paradise Beach (LARM 4.5) due to such factors as mentioned above.

Temperature

Based on differences between modeled and observed diel plots of temperature versus time, water temperature model calibration from Nimbus Dam to Watt Avenue Bridge was roughly within about 0.7 °C (1.3 °F) when accounting for error introduced by data gaps in input boundary conditions, backwater effects not modeled, and observed data that is suspect because it is greatly outside the normal range. Tailwater temperatures vary largely due to diurnal variations in meteorology. Figure 29 shows a snapshot in time for modeled (line) and observed (circles) Nimbus Dam tailwater temperatures from Nimbus Dam (LARM 22.6) to the mouth of the lower American River (LARM 0.0) for August 8, 2001, at 6 p.m. (day 220) which is typically when the warm late afternoon conditions is seen at Watt Avenue Bridge. Figure 29 indicates that water temperatures vary more than 5 °C (9 °F) degrees from Nimbus Dam to Watt Avenue Bridge during a warm day with 18 °C (64.4 °F) Nimbus Dam release temperature.

Calibration appendix figure C7 shows modeled and instantaneous observed release temperature versus time at Watt Avenue Bridge from July 28, 2001, through August 12, 2001. Figure 30 shows the diurnal variations at Watt Avenue Bridge are about 3 °C (5.4 °F) during the warm summer days from July 30, 2001, through August 3, 2001, at flows dropping from about 2,100 cfs to 1,500 cfs. The slightly warmer maximum modeled temperatures than observed is partially due to a conservatively warm calibration.

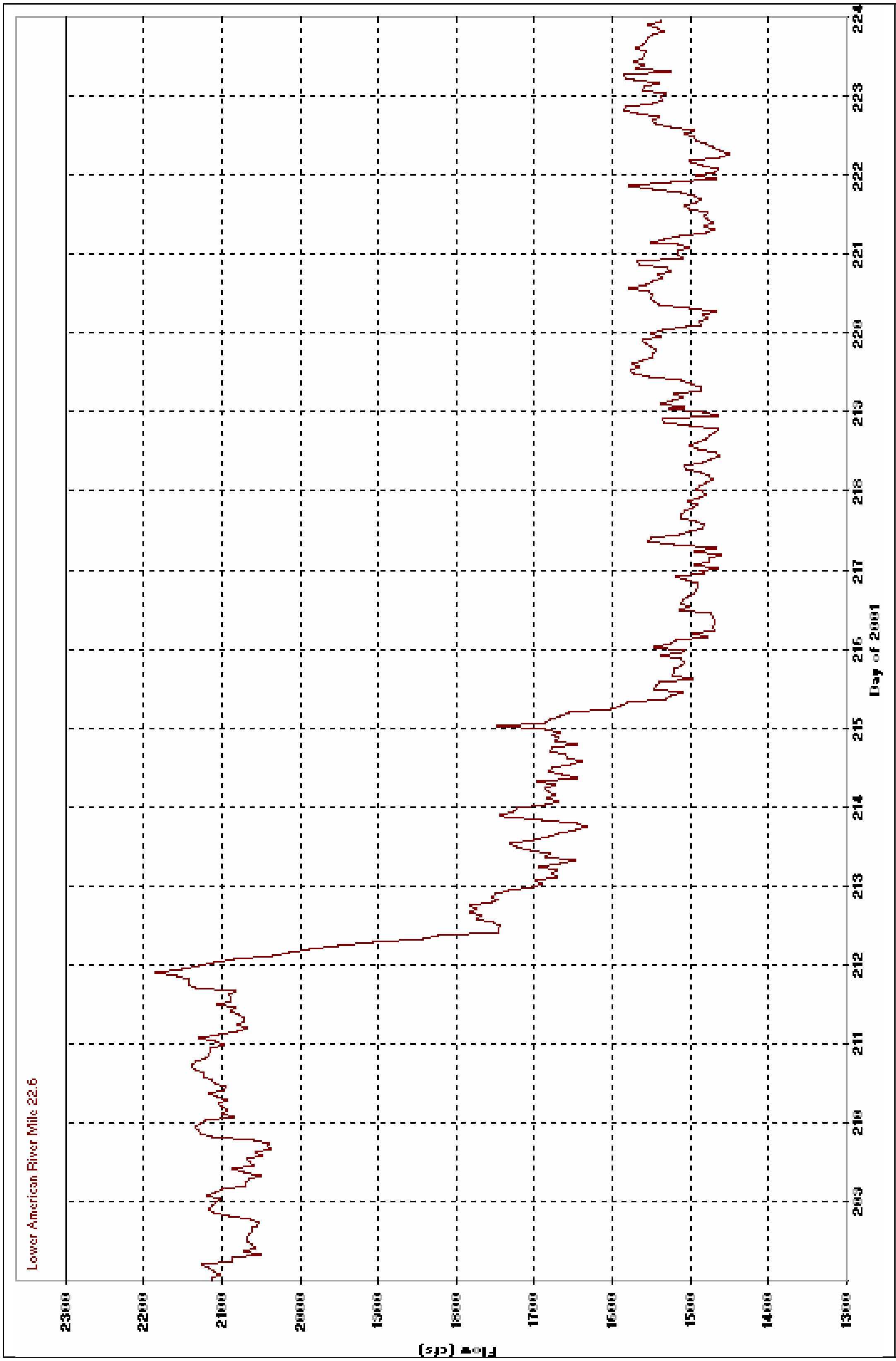


Figure 28.—Modeled Lake Natoma releases for July 27, 2001 (day 208), through August 12, 2001 (day 224).

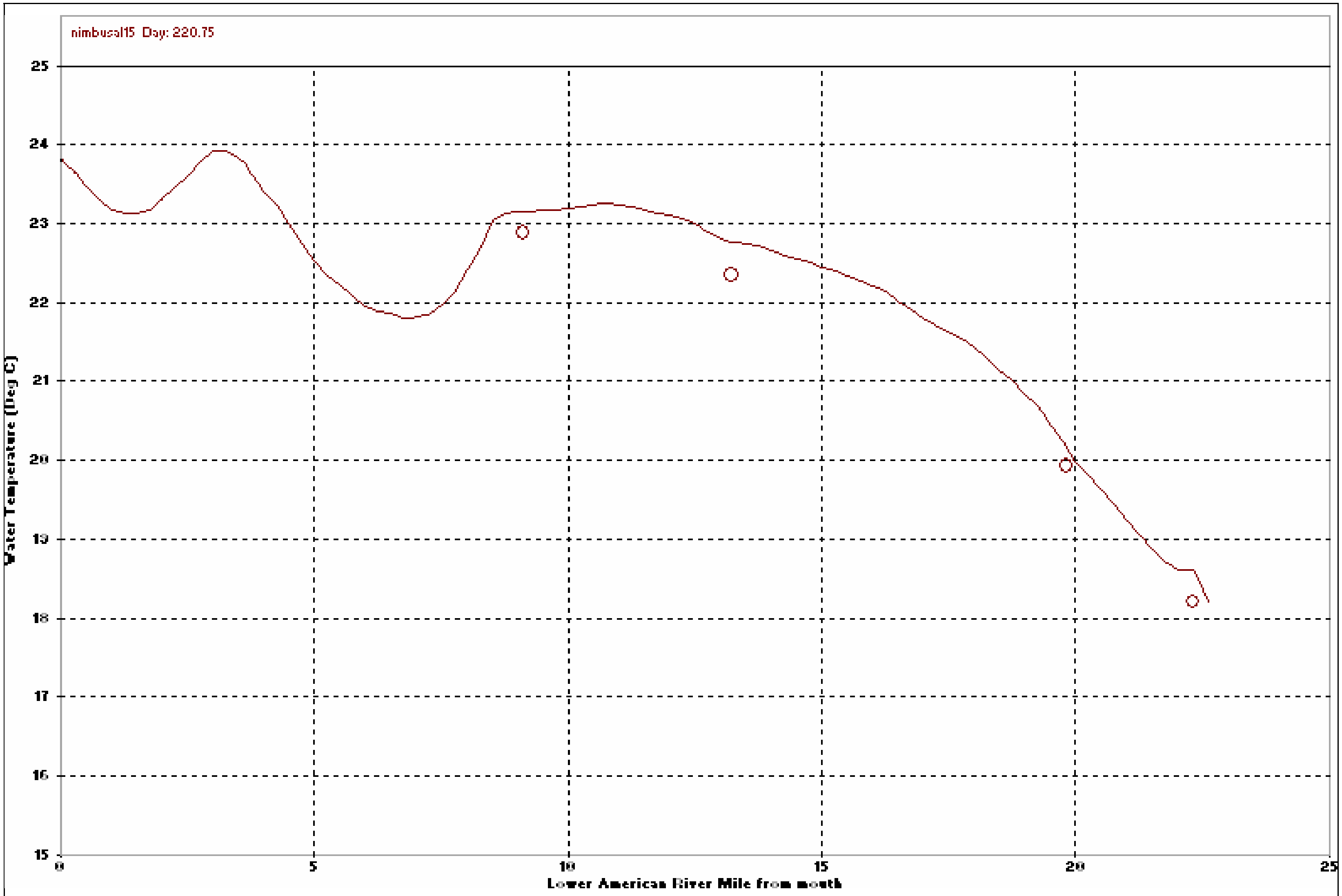


Figure 29.—Modeled versus observed snapshot of Nimbus Dam tailwater temperatures for August 8, 2001, at 6 p.m. (day 220).

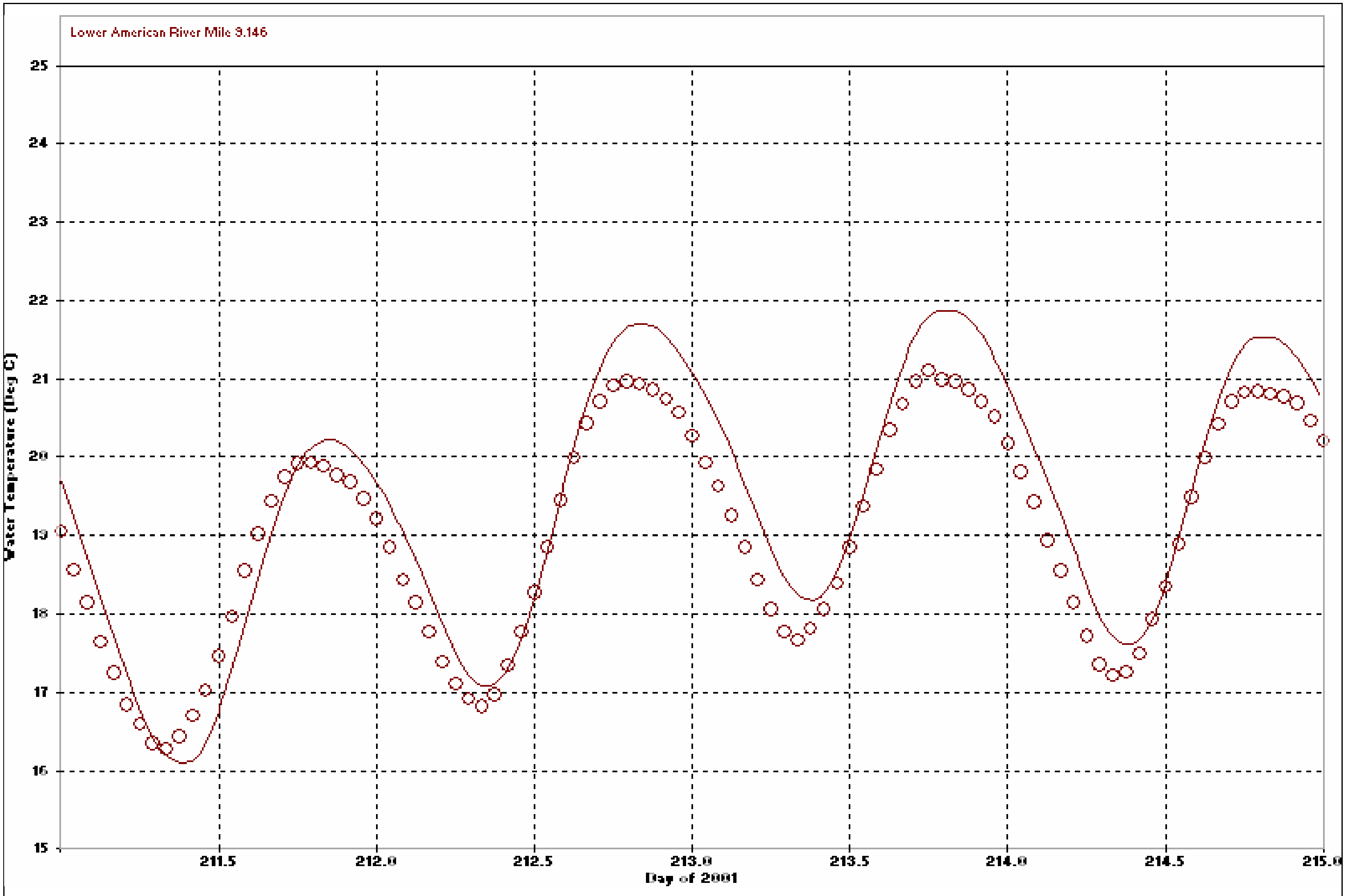


Figure 30.—Modeled and instantaneous observed temperatures versus time at Watt Avenue Bridge during July 30, 2001, through August 3, 2001.

Figure 31 shows the maximum, mean, and minimum water temperature ranges for the Nimbus Dam tailwater during July 28, 2001, to August 12, 2001, and does not include July 27, 2001, the initial day of simulation, to allow damping of initial conditions. For many miles of tailwater upstream of Watt Avenue Bridge, the range of water temperatures varied by more than 7 °C (12.6 °F). Tailwater temperatures fluctuate widely due to variations in Nimbus Dam release temperature, meteorology (warm sunny day versus cool cloudy day), and flow. Results presented in Appendix C shows that the Nimbus Dam tailwater temperature model is calibrated to within 1 °C (1.8 F) at Watt Avenue Bridge. Appendix figures C6 and C7 show the modeled and observed water temperatures at Watt Avenue Bridge over a 2-week period during a warm summer period for two sets of observed data independently collected at essentially the same temperature management target location.

Sensitivity to Variables Affecting Tailwater Temperature

Modeling sensitivity analyses for major hourly input variables—meteorology, Nimbus Dam release temperature, and Nimbus Dam release rate—affecting tailwater temperatures were conducted and compared to salmon and steelhead temperature criteria. Those temperature criteria are provided in Appendix D. A sensitivity analysis of the effect of American River water temperatures on the Sacramento River using flow-weighted temperatures was also done and provided in Appendix E. Appendix E shows examples of completely mixed, flow-weighted temperatures downstream from the confluence of the lower American River and the Sacramento River, as well as for simple two-layer selective withdrawal from the epilimnion and hypolimnion of Lake Natoma.

A near-worst case low flow and warm weather condition during late summer 2001 was selected for modeling sensitivity scenarios. Figures 32a, b, and c show modeled mean longitudinal temperature patterns during drought lateral inflow conditions for the three major variables affecting tailwater temperatures. For comparing plot lines on Figures 32a, 32b, and 32c, the plot line of mean temperature versus river mile (for a flow of 2,000 cfs released at 18 °C (64.4 °F) under warm August 8, 2001, meteorological conditions) is identical on figures 32a, 32b, and 32c.

During warm weather, the tailwater temperature increases in the downstream direction due to warm meteorology and minimal inflow from tributaries. Temperature patterns can be compared to the operational temperature target of 18.3 °C (65 °F), operational temperature threshold of 20.0 °C (68.0 °F), and an instantaneous maximum temperature target of 25.0 °C (77.0 °F) at Watt Avenue Bridge as discussed in appendix D.

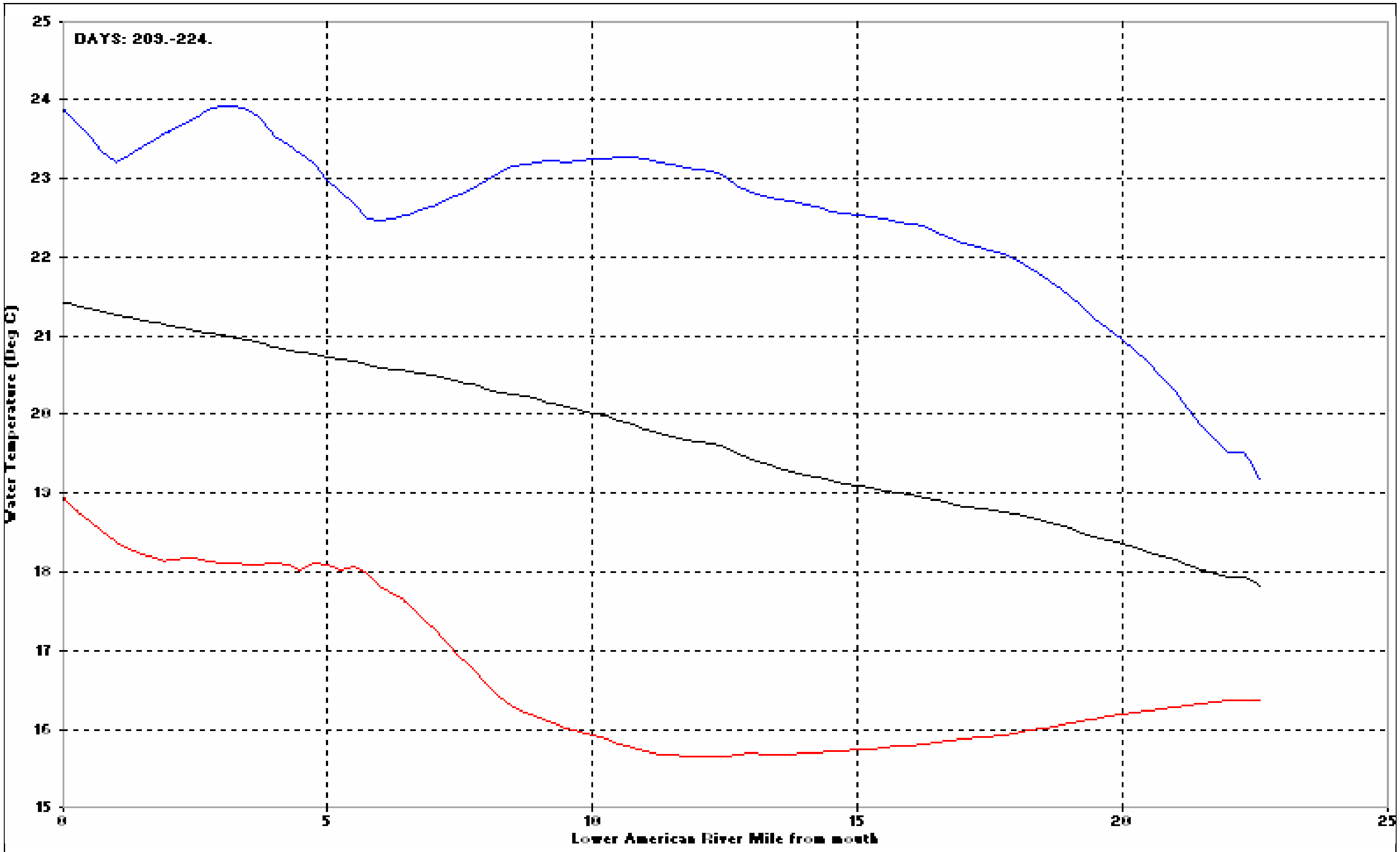


Figure 31.—Modeled maximum, mean, and minimum Nimbus Dam tailwater temperature ranges during July 28, 2001, through August 12, 2001.

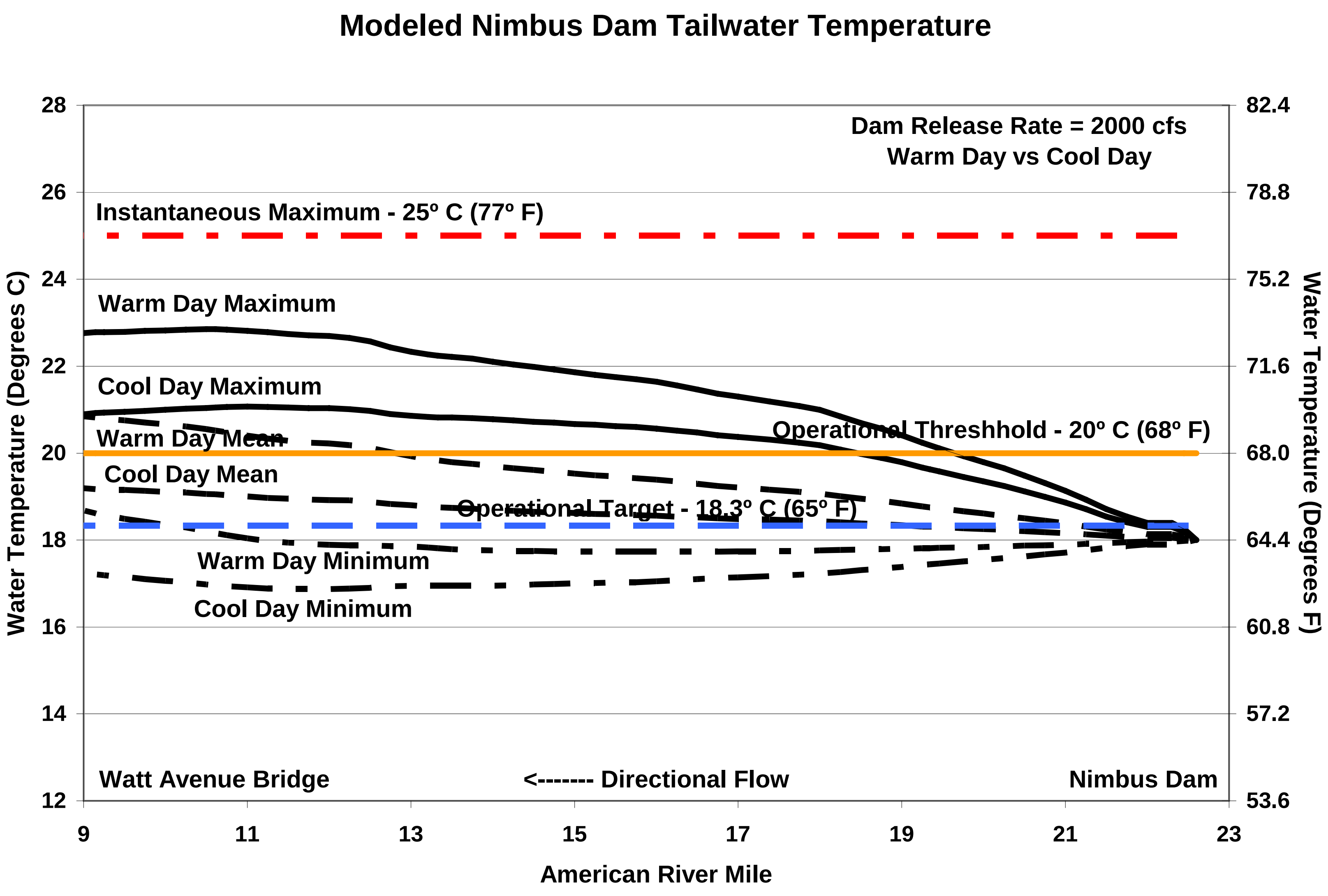


Figure 32a.—Modeled mean summer Nimbus Dam tailwater temperatures for varying meteorology.

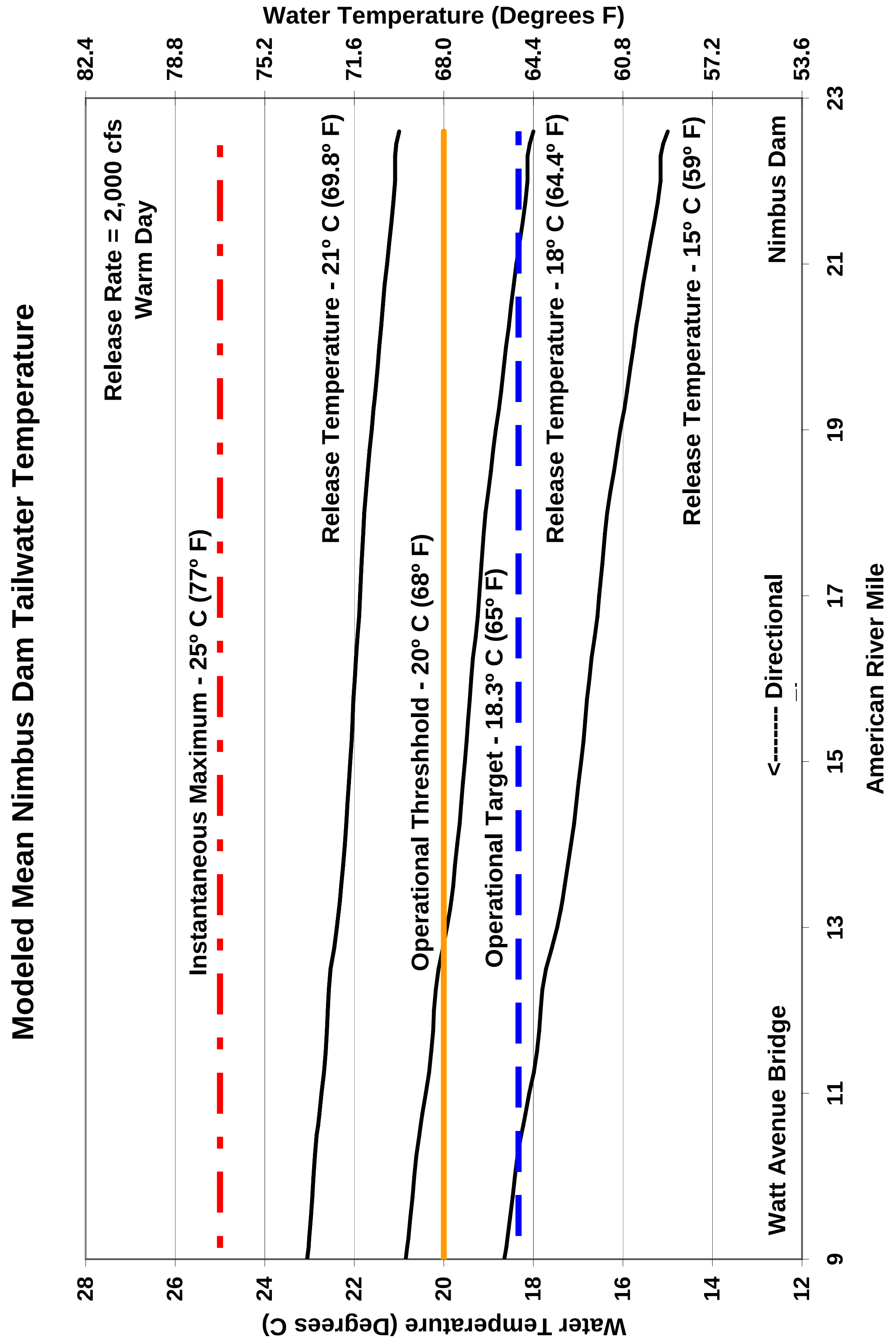


Figure 32b.—Modeled mean summer Nimbus Dam tailwater temperatures for varying dam release temperature.

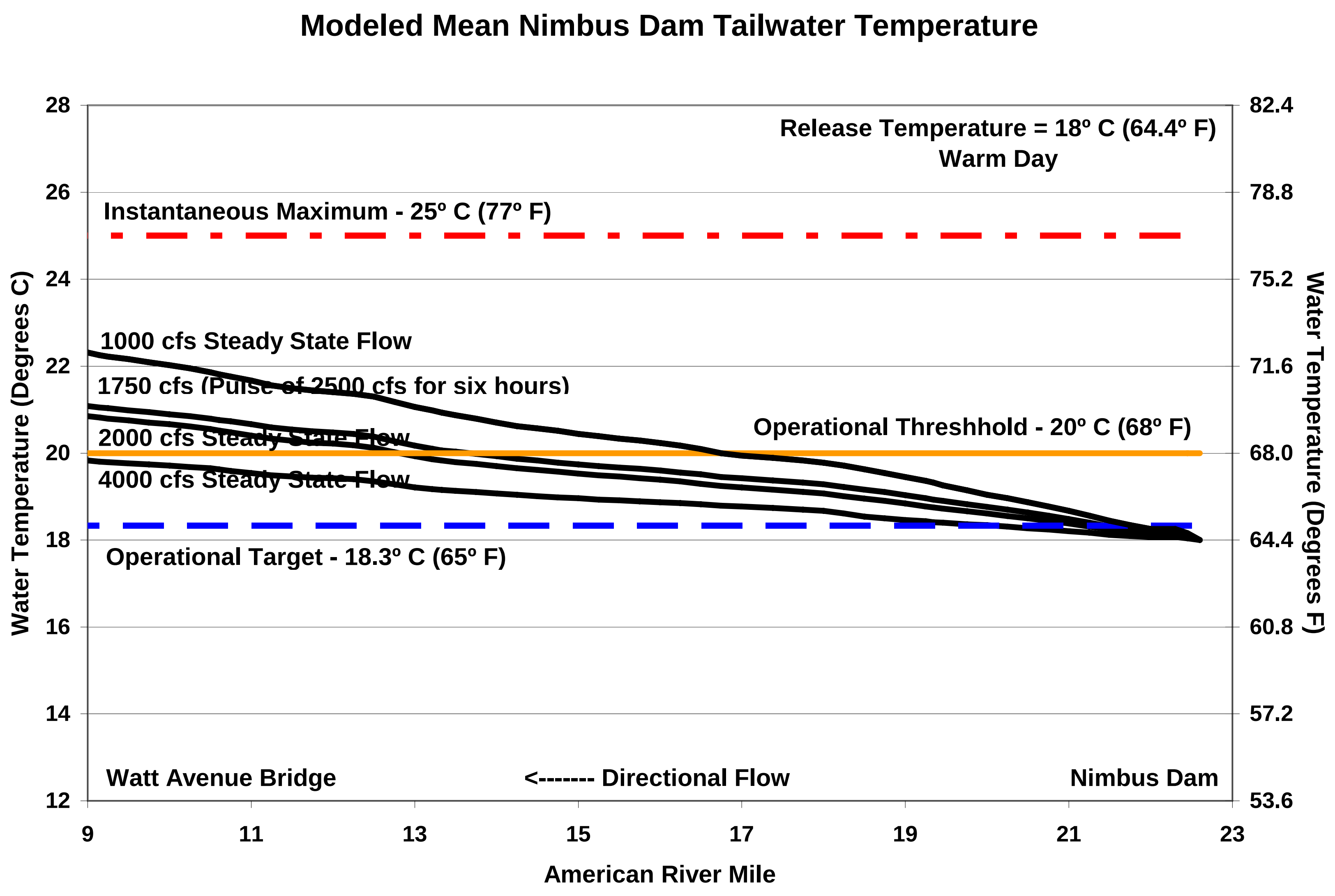


Figure 32c.—Modeled mean summer Nimbus Dam tailwater temperatures for varying release rate (drought lateral inflows).

Meteorology has a significant effect on tailwater temperature (figure 32a). During summer and autumn, solar radiation is fairly consistent with many sunny days. On warm sunny days, rapid heating of relatively cool tailwater temperatures occurs primarily because Nimbus Dam releases are much cooler than the air temperature on a hot day. Figure 32a shows minimum, mean, and maximum modeled tailwater temperatures at a release rate of 2,000 cfs. Mean daily tailwater temperature during late summer increases on the order of 1 to 3 °C (1.8 °F to 5.4 °F), depending on meteorological conditions and mass of water released. Figure 32a shows maximum and minimum tailwater temperatures. Diurnal tailwater temperature variations at Watt Avenue Bridge were significant and typically ranged from 2 to 6 °C (3.6 °F to 10.8 °F).

Nimbus Dam release temperature has the greatest influence on mean tailwater temperature (figure 32b). Mean tailwater temperature curves for 15 °C (59.0 °F), 18 °C (64.4 °F), and 21 °C (69.8 °F) Nimbus Dam release temperatures are shown in figure 32b. This range was typical for release temperature during late summer and early autumn of 2001. The slopes of the temperature versus river mile curves decrease moving downstream due to the water temperatures approaching equilibrium temperature conditions. The distance between curves is fairly consistent at 2,000 cfs release rate. An approximate Nimbus Dam release temperature of 15 °C (59 °F) is required to maintain temperatures less than the 18.33 °C (65 °F) at Watt Avenue Bridge, the operational target corresponding to preferred steelhead rearing temperatures from Nimbus Dam to Watt Avenue Bridge on a warm day at 2,000 cfs. An approximate release temperature of 18 °C (64.4 °F) is required to stay below the operational threshold of 20 °C (68.0 F) at Watt Avenue Bridge. An approximate release temperature of 21 °C (69.8 °F) is required to stay below a lethal instantaneous maximum temperature of 25 °C (77 °F) for all cold water species of salmon such as coho salmon (Myrick and Cech, 2001).

Nimbus dam release flow rate also affects tailwater temperature. Figure 32c shows sensitivity to 1,000 cfs, 2,000 cfs, and 4,000 cfs steady state flow, as well as one pulsing flow averaging 1,750 cfs (6 hours at 2,500 cfs and 18 hours at 1,500 cfs) to show the effect of a larger flow during the warm portion of the day. Increased flow decreases the travel time and increases the depth, which decreases the time for the riverine water to warm and increases the riverine volume to warm. Therefore, tailwater temperatures decrease as flow increases. Doubling the flow from 1,000 cfs to 2,000 cfs reduces the mean daily American River water temperature at Watt Avenue Bridge by about 1.3 °C (2.3 °F) during warm conditions with a Nimbus Dam release temperature of 18 °C (64.4 °F).

Pulsing 2,500 cfs for 6 hours (8:00 pm to 2:00 am) and 1,500 cfs for 18 hours for a total daily average release of 1,750 cfs would slightly reduce the afternoon temperature peaks at Watt Avenue Bridge. However, when compared to the 2,000 cfs model run, the mean temperatures at Watt Avenue Bridge are 0.2 °C (0.36 °F) warmer due to the 12.5 percent decrease in released water volume.

1-D Modeling Conclusions and Recommendations

An examination of the ADYN/RQUAL one-dimensional reservoir model results lead to the following conclusions and recommendations.

1. On a daily basis, lower American River temperatures vary more than 7 °C (12.6 °F) during warm periods due to diurnal meteorological variations and variations in Nimbus Dam release temperatures and flowrates.

2. Nimbus Dam release temperature greatly affects tailwater temperature down to Watt Avenue Bridge. Folsom Dam release temperatures largely drive Nimbus Dam release temperatures. Therefore, cool Folsom Dam releases are important in maintaining cool tailwater temperatures between Nimbus Dam and Watt Avenue Bridge.

3. Increasing Nimbus Dam releases decreases the amount of warming at Watt Avenue Bridge.

4. Modifying the existing nearly continuous Nimbus Dam release pattern does not provide significant temperature reduction. However, the timing of peaking operations at Folsom Dam can significantly affect temperature reduction.

5. Timing of Folsom peaking power releases affects Nimbus Dam tailwater temperature and requires more study. Depending on travel time of cool water released from Folsom Dam and sliding under the warm layers of Lake Natoma, the current Folsom peaking power operations might be shifted to later in the day to allow more cool water released from Nimbus Dam at midnight the time to reach Watt Avenue Bridge by 4:00 pm (about a 16-hour tailwater water travel time at 2,000 cfs continuous release from Nimbus Dam) to cool the lower American River reach just upstream of Watt Avenue Bridge during the warmest portion of the day.

6. The most effective way to reduce lower American River temperatures downstream of Nimbus Dam is to first reduce release temperatures and then to increase releases. Both of these actions would draw upon the Folsom Lake cold water pool with possible adverse water temperature consequences at other times.

7. Nimbus Dam releases of less than 2,000 cfs should be avoided during warm weather operational periods to prevent warm temperatures at Watt Avenue Bridge.

VIII. Options, Conclusions, and Recommendations for Decision Makers

Based on cursory information described in the Lower American River Temperature Improvement Study Function Analysis Report (FA study) and the detailed temperature modeling study described in this report, the following overall conclusions and recommendations are provided:

1. Structural and operational changes to Folsom Dam and Lake could be more effective at reducing river temperatures downstream of Nimbus Dam than changes to Nimbus Dam and Lake Natoma and might be further investigated. The Folsom Lake and Headwaters (Group A) proposals recommended for consideration and implementation in the FA study (Reclamation, 2001, page 24) might be revisited for refinement of potential temperature reduction strategies at Folsom Dam. Structural and operational changes at Folsom Dam and Lake may have less impact on human activities, safety, and recreation when compared to those proposed for Nimbus Dam and Lake Natoma.

2. Changing Folsom Dam power generation from peak loading to baseloading is not recommended because it has the negative overall effect of increasing Nimbus Dam release temperatures.

3. If safety and recreational concerns are not limiting factors, a Nimbus Dam forebay curtain acting as a skimmer wall located just upstream of the Nimbus Powerplant intakes provides more temperature reduction than other modeled Nimbus Dam or Lake Natoma cooling alternatives. Under conditions of strong stratification, a temperature curtain in front of the powerplant might reduce release temperatures during short periods of time by as much as 1.2 °C (2.2 °F) based on quasi-steady state strongly stratified conditions or 0.2 °C (0.36 °F) based on a two week moving average during warm conditions. Complete removal of the debris wall and large dredging of Lake Natoma produce smaller temperature reductions. However, partial debris wall removal and localized dredging may enhance temperature reduction in combination with a Nimbus Dam curtain around the powerplant intakes and might be further investigated as part of a physical modeling study.

4. Installing a mid-reservoir curtain at the plunge zone increases release temperatures due to additional mixing and is not recommended.

5. Localized dredging in Nimbus Dam forebay and the Lake Natoma boat course provide minimal additional temperature reduction; however, dredging may be necessary to optimize dam curtain installation or provide other benefits, such as minimizing shallow depths which affect boats in the race course.

6. Prior to taking actions in the vicinity of the Nimbus Dam powerplant, further detailed studies of the vortex under varying structural configurations, flows, and water surface elevations should be conducted. Designs which reduce the vortex may reduce Nimbus Dam release temperatures and have ancillary benefits associated with power generation. Studies, such as an American River operational study of the entire storage system, a Nimbus Powerplant intake physical modeling study, curtain velocity and flow field physical modeling studies, design studies, and value engineering studies, may be necessary to investigate additional factors and costs.

The following "potential options" are suggested for Nimbus Dam and Lake Natoma, followed by those for Folsom Dam and Folsom Lake. Temperature reduction benefit refers to cooling of Folsom Dam releases, cooling of Nimbus Dam releases, or reducing Folsom Dam releases and conserving the cold water pool due to temperature reduction in the system.

Nimbus Dam Options

NDOP1: No action at Nimbus Dam and Lake Natoma.

Temperature Reduction Benefits: None.

Cost: No costs.

Reason for Ranking: Temperature reduction management alternatives at Nimbus Dam are less effective than those at Folsom Dam.

NDOP2: Flexible Nimbus Dam temperature curtain around the powerplant penstock intakes (L-Shaped) — roll up or remove in winter or high flow season. This option could be an in-the-field, full-scale-prototype testing facility for a potential permanent dam forebay curtain design to experiment with the location of the curtain relative to the debris wall and Nimbus Dam. However, a more cost-effective scaled physical model for curtain and anchor positioning, for investigation of forebay dredging for hanging a deep curtain, investigation of potential partial removal the top portion of the debris wall to improve powerplant intake hydraulics with a curtain in place, for investigation of sediment entrainment and debris removal, and for vortex modeling studies to optimize design would likely be necessary to see if the field installation of a flexible curtain minimizes the existing vortex by straightening out the flow patterns and improves generation efficiency of the turbines.

Temperature Reduction Benefits: About 1.2 °C maximum summer cooling benefit with 0.2 °C two week moving average summer cooling benefit.

Cost: The initial capital investment for a flexible curtain that can be removed during flood season may be less expensive than a permanent concrete temperature curtain (see NDOP3). However, operational and maintenance costs may outdistance initial capital investment savings over the long term.

Reason for Ranking: A Nimbus Dam forebay curtain provides the most cooling benefit of the Nimbus Dam structural alternatives listed in the identified actions. A flexible curtain could be manufactured off-site and tested for safety concerns at an off-site location before installation near the often crowded Lake Natoma Aquatic Recreation Center. Safety concerns about people swimming or boating at the surface as well as self-contained underwater breathing apparatus (SCUBA) divers swimming at depth would need to be investigated. During the anticipated winter-spring flood season, a flexible curtain could be removed from the anchors or stored in place to allow large unimpeded flow much like a window roller shade that is rolled up to let in sunlight. The flexible curtain may provide some floating trash collection for facilitating trash removal if designed for that purpose. A flexible curtain designed using a laboratory physical model such that the horizontal or plan view location might be adjusted to minimize vortex formation and optimize cooling benefits is desirable. Coarse 1.5 meter (5-foot) grid three-dimensional mathematical modeling suggests that a dam curtain may alter the strength and location of the existing vortex under some flow and approach velocity conditions. However, that effect would need to be verified with a laboratory-scale model at a variety of submergence and approach conditions. If an optimum dam curtain solution is found, a more permanent (concrete) structure might be installed to minimize or eliminate long term operational and maintenance costs of a flexible curtain. If a dam curtain is not technically or operationally feasible or safe, the option could be abandoned without major economic losses likely incurred if a more permanent feature was installed and then needed to be removed for reasons not foreseen. Mathematical modeling indicates that with installation of a dam curtain upstream of the debris wall, the debris wall could be left in place without significant loss of temperature reduction benefits of the dam curtain. A flexible curtain may not allow people to comfortably stand on the top of the curtain, as a permanent concrete curtain might. A flexible curtain that can be rolled up or removed during flood season may not interfere with a flood as much as a concrete curtain.

NDOP3: Permanent Nimbus Dam temperature curtain (concrete) around the powerplant penstock intakes, replacing flexible curtain prototype (if potential action NDOP2 works and does not cause difficult-to-remove trash buildup, safety concerns, or other problems).

Temperature Reduction Benefits: About 1.2 °C maximum summer cooling benefit with 0.2 °C two week moving average summer cooling benefit.

Cost: The savings in long-term operational costs for a solid permanent curtain may be less expensive than a flexible curtain that may need to be maintained.

Reason for Ranking: Same temperature reduction benefits of a flexible curtain, plus some cooling benefits during periods when a flexible curtain would be removed. A concrete curtain may be installed and minimal maintenance might be required. A concrete curtain may prevent logs or other floating debris (or boats) from damaging the penstocks year round.

NDOP4: Cut ports into the debris wall, to potentially optimize hydraulics at Nimbus Dam by straightening flow patterns into the turbines or reduce vortex strength and formation (much like a honeycomb baffle with octagonal ports or squares) to provide some temperature reduction by allowing cold bottom water through the ports rather than mixing over the debris wall with warm surface water.

Temperature Reduction Benefits: Some temperature reduction is expected; however, the extent is unknown and likely less than other options.

Cost: Mostly demolition construction costs potentially making this a relatively inexpensive structural option.

Reason for Ranking: By causing more uniform flow patterns, this option may minimize or eliminate the existing air-entraining vortex above the turbine penstock intakes and provide some temperature reduction.

NDOP5: Open the Nimbus Dam spillway gates slightly, which are lower (crest at 31.2 m (102.4 feet)) than the top of the debris wall (32.0 m (105.0 feet)) (by-passing these flows would result in lost hydropower).

Temperature Reduction Benefits: Some temperature reduction is expected; however, the extent is unknown and likely minimal.

Cost: Lost hydropower generation revenue.

Reason for Ranking: This option does not require additional structural modifications and uses existing spillway gates.

NDOP6: Cut 1 to 3 meters (3 to 10 feet) off the top of the debris wall, to optimize thermal curtain hydraulics, which might change the size and location of the existing vortex. This is a relatively inexpensive partial debris wall removal option; however, potential undesirable structural impacts to Nimbus Dam and potential powerplant turbine damage due to additional sediment and debris passing through the penstocks would need to be analyzed. This potential action is not as effective for temperature reduction as a Nimbus Dam Powerplant intake curtain option. This option may be done in combination with a powerplant intake curtain to optimize hydraulics and hydrogeneration.

Temperature Reduction Benefits: About 1.0 °C maximum summer cooling benefit with 0.15 °C two week moving average summer cooling benefit for full debris wall removal. Therefore temperature reduction effects of this partial debris wall removal option are less than complete removal and would require further study if selected.

Cost: Mostly demolition construction costs, making this a less expensive structural option relative to other options.

Reason for Ranking: The smaller temperature reduction benefits, the risk of weakening Nimbus Dam, the potential for more sediment and debris entering the penstocks, and the chance of making the existing vortex even worse makes this a less desirable option than a dam curtain. However, partial debris wall removal is likely a more desirable option than entire debris wall removal. The FA study mentioned an option to remove the portion of the debris wall perpendicular to the dam face and extend vertically the portion parallel to the dam face. However, such an option would direct water to move along the deep channel parallel to the dam formed by the dam apron. The perpendicular flow patterns may cause a more severe penstock vortex and may make this an undesirable option, which would need to be studied with a laboratory physical model.

Folsom Dam Options

FDOP1: No action at Folsom Dam and Lake.

Temperature Reduction Benefits: None.

Cost: No costs.

Reason for Ranking: Significant temperature reduction has been achieved with the existing TCDs and operational fine tuning. To reduce the stair step temperature effect of intermittent TCD shutter pulls, cold water releases from varying levels in Folsom Lake are currently being done by setting the temperature shutters at different levels on each turbine unit, and then varying the percentage of time that each unit is operated.

FDOP2: Folsom Dam low-level river outlet works turbine bypass flows. Note that this option has been utilized and results in loss of hydropower generation due to bypassing the turbines. This significant cooling option has been utilized during late autumn and depletes the otherwise inaccessible cold water resources.

Temperature Reduction Benefits: More temperature reduction than options for Nimbus Dam or Lake Natoma.

Cost: The cost of purchasing replacement power could be substantial depending on the amount of water that is bypassed Folsom Dam powerplant turbines.

Reason for Ranking: This has been the historical fix, and significant experience and data exist to estimate temperature reduction management capability downstream from Nimbus Dam. No additional structural changes are required and existing gates can be used.

FDOP3: El Dorado Irrigation District (EID) selective withdrawal retrofit on the water intake. This selective withdrawal retrofit (Reclamation, 2002) has already been planned, designed, authorized, and partially funded.

Temperature Reduction Benefits: Only about an annual average of 10.6 cfs is currently withdrawn and was modeled; however, the impact of EID selective withdrawal near Folsom Dam to conserve cold water is more significant than a similar selective withdrawal amount at Nimbus Dam. The EID intake capacity may be increased in the future.

Cost: The cost of selective withdrawal retrofit is an integral part of expanding the capacity of the intake.

Reason for Ranking: This alternative is being designed and will be constructed.

FDOP4: Reconfiguration of one existing temperature shutter assembly on one Folsom penstock intake, to potentially provide additional flexibility to remotely fine-tune selective withdrawal and reduce shutter leakage.

Temperature Reduction Benefits: The impact of selective withdrawal at Folsom Lake which strongly stratifies is more significant than selective withdrawal at Nimbus Dam. The ability to remotely fine-tune one existing TCD on an hourly basis may provide additional temperature control flexibility.

Cost: The shutters are already installed and modification or automation may be less costly than new structure installation or construction costs. Shutter leakage on one unit may be reduced by redesign of the seals. The potential for more effectively managing the Folsom Lake cold water pool with more selective withdrawal flexibility which may help avoid bypassing the turbines during autumn requires more study.

Reason for Ranking: See proposal on page 25 of the FA study (Reclamation, 2001). No additional structural changes are required because existing gates can be used so that most of the temperature reduction benefits may be accomplished with existing infrastructure. Furthermore, the decision process could be expedited and modification of one unit can be optimized to determine potential modifications for the remaining two intakes. Currently, several of the shutters for one penstock are welded together and operate as a group. By separating the shutters, additional selective withdrawal flexibility might be achieved. Automating one shutter assembly for remote opening and closing may also provide the ability to fine-tune operations for temperature control on an hourly basis.

FDOP5: Shutter reconfiguration on all three of Folsom penstocks, if potential action FDOP4 shows potential for cooling.

Temperature Reduction Benefits: The impact of selective withdrawal at Folsom Lake which strongly stratifies is more significant than selective withdrawal at Nimbus Dam. The ability to remotely fine-tune all three existing TCDs on an hourly basis may provide additional temperature control flexibility. Shutter configuration on all three units allows for continued selective withdrawal if hydro units are shut down for maintenance. However, if one unit alone provides enough flexibility for operation to optimally manage Folsom cold water resources, modification to the remaining two units may not be necessary.

Cost: The shutters are already installed and modification or automation may be less costly than new structure installation or construction costs. Furthermore, shutter leakage may be reduced by redesign of the seals.

Reason for Ranking: If Folsom Lake drawdown is required for shutter gate modifications, it might be more cost effective to modify all three penstock shutters at one time. If one penstock shutter optimization proves beneficial, all three might be optimized if additional cooling benefits can be realized. Most of the cooling benefits might be accomplished with modifications to the existing shutters.

FDOP6: Folsom Dam re-operation study of the entire American River system, to consider optimizing upstream cold water storage from winter cooling while potentially improving total American River system hydrogeneration output. This complicated option may require moving cold water from upstream reservoirs to Folsom Lake by seasonally adjusting storage volume of individual reservoirs in the American River system.

Temperature Reduction Benefits: The impact of system-wide operational as well as structural changes may provide significant temperature reduction benefits by conserving and utilizing the cold water pools of several reservoirs.

Cost: A system-wide operational and structural study would involve many operational, flow, and temperature models and could be expensive. There may be potential for both tangible and intangible economic benefits from additional beneficial uses from an optimized system.

Reason for Ranking: This expensive option in combination with potential proposed auxiliary spillway improvements at Folsom Dam and Lake may provide additional temperature reduction and improvements in hydropower generation. However, the extensive time and funding as well as the cooperation of many agencies makes this alternative less likely unless such an operational study is undertaken for additional reasons such as changes to other portions of the system including structural changes to accommodate more storage and reduce flooding events.

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Appendices

Appendix A: 2001-2003 Folsom Lake Model Calibration and Sensitivity Analysis

Comparison Statistics

To calibrate the two-dimensional CE-QUAL-W2 Folsom Lake model, observed and modeled water temperature profiles were plotted for sampling days through the spring, summer, and autumn months of 2001, 2002, and 2003.

Two statistical measures for each pair of observed (circles) and modeled (line) profiles for a snapshot in time are shown on each of the profile plots to provide a measure of model performance:

ABS - absolute error = SUM $|Mi-D_i|$ /N
RMS - root mean square error = SQRT[SUM($(Mi-D_i)^2$)/N]

where
i is the field data point index
N is the number of field data points
D_i is the ith field data point
Mi is the model output (interpolated) corresponding to the field data point

Absolute error provides an indication of model performance. For example, an absolute error (ABS value in °C on the Appendix plots) of 0.5 °C (0.9 °F) indicates that the model results are, on the average, within 0.5 °C (0.9 °F) of the observed data points for that reservoir profile location at one snapshot in time. A modeled temperature profile to within 1 °C (1.8 °F) absolute error of observed data is good for dynamic reservoirs with strong stratification. The root mean square error is the standard error of the sampling distribution of the group means if there are N cases in each group. RMS is the positive square root of the variance and is another measure of model performance in °C. The smaller the RMS, the better is the performance of the model. A modeled temperature profile to within 1.5 °C (2.7 °F) root mean square error of observed data is good for dynamic reservoirs with strong stratification.

Description of Folsom Lake Sampling Sites

The format of the Appendix A figures is to first show days from 2001 through 2003 observed versus modeled data at the Folsom Dam forebay (model segment 19). Profiles are similar at other locations in this large, deep lake with strong stratification. Therefore, at the other Folsom Lake temperature profile sites upstream of Folsom Dam, only snapshots during autumn of 2001, 2002, and 2003 are shown. Data for a warm autumn day in each year at Folsom Lake sampling locations A, B, C, D, and E were plotted. Sampling site A corresponds to model segment 11 which is nearest the inflow area of the north fork arm of Folsom Lake of the American River near Anderson Creek. Model segment 13 corresponds to temperature profile sampling site E mid-reservoir on the north fork arm upstream of the confluence, and model segment 16 corresponds to sampling site C on the north fork arm near Mooney Ridge. Sampling site B corresponds to model segment 32 and is located near the El Dorado Irrigation District (EID) pumping plant intake on the south fork arm nearest the inflow area. Sampling site D corresponds to model segment 37 near Mormon Island Dam on the south fork arm upstream of the confluence with the north fork.

The latitude and longitude of the Folsom Lake sampling locations are:

Folsom Dam Forebay site (model segment 19): (N38° 42.54' W121° 9.32');

Site A: North Fork Arm near Anderson Creek (N38° 47.03' W121° 6.40');

Site B: South Fork Arm near El Dorado Irrigation District pumping plant (38° 44.20' W121° 5.63');

Site C: North Fork Arm near Mooney Ridge (N38° 44.00' W121° 8.70');

Site D: South Fork Arm near Mormon Island Dam (N38° 42.77' W121° 7.32');

Site E: North Fork Arm (N38° 46.03' W121° 7.31)

Temperature Calibration

The model was calibrated initially to a starting water surface that was 1.5 meters (5 ft) too low. The error was found during review, the initial water surface elevation corrected, the Folsom Lake W2 model calibration and water mass balance redone, and modeled alternatives were rerun. Fortunately, this recalibration exercise provided an additional sensitivity scenario for investigation of temperature changes due to a change in water surface elevation such as those that might be expected from additional flood surcharge due to potential raising of Folsom Dam and dikes, system operational changes which drop Folsom Lake water surface elevations, or lower Folsom Lake elevation during a drought condition. Therefore both the initial incorrect calibration (figure A-1 through A-9) for Folsom Calibration run 21 (FC21) and the correct calibration plots (figures A-10 through A-22) for Folsom Calibration run 23 (FC23) are shown in this appendix. However, the set of incorrect plots and the corrected plots are shown in a different format to show the differences between sites as well as the differences over time at each site in a more compact or digestible format.

Absolute mean error and root mean square error statistics between the initial calibration and the corrected calibration plots were compared and differences were minimal. This indicated that simulated Folsom Lake temperature profiles are only slightly sensitive to water surface elevation changes. Recalibration also provided a check and therefore improved the confidence in the Folsom Lake W2 modeling.

Modeled temperature profiles for 2001 through 2003 matched observed data to less than 2 °C (3.6 °F) as seen in the profile plots (A-1 through A-9). Strong thermal stratification, strong interflows, and autumn drawdown caused large changes in temperature throughout the reservoir. Overall, the Folsom Lake temperature calibration is good due to the strong stratification of this deep storage reservoir with large temperature ranges from the surface to the bottom. Both Bender, et. al., 1990 and Cole and Wells, 2002 provide guidance on temperature calibration procedures for deep storage reservoirs such as Folsom Lake. Corrected modeled temperature profiles for 2001 through 2003 matched observed data also to within less than 2 °C (3.6 °F) as seen in the profile plots (A-10 through A-22). Some corrected profiles match slightly better and some slightly worse than the initial calibration. However, overall the calibration statistics changed minimally.

Sensitivity Analysis to Reduced Water Surface

Modeling an initial water surface elevation that is 1.5 m (5 ft) lower than historical conditions indicated warmer overall release temperatures during warm seasons and cooler releases during winter (figure A-23). The water mass balance was corrected and the correction factored into the distributed flow of the south fork arm (branch 2) for both scenarios. The water surface elevation was checked and is now on average within 0.15 m (0.5 ft) of observed water surface elevation for the three year calibration period from calendar years 2001 through 2003. The available historical temperature profile from January 17, 2001 was used as the initial starting condition for modeled day 1 (January 1, 2001) for both the reduced pool and historical pool scenarios.

Figure A-23 is the flow-weighted average release temperature from all dam outlets including the municipal and industrial (M&I) temperature control device (TCD) and the spillway and river outlet works modeled as withdrawal structures at Folsom Dam. A 14-day moving average is shown on Figure A-23 as a blue line. More warming occurs during dry low pool years such as 2001 than wetter high pool years such as 2003. Based on a two-week moving average, warm season releases warmed 1.5 °C (2.7 °F) for 2001 to 0.5 °C (0.9 °F) for 2003. Wintertime conditions during 2001 are nearly identical due to using the same initial temperature profile condition in both scenarios. Wintertime releases cooled as much as 0.3 °C (0.5 °F) during 2002 and 2003 likely due to less winter carry-over volume in the reduced pool scenario.

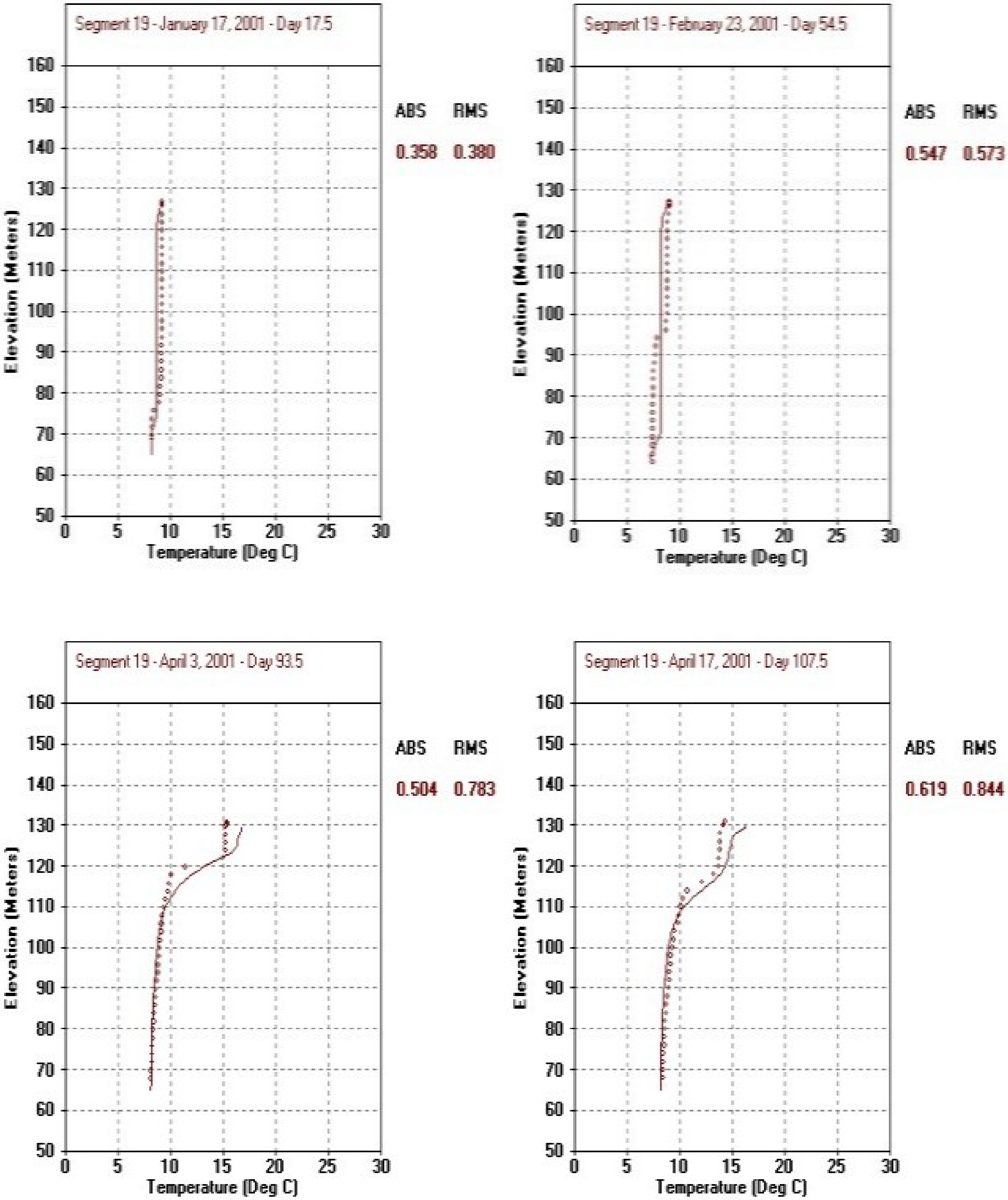


Figure A-1.—Modeled versus observed Folsom Dam forebay water temperature profiles for 2001.

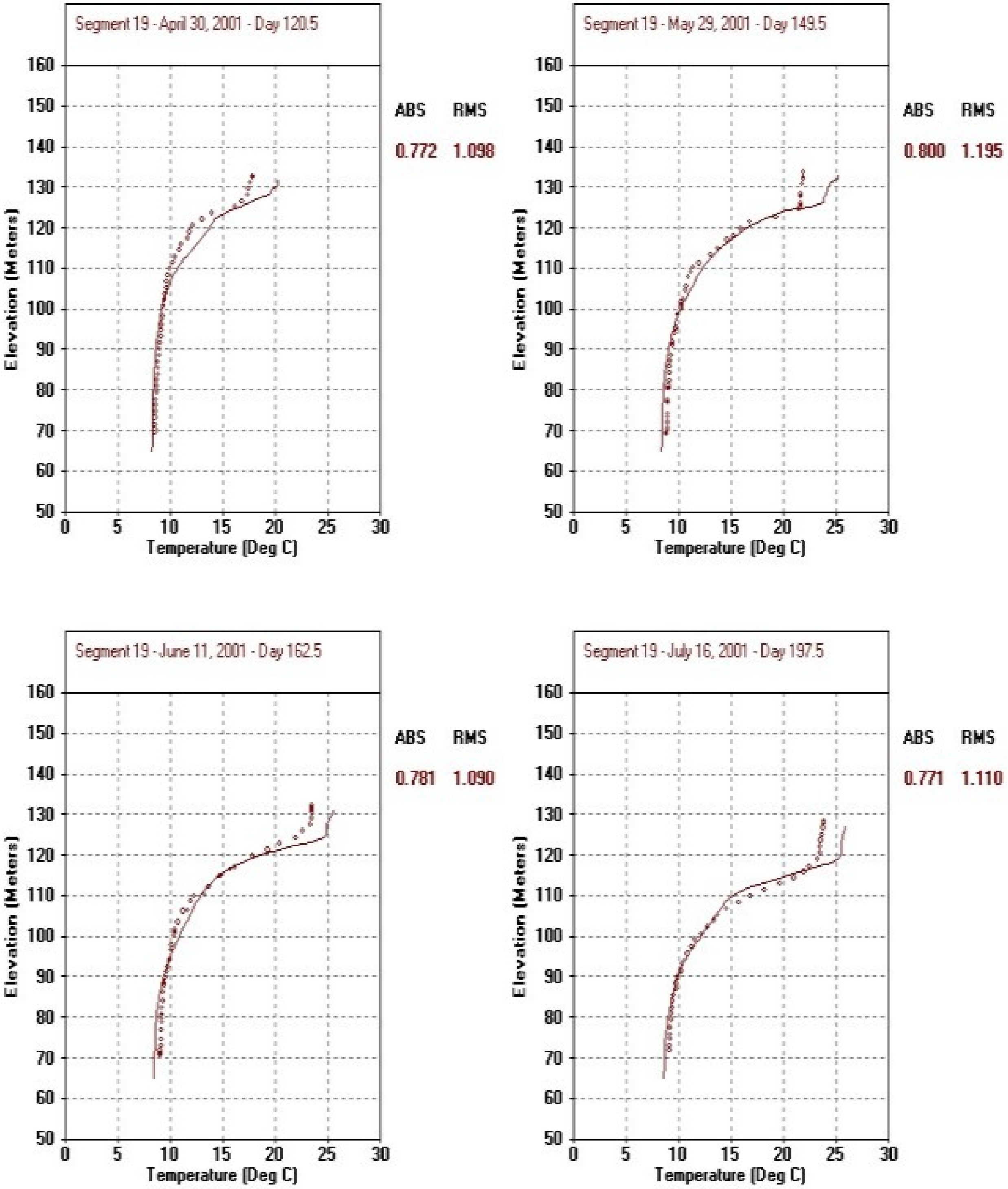


Figure A-1 (cont'd).—Modeled versus observed Folsom Dam forebay water temperature profiles for 2001.

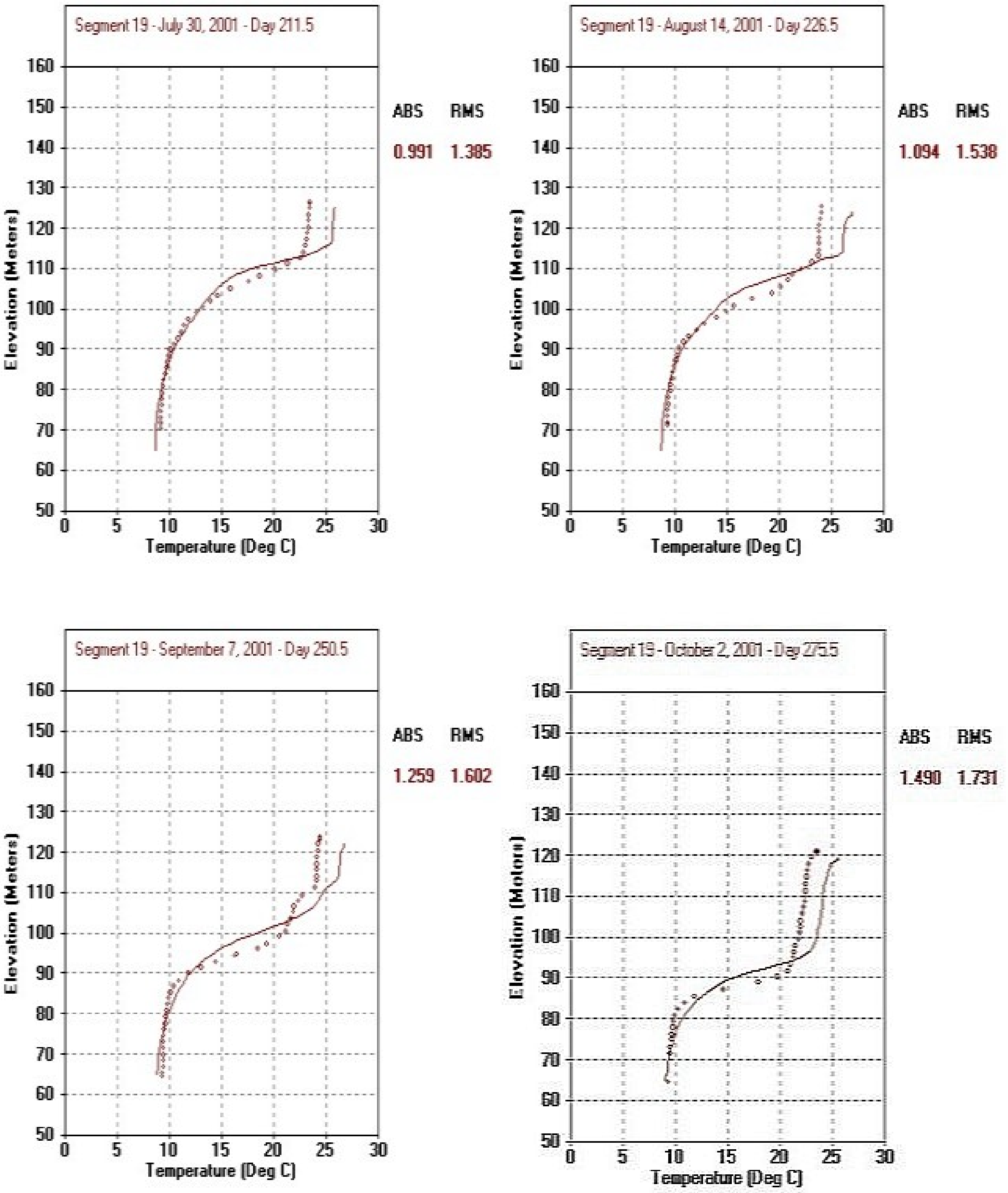


Figure A-1 (cont'd).—Modeled versus observed Folsom Dam forebay water temperature profiles for 2001.

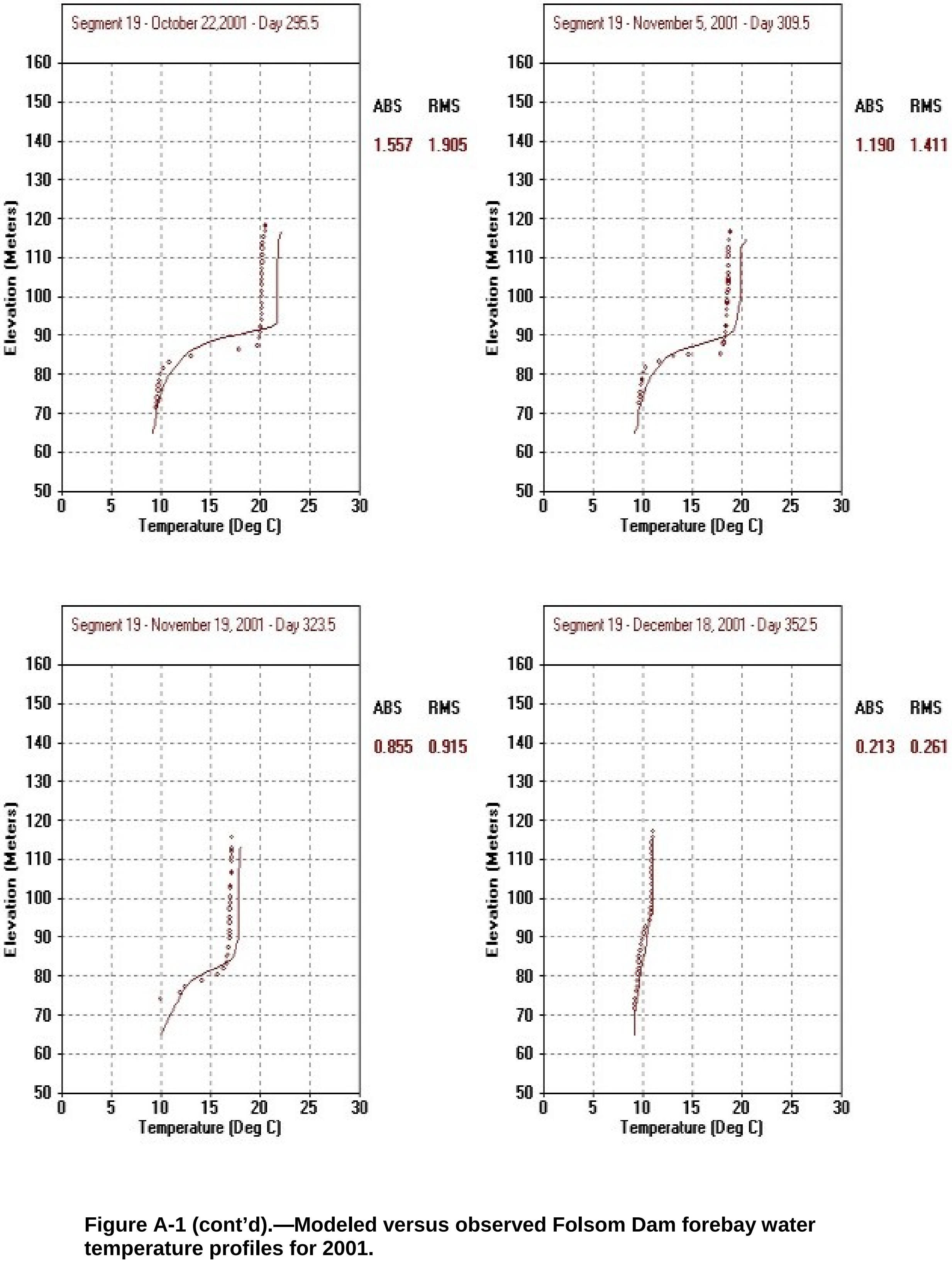


Figure A-1 (cont'd).—Modeled versus observed Folsom Dam forebay water temperature profiles for 2001.

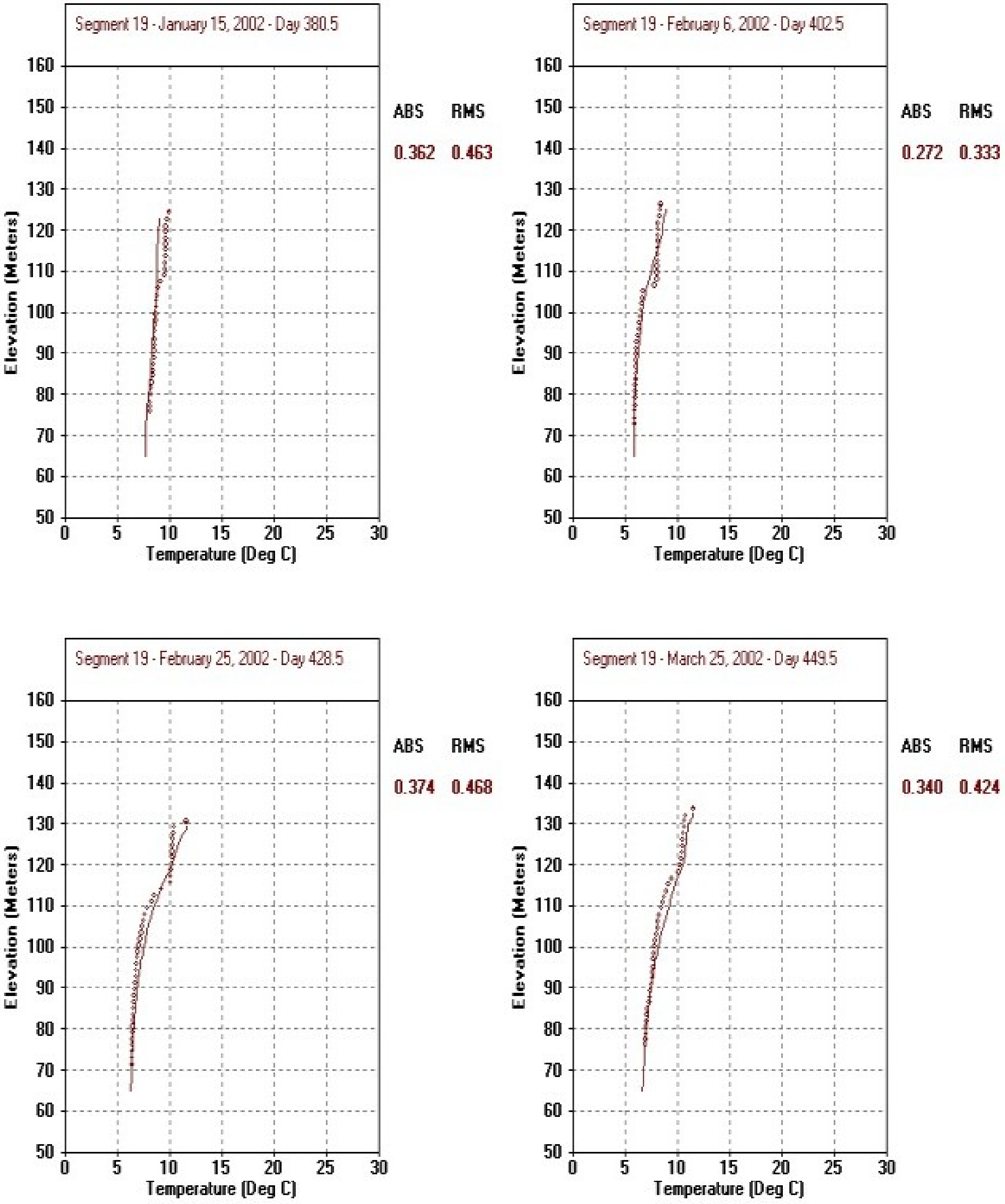


Figure A-2.—Modeled versus observed Folsom Dam forebay water temperature profiles for 2002.

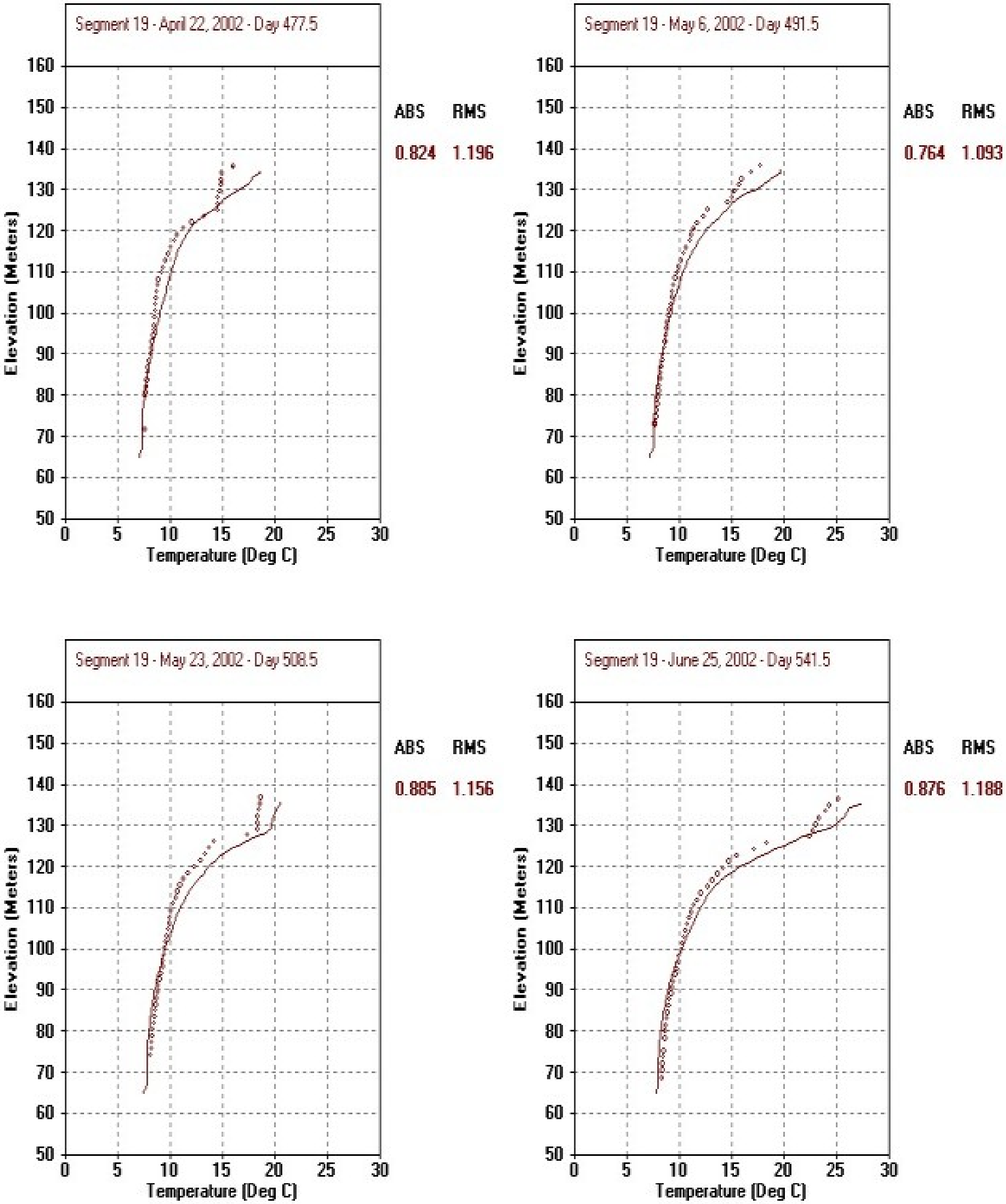


Figure A-2 (cont'd).—Modeled versus observed Folsom Dam forebay water temperature profiles for 2002.

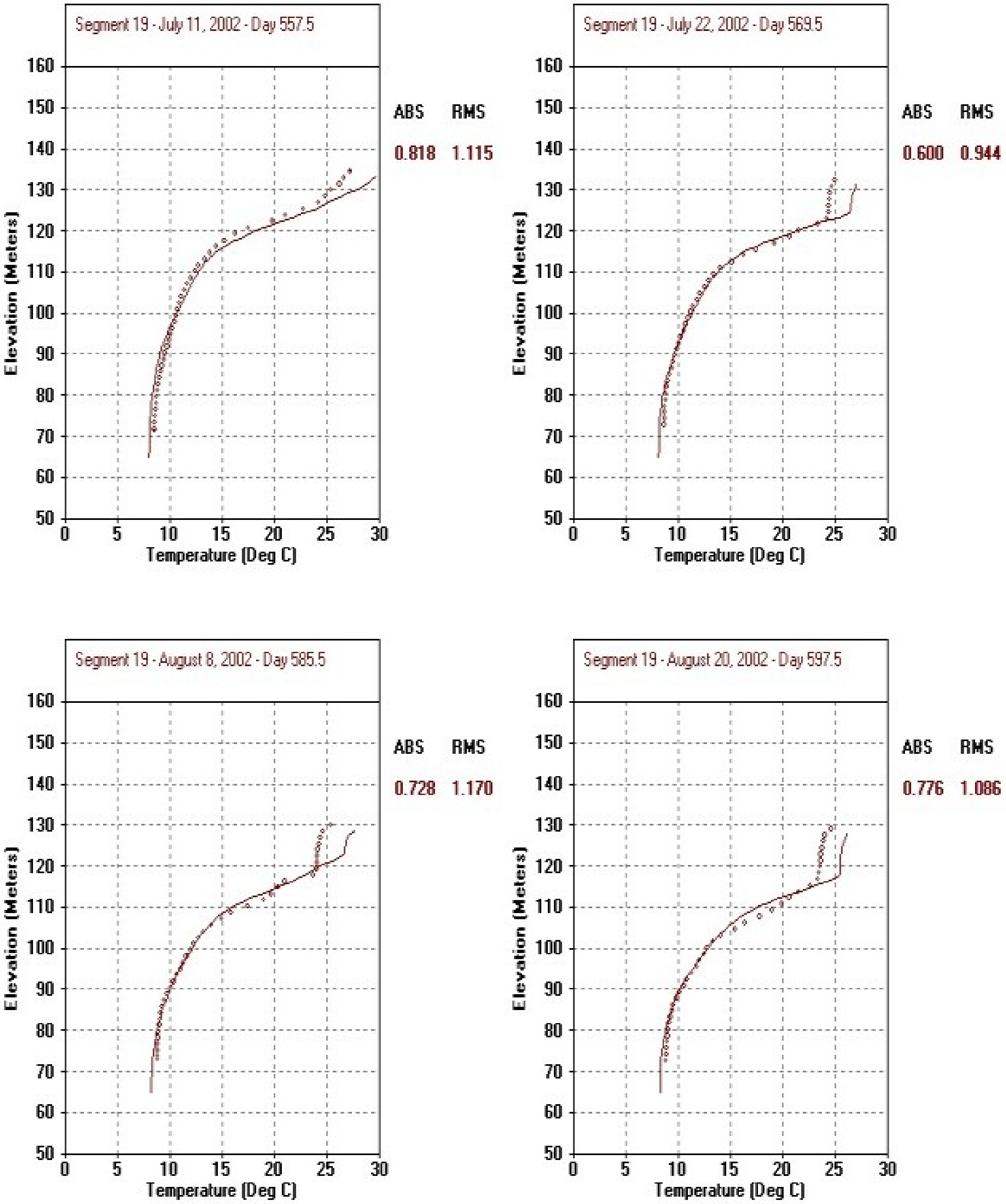


Figure A-2 (cont'd).—Modeled versus observed Folsom Dam forebay water temperature profiles for 2002.

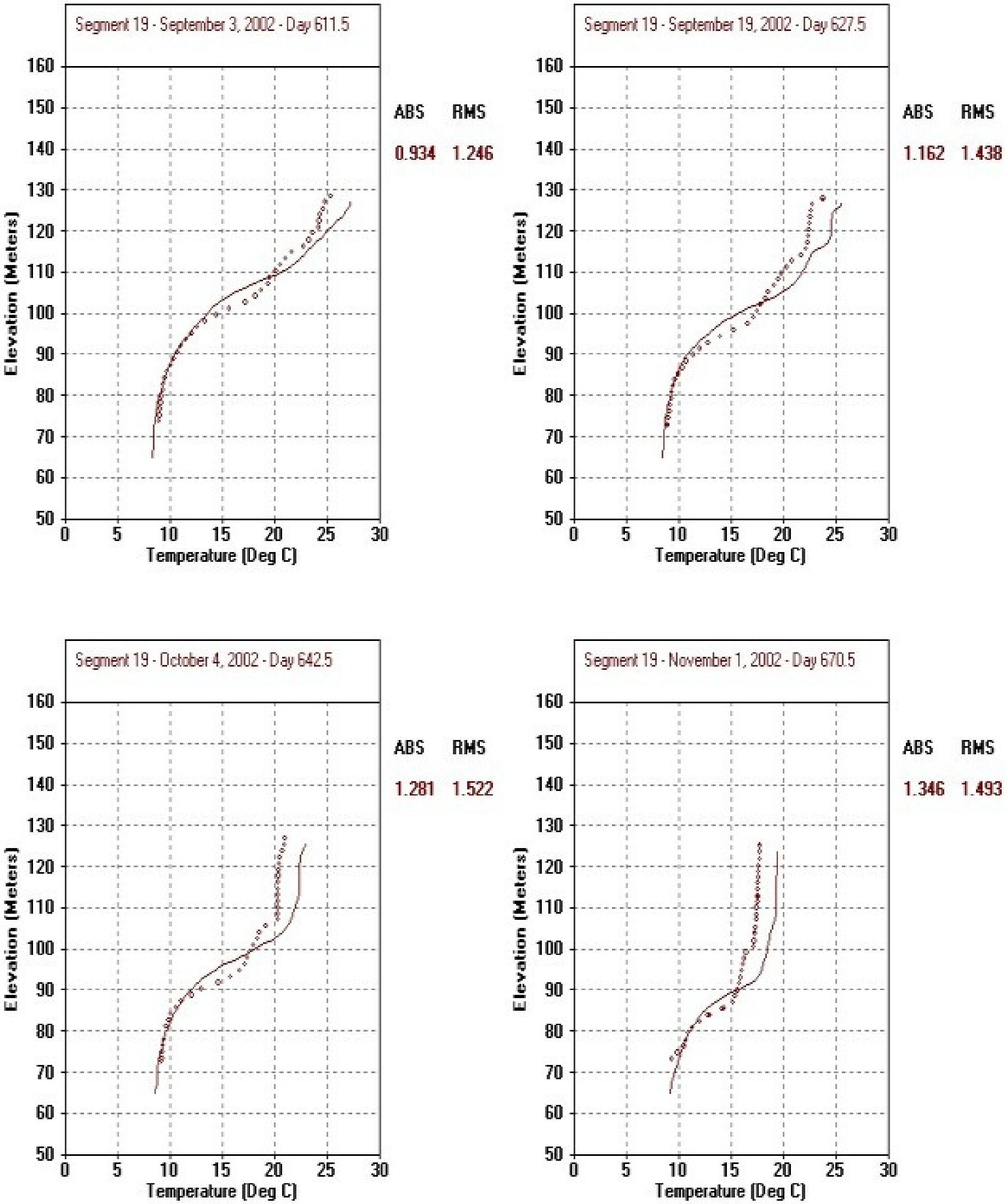


Figure A-2 (cont'd).—Modeled versus observed Folsom Dam forebay water temperature profiles for 2002.

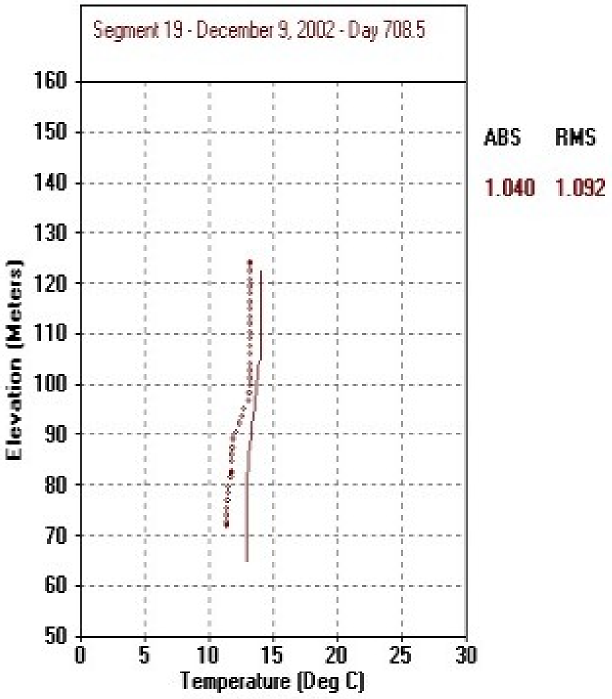


Figure A-2 (cont'd).—Modeled versus observed Folsom Dam forebay water temperature profiles for 2002.

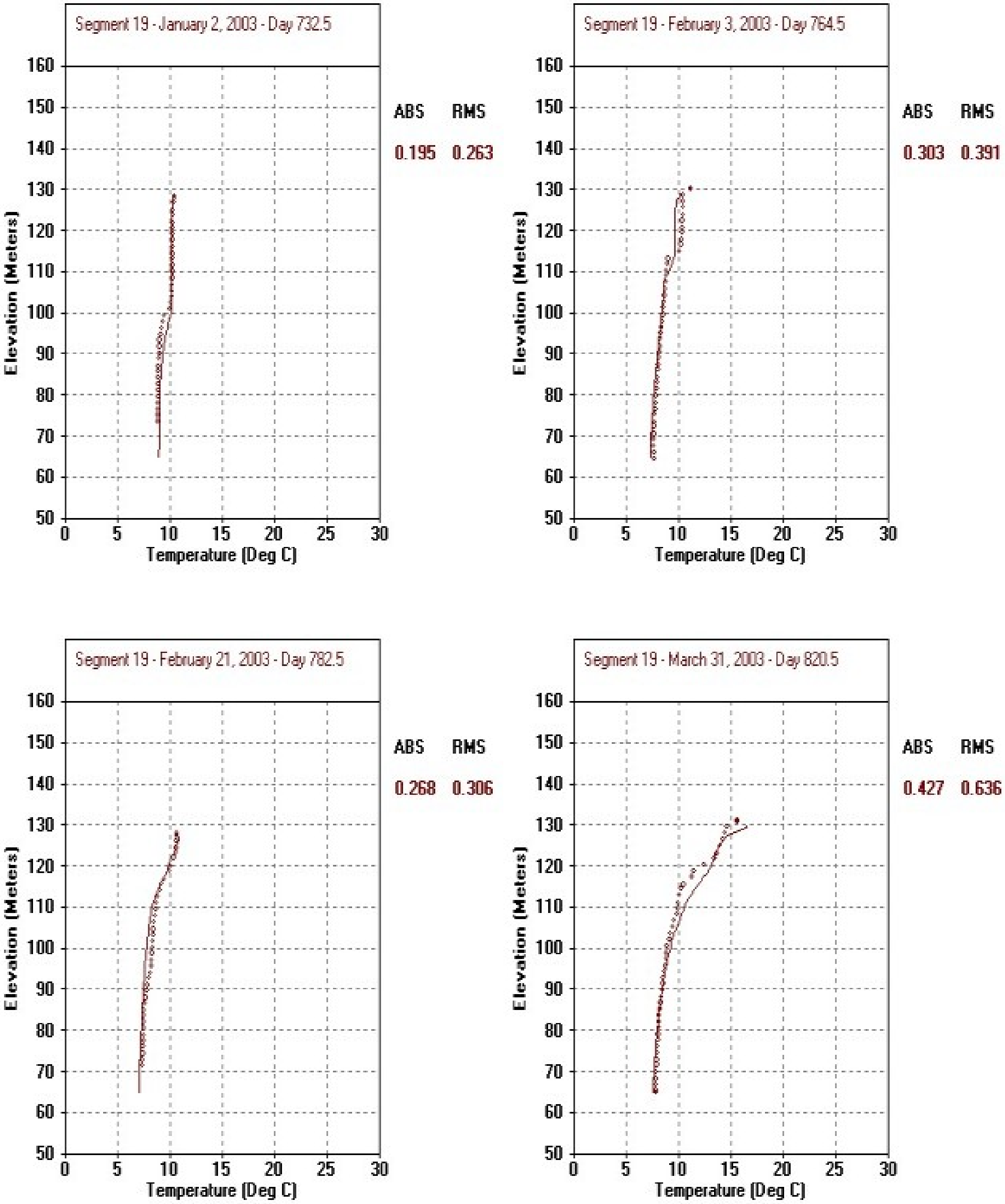


Figure A-3.—Modeled versus observed Folsom Dam forebay water temperature profiles for 2003.

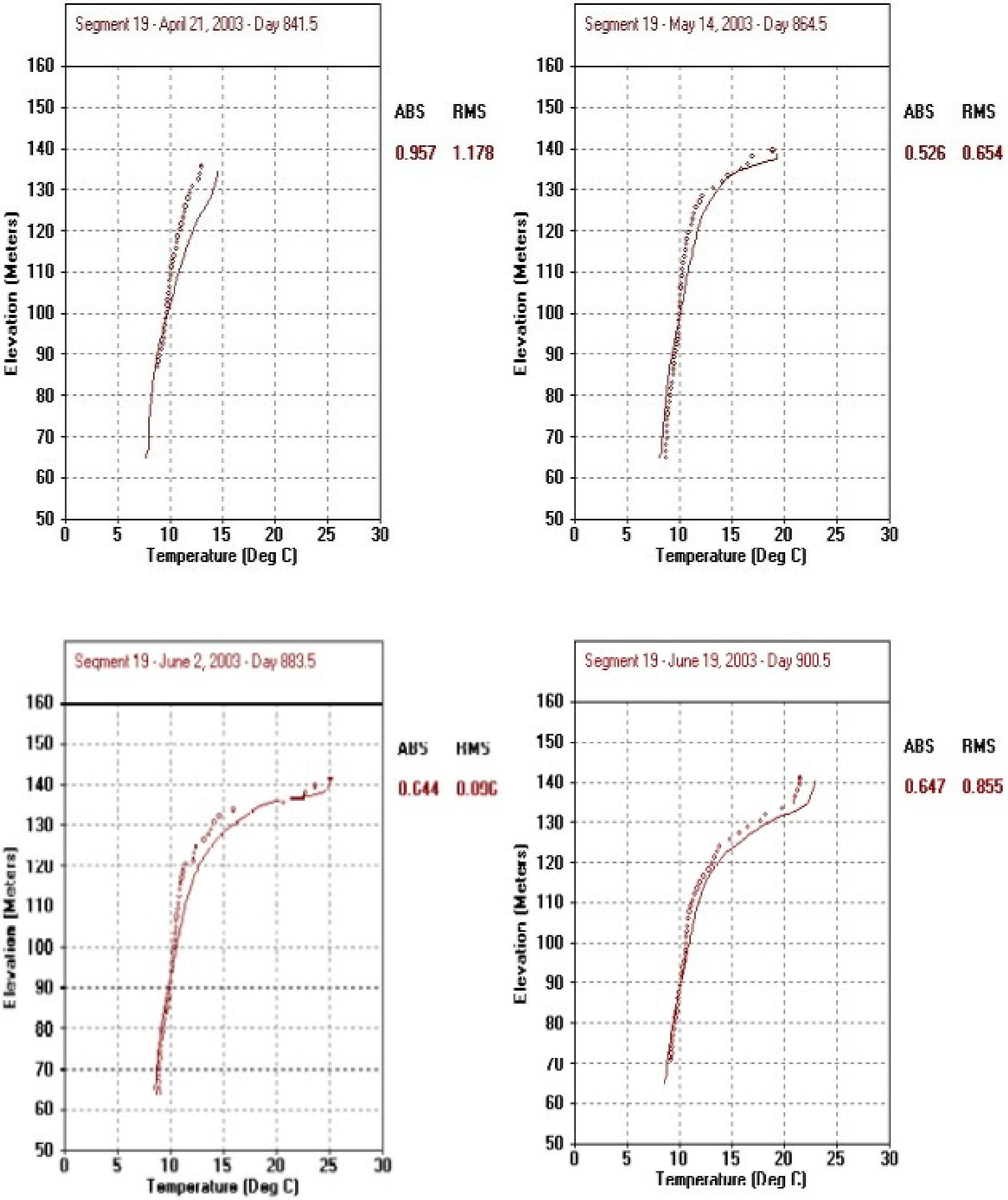
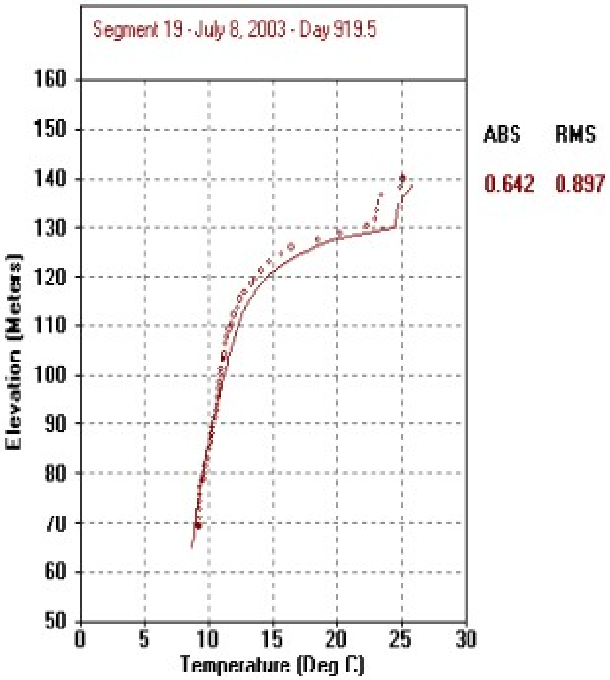
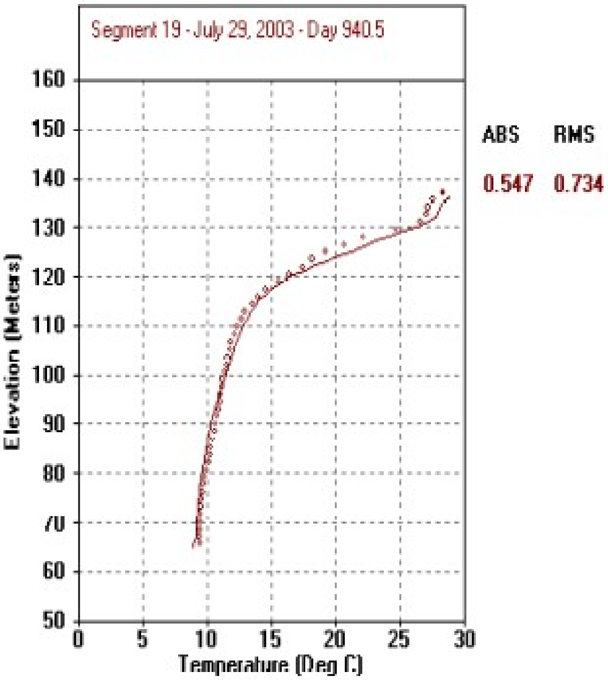


Figure A-3 (cont'd).—Modeled versus observed Folsom Dam forebay water temperature profiles for 2003.





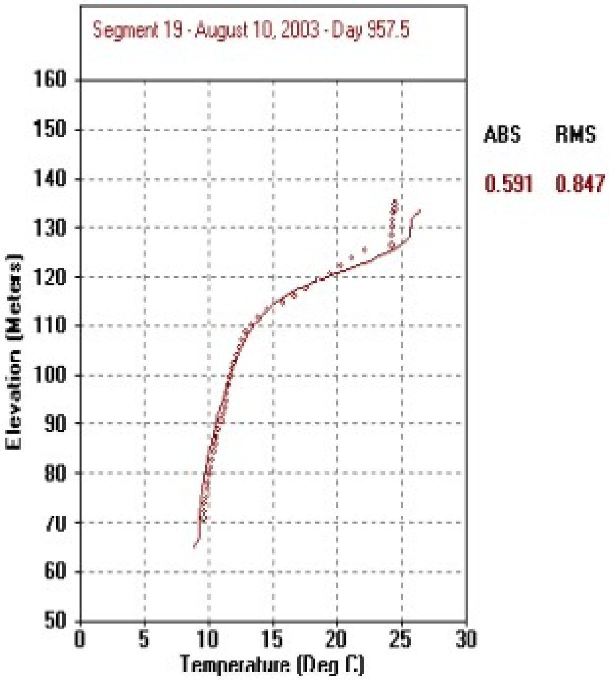


Figure A-3 (cont'd).—Modeled versus observed Folsom Dam forebay water temperature profiles for 2003.

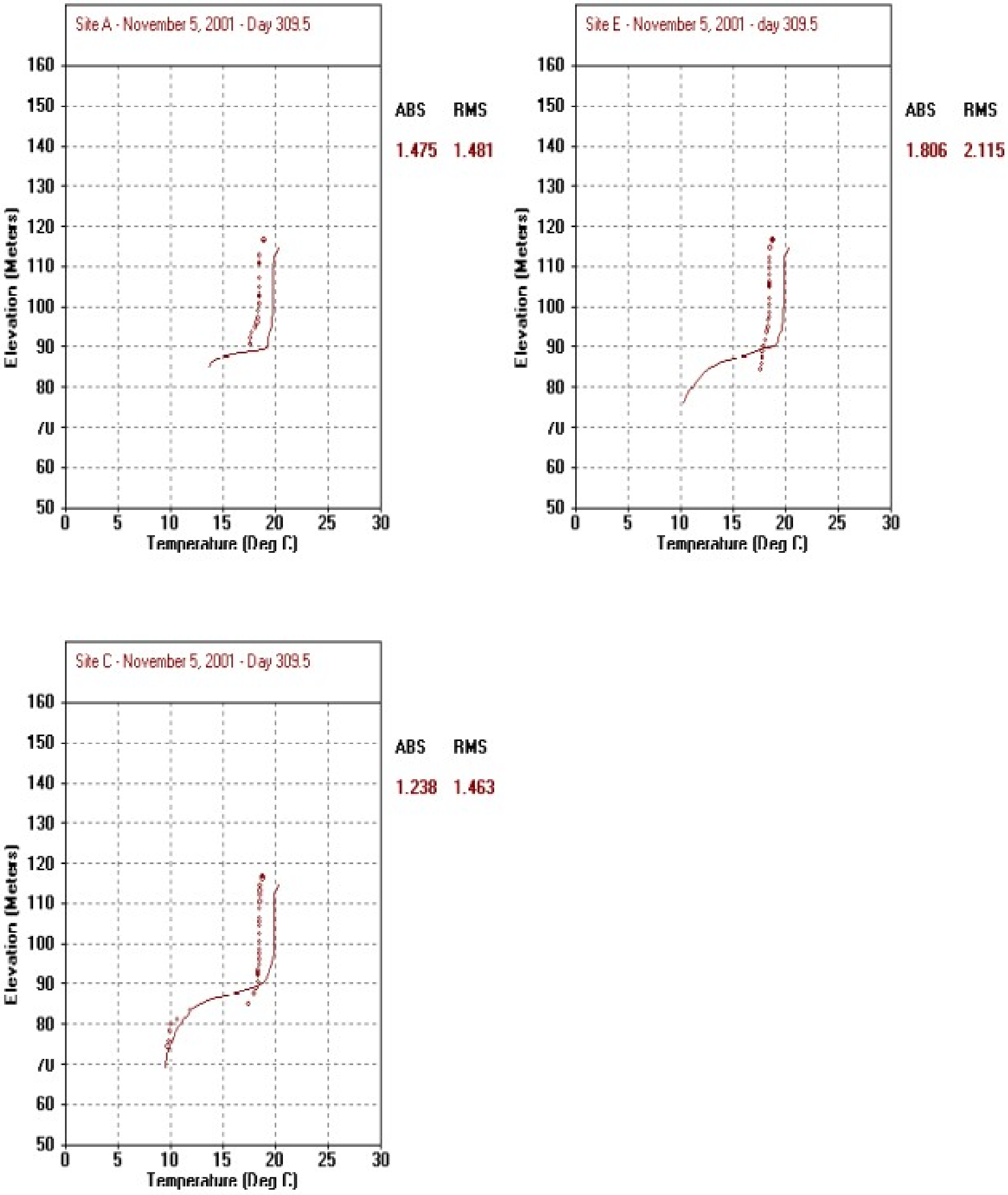


Figure A-4.—Modeled versus observed Folsom Lake North Fork arm water temperature profiles for November 5, 2001 (sample sites A, C, and E).

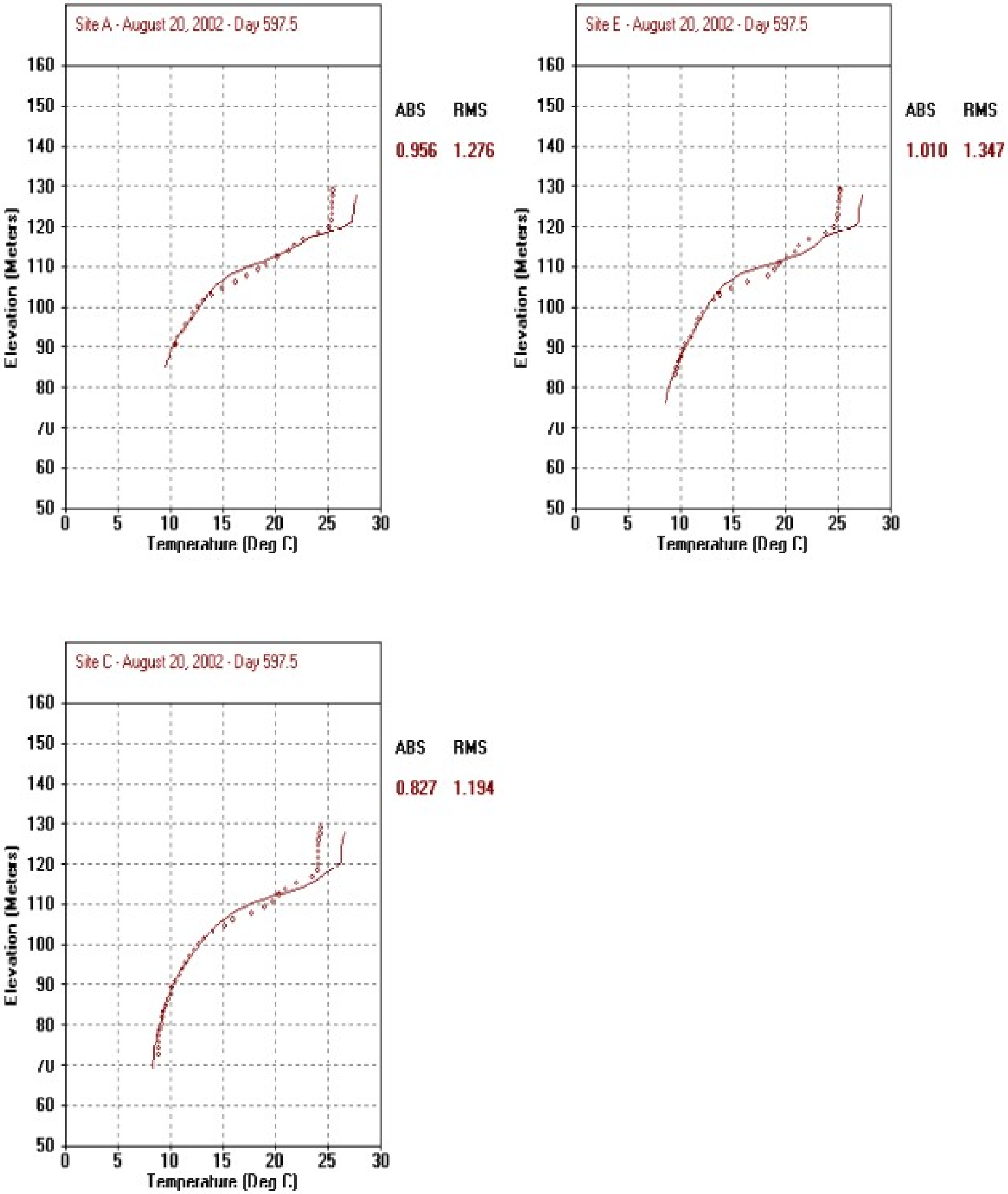


Figure A-5.—Modeled versus observed Folsom Lake North Fork arm water temperature profiles for August 20, 2002 (sample sites A, C, and E).

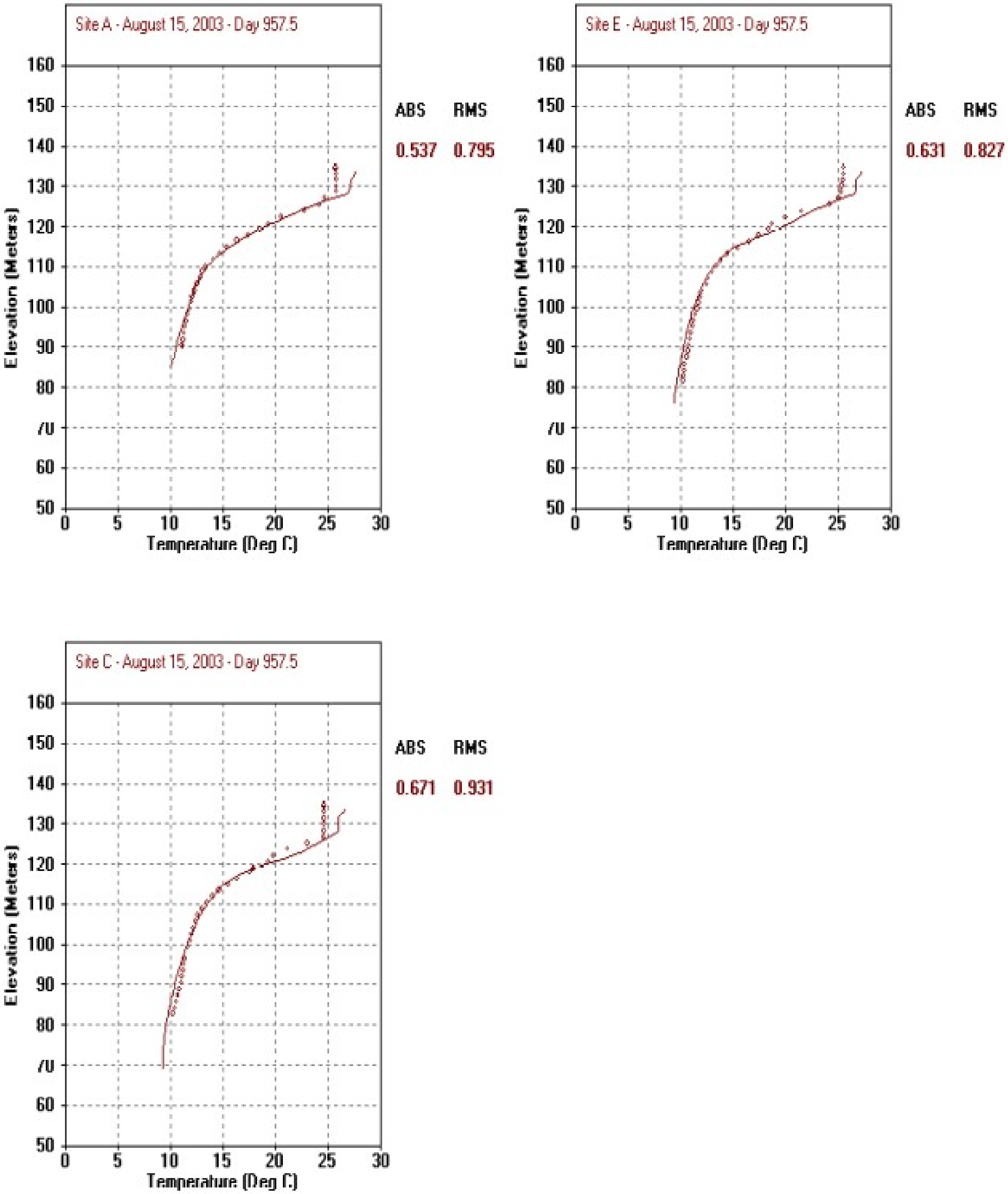


Figure A-6.—Modeled versus observed Folsom Lake North Fork arm water temperature profiles for August 15, 2003 (sample sites A, C, and E).

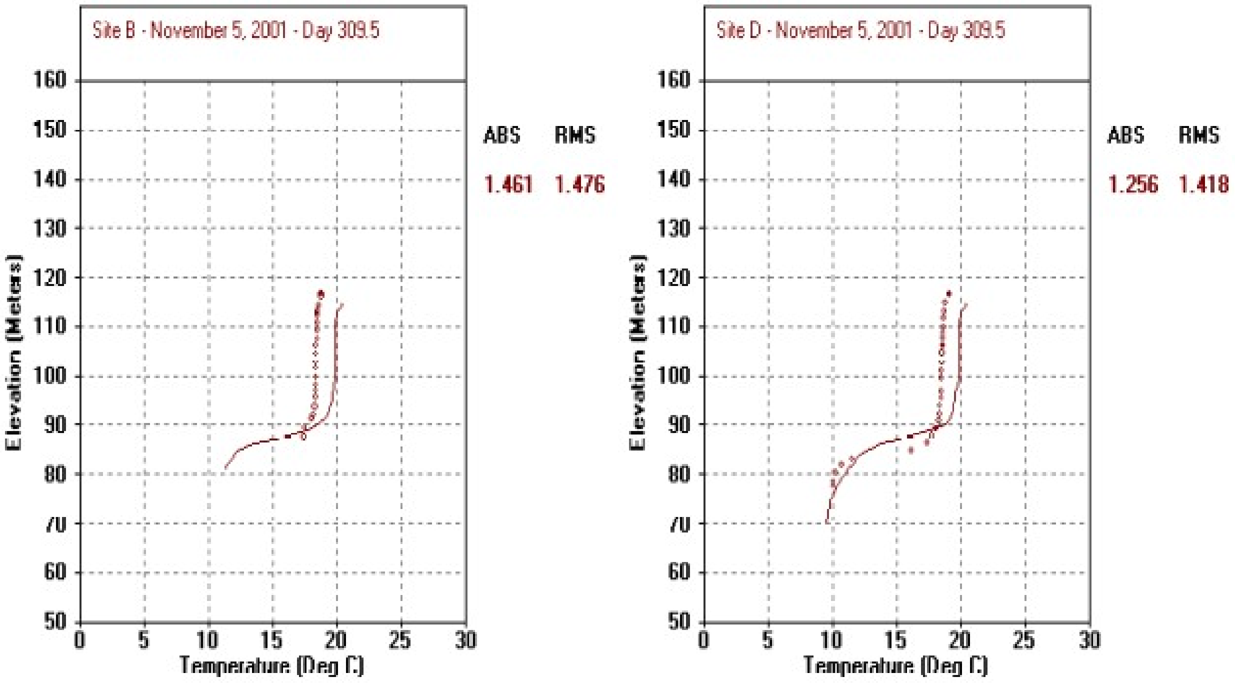


Figure A-7.—Modeled versus observed Folsom Lake South Fork arm water temperature profiles for November 2001 (sample sites B and D).

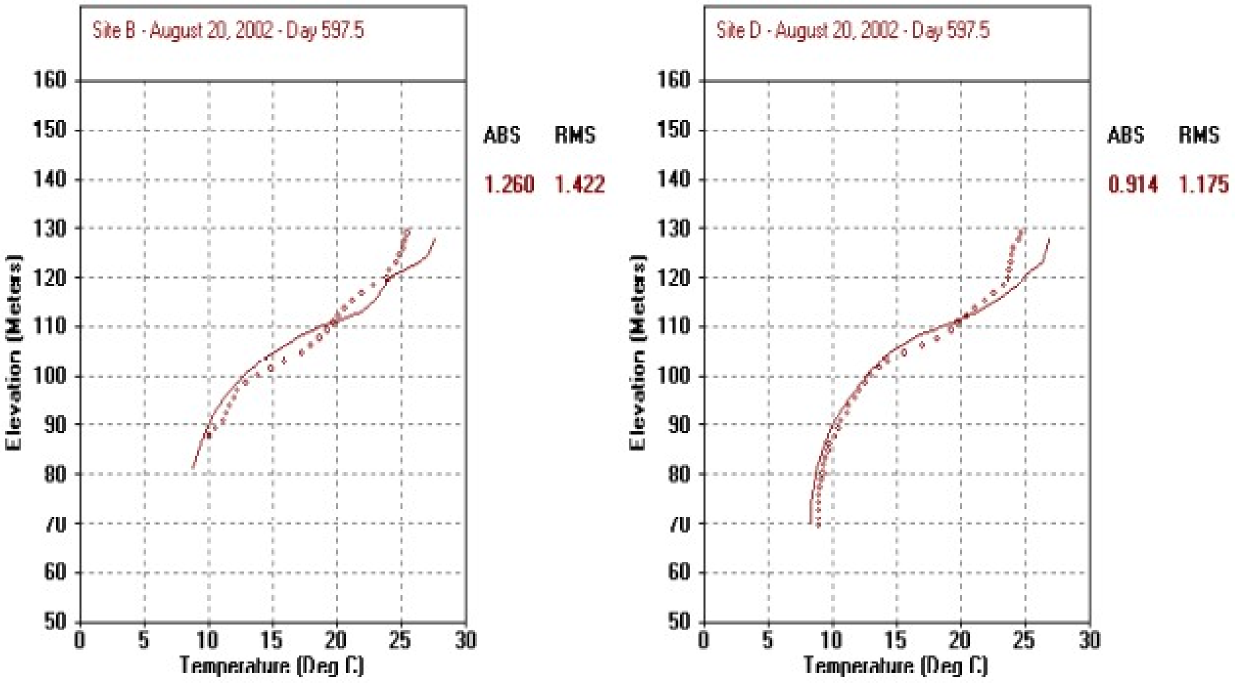


Figure A-8.—Modeled versus observed Folsom Lake South Fork arm water temperature profiles for August 2002 (sample sites B and D).

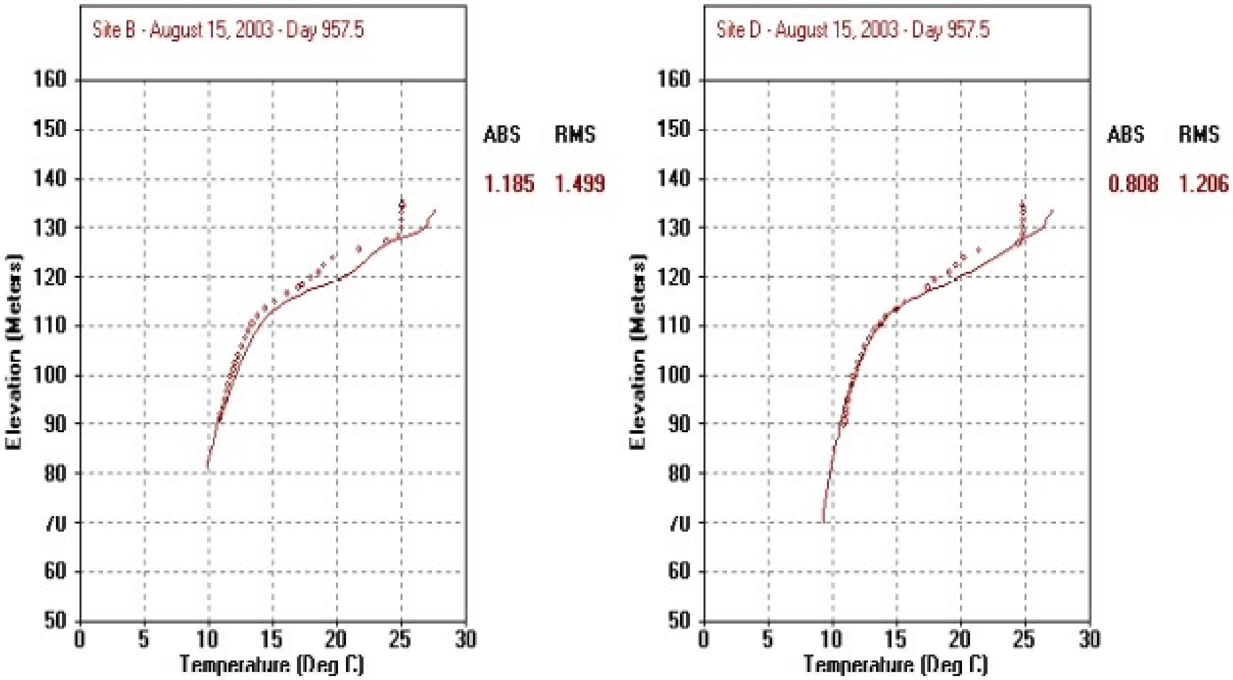


Figure A-9.—Modeled versus observed Folsom Lake South Fork arm water temperature profiles for August 2003 (sample sites B and D).

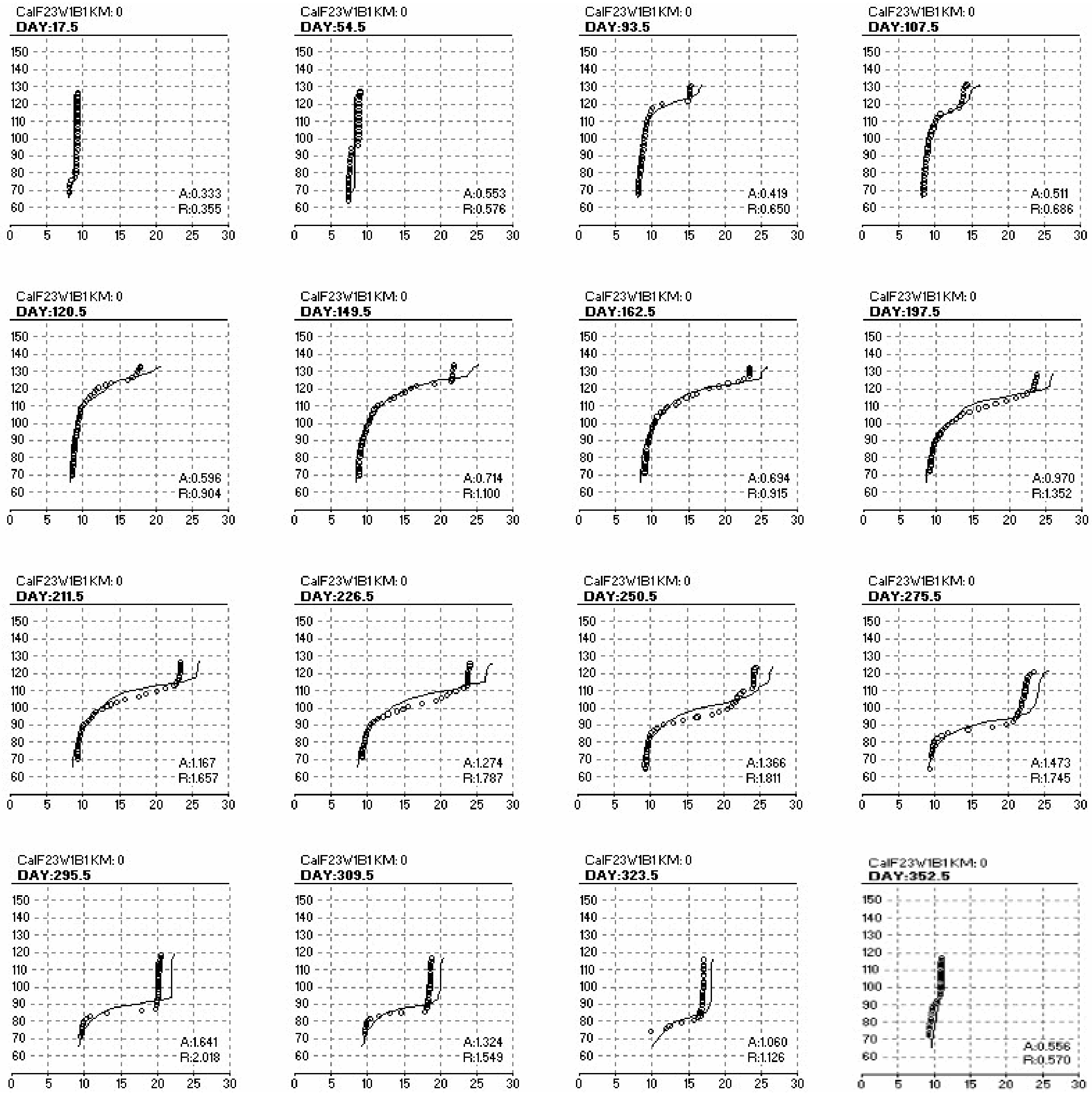


Figure A-10.—Corrected modeled versus observed Folsom Dam forebay water temperature profiles for 2001.

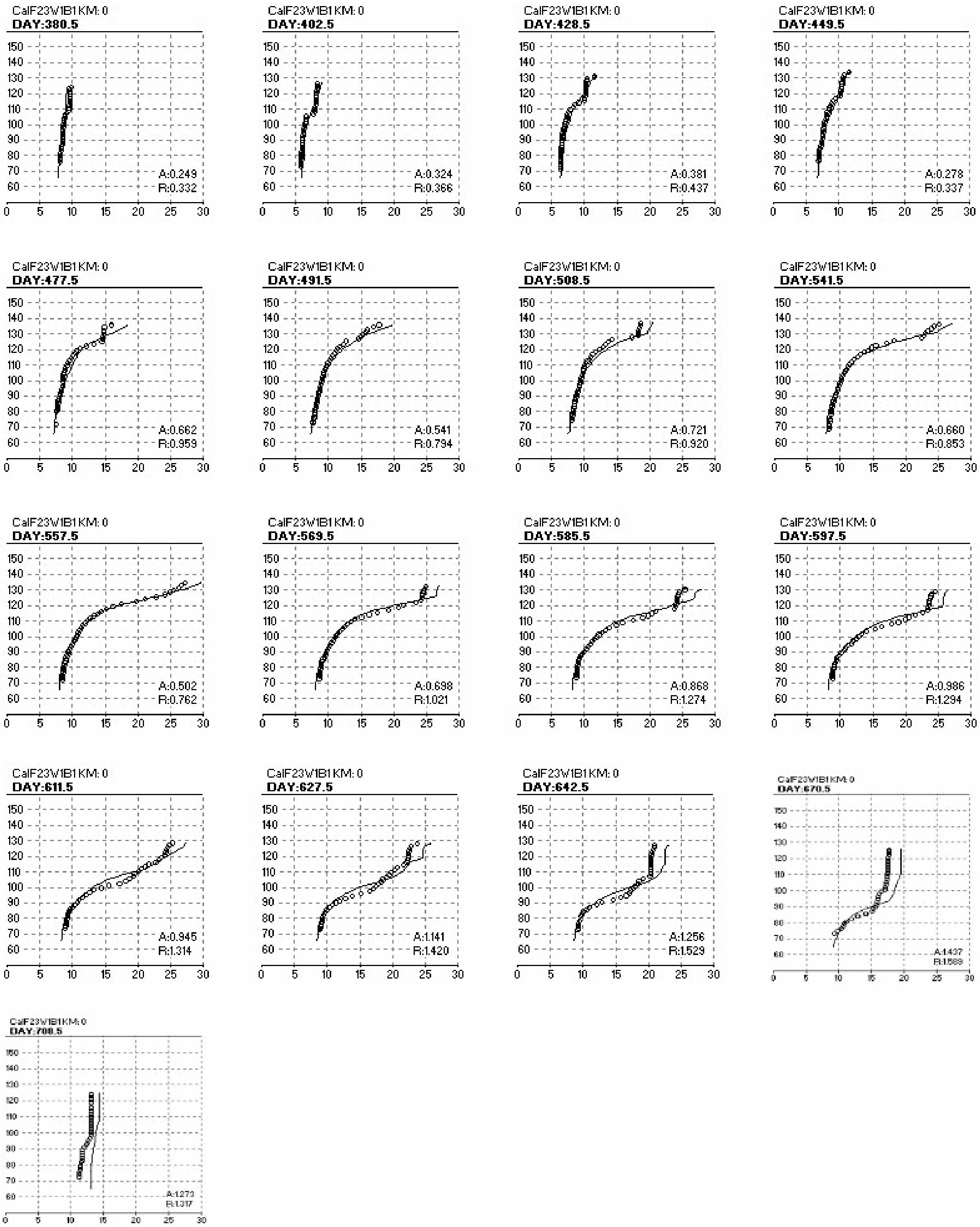


Figure A-11.—Corrected modeled versus observed Folsom Dam forebay water temperature profiles for 2002.

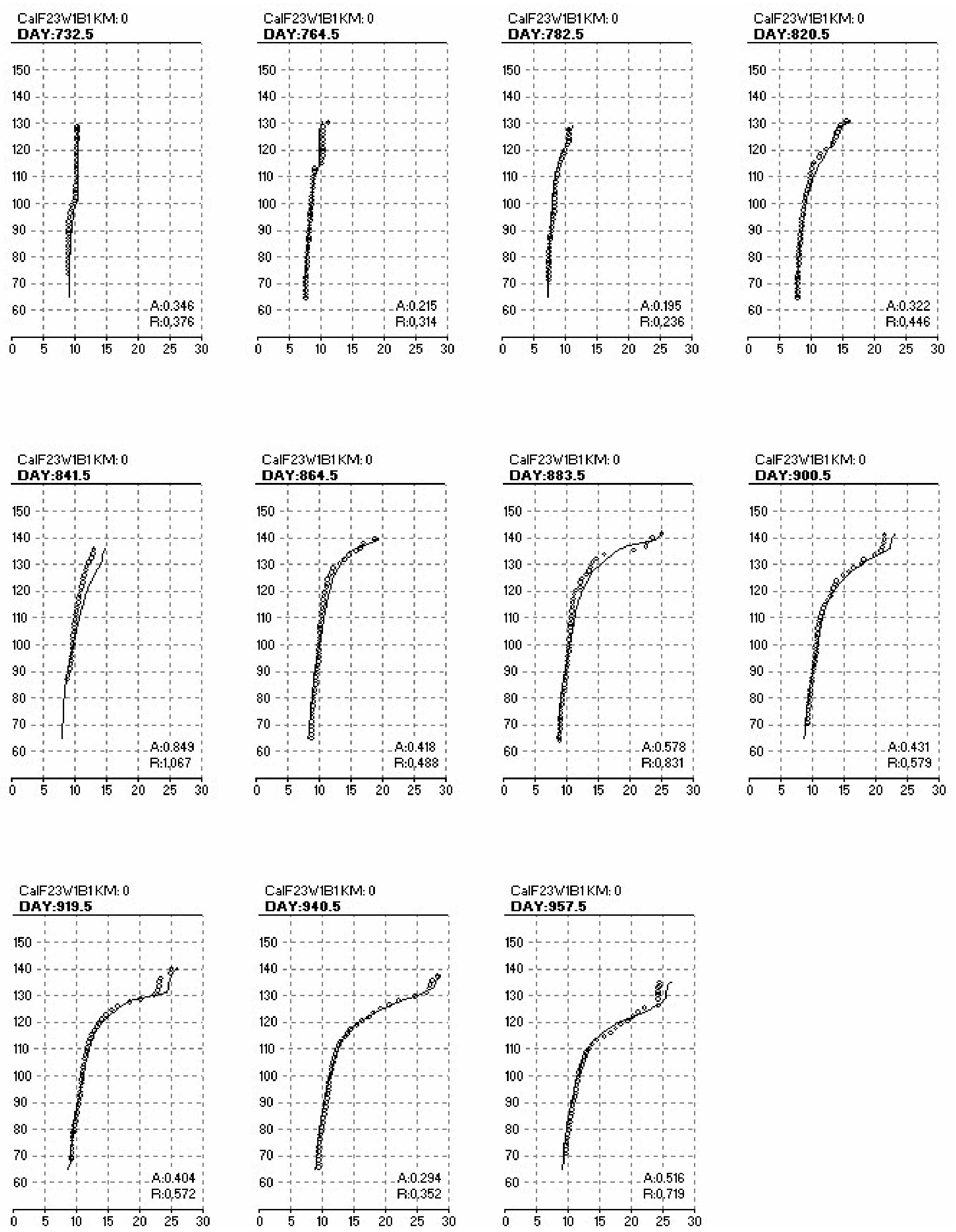


Figure A-12.—Corrected modeled versus observed Folsom Dam forebay water temperature profiles for 2003.

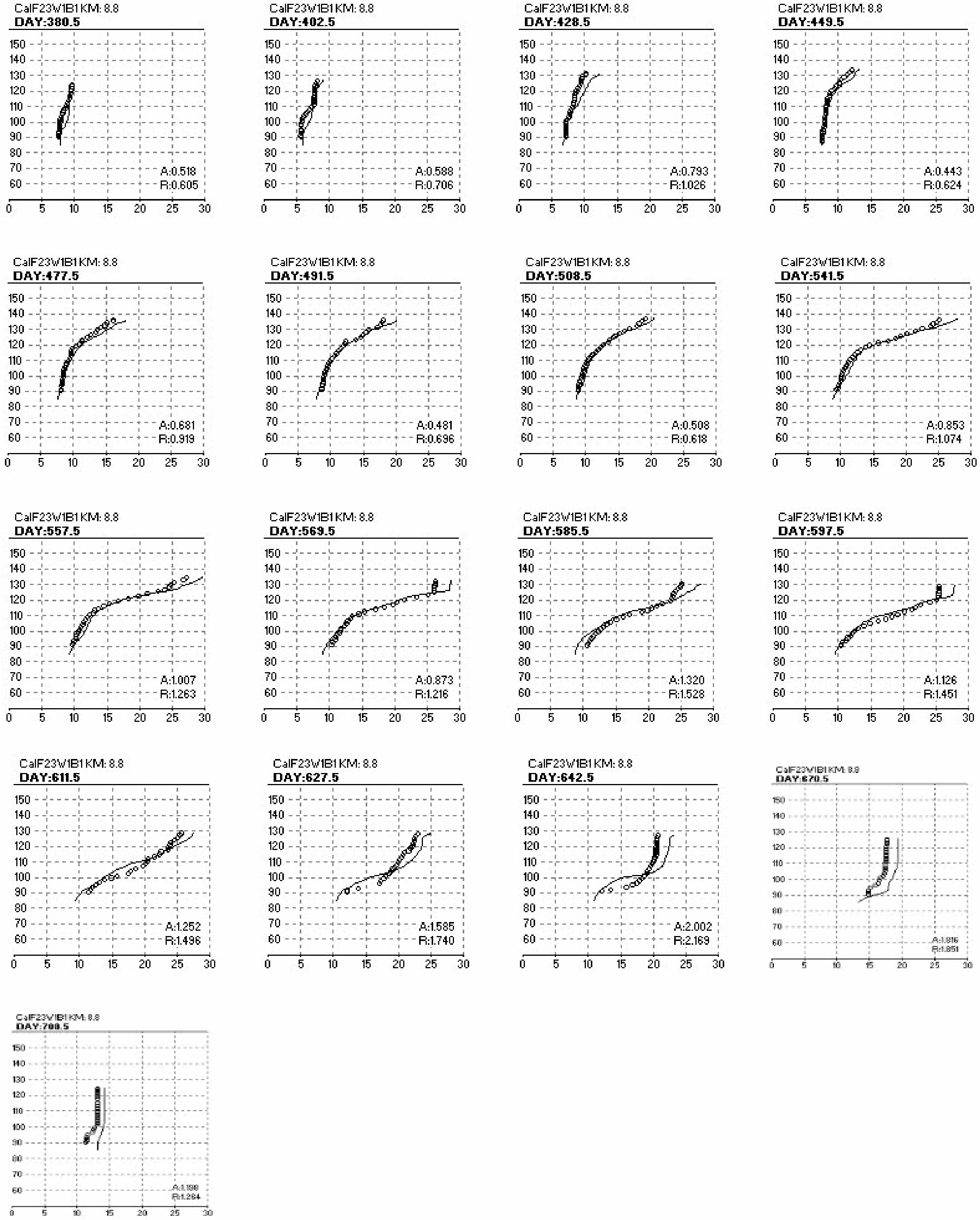


Figure A-13.—Corrected modeled versus observed Folsom Lake North Fork arm water temperature profiles for sample site A (segment 11) for 2002.

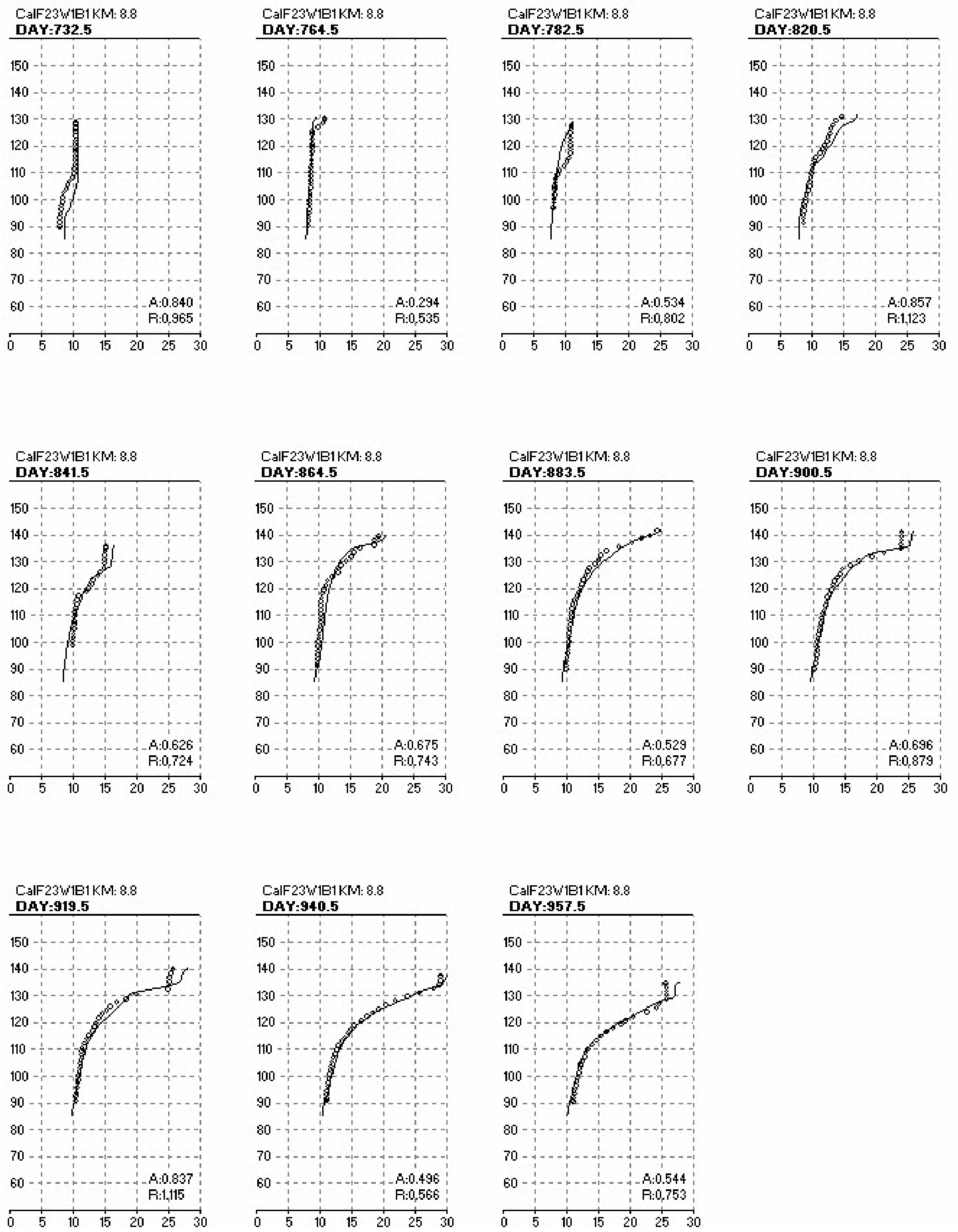


Figure A-14.—Corrected modeled versus observed Folsom Lake North Fork arm water temperature profiles for sample site A (segment 11) for 2003.

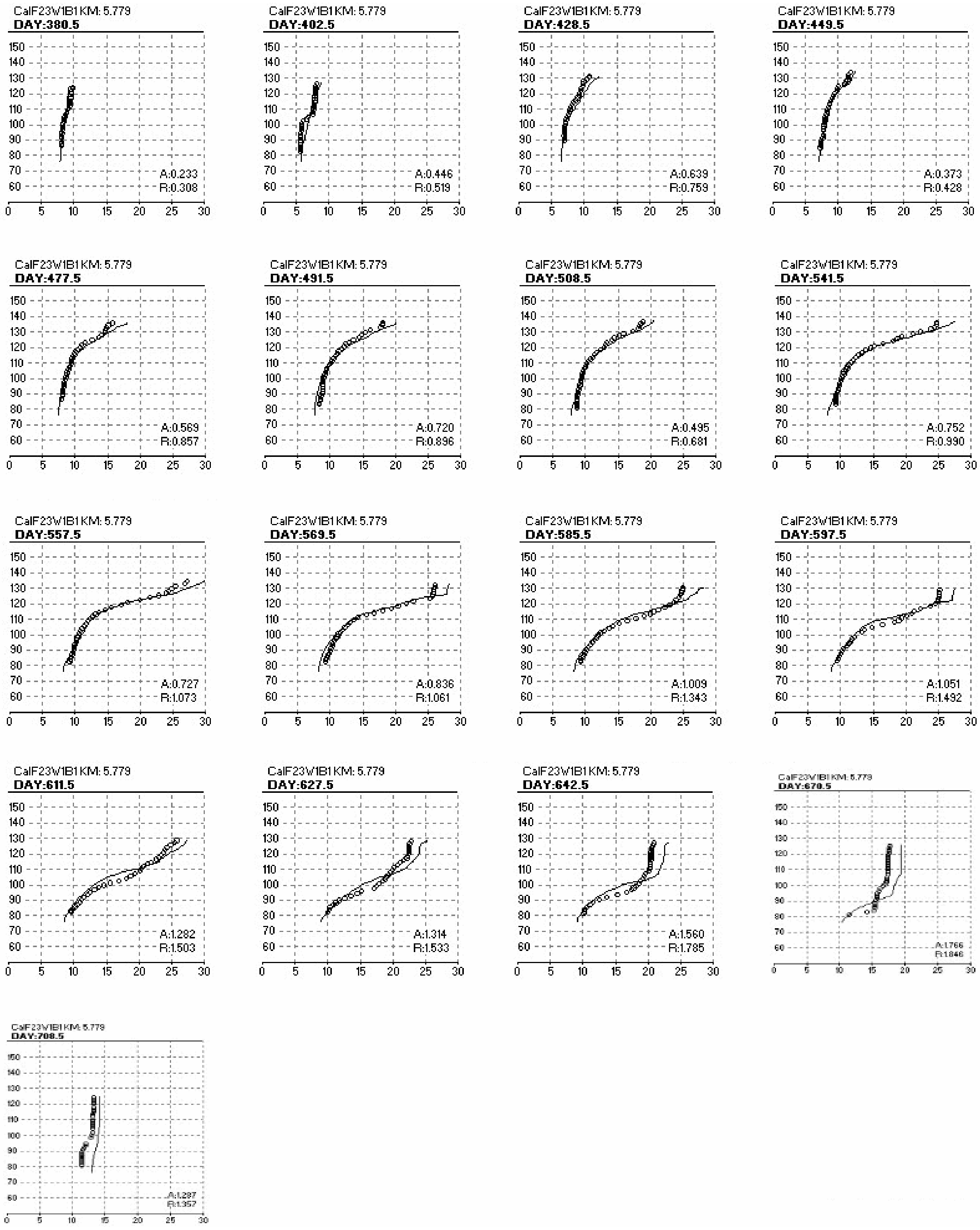


Figure A-15.—Corrected modeled versus observed Folsom Lake North Fork arm water temperature profiles for sample site E (segment 13) for 2002.

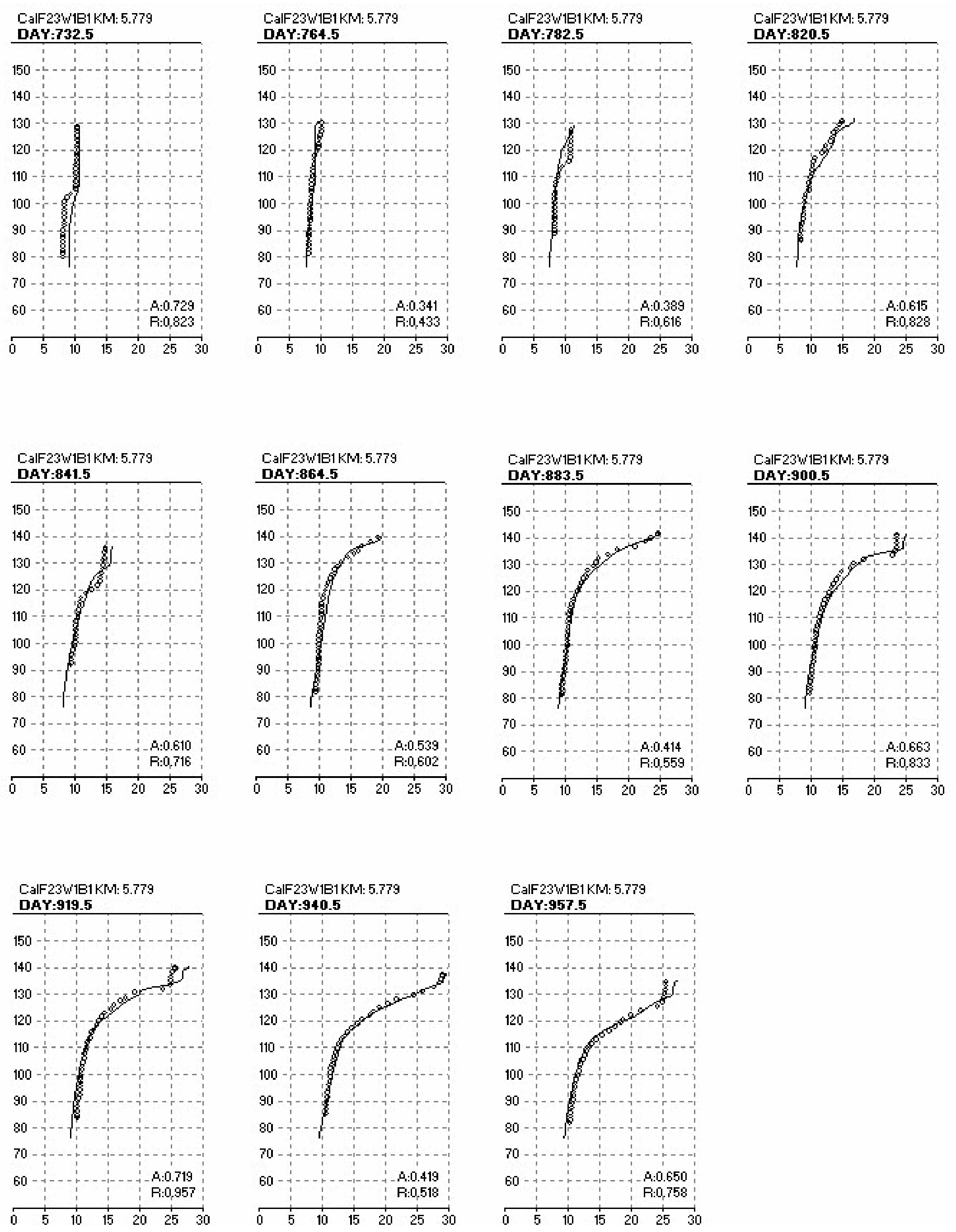


Figure A-16.—Corrected modeled versus observed Folsom Lake North Fork arm water temperature profiles for sample site E (segment 13) for 2003.

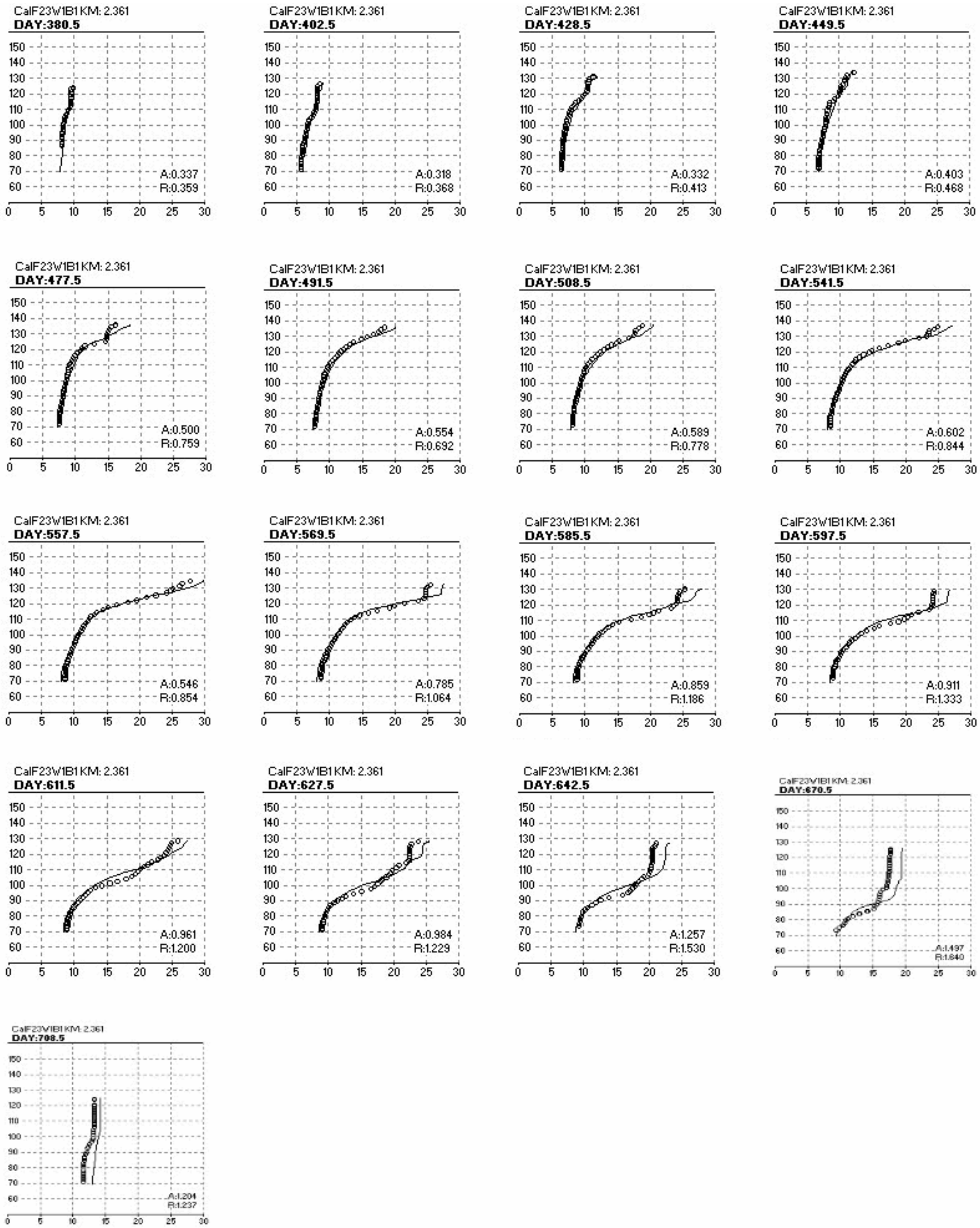


Figure A-17.—Corrected modeled versus observed Folsom Lake North Fork arm water temperature profiles for sample site C (segment 16) for 2002.

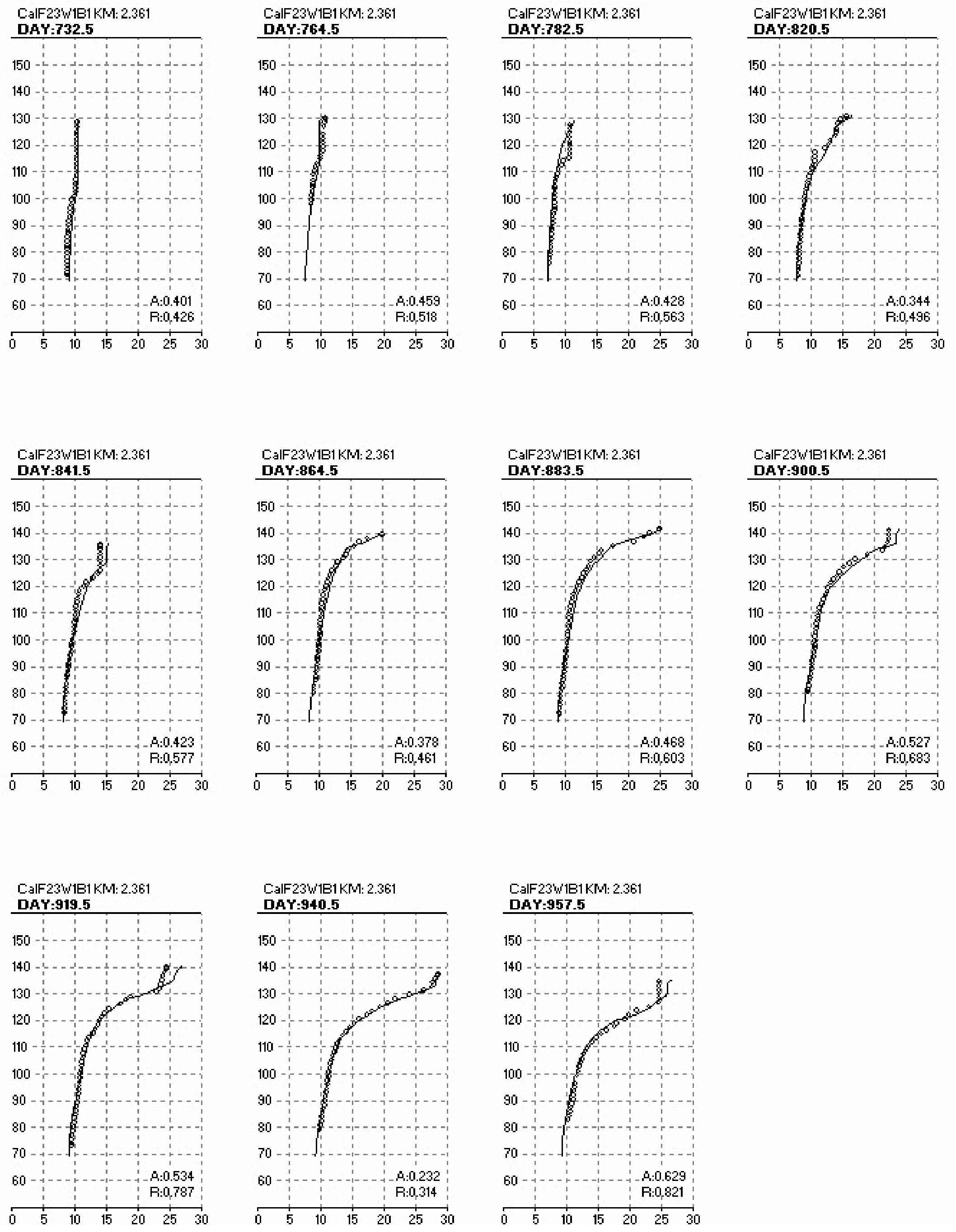


Figure A-18.—Corrected modeled versus observed Folsom Lake North Fork arm water temperature profiles for sample site C (segment 16) for 2003.

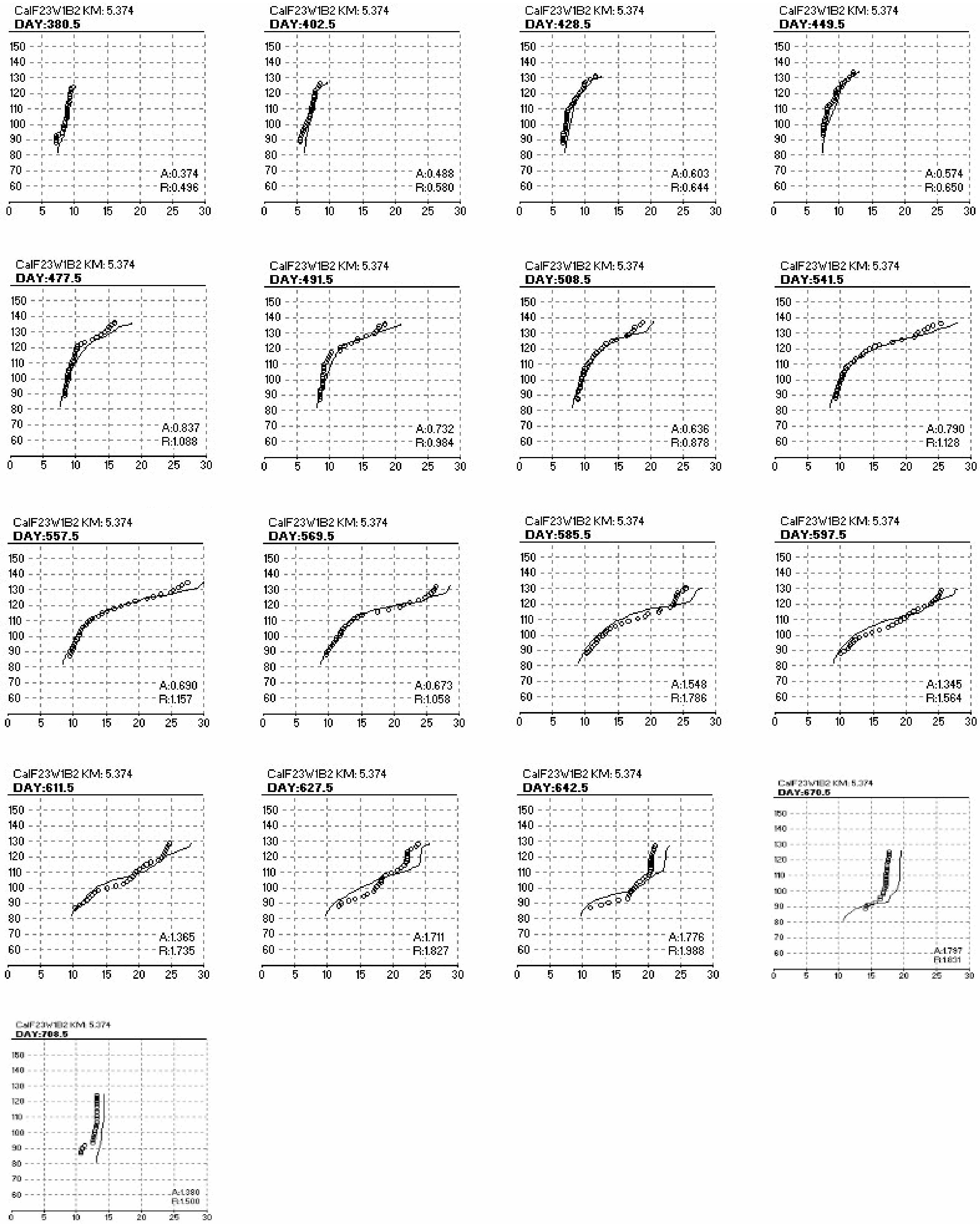


Figure A-19.—Corrected modeled versus observed Folsom Lake South Fork arm water temperature profiles for sample site B (segment 32) for 2002.

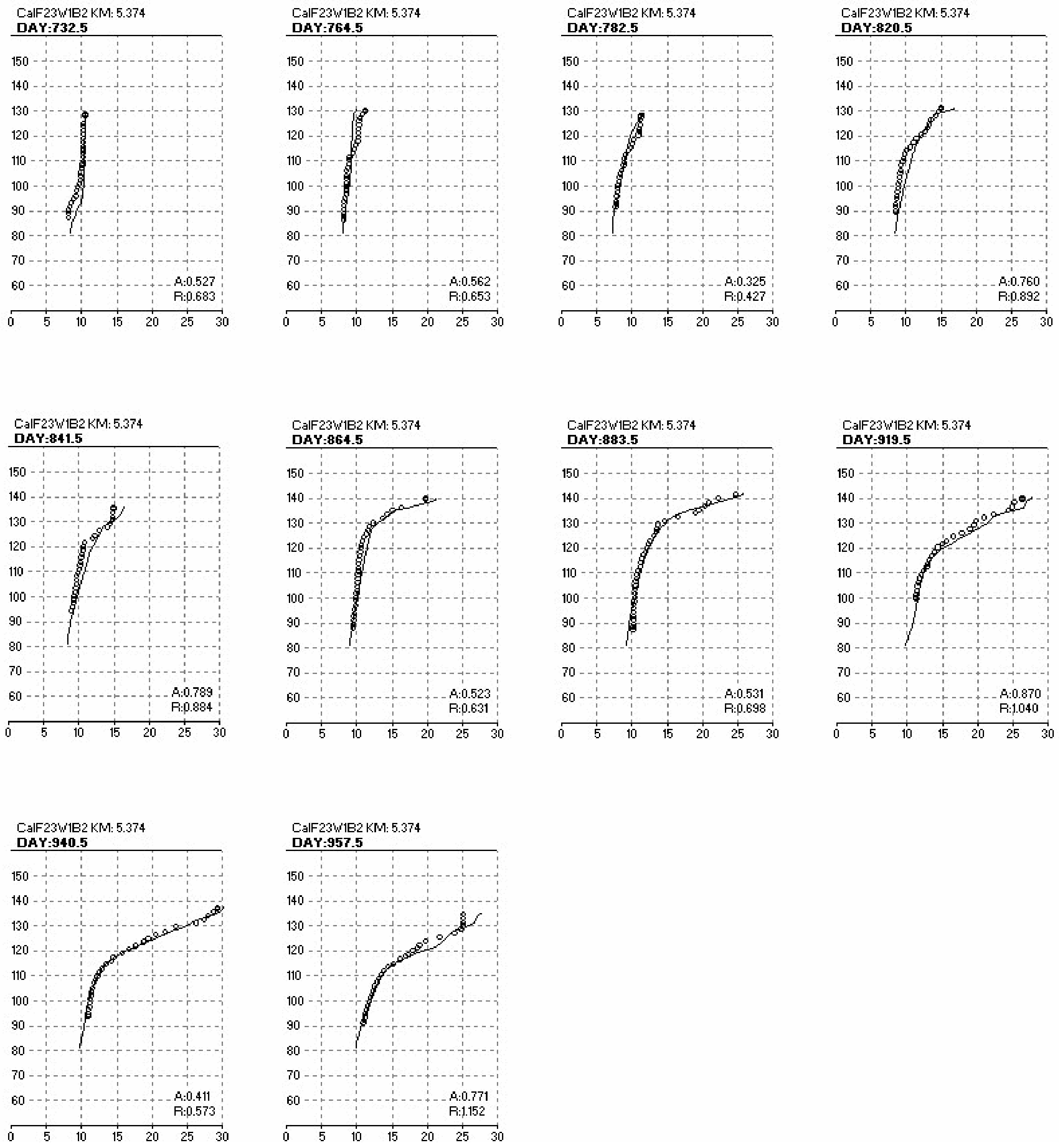


Figure A-20.—Corrected modeled versus observed Folsom Lake South Fork arm water temperature profiles for sample site B (segment 32) for 2003.

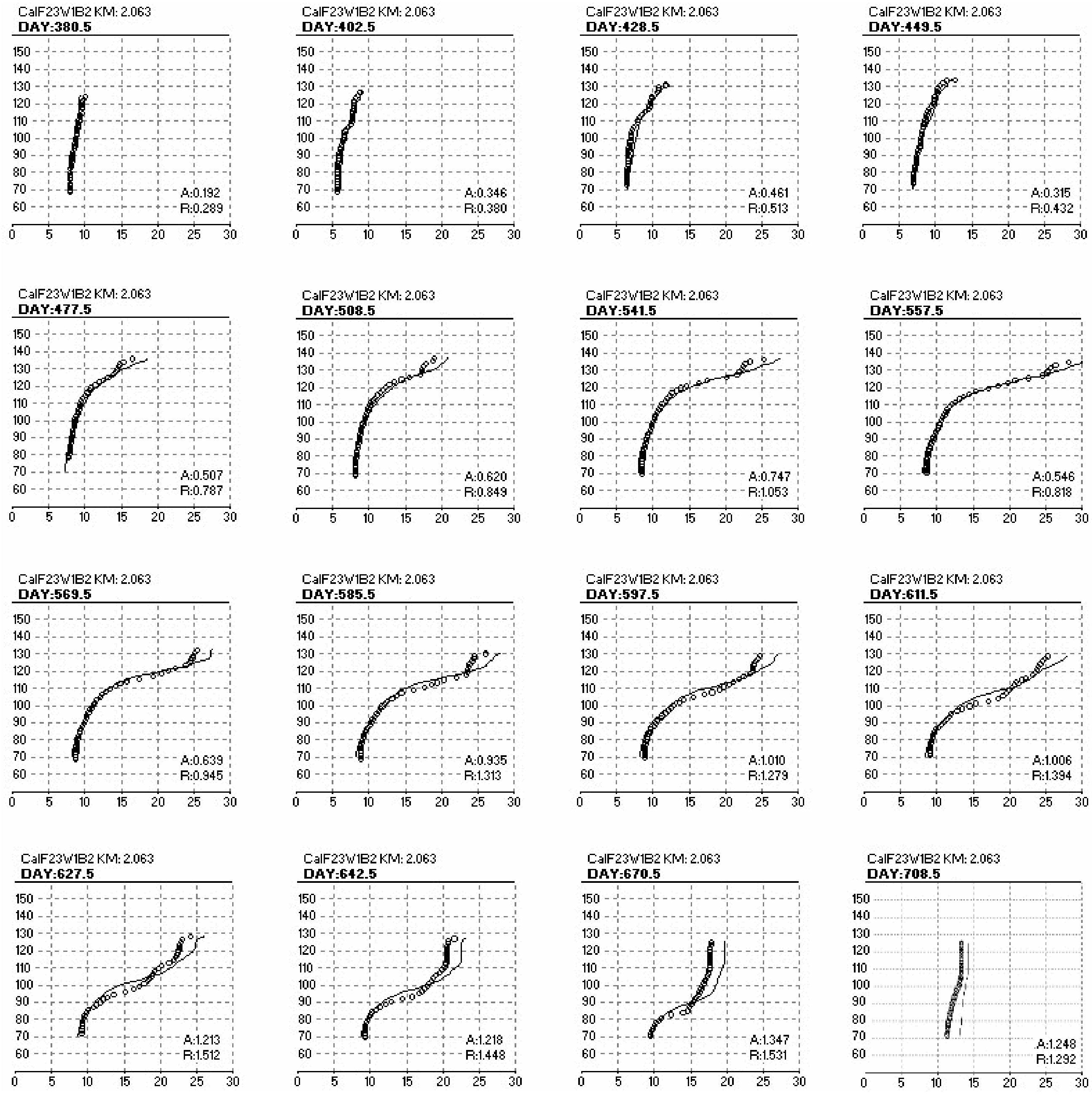


Figure A-21.—Corrected modeled versus observed Folsom Lake South Fork arm water temperature profiles for sample site D (segment 37) for 2002.

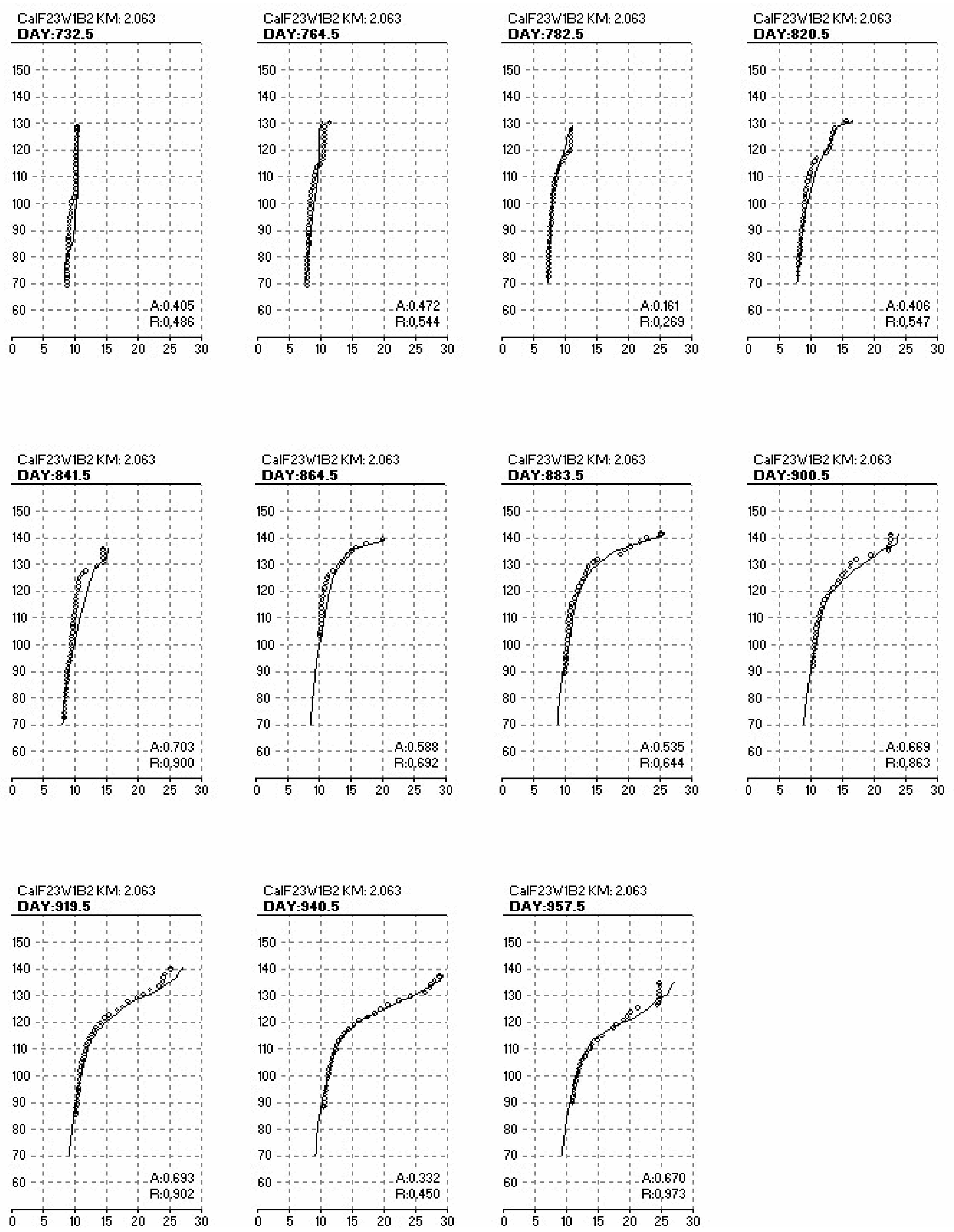


Figure A-22.—Corrected modeled versus observed Folsom Lake South Fork arm water temperature profiles for sample site D (segment 37) for 2003.

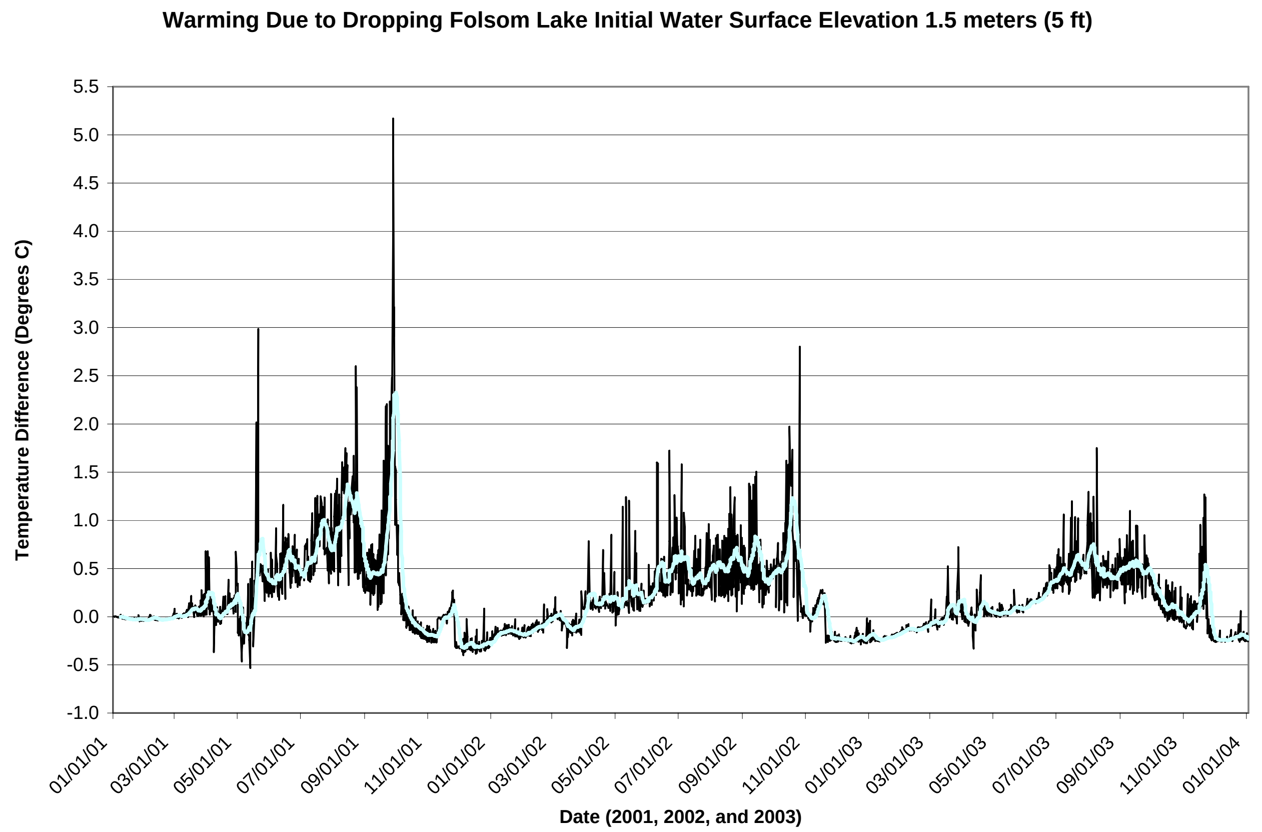


Figure A-23.—Modeled Folsom Dam release temperature differences versus time showing warming due to dropping Folsom Lake initial water surface elevation 1.5 meters (5 ft) for 2001, 2002, and 2003.

Appendix B: 2001-2003 Lake Natoma Model Calibration

See appendix A for a description of the comparison statistics used for Lake Natoma model calibration. Nimbus Dam forebay was the primary temperature calibration site for this relatively short reservoir with fairly continuous flow.

Temperature Calibration

Overall the Lake Natoma calibration is intermittently excellent based on ABS and RMS error statistics in °C on the Nimbus Dam forebay (model segment 20) profile plots in this appendix. Modeled Nimbus Dam forebay temperature for 2001, 2002, and 2003 matched observed data well usually within 1 °C (1.8 °F) as seen in the profile plots (B-1 through B-3). On most days, modeled Lake Natoma temperature for 2001 through 2003 statistically matched observed data to less than 1 °C (1.8 °F) and overall better than the Folsom Lake calibration. However, on rare occasions, modeled data did not match the data reportedly observed for that day. For those rare occasions, the field data, the time of sampling, or the model input data are suspect. The short water residence time of Lake Natoma dampens those anomalies within a day or two.

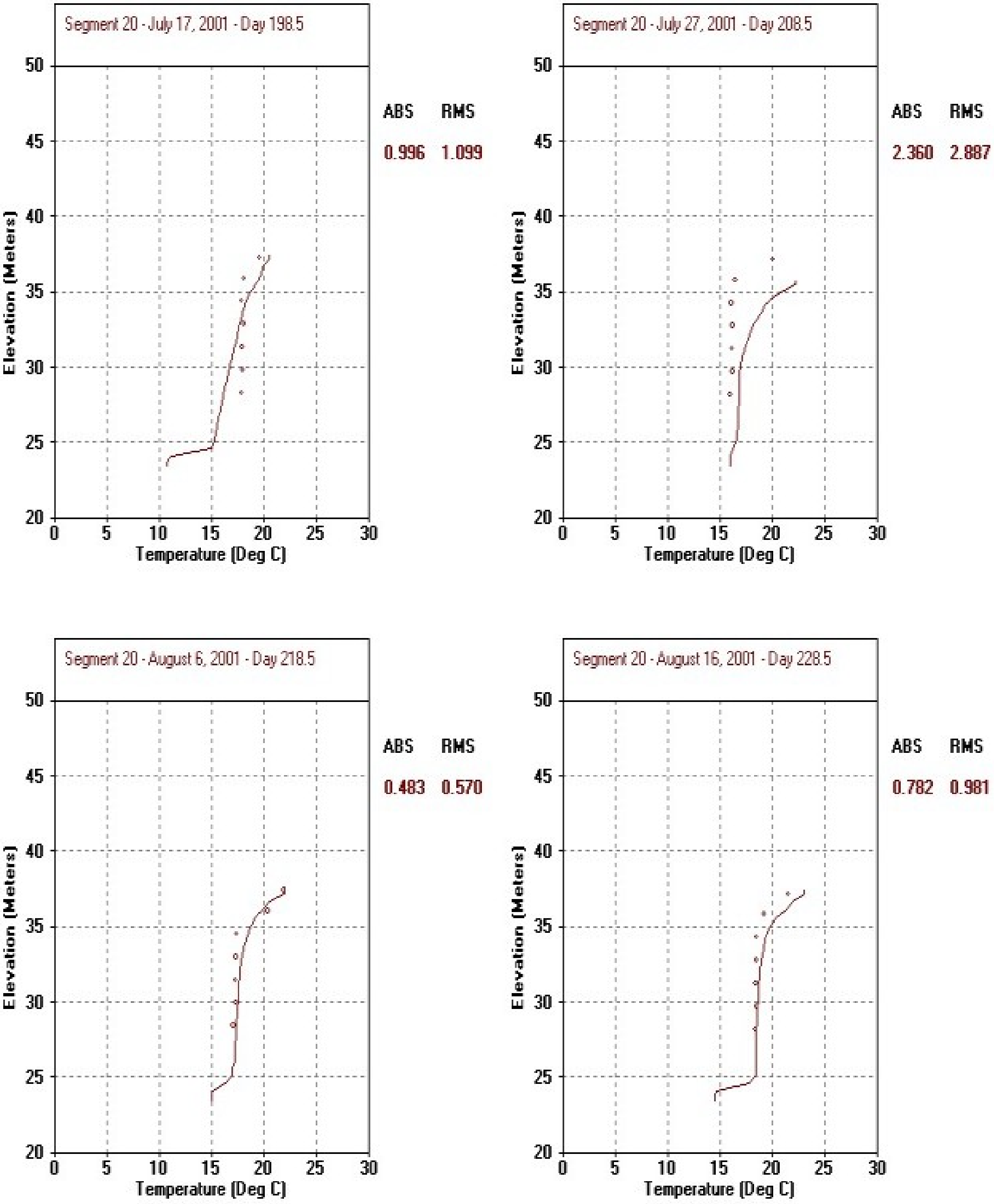


Figure B-1.—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2001.

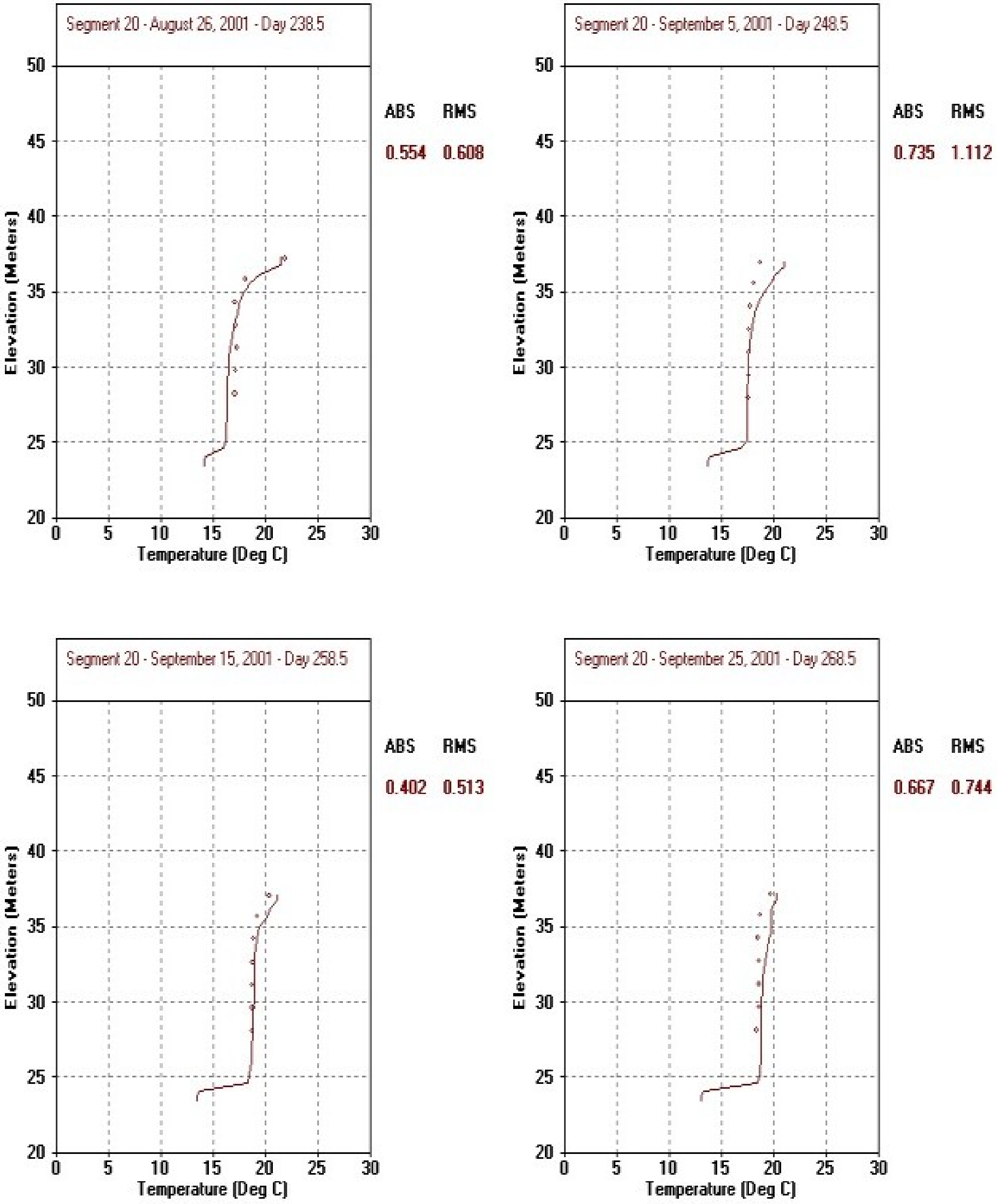


Figure B-1 (cont'd).—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2001.

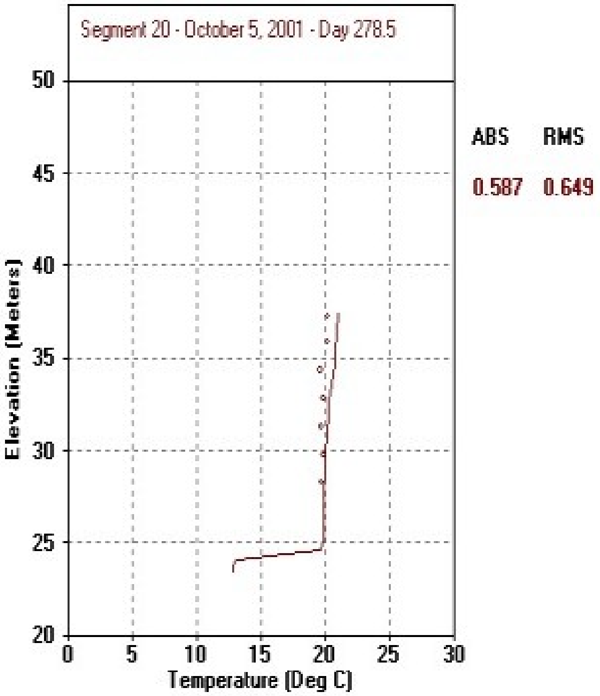


Figure B-1 (cont'd).—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2001.

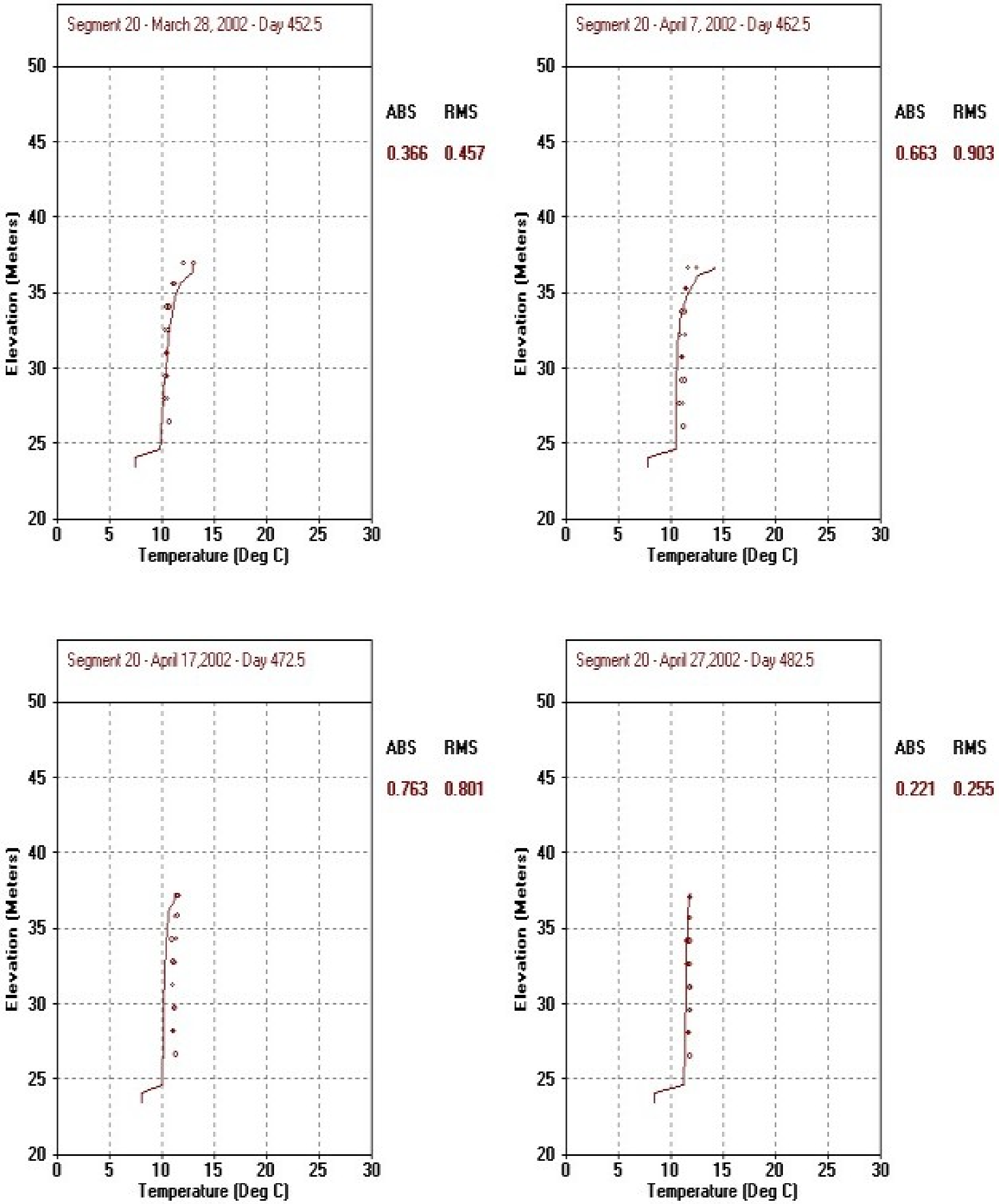


Figure B-2.—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2002.

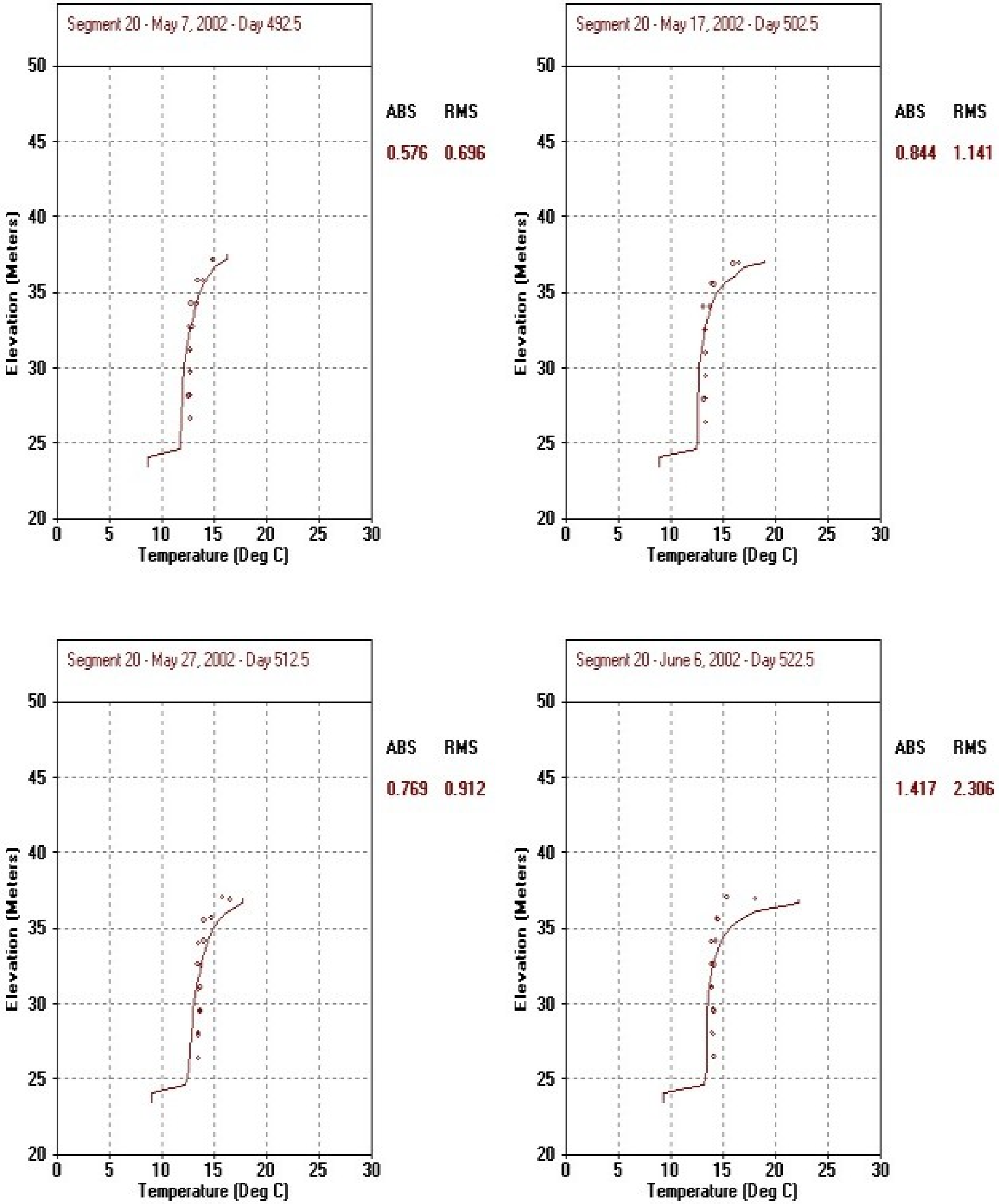


Figure B-2 (cont'd).—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2002.

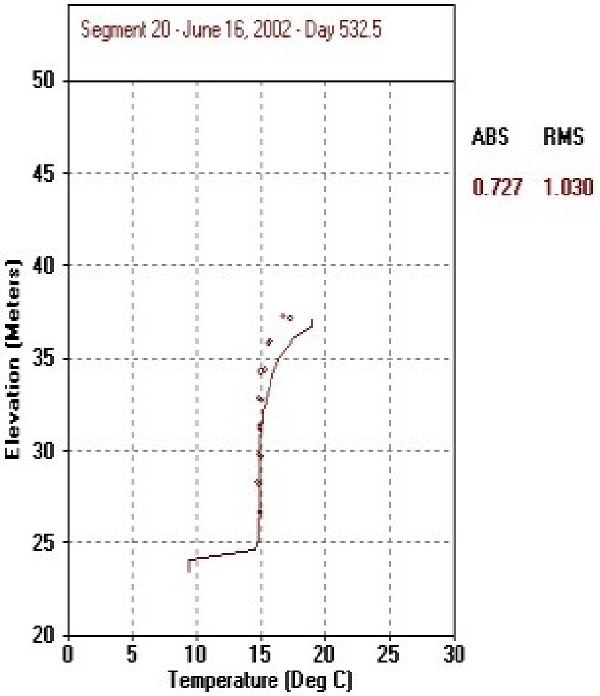


Figure B-2 (cont'd).—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2002.

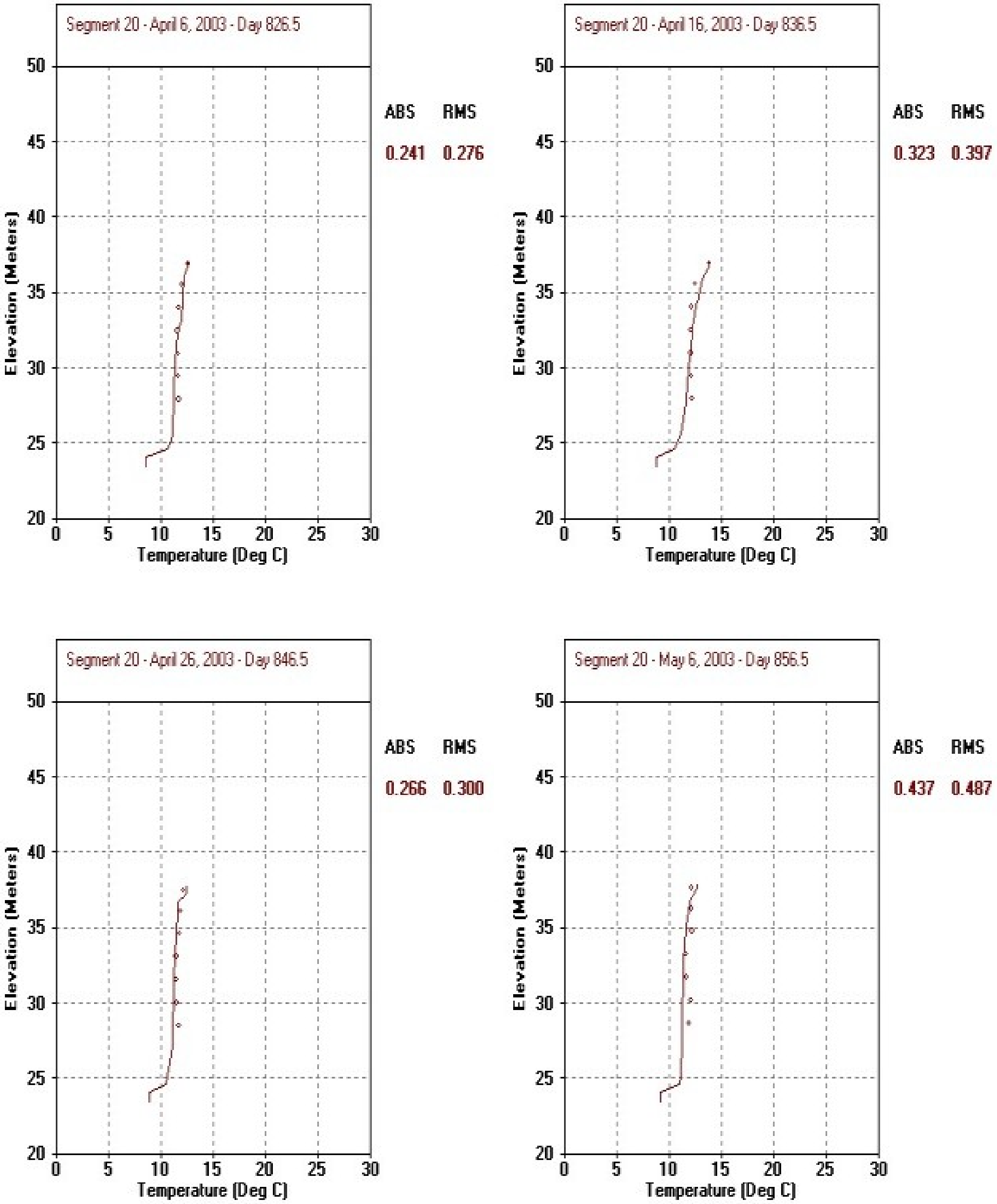


Figure B-3.—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2003.

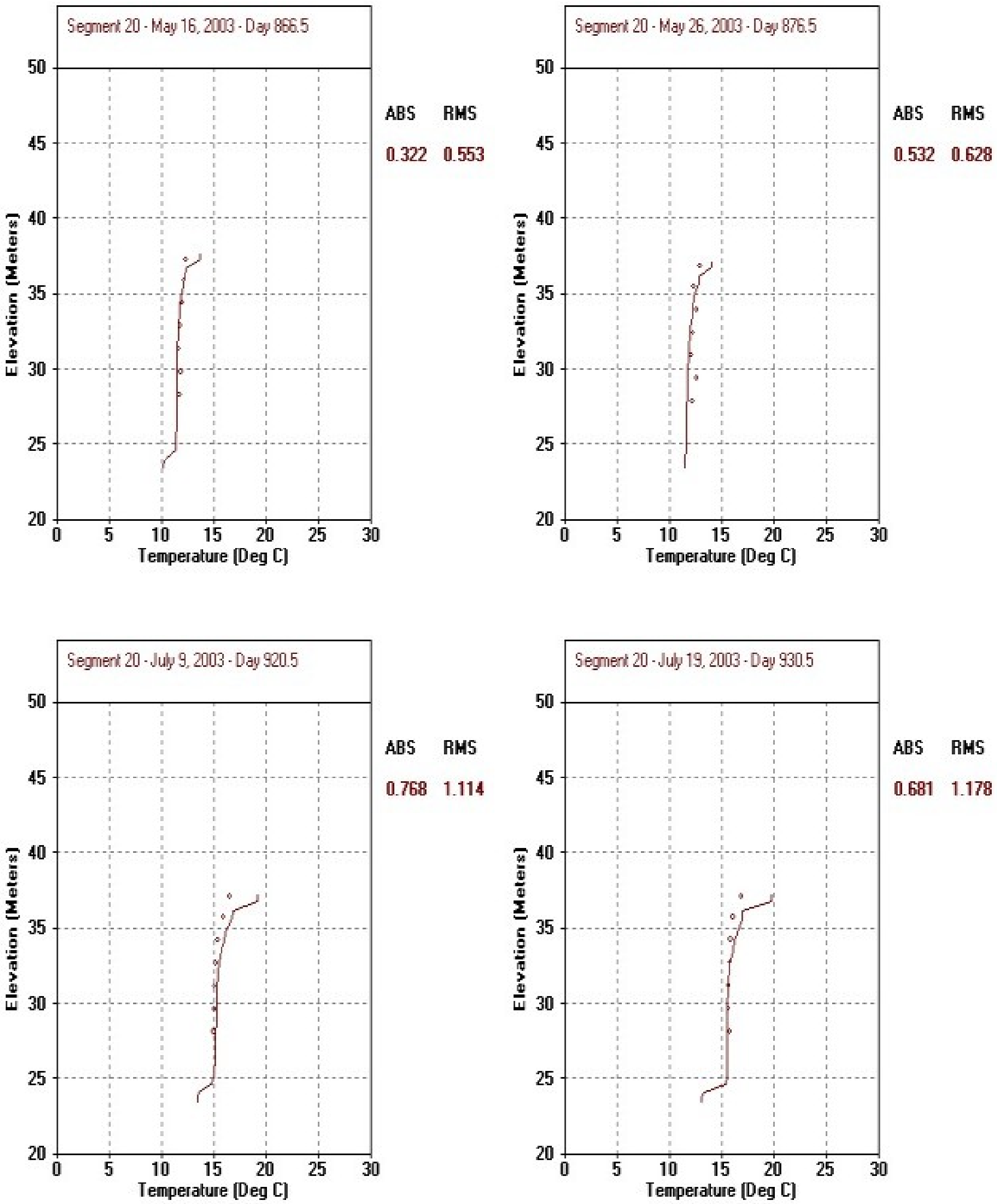


Figure B-3 (cont'd).—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2003.

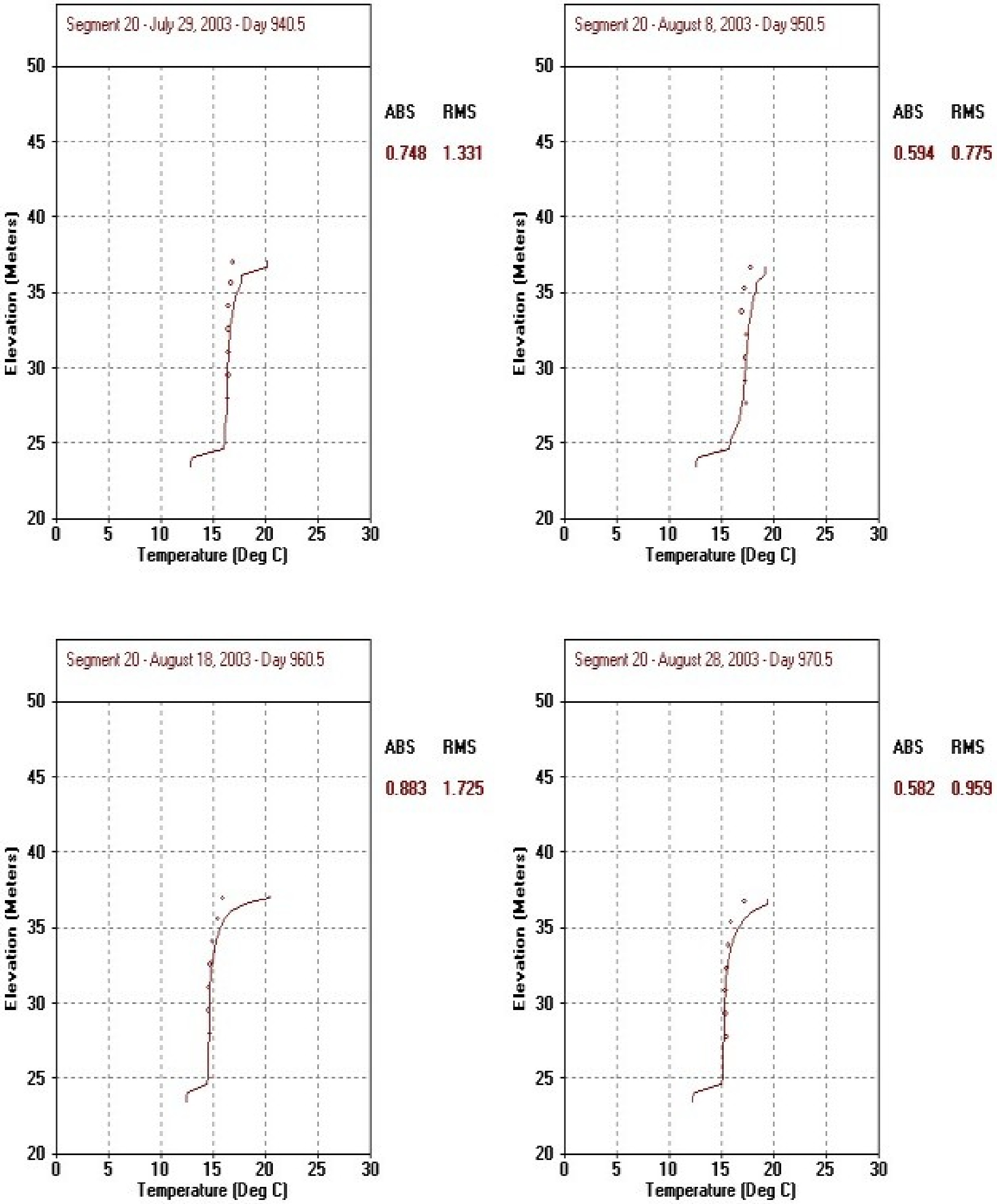


Figure B-3 (cont'd).—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2003.

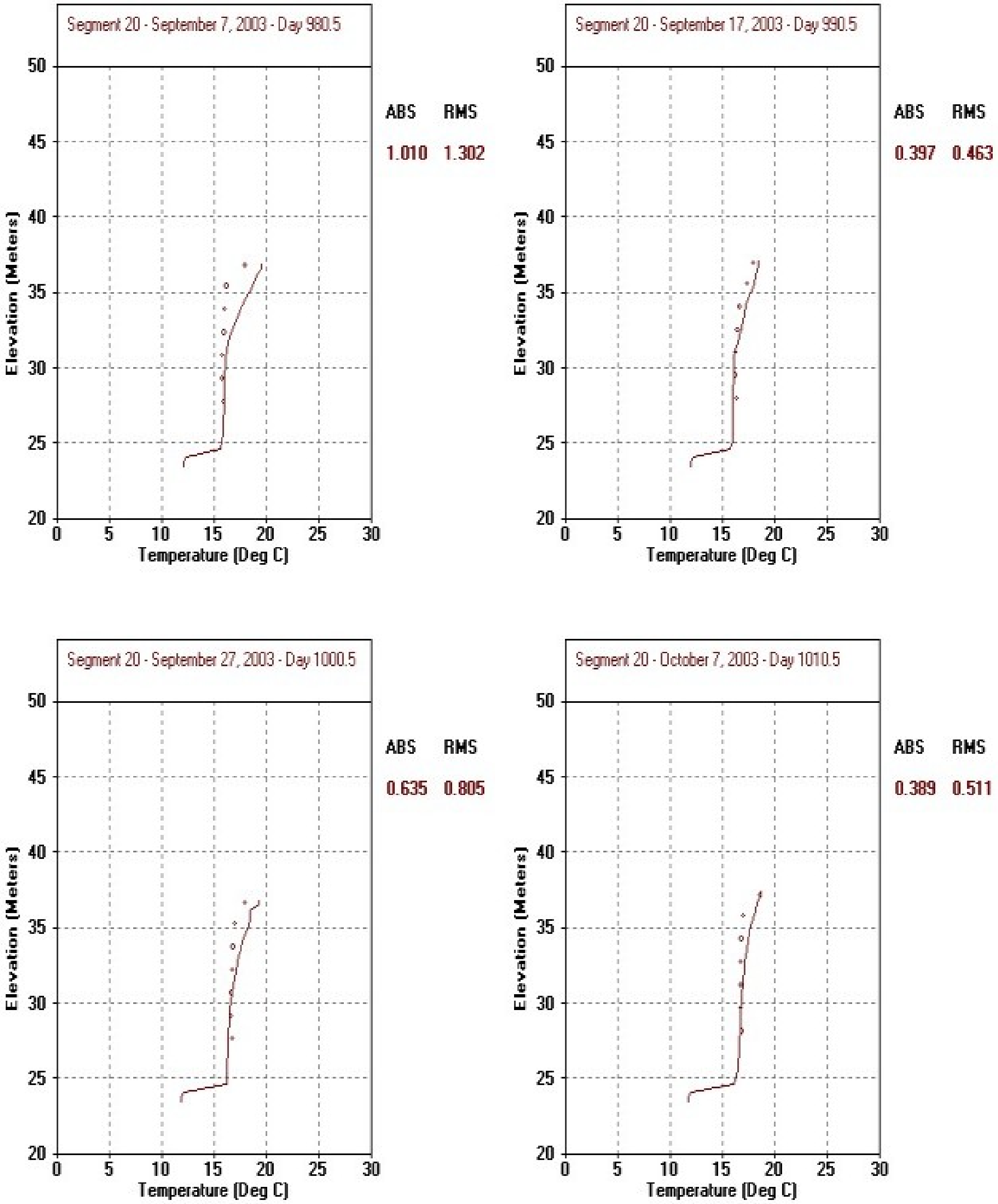


Figure B-3 (cont'd).—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2003.

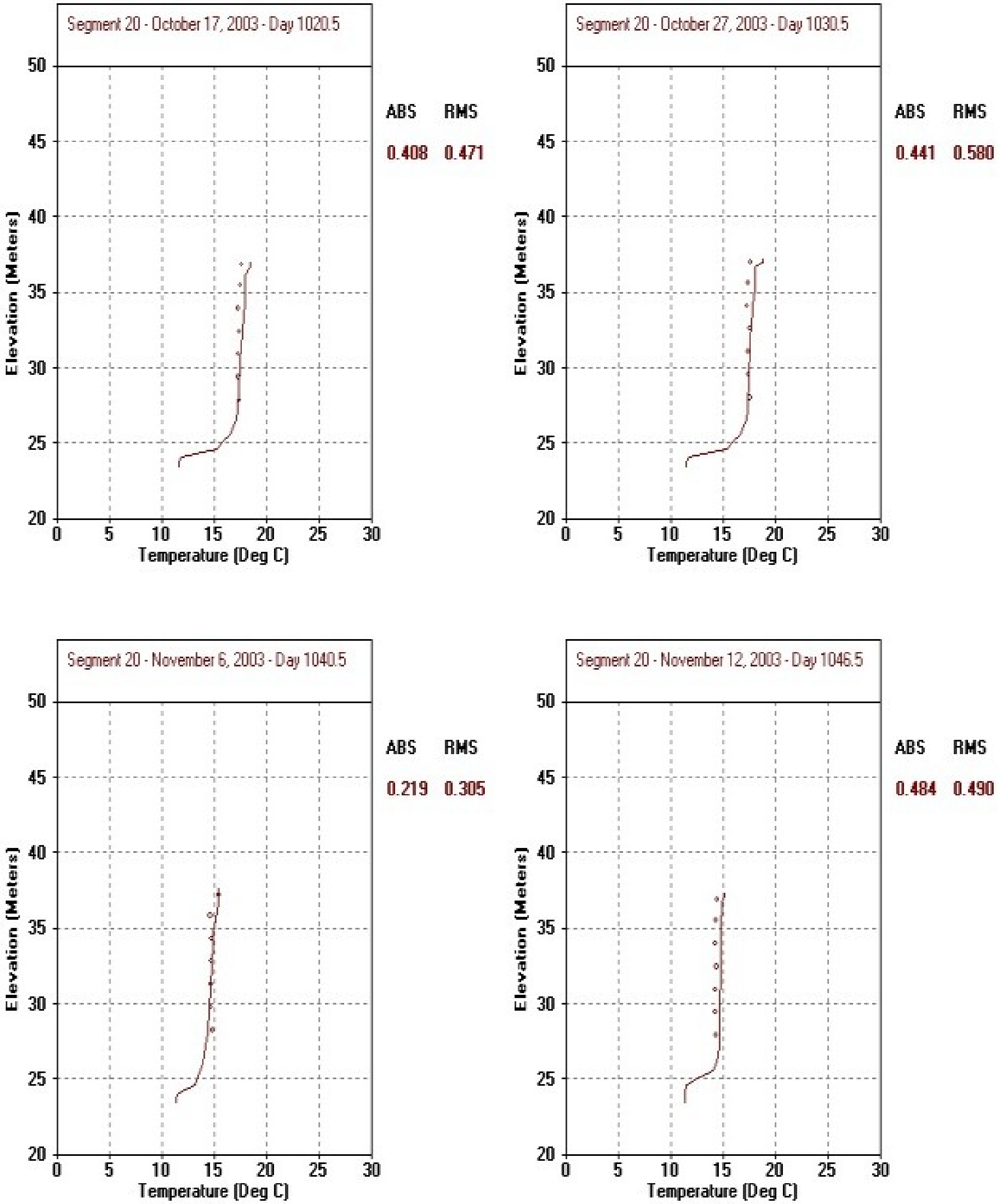


Figure B-3 (cont'd).—Modeled versus observed Nimbus Dam forebay water temperature profiles for 2003

Appendix C: Nimbus Dam 1-Dimensional Tailwater Temperature Model Calibration

The temperature model calibrated between Nimbus Dam and Watt Avenue Bridge, the temperature target location. Overall, the temperature model calibrates to within 1 °C (1.8 °F) of maximum and minimum values. Daily average values are within 0.5 °C (0.9 °F).

Reclamation calibrated the flow and temperature tailwater model by eliminating supercritical flow conditions from the geometry, ensuring a water mass balance, and matching temperature diurnal variations at locations between Nimbus Dam and at Watt Avenue Bridge. The flow model was calibrated by varying the thalweg Manning n globally (n = 0.04) and with reach full channel depth (RFC = 10.0 feet). The model was not calibrated to water travel time because the only travel time data available were raft float times.

The ratio of modeled water travel time to raft travel time was compared to roughly check the pattern of travel time even though a large disparity was expected between the different types of travel time. A raft floating at the water surface travels faster than a particle in the water column. Nimbus Dam tailwater observed raft travel times are typically 0.3 to 0.5 of the modeled water travel times, as seen in table C-1, which is in the range of expected ratios. Table C-1 shows modeled water particle and raft travel times from Nimbus Dam to Watt Avenue Bridge for a range of flows. The modeled particle travel times are likely accurate at the releases shown in table C-1 due to many detailed cross sections being used for the model geometry and due to an adequate lower American River temperature model calibration to Watt Avenue Bridge that matches diurnal variations of observed data.

Table C-1.—Modeled estimated water particle and observed raft float travel times for Nimbus Dam tailwater

Nimbus Dam release (cfs)	William B. Pond		Watt Avenue Bridge	
	Particle travel time (hours)	Raft float time (hours)	Particle travel time (hours)	Raft float time (hours)
1,000	17.8	--	23.8	--
1,500	14.1	4.6	18.9	7.7
2,000	11.8	4.1	16.0	6.7
2,500	10.2	3.8	13.9	5.9
3,000	9.1	3.4	12.5	5.3
3,500	8.4	3.0	11.5	4.6
4,000	7.8	2.8	10.7	4.2

Figures C-1 through C-8 compare modeled and observed tailwater temperatures at several locations downstream from Nimbus Dam using data retrieved from California Data Exchange Center (CDEC) or data provided by Mike Brown of the California Department of Fish and Game (CDFG) (2004 personal communication). Figures C-1 through C-8 show diurnal variations for the calibration period. The calibration period was from July 27, 2001 (day 208), to August 12, 2001 (day 224). Temperatures were compared at the following lower American River mile (LARM) locations:

Table C-2.—Observed tailwater temperature data locations

LARM	Description	Data Source
22.30	Hazel Avenue Bridge	CDEC (site AHZ)
22.20	Fish Hatchery weir pier	CDFG
22.00	at Fair Oaks gage site	CDEC (site AFO)
13.20	at William B. Pond Park	CDEC (site AWP)
12.25	at Gristmill Recreation Area	CDFG
9.15	at Watt Avenue Bridge	CDFG
9.10	at Watt Avenue Bridge	CDEC (site AWB)
4.50	at Paradise Beach	CDFG

Temperatures compared well at lower American River Mile (LARM) 22.3 (figure C-1) just downstream from Nimbus Dam at the Hazel Avenue Bridge. Inputs to the model were derived from the Hazel Avenue Bridge temperatures and incorrect data points discarded based on CDFG data collected at LARM 22.2 which is at the Fish Hatchery weir pier (figure C-2). Observed temperatures at Fair Oaks gage (figure C-3) were warm due to side channel eddies and modeled data at that location are more representative. The Hazel Avenue Bridge data were more accurate than data collected at Fair Oaks. The model matched observed water temperature at William B. Pond Park at LARM 13.2 (figure C-4) just upstream of Arden Rapids, at the Gristmill Recreation Area at LARM 12.25 (figure C-5), at Watt Avenue Bridge (CDFG site) at LARM 9.15 (figure C-6), and at Watt Avenue Bridge (site AWB) at LARM 9.10 (figure C-7). The 1-D model accurately predicts water temperature from Nimbus Dam to Watt Avenue Bridge and matches warming and cooling trends below Watt Avenue Bridge.

The one-dimensional model did not match observed data downstream from Paradise Beach at LARM 4.5 (figure C-8) due to tidal backwater influences of the Sacramento River. Tidal influences were not modeled due to lack of data, and a continuous downstream elevation boundary condition was assumed. On rare occasions at high tide or high Sacramento River flow, the backwater of the Sacramento River can extend to the Gristmill Dam Recreation Area at LARM 12.25. However, a steep river slope or gradient exists past the golf course near LARM 5.5. At low to average flows, backwater minimally influences water temperatures upstream of Watt Avenue Bridge.

To ensure stable starting hydraulic conditions, the ADYN model was run for 24 hours starting a few days after an observed spike of spillway water flushed the tailwater of warm stagnant conditions. The ending flow and water surface elevations at each node were then input as model boundary initial conditions. The velocity stability criteria (dx/dt) were checked at all nodes because the explicit Holly-Priessman scheme was used and many cross sections were input. A concern arose about too many cross sections near the bridges (13 bridges) causing small dx/dt and model instability. Upstream cross sections were removed in the steeper gradients down to river mile 5.5 to alleviate this concern.

The temperature model was sensitive to changes in Manning's n. At high Manning's n, the modeled diurnal lags were significantly greater than observed. At low Manning's n, the modeled temperature maximums and minimums (amplitude) did not match.

The temperature model was fine-tuned by calibrating the heat transfer terms (AA and BB) that affect the evaporative cooling equation. At times, the model predicted conservatively warmer maximum temperatures than observed.

The weir with pickets near the fish hatchery was modeled as an interior boundary condition with pickets (zero flow is at elevation 26.67 m (87.5 feet) AMSL) to prevent stability problems caused by supercritical flow condition. Pickets are removed during the winter, spring, and early summer.

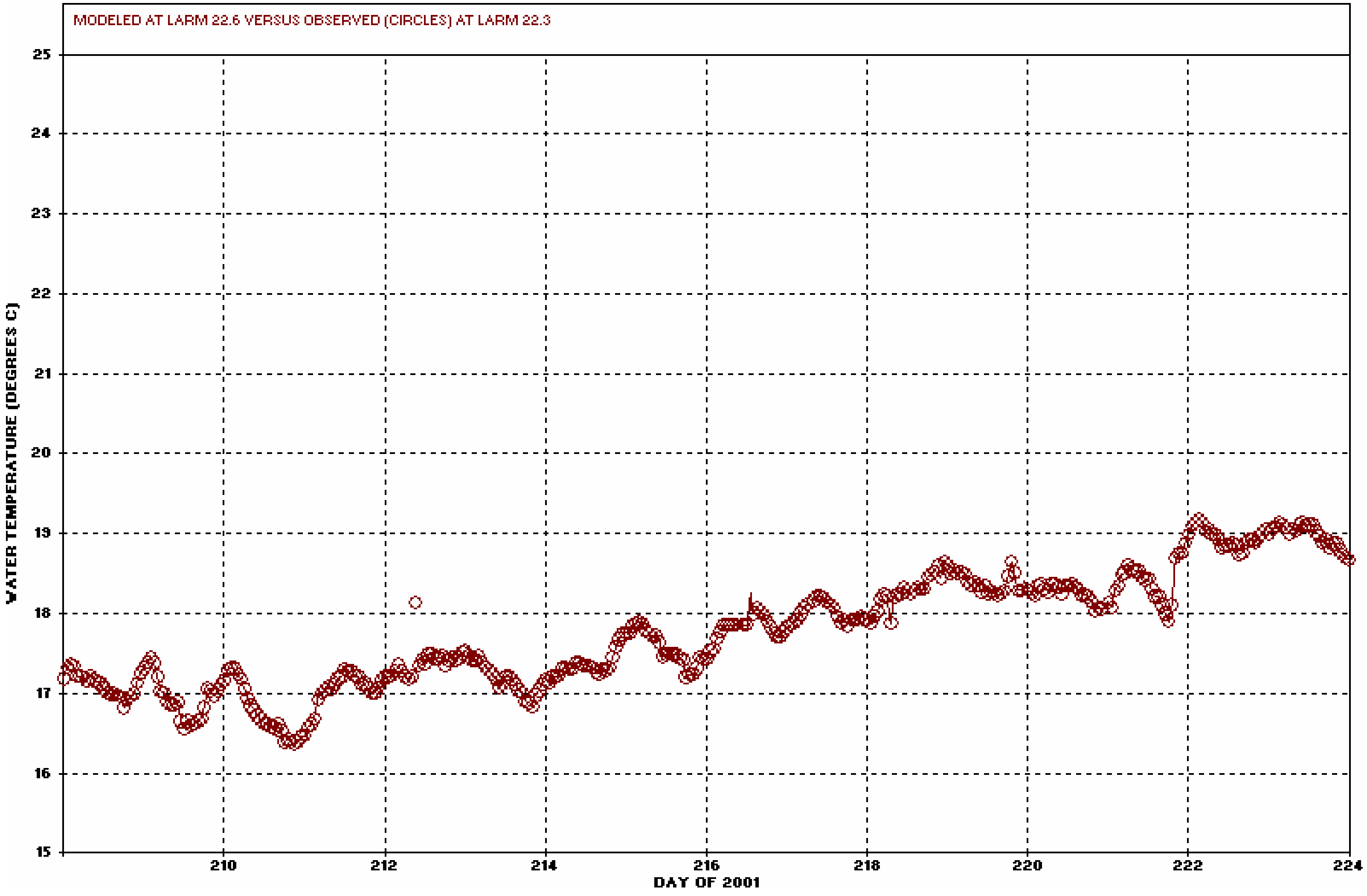


Figure C-1.—Modeled and instantaneous observed release temperature versus time near Nimbus Dam at Hazel Avenue Bridge (CDEC sample site AHZ - LARM 22.3) from July 27, 2001 to August 12, 2001.

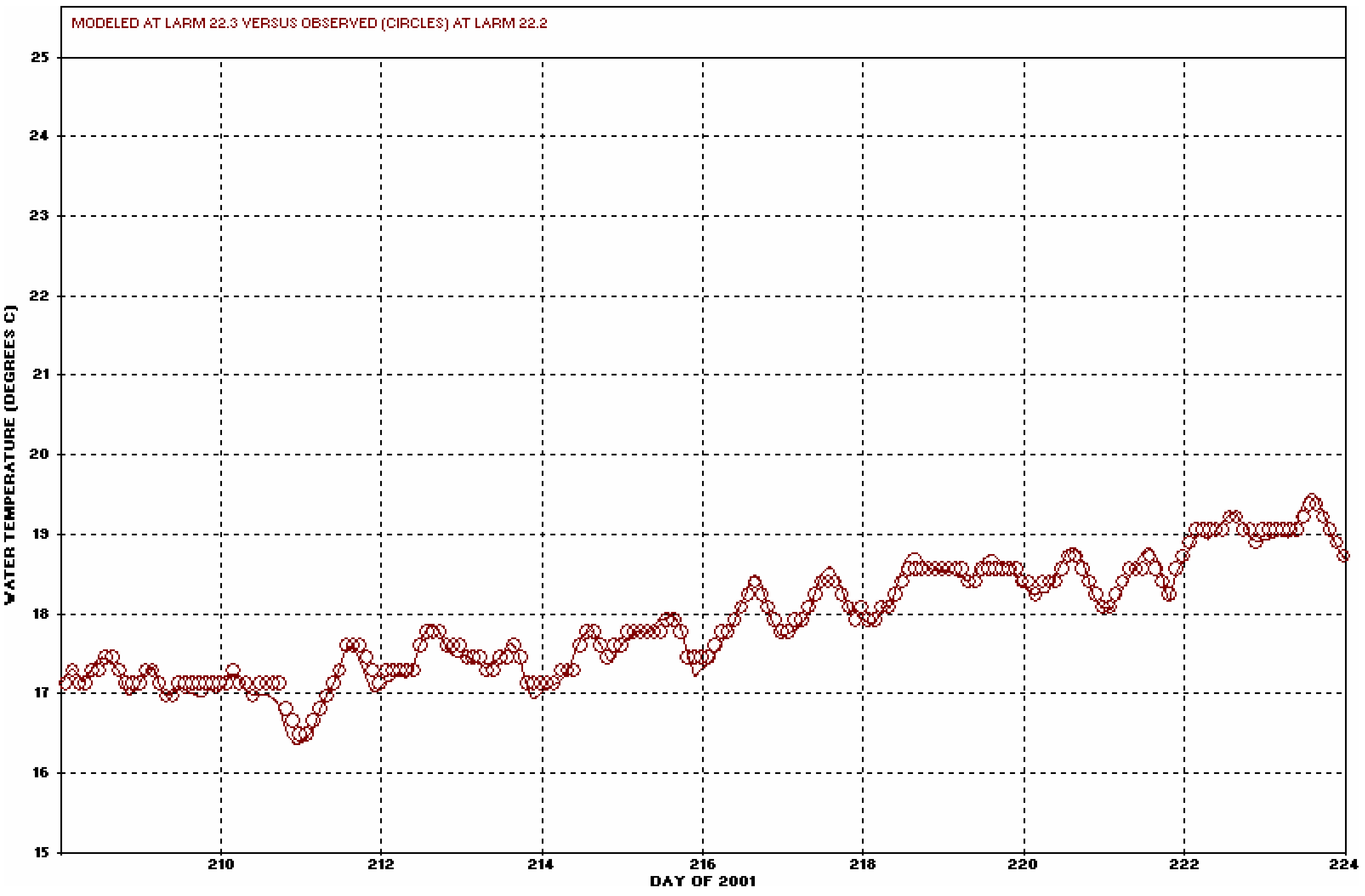


Figure C-2.—Modeled and instantaneous observed water temperature versus time at fish hatchery weir pier (CDFG sample site – LARM 22.2) from July 27, 2001 to August 12, 2001.

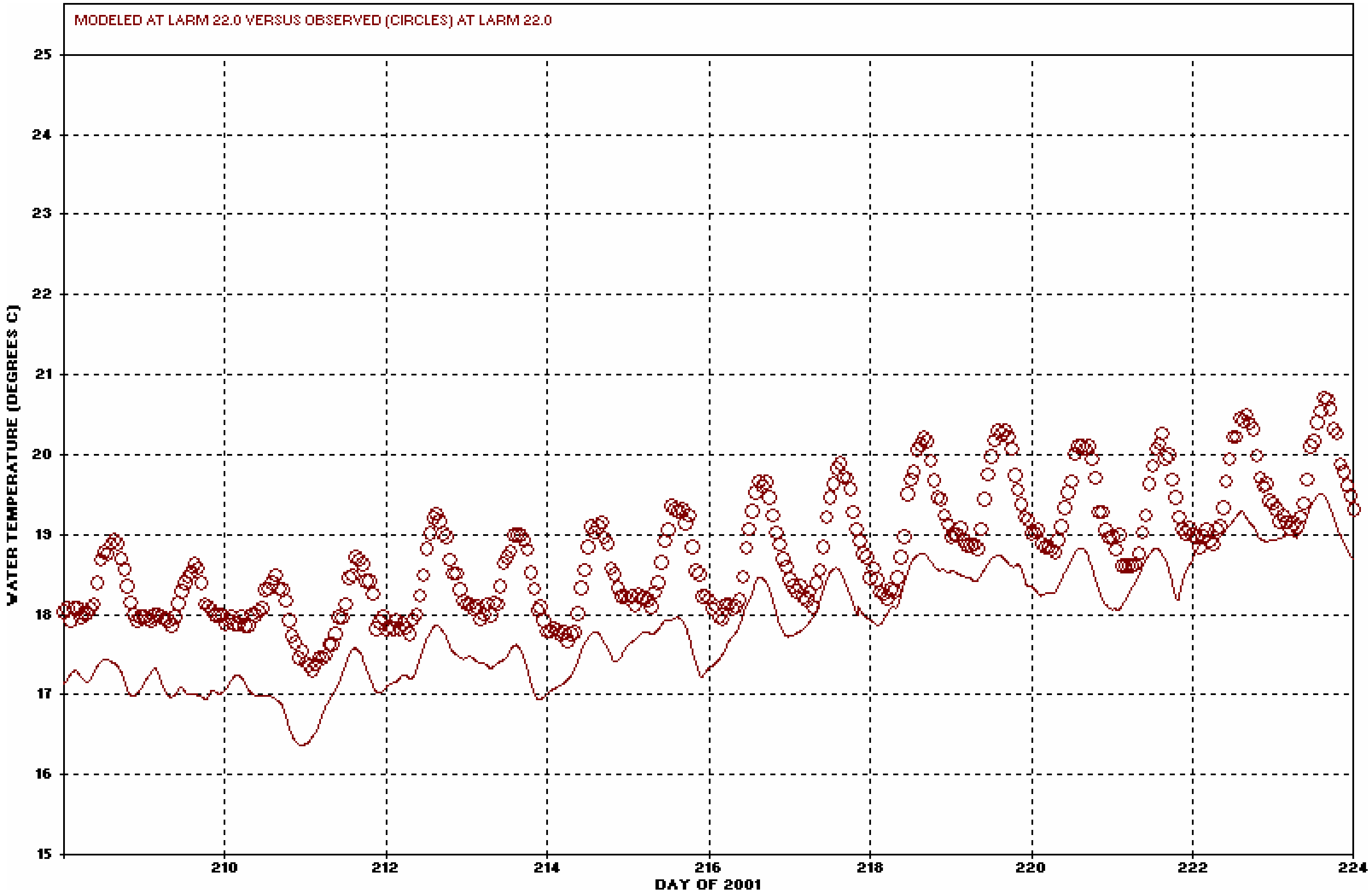


Figure C-3.—Modeled and instantaneous observed water temperature versus time at Fair Oaks Gauge (CDEC sample site AFO – LARM 22.0) from July 27, 2001 to August 12, 2001.

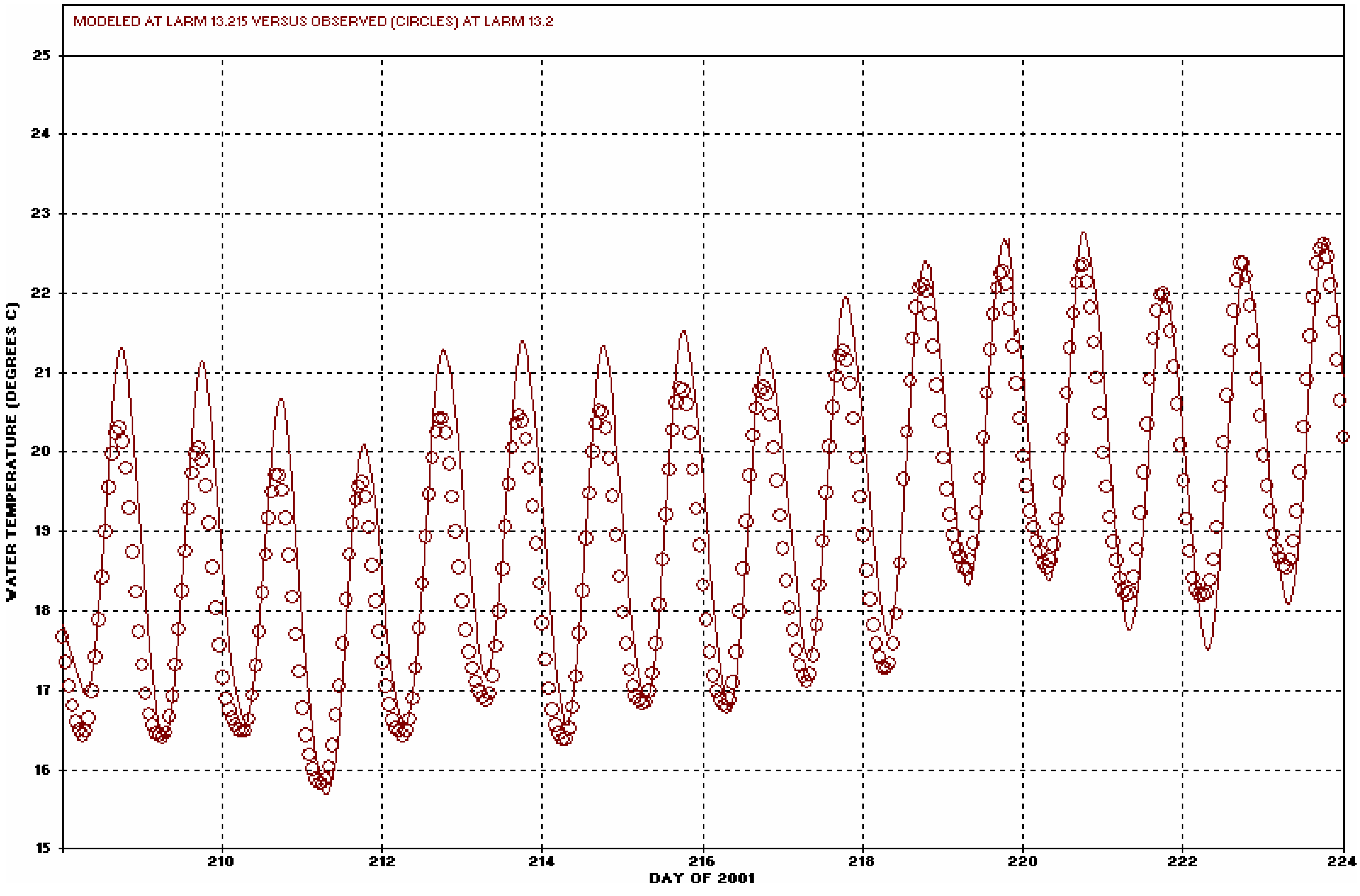


Figure C-4.—Modeled and instantaneous observed water temperature versus time at William B. Pond Park (CDEC sample site AWP – LARM 13.2) from July 27, 2001 to August 12, 2001.

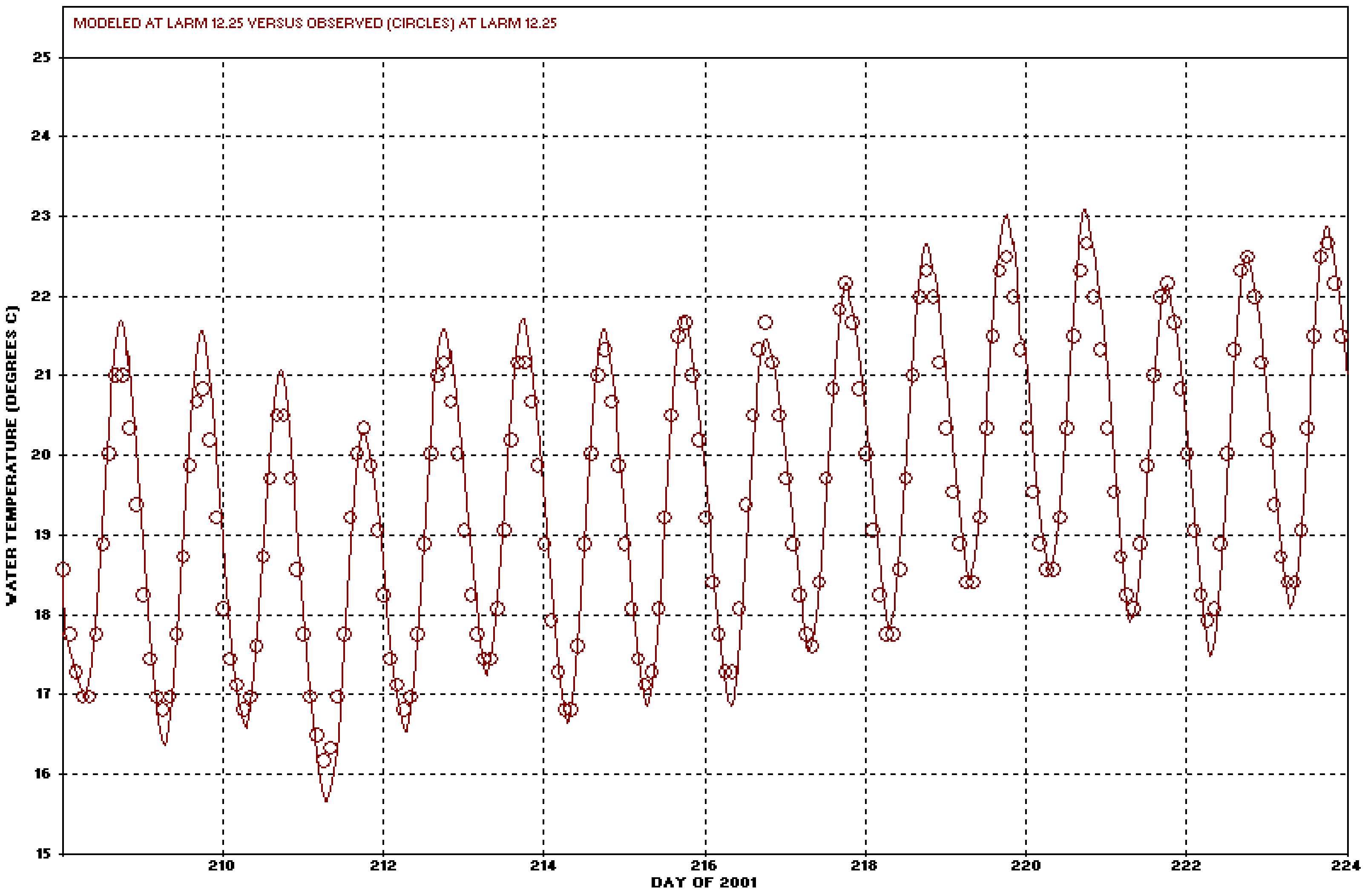


Figure C-5.—Modeled and instantaneous observed water temperature versus time at Gristmill Recreation Area (CDFG sample site – LARM 12.25) from July 27, 2001 to August 12, 2001.

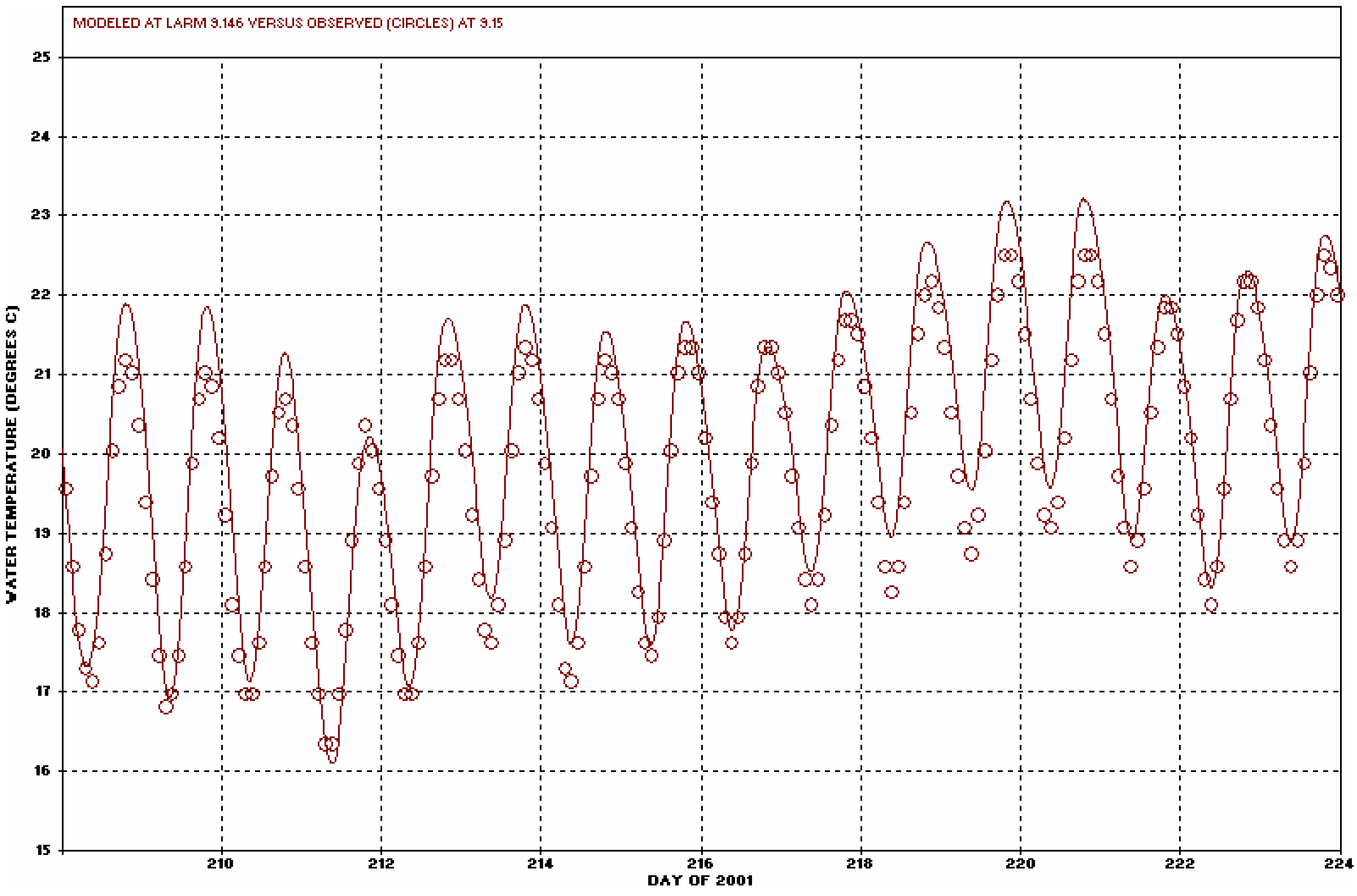


Figure C-6.—Modeled and instantaneous observed water temperature versus time at Watt Avenue Bridge (CDEC sample site AWB – LARM 9.15) from July 27 to August 12, 2001.

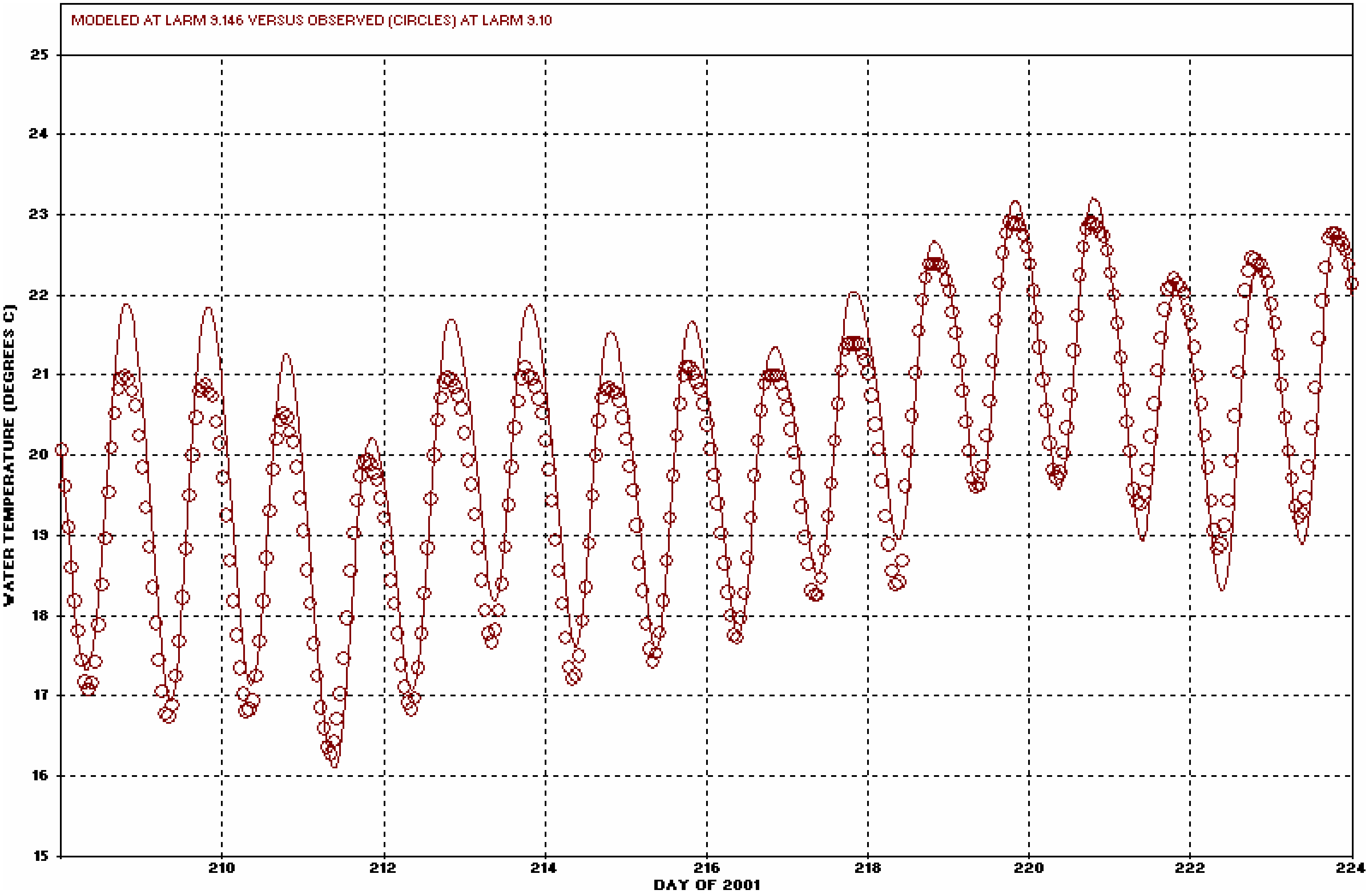


Figure C-7.—Modeled and instantaneous observed water temperature versus time at Watt Avenue Bridge (CDFG sample site – LARM 9.10) from July 27 to August 12, 2001.

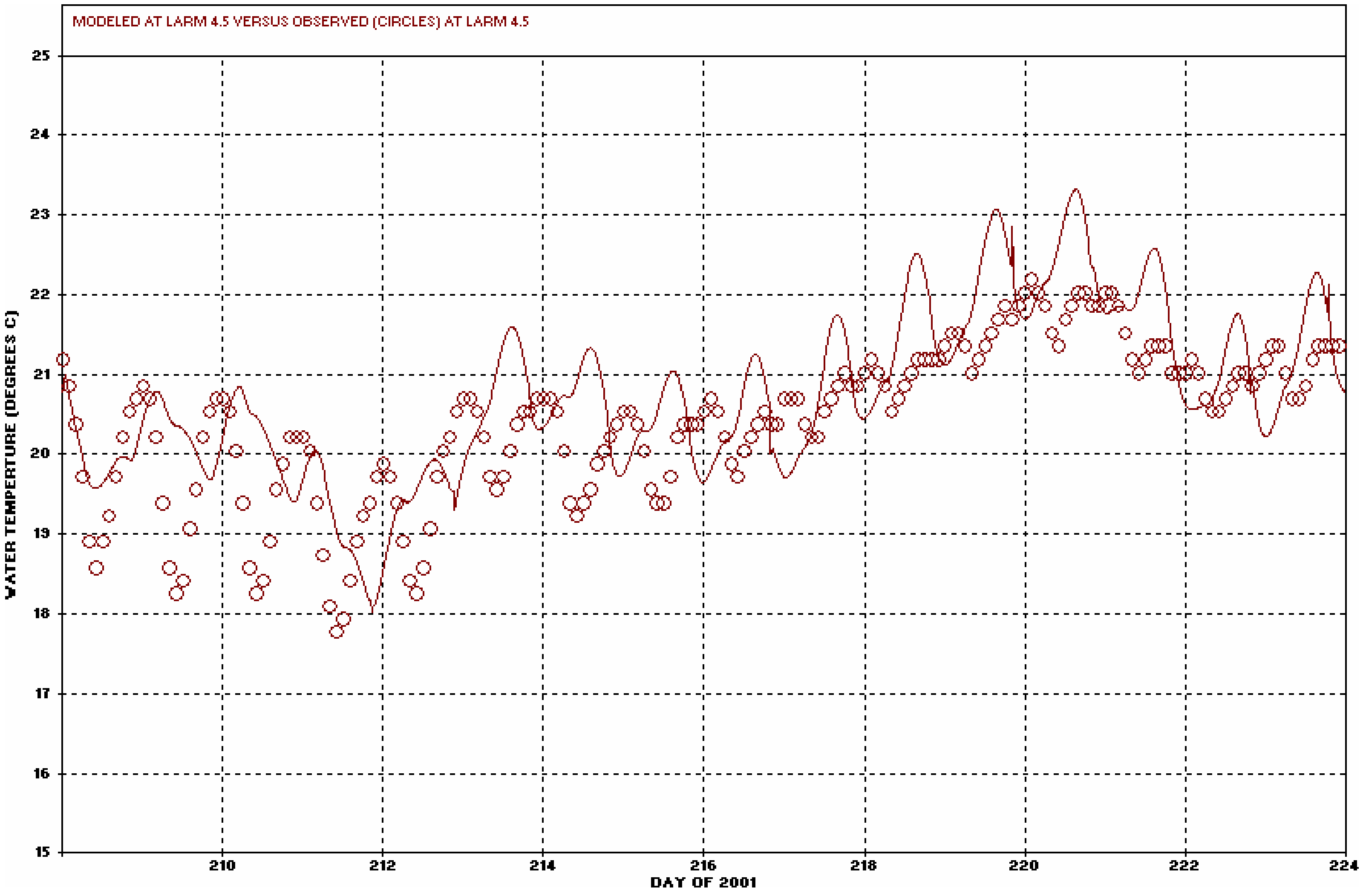


Figure C-8.—Modeled and instantaneous observed water temperature versus time downstream from Paradise Beach (CDFG sample site – LARM 4.5) from July 27 to August 12, 2001.

Appendix D: Steelhead and Salmon Temperature and Flow Criteria

Nimbus Dam tailwater is managed for many fish species. However, the primary focus is to increase and maintain viable populations of naturally spawning fall-run Chinook (king) salmon and steelhead (anadromous rainbow trout) (Water Forum FISH Plan, 2001). Reclamation (1971) summarized the lower American River fishery as follows:

> The lower American River supports about 40 species of fish, about half of which are game fish. Of particular importance are the anadromous fish species: Chinook salmon, steelhead trout, striped bass, and American shad. The fall run of Chinook salmon is presently the most important, even though more angling is done for steelhead, American shad, and rainbow trout. This is because Chinook salmon, in addition to providing a river sport fishery, also provides a substantial contribution to the ocean sport fishery and the commercial fishery.
>
> Nimbus Salmon and Steelhead Hatchery, constructed as a mitigation feature of the Folsom Unit, Central Valley Project, was completed by the Bureau of Reclamation in 1955.

Steelhead in the lower American River are listed as threatened pursuant to the Federal Endangered Species Act (ESA) and the National Marine Fisheries Service (NMFS) has imposed temperature requirements in the LAR from June through October to protect rearing juvenile steelhead (NMFS, 2004). A species, subspecies, or population is considered endangered if it is in danger of extinction throughout all or a significant portion of its range. A species, subspecies or population is considered threatened if it is likely to become an endangered species within the foreseeable future. Subsequent to a significant fish stranding incident, resulting from a spring flood control operation that beached fish under receding flow conditions, the Bureau of Reclamation (Reclamation) was seeking biological input to its operational decisions and convened the American River Operations Work Group (AROG) in 1996 (March 8, 2004, AROG meeting handouts). In 1996, Reclamation entered into an agreement with the California Department of Fish and Game (CDFG) to generate information pertinent to development of flow fluctuation standards for operating the Folsom Project to improve protection of salmon and steelhead using the lower American River (CDFG, November 2001). On March 19, 1998, the California Central Valley steelhead evolutionary significant unit (ESU) was listed as threatened. The effective date of listing Central Valley steelhead was May 18, 1998. The final listing for 10 distinct population segments of West Coast Steelhead was February 6, 2006 (Federal Register, 2006).

The National Marine Fisheries Service (NOAA Fisheries) completed its review of the Central Valley Project (CVP) and State Water Project (SWP) (collectively referred to as the Project) and then transmitted a *Supplemental Biological Opinion* (supplemental BO) *to the September 20, 2002, Spring-Run/Steelhead Operating Criteria and Plan Biological Opinion* (2002 SR/S OCAP) on February 27, 2004. The supplemental BO re-assessed the impacts of Project operations on threatened Central Valley spring-run Chinook salmon and threatened Central Valley steelhead in accordance with section 7 of the Endangered Species Act of 1973 (ESA), as amended (16 U.S.C. 1531 et seq.). The long term CVP Operations Criteria and Plan (OCAP) and a Biological Assessment for the OCAP were issued June 30, 2004. The Biological Opinion (Enclosure 1) and the NOAA Fisheries Essential Habitat Consultation (EFH Enclosure 2) were issued October 22, 2004, and are referred collectively herein as the October 2004 CVP-OCAP BO (NMFS, 2004).

Steelhead and fall-run Chinook salmon production in the lower 23 miles of the American River is affected by warm water temperatures in spawning and rearing habitat during critical freshwater residency life stages. Therefore, managing the temperature of water flowing in the American River from Folsom Lake, through Lake Natoma, through Nimbus Dam, and into the lower American River has become a critical component to restoring healthy anadromous salmonid populations (CCOMWP-Reclamation Agreement, 2003).

California Fish and Game (Brown, 2004) indicated that a steelhead rearing temperature of less than or equal to 18.33 °C (65 °F) and an instantaneous maximum temperature for steelhead of less than or equal to 21.11 °C (70 °F) is desired. However, the lower American River strain of steelhead is more temperature tolerant. A detailed review of the effects of temperature on steelhead and Chinook salmon was done by Myrick and Cech (2001). Myrick and Cech (2001) indicated:

> "Juvenile Chinook salmon and steelhead thermal tolerances are a function of acclimation temperature and exposure time. Fish acclimated to high temperatures tend to show greater heat tolerance than those acclimated to cooler temperatures. Once temperatures reach a chronically lethal level (approximately 25 °C [77 °F]), the time to death decreases with increasing temperature. The chronic upper lethal limit for Central Valley Chinook salmon is approximately 25 °C (77 °F), with higher temperatures (up to 29 °C [84.2 °F]) tolerated for short periods of time. Central Valley steelhead can be expected to show significant mortality at chronic temperatures exceeding 25 °C (77 °F), although they can tolerate temperatures as high as 29.6 °C (85.3 °F) for short periods of time. It is important to note that both species begin to experience serious sub-lethal effects at temperatures below their chronic lethal limits."

A temperature modeling study of the McKay Dam tailwater used a maximum instantaneous temperature of less than or equal to 25 °C (77 °F) (Bender, 2001) for coho (silver) salmon. Therefore, an instantaneous maximum temperature of 25 °C (77 °F) was used for plotting purposes for comparison of all salmon species in general.

Since fall-run Chinook salmon are not protected, thermal tolerances for fall Chinook salmon were not used. However, adult fall-run Chinook enter the American River in August and peak migration occurs in October although a few may show up as early as May. Spawning generally begins in late October or early November and continues through December with a few later fish still spawning in January. (NMFS, enclosure 2, 2004).

For the lower American River, the general temperature criterion is temperature less than 18.33 °C (65 °F) for young and juvenile steelhead and young Chinook salmon rearing. Water temperatures during the summer and early fall months are a major concern, especially for over-summering juvenile steelhead and holding adult Chinook salmon. The Watt Avenue gage is the compliance point for meeting summer water temperatures for steelhead in accordance with the National Marine Fisheries Services biological opinion because water temperatures are cooler upstream during warm months. The Hazel Avenue gage is used in the autumn because water is generally cooler downstream. The Folsom Lake cold water pool is defined as water below 15.56 °C (60 °F) and is a limited resource for maintaining cool downstream temperatures; therefore, temperature criteria change based on flow as shown in table D-1.

Table D-1.—Flow regime and temperature targets

Period	Stream Flows in cfs[1]	Temperature at Watt Avenue[2]
Oct 1 – April 20	2,000 to 2,500/2,625[3]	less than 15.56 ° Celsius (60 F)
April 21 – Sept 30	1,500 to 2,000	less than 18.33 ° Celsius (65 F)

[1] Measured at the U.S. Geological Survey Fair Oaks gage.

[2] Temperature monitored at the Watt Avenue monitoring station, river kilometer 15.1 (mile 9.4).

[3] Optimum spawning conditions for a population of 70,000 Chinook salmon spawners with the lowest percent of redd super-imposition (CDFG, Snider, et al. 2001. *Evaluation of Effects of Flow Fluctuations on the Anadromous Fish Populations in the lower American River. Stream Evaluation Program Technical Report No. 01-2,* California Department of Fish and Game, prepared for the Bureau of Reclamation by California Department of Fish and Game).

The flow and temperature regime shown in table D-1 integrates quantity, duration of flow, and temperature targets to meet the life history needs of Chinook salmon and steelhead. A major concern is satisfying ramping criteria (the rate of increasing or decreasing flows) and temperature needs of salmon and steelhead along with Federal and State laws. Evaluation of the effects of flow fluctuations on the anadromous fish populations in the Lower American River were done by the California Department of Fish and Game for the Bureau of Reclamation (CDFG, Snider, et al., 2001).

A range of temperature target alternatives exists, depending on hydrologic conditions and cold water in storage. A letter dated June 20, 2005, from the Reclamation Central Valley Operations Office to the National Marine Fisheries Service listed four temperature alternatives of 20 °C (68 ^{0}F), 19.4 °C (67 ^{0}F), 18.9 °C (66 ^{0}F), and 18.33 °C (65 ^{0}F) degrees at Watt Avenue Bridge and recommended 18.9 °C (66 ^{0}F) at Watt Avenue Bridge as the most reliable target since the 18.33 °C (65 ^{0}F) alternative had some risk of over-utilization of the available coldwater resource. During 2004, the target at Watt Avenue Bridge was relaxed to 20.56 °C (69 ^{0}F) due to a shortage of coldwater resources. This was an extreme case during a drought. Therefore, the range of 18.33 °C to 20 °C (65 ^{0}F to 68 ^{0}F) was used for tailwater temperature sensitivity analysis for this temperature modeling study.

Dave Robinson in a June 3, 2005, email suggested using the NOAA Fisheries NMFS October 2004 BO (NMFS, Enclosure 1, 2004) as the basis for the comparison criteria used on plots. The BO states on page 223, under D, Terms and Conditions – Formal Consultation bullet 9, American River Division.

> "The water temperature control plan will give a preference to utilization of available cold water resources and Folsom Dam shutter management for the protection of steelhead by targeting 20 °C (68 ^{0}F) at Watt Avenue Bridge, before assessing cold water reserves available for the fall. A target of 20 °C (68 ^{0}F) at Watt Avenue will likely provide a limited section of habitat between Nimbus Dam and Watt Avenue in the preferred 18.33 °C (65 ^{0}F) range without seasonally exhausting the limited cold water available. If sufficient cold water availability exists to seasonally provide 20 °C (68 ^{0}F) at Watt Avenue, then and only then would the potential to reserve the last shutter pull for the fall season exist."

While wandering above the temperature operational target of 18.3 ^{0}C (65 ^{0}F) and the temperature threshold target of 20.0 ^{0}C (68 ^{0}F), conditions would provide for short-term survival; however, the associated stress would disrupt normal metabolic functions, reduce or cease feeding behavior, and affect growth and weight gain. Salmon may be able to tolerate short periods of exposure to warm conditions at the expense of normal growth and behavior until habitat conditions improve and normal functions and activities resume. Alternatively, cold water species of fish may seek out cool thermal refugia in small areas of the Nimbus Dam tailwater, such as at the bottom of slightly stratified pools. Due to crowding, salmon in cool thermal refugia may be more susceptible to predation, disease, and other factors affecting acute and chronic survival.

Although not modeled, conditions during 2004 were indicative of warm releases from Folsom Dam even when the bottom penstock shutters were raised completely. Warmer releases that remained within tolerance limits increased biological productivity and fish growth rates due to additional forage. However, warmer temperatures also increased the likelihood of infectious diseases for cold water species. American River steelhead were detected with more fish disease (such as Rosy Anus) during August and September 2004 likely due to warm water temperatures in the high 60s and lower 70s °F (Bacher, 2005). During this period, the temperature target at Watt Avenue Bridge was increased from 18.33 °C (65 °F) to 20.56 °C (69 °F) because there was not sufficient cold water in Folsom Lake to meet temperature at 18.33 °C (65 °F). Therefore, the temperature and flow criteria discussed in this appendix should be considered to be guidelines rather than inflexible criteria.

Appendix E: Completely Mixed Flow-Weighted Temperatures

The lower American River temperature conditions downstream from Nimbus Dam are extremely variable. Therefore, Reclamation conducted a sensitivity analysis using completely-mixed flow-weighted temperature calculations in a spreadsheet to approximate the many combinations of mixed temperatures just below the confluence of Sacramento River and the lower American River. Though immediate complete mixing just below the confluence is not realistic, this method compares the sensitivity of mixed water temperature below the confluence to a wide range of changes in flows and temperatures without running a computationally intensive model.

The flows in cfs and temperatures in °C shown in table E-1 can be used to compare mixed temperature just downstream from the confluence of the Sacramento River and lower American River under various combinations of lower American River flows and temperatures at the confluence. The first block of numbers is for lower American River flow of 2,000 cfs and lower American River temperature at the confluence of 20 °C (68 °F). The second block shows the same conditions for temperatures of 22 °C (71.6 °F). The third block of numbers shows conditions with lower American River flow of 1,500 cfs and temperature of 20 °C (68 °F). Column headings indicate Sacramento River temperature just upstream of the confluence, while row labels indicate Sacramento River flows in cfs.

For example, flows of 2,000 cfs at a temperature of 20 °C (68 °F) at the downstream end of the lower American River and 20,000 cfs at 21 °C (69.8 °F) from the upstream Sacramento River mix to 20.9 °C (69.6 °F). If lower American River temperature increases from 20 °C to 22 °C (68 °F to 71.6 °F), the mixed temperature increases to 21.1 °C (70 °F). If the lower American River flow decreases to 1,500 cfs from 2,000 cfs, the mixed temperature remains near 20.9 °C (69.6 °F). This simple example indicates that a 2 °C (3.6 °F) increase in Nimbus Dam release temperature has a greater warming effect on Sacramento temperature than a 500 cfs decrease in flow from Nimbus Dam has on warming due to the much larger Sacramento River flow. Therefore, the American River has little effect on the Sacramento River temperatures downstream from the confluence.

Reclamation also conducted a sensitivity analysis to approximate simple two-layer selective withdrawal mixing from the epilimnion and hypolimnion of Lake Natoma with a similar spreadsheet layout.

The flows in cfs and temperatures in °C in table E-2 can be used to compare mixed temperature under various flows or temperatures released from the hypolimnion and epilimnion. The first block of numbers is for hypolimnetic release of 1,000 cfs and a hypolimnetic release temperature of 10 °C (50 °F). The second block shows the same conditions for hypolimnetic release temperatures at 15 °C (59 °F). The third block of numbers shows conditions with hypolimnetic release of 500 cfs and hypolimnetic release temperature of 10 °C (50 °F). Column headings indicate epilimnetic release temperature just upstream of the confluence, and row labels indicate epilimnetic releases in cfs.

For example, 1,000 cfs released at a temperature of 10 °C (50 °F) from the hypolimnion and 1,000 cfs released at 18 °C (64.4 °F) from the epilimnion mix to 14 °C (57.2 °F). If hypolimnetic temperature increases from 10 °C to 15 °C (50 °F to 59 °F), the mixed temperature increases to 16.5 °C (61.7 °F). If the hypolimnetic flow at 10 °C (50 °F) is reduced to 500 cfs from 1,000 cfs while the epilimnetic release at 18 °C (64.4 °F) is increased to 1,500 cfs, the mixed temperature is 16 °C (60.8 °F). This simple example indicates that both increases in hypolimnetic temperature and changes in the proportions of flow from the epilimnion and hypolimnion affect mixed release temperature. This indicates that selective withdrawal at Nimbus Dam could have potential to cool releases during critical warm periods.

Table E1.—Completely-mixed flow-weighted temperatures (°C) downstream from the confluence of lower American River and the Sacramento River

LAR flow & temp ->		2000	20				
SR q\T	12C/53.6F	15C/59.0F	18C/64.4F	21C/69.8F	24C/75.2F	27C/80.6F	30C/86.0F
cfs\C	12	15	18	21	24	27	30
6000	14.0	16.3	18.5	20.8	23.0	25.3	27.5
8000	13.6	16.0	18.4	20.8	23.2	25.6	28.0
10000	13.3	15.8	18.3	20.8	23.3	25.8	28.3
12000	13.1	15.7	18.3	20.9	23.4	26.0	28.6
14000	13.0	15.6	18.3	20.9	23.5	26.1	28.8
16000	12.9	15.6	18.2	20.9	23.6	26.2	28.9
18000	12.8	15.5	18.2	20.9	23.6	26.3	29.0
20000	12.7	15.5	18.2	20.9	23.6	26.4	29.1

LAR flow & temp ->		2000	22				
SR q\T	12C/53.6F	15C/59.0F	18C/64.4F	21C/69.8F	24C/75.2F	27C/80.6F	30C/86.0F
cfs\C	12	15	18	21	24	27	30
6000	14.5	16.8	19.0	21.3	23.5	25.8	28.0
8000	14.0	16.4	18.8	21.2	23.6	26.0	28.4
10000	13.7	16.2	18.7	21.2	23.7	26.2	28.7
12000	13.4	16.0	18.6	21.1	23.7	26.3	28.9
14000	13.3	15.9	18.5	21.1	23.8	26.4	29.0
16000	13.1	15.8	18.4	21.1	23.8	26.4	29.1
18000	13.0	15.7	18.4	21.1	23.8	26.5	29.2
20000	12.9	15.6	18.4	21.1	23.8	26.5	29.3

LAR flow & temp ->		1500	20				
SR q\T	12C/53.6F	15C/59.0F	18C/64.4F	21C/69.8F	24C/75.2F	27C/80.6F	30C/86.0F
cfs\C	12	15	18	21	24	27	30
6000	13.6	16.0	18.4	20.8	23.2	25.6	28.0
8000	13.3	15.8	18.3	20.8	23.4	25.9	28.4
10000	13.0	15.7	18.3	20.9	23.5	26.1	28.7
12000	12.9	15.6	18.2	20.9	23.6	26.2	28.9
14000	12.8	15.5	18.2	20.9	23.6	26.3	29.0
16000	12.7	15.4	18.2	20.9	23.7	26.4	29.1
18000	12.6	15.4	18.2	20.9	23.7	26.5	29.2
20000	12.6	15.3	18.1	20.9	23.7	26.5	29.3

SR = Sacramento River

Assumptions: Drought Lateral Inflow Conditions and Sunny Day Meteorology

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Table E2.—Completely-mixed flow-weighted two-layer selective withdrawal Temperatures (°C) for Lake Natoma

hypo. rel. flow&temp->		1000	10				
epi. q\T	9C/48.2F	12C/53.6F	15C/59.0F	18C/64.4F	21C/69.8F	24C/75.2F	27C/80.6F
cfs\C	9	12	15	18	21	24	27
250	9.8	10.4	11.0	11.6	12.2	12.8	13.4
500	9.7	10.7	11.7	12.7	13.7	14.7	15.7
750	9.6	10.9	12.1	13.4	14.7	16.0	17.3
1000	9.5	11.0	12.5	14.0	15.5	17.0	18.5
1250	9.4	11.1	12.8	14.4	16.1	17.8	19.4
1500	9.4	11.2	13.0	14.8	16.6	18.4	20.2
1750	9.4	11.3	13.2	15.1	17.0	18.9	20.8
2000	9.3	11.3	13.3	15.3	17.3	19.3	21.3

hypo. rel. flow&temp->		1000	15				
epi. q\T	9C/48.2F	12C/53.6F	15C/59.0F	18C/64.4F	21C/69.8F	24C/75.2F	27C/80.6F
cfs\C	9	12	15	18	21	24	27
250	13.8	14.4	15.0	15.6	16.2	16.8	17.4
500	13.0	14.0	15.0	16.0	17.0	18.0	19.0
750	12.4	13.7	15.0	16.3	17.6	18.9	20.1
1000	12.0	13.5	15.0	16.5	18.0	19.5	21.0
1250	11.7	13.3	15.0	16.7	18.3	20.0	21.7
1500	11.4	13.2	15.0	16.8	18.6	20.4	22.2
1750	11.2	13.1	15.0	16.9	18.8	20.7	22.6
2000	11.0	13.0	15.0	17.0	19.0	21.0	23.0

hypo. rel. flow&temp->		500	10				
epi. q\T	9C/48.2F	12C/53.6F	15C/59.0F	18C/64.4F	21C/69.8F	24C/75.2F	27C/80.6F
cfs\C	9	12	15	18	21	24	27
250	9.7	10.7	11.7	12.7	13.7	14.7	15.7
500	9.5	11.0	12.5	14.0	15.5	17.0	18.5
750	9.4	11.2	13.0	14.8	16.6	18.4	20.2
1000	9.3	11.3	13.3	15.3	17.3	19.3	21.3
1250	9.3	11.4	13.6	15.7	17.9	20.0	22.1
1500	9.3	11.5	13.8	16.0	18.3	20.5	22.8
1750	9.2	11.6	13.9	16.2	18.6	20.9	23.2
2000	9.2	11.6	14.0	16.4	18.8	21.2	23.6

epi. = epilimnion   hypo. = hypolimnion

Assumption: Withdrawal layer thickness does not change over time.

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