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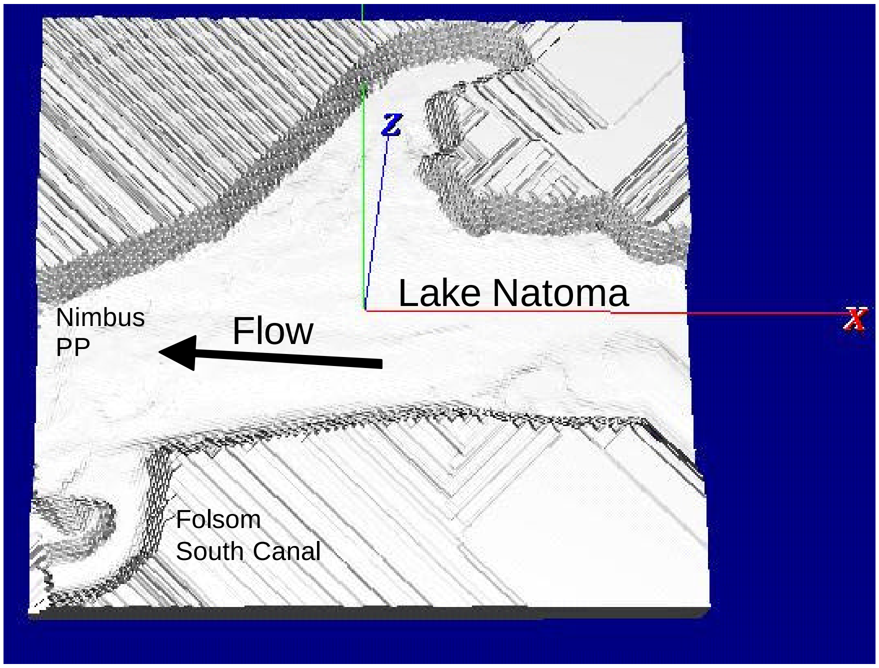
Hydraulic Laboratory Report HL-2005-02

Lake Natoma Temperature Curtain and Channel Modification Study, 2001- 2002

Central Valley Project, Central California Area Office



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Water Resources Research Laboratory
Denver, Colorado

September 2005

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
08-11-2005

2. REPORT TYPE
Technical

3. DATES COVERED *(From - To)*
March 15, 2002 - January 31, 2003

4. TITLE AND SUBTITLE
Lake Natoma Temperature Curtain and Channel Modification Study, 2001-2002.

5a. CONTRACT NUMBER
SAFCA Contract No. 463

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Vermeyen, Tracy

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Department of the Interior, Bureau of Reclamation
Water Resources Research Laboratory
PO Box 25007
Denver, CO 80225

8. PERFORMING ORGANIZATION REPORT NUMBER
HL-2005-02

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
Central California Area Office
7794 Folsom Dam Road
Folsom, CA 95630

Sacramento Area Flood Control Agency
1007 7th Street, 5th Floor
Sacramento, CA 95814

10. SPONSOR/MONITOR'S ACRONYM(S)
SAFCA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
n/a

12. DISTRIBUTION/AVAILABILITY STATEMENT
Available from:
National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield, Virginia 22161
http://www.ntis.gov

13. SUPPLEMENTARY NOTES
None

14. ABSTRACT

This report describes, in a conceptual way, the hydrodynamics of cold water movement in Lake Natoma and how it impacts water temperatures in the lower American River. Selective withdrawal from Folsom Lake allows the cool water releases from the reservoir to be delivered to the lower American River. Unfortunately, the temperature of the Folsom releases can increase up to 3 °F because of mixing with warmer water stored in Lake Natoma. Mixing and the associated temperature gain in Lake Natoma contribute to releases from Nimbus Dam that are too warm for anadromous fish species in the lower American River. The purpose of this study was to evaluate the potential of: 1) Temperature curtain(s) within Lake Natoma to control mixing and reduce temperatures in the lower American River, 2) Channel modifications within Lake Natoma to reduce mixing in shallow areas and improve temperatures in the lower American River, and 3) Modifying the Nimbus Powerplant intakes to eliminate the surface oriented withdrawal from Lake Natoma.

15. SUBJECT TERMS
Selective withdrawal, temperature curtains, channel modifications, computational fluid dynamics modeling, reservoir stratification, hydropower, powerplants American River, Lake Natoma, Folsom Lake, mixing, thermal pollution

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
UL	UL	UL	SAR		Clifford A. Pugh

19b. TELEPHONE NUMBER *(Include area code)*
303-445-2151

Hydraulic Laboratory Report HL-2005-02

Lake Natoma Temperature Curtain and Channel Modification Study, 2001- 2002

Central Valley Project, Central California Area Office

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Acknowledgments

This project was managed by Rod Hall (USBR, retired) and Brian Deason from Reclamation's Central California Area Office. This report was peer reviewed by Merlynn Bender from Reclamation's Water Quality and Land Suitability Group. Rod Hall, Brian Deason, and Tim Washburn (Sacramento Area Flood Control Agency) also reviewed the report and provided many useful suggestions. Jim Higgs was responsible for the computational fluid dynamics modeling, and Connie DeMoyer performed the temperature data analysis. Bob Whitford assisted by supplying a boat and operators from the California State University-Sacramento Aquatic Center.

Hydraulic Laboratory Reports

The Hydraulic Laboratory Report series is produced by the Bureau of Reclamation's Water Resources Research Laboratory (Mail Code D-8560), PO Box 25007, Denver, Colorado 80225-0007. At the time of publication, this report was also made available online at the following website: <http://www.usbr.gov/pmts/hydraulics_lab/pubs/HL/HL-2005-02.pdf>.

Disclaimer

Cover figure: This figure is the Flow-3D stereolithography representation of the forebay bathymetry at Nimbus Dam.

This project was performed by Reclamation's Technical Service Center for the Central California Area Office and the Sacramento Area Flood Control Agency under a cost-sharing agreement (SAFCA Contract No. 463).

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Abstract

This report describes, in a conceptual way, the hydrodynamics of cold water movement in Lake Natoma and how it impacts water temperatures in the lower American River. From late spring through early autumn, elevated water temperatures in the lower American River diminish habitat for fall-run Chinook salmon and steelhead. Temperature control shutters on the penstock intakes at Folsom Dam are used to selectively withdrawal water from Folsom Lake. Selective withdrawal allows the cool water in the bottom of Folsom Reservoir to be conserved and slowly released throughout the summer and fall to manage temperatures in the lower American River. Unfortunately, the temperature of the Folsom releases can increase up to 3 °F because of mixing with warmer water stored in Lake Natoma. There are many complicating factors, which makes studying Lake Natoma mixing processes a challenge. Peaking powerplant operations at Folsom create rapid fluctuations to Lake Natoma inflows. For example, when demand for electricity is high, Folsom releases large volumes of cool water for 6 to 8 hours. This cold water flows along the bottom of Lake Natoma because it is denser than the warm water. During the rest of the day, very little water is release from Folsom powerplant. Conversely, warm surface water is released from Nimbus powerplant at a constant flow rate all day long. Powerplant operations result in a 2- to 3-foot change in reservoir level each day and generate significant mixing between the warm water in Lake Natoma and cool water from Folsom Reservoir. The effect of these different hydropower operations is a daily draining and filling of Lake Natoma, which creates a dynamic mixing process. Mixing and the associated temperature gain in Lake Natoma contribute to releases from Nimbus Dam that are too warm for anadromous fish species in the lower American River.

Based on a fundamental understanding of how cold water moves through Lake Natoma and the tools developed during this study, the goal of this study was to evaluate the potential of:

- Temperature curtain(s) within Lake Natoma to control mixing and improve temperatures in the lower American River.

- Channel modifications within Lake Natoma to reduce mixing in shallow areas and improve temperatures in the lower American River.

- Modifying the Nimbus Powerplant intakes to eliminate the surface oriented withdrawal from Lake Natoma.

This report describes data collection, analysis, and techniques used to evaluate temperature curtain and channel modification alternatives within Lake Natoma. A channel modification alternative was proposed that involved estimating the benefits of channel dredging in a shallow area near the reservoir headwaters.

Three temperature curtain alternatives were proposed for evaluation, including:

- a curtain located where cool water from Folsom plunges below the warm water in Lake Natoma
- a curtain that is perpendicular to the north bank of the lake, approximately 500 feet upstream of Nimbus Dam, and angles back to the dam south of the powerhouse
- a curtain that spans the entire lake approximately 1,000 feet upstream of Nimbus Dam.

Alternatives were evaluated for effectiveness based on: (1) temperature differences between sampling sites, (2) travel times between sampling sites, (3) average speed of water between sites, (4) reservoir stratification animations, and (5) computational fluid dynamics modeling. Additional analyses were performed to evaluate the benefits of completely removing the debris wall at the powerhouse intake and lowering the debris wall to El. 90 feet mean sea level.

Executive Summary

A large amount of reservoir operations data and temperature profiles was collected and analyzed to quantify the hydrodynamic and thermal characteristics of flows released from Folsom Lake and moving through Lake Natoma. Analysis of temperature profile data collected in 2001 showed that there is approximately a 1- to 3.0-degree Fahrenheit (°F) temperature gain as water flows through Lake Natoma. Based on this data set, 3.0 °F is the maximum temperature reduction that can be expected if the Folsom releases are conveyed through Lake Natoma with no temperature gain. Realistically, a temperature reduction of less than a degree Fahrenheit is more likely for the current reservoir operations.

Two computational fluid dynamics (CFD) models were constructed and modeled with FLOW-3D to evaluate the feasibility of several concepts that might reduce release water temperatures from Nimbus Powerplant. An analysis of the data and modeling results has revealed that Lake Natoma is a very dynamic reservoir that is too large to be effectively modeled using the FLOW-3D software on a personal computer. For this preliminary study, Flow 3D was used to describe two brief snapshots of hydraulic and thermal conditions in Lake Natoma. While the FLOW-3D model runs indicated there was little to no reduction in Nimbus Powerplant release temperatures, there may be other combinations of alternatives that could reduce the temperature gain in Lake Natoma.

After a review of the modeling results, it was apparent that too many simplifying assumptions were necessary to make the FLOW-3D model a practical tool for evaluating the long-term impacts of structural and operational modifications proposed to deliver cooler water to the lower American River. In addition, Flow-3D modeling results presented in this report should be considered provisional because of concerns about the accuracy of model boundary conditions and incomplete model development resulting from budgetary constraints. This modeling was valuable as a proof-of-concept exercise, but additional model development will be necessary to produce reliable predictions.

It became apparent during the course of this study that a two-dimensional (2D) reservoir water quality model would be necessary to identify the most beneficial alternative(s) for the time period that Lake Natoma is thermally stratified. A 2D model should be able to handle the complex reservoir operations and to simulate an entire year of reservoir operations. Furthermore, a 2D model should be able to model the upstream curtain concept and various amounts of channel dredging. Lake Natoma appears to be well suited for 2D modeling because it is a long and narrow water body. However, it is unlikely that a 2D reservoir model would have the spatial resolution necessary to accurately design and locate a close-in intake curtain or resolve the effects of near-field power intake modifications associated with dredging or removal of the existing debris wall surrounding Nimbus Powerplant. To help answer these questions, FLOW-3D can be used in a similar manner as it was used in this study to fine tune the design and effectiveness of the proposed alternatives or a combination thereof.

Given the inconclusive results of this preliminary modeling effort, it is recommended that 2D reservoir water quality models for Lake Natoma and Folsom Lake be developed, in tandem with the existing CFD models, to further evaluate the effectiveness of proposed structural and operational modifications to the Folsom and Lake Natoma reservoir system. As a result, a proposal was prepared and submitted to CALFED Bay-Delta Program to develop the models necessary to evaluate the best alternatives, both operational and structural, for reducing water temperatures in the lower American River.

Background

The American River Division of the Central Valley Project was authorized by Congress to provide water for irrigation, municipal and industrial use, hydroelectric power, and recreation. Flood control is provided through a system of dams, canals, and powerplants. The division consists of the Folsom and Sly Park Units, both authorized in 1949, and the Auburn-Folsom South Unit, authorized in 1965. There are six authorized purposes for the Folsom Unit: flood control, water supply, hydroelectric power, water quality, fish and wildlife, and recreation. The Folsom Unit consists of Folsom Dam, Lake, and Powerplant; Nimbus Dam and Powerplant; and Lake Natoma, all of which are located on the American River.

Folsom Dam and Folsom Lake

Folsom Dam is located on the American River upstream and approximately 20 miles northeast of Sacramento, California. The dam was constructed between the years of 1948 and 1956 by the U.S. Army Corps of Engineers and, upon completion, was transferred to the Bureau of Reclamation for coordinated operation as part of the Central Valley Project. The dam has a concrete gravity main river section with a structural height of 340 feet and a crest length of 1,400 feet. The crest of the dam is at elevation (El.) 480.5 (268 feet above the riverbed) and accommodates a 30-foot-wide roadway.

Folsom Lake has about 975,000 acre-feet capacity to the top of active conservation level, El. 466 feet. The area-capacity table, as of January 1, 1992, shows a capacity of 974,460 acre-feet at water surface El. 466.

Three 15-foot-diameter steel penstocks deliver water to the turbines in the powerplant. The centerline of each penstock intake is at El. 307.0 feet, and the minimum power pool is at El. 328.5 feet.

Reinforced concrete trashrack structures with steel trashracks protect each penstock intake. The top of the trashrack structure is at El. 428.0 feet. Steel trashracks, located in five bays around the structure, extend the full height of the trashrack structure. In the late 1960s, Reclamation designed a modification to the trashrack structures to permit selective withdrawal from higher elevations in the reservoir. Steel guides were attached to the existing trashrack panels, and 45 steel shutter panels (9 per bay), operated by the gantry crane, were installed in these guides to select the level of withdrawal from the reservoir. Because the shutters were installed upstream of the trashracks, they experience problems with debris accumulation.

Modernization of the temperature shutters on the penstock intakes at Folsom Dam has been identified as a potential solution to improve downstream water temperatures in the lower American River. Feasibility studies conducted in 2001 and 2002 identified several alternatives to the existing temperature shutter system.

Nimbus Dam and Lake Natoma

Nimbus Dam is located on the American River, 7 miles downstream from Folsom Dam. Nimbus Dam, which created Lake Natoma, was constructed to reregulate the releases from the Folsom Powerplant. The dam, completed in 1955, is a concrete gravity structure with a gated control overflow section. The dam is 87 feet high with a crest length of 1,093 feet. Eighteen radial gates, each 40 feet by 24 feet, control the flows. The total volume of material used in the dam is 121,100 cubic yards. Nimbus Dam and Powerplant were completed in July 1955 and are operated by Reclamation. Nimbus Dam created Lake Natoma, with a capacity of 8,760 acre-feet and a surface area of 540 acres. Lake Natoma is a shallow reservoir with an average depth of 16 feet.

Nimbus Powerplant was constructed and is operated by Reclamation. The 13.5-megawatt (MW) powerplant is located on the right abutment of Nimbus Dam, on the north side of the river. There are two generators, each with a capacity of 7,763 kilowatts. Water is supplied to two 9,400-horsepower turbines that drive the generators through six 46.5-foot-long by 13.75-foot by 15.95-foot penstocks. The penstock intakes are surrounded by an upstream apron wall that extends from El. 80 feet to El. 105 feet. This apron was constructed to keep sediment and other submerged debris from entering the penstocks.

Nimbus Salmon and Steelhead Hatchery

The Nimbus Salmon and Steelhead Hatchery is mitigation for the loss of salmon and steelhead spawning and rearing habitat as a result of the construction of Nimbus and Folsom Dams. The hatchery is located approximately a quarter of a mile downstream of Nimbus Dam on the left (south) side of the river. It is operated by the State of California with Reclamation funds. Construction began in April 1955 and was completed October 17, 1955. The Nimbus Salmon and Steelhead Hatchery has a capacity of 30,000,000 eggs. Water for the hatchery is supplied through a 1,415-foot-long, 60-inch-diameter concrete pipeline. The pipeline runs from the left abutment of Nimbus Dam to the hatchery.

Project Objectives

Based on a fundamental understanding of how cold water moves through Lake Natoma, a scoping study was initiated to collect data necessary to begin the evaluation of the potential of temperature improvement concepts developed in a Function Analysis Workshop on lower American River Water Temperature Improvement Study (Bureau of Reclamation, 2001). While several recommended improvements involved structural changes at Folsom Dam, the primary focus of this study was on temperature improvements suggested for Lake Natoma. The two concepts recommended for further consideration were:

- Install temperature curtain(s) within Lake Natoma to control mixing and improve temperatures in the lower American River.

- Channel modifications within Lake Natoma to reduce mixing in shallow areas and improve temperatures in the lower American River.

This report will summarize data collection, analyses, and modeling techniques used to evaluate the effectiveness of proposed temperature curtain and channel modification alternatives within Lake Natoma.

Midway through the project, the project manager modified the scope of work to concentrate the modeling efforts on temperature curtains and removing the existing apron wall surrounding the penstock intakes. This management decision was based on unexpected problems encountered while developing the Flow-3D model to evaluate the effectiveness of channel modifications in Lake Natoma.

Project Location

The project location for the modeling study is in the Sacramento Region, Ecological Management Zone 9.2; with geographical coordinates N38° 38’ W121° 11’. The site encompasses Lake Natoma and Folsom Lake in Sacramento County. Considered part of the lower American River Watershed (LARW), Lake Natoma is located approximately 23 miles upstream of the river’s confluence with the Sacramento River. The LARW originates in California’s central Sierra Nevada. The North and Middle Forks of the American River join near the city of Auburn before emptying into Folsom Lake. The South Fork of the American River also discharges into Folsom Lake, where flows are impounded by Folsom

Dam. Folsom Dam releases enter Lake Natoma, and are impounded by Nimbus Dam (located approximately 7 miles downstream from Folsom Dam) before being discharged into the lower American River.

The lower American River includes 23 river miles (RM) between Nimbus Dam and the river's confluence with the Sacramento River. Flood protection levees begin at the confluence with the Sacramento River and extend upstream to approximately 14 RM on the north bank and 11 RM on the south bank.

Temperature Curtains

One of the proposed temperature improvements was to install temperature curtains within Lake Natoma to control mixing and improve water temperatures in the lower American River. Temperature curtains are surface-suspended, flexible barriers that can be used in reservoirs to limit mixing or provide selective withdrawal for a water intake. Temperature curtains have been shown to be an effective means of reducing downstream water temperatures at Lewiston and Whiskeytown Lakes in northern California (Vermeyen, 1997). Figure 1 is a schematic of a temperature control curtain and its components as installed in Whiskeytown Reservoir.

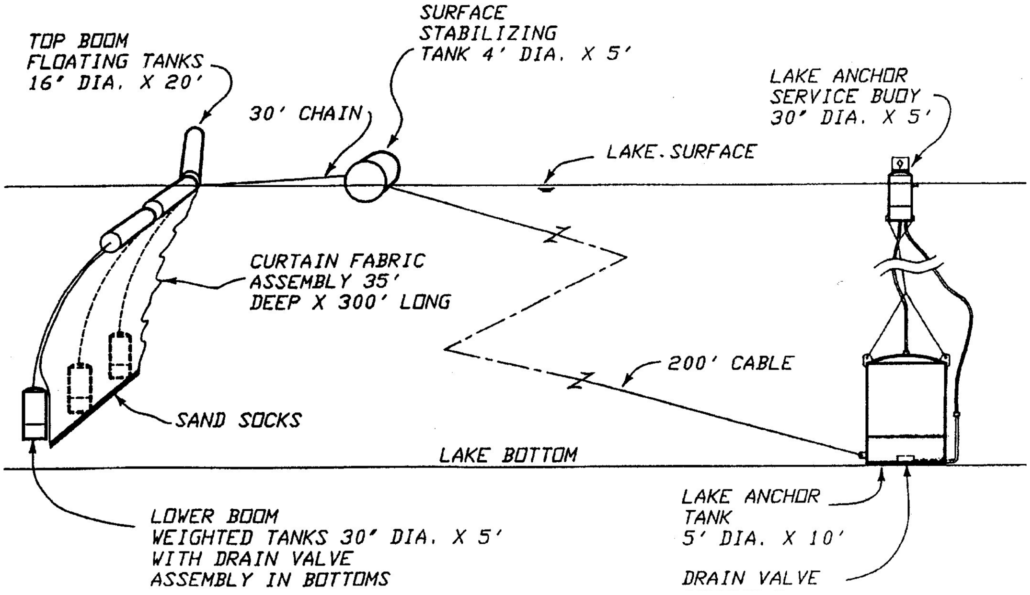

Figure 1. Schematic of the curtain design used at Whiskeytown Reservoir, California.

Shutter System Description

In the late 1960s, Reclamation designed a modification to the Folsom Dam trashrack structures to permit withdrawal from higher elevations in the reservoir. In 1967, Reclamation installed temperature shutters on all three penstock trashrack structures at Folsom Dam. The top of the trashrack structure is at El. 428.0 feet. Steel trashracks, located in five bays around the structure, extend the full height of the trashrack structure. Steel guides were attached to the existing trashrack panels, and 45 steel shutter panels (9 per bay) were installed in these guides to select the level of withdrawal from the reservoir (figure 2). Shutter panels are moved using a gantry crane. A steel superstructure was constructed on top of the concrete trashrack structure up to El. 480.5. The superstructure supports the shutter guides and an operating deck. The temperature shutter panels are 7 feet wide by 13 feet high. In late 1995, the shutters were reconfigured into a 4-2-3 series. The bottom four panels were ganged together, the middle set has two ganged panels, and the top set has three panels ganged together (figure 3). Shutter panels are raised or lowered to provide a flow opening.

Initially, the top two rows of shutters were operated independently and the seven lower rows of shutters were operated as a single unit. Currently, the top three panels, the middle two panels, and the bottom four panels are moved as three separate units to provide better temperature release control. The shutters must be opened a minimum of 27 feet to prevent vortex formation. A three-person crew is required to manually change the temperature shutter settings.

The shutters can currently be set at four operating elevations: (1) El. 401(all shutters lowered), (2) El. 362 (upper shutters raised), (3) El. 331 (middle shutters raised), and (4) El. 284 (bottom shutters raised). Although the trashrack sill El. is 284 feet, the invert of the penstock intake is at El. 299.25 feet. If releases through the shutter system do not meet river temperature guidelines, project operators can open the lower river outlets at El. 205.5 feet) to access colder water.

Figure 2. Photograph of Folsom shutter guides and panels.

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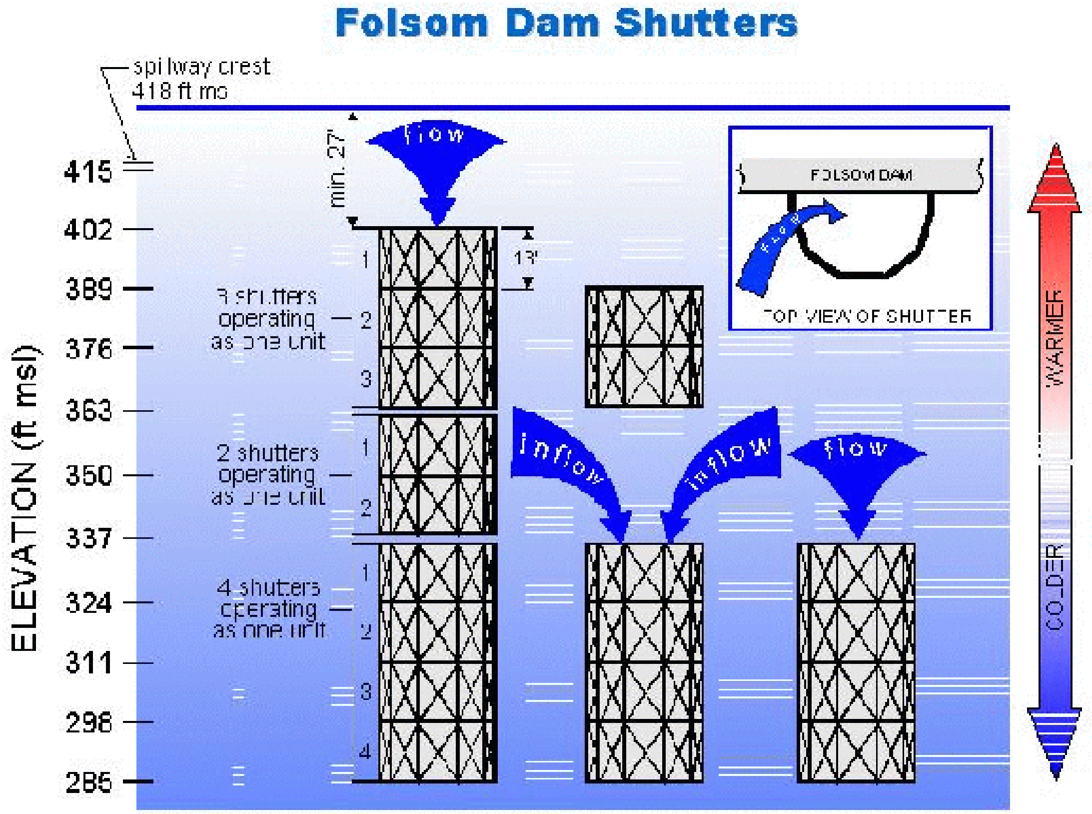

Figure 3. Schematic of the 1995 Folsom temperature shutter configuration. The shutter panels are grouped in a 4-2-3 series for managing release temperatures

However, this operation has the undesirable consequence of bypassing the powerplant.

Reclamation has used temperature curtains to minimize interfacial shear mixing that occurs in the Whiskeytown plunge zone. The first curtain at Lake Natoma is proposed to limit mixing at Folsom inflow's plunge zone. A second curtain is being considered near the penstock intakes at Nimbus Dam. Temperature curtains can be positioned around intake structures to control the withdrawal elevation. At Nimbus Dam, a curtain around the penstock intakes would be designed to exclude warm surface water and to pull cool water under the curtain and create a cool water area behind the curtain. This cool water could then be released through the turbines to the lower American River. Evaluating the potential effectiveness of temperature curtains in Lake Natoma and determining their location were important objectives for this study.

Summary of Data Collection

Folsom Forebay Temperature Profiles

Reservoir temperature profiles were collected in the forebay of Folsom Dam in 2001 to quantify the amount of cold water storage. This data is important for any study on lower American River temperatures because Folsom Lake is the major source of inflow to the river.

Folsom Dam forebay temperature profiles were collected every 15 minutes from May 8 to November 28, 2001, using a series of Onset Stowaway® Tidbit® temperature loggers. The Onset temperature loggers have an uncertainty of ± 0.4 °F. Positions of temperature loggers in the water column are listed below in Table 1.

Table 1. Location of temperature loggers

Onset temperature logger ID	Depth (feet)
FD01	5
FD02	15
FD03	25
FD04	35
FD05	45
FD06	55
FD07	70
FD08	90
FD09	110
FD10	130
FD11	150
FD12	170
FD13	200
FD14	225

The temperature profiling string was attached to the log boom near the deepest part of the forebay. This profiling site was chosen because bimonthly manual temperature profiles are currently collected at the same location.

Lake Natoma Temperature Profiles

Reservoir temperature profiles were collected at various locations in Lake Natoma in 2001 to quantify the temperature dynamics throughout Lake Natoma. One objective was to determine the location of the Folsom inflow plunge zone. The plunge zone is an important feature that moves with changes in reservoir operations (inflow and storage volume) and thermal stratification. The plunge zone is where cool, dense water plunges beneath the warm surface water. The plunge zone location is a critical parameter when designing a temperature curtain. Another objective of the temperature monitoring was to develop a time series record that could be used to determine travel times and temperature gain of cool water moving through Lake Natoma.

Temperature profiles were measured over the period from July 17 to October 18, 2001, at six sampling sites along Lake Natoma between Folsom and Nimbus Dams. Strings of Onset Stowaway® Tidbit® temperature loggers were attached to buoys located throughout the reservoir. The temperature strings were weighted so they remained vertical during reservoir level changes. Temperature loggers were spaced at 5-foot intervals throughout the water column and were programmed with a 15-minute sampling interval. The shallowest temperature logger was placed 0.5 feet below the water surface to limit temperature gain from solar radiation. Personnel from Reclamation's Central California Area Office deployed and maintained the temperature strings in Lake Natoma.

The profiling locations are described in table 2 and are illustrated in figure 4. In table 2, AFD and AHZ are single point stations and are operated by the U.S. Geological Survey, under a multi-year contract with Reclamation. Table 3 contains the vertical position of the temperature measurements for each location. Table 4 summarizes the deployment periods for each temperature profiling site.

Table 2. Temperature monitoring names, locations, and GPS[1] coordinates

Name	Location	Coordinates
AFD	American River site below Folsom Dam	38^{o} 42.240N 121^{o} 09.780W
NB	Negro Bar	38^{o} 40.8575N 121^{o} 10.737W
CEM	Cemetery	38^{o} 40.4062N 121^{o} 11.478W
BUFAVE	Buffalo Avenue	38^{o} 39.7672N 121^{o} 11.343W
WILLOW	Willow Creek site confluence	38^{o} 38.9822N 121^{o} 11.599W
BLUE	Blue buoy near Nimbus Dam	38^{o} 38.1539N 121^{o} 13.126W
DAM	White buoy at Nimbus Powerplant	38^{o} 38.2456N 121^{o} 13.187W
AHZ	American River at Hazel Avenue Bridge	38^{o} 36.1600N 121^{o} 13.440W

GPS = global positioning system

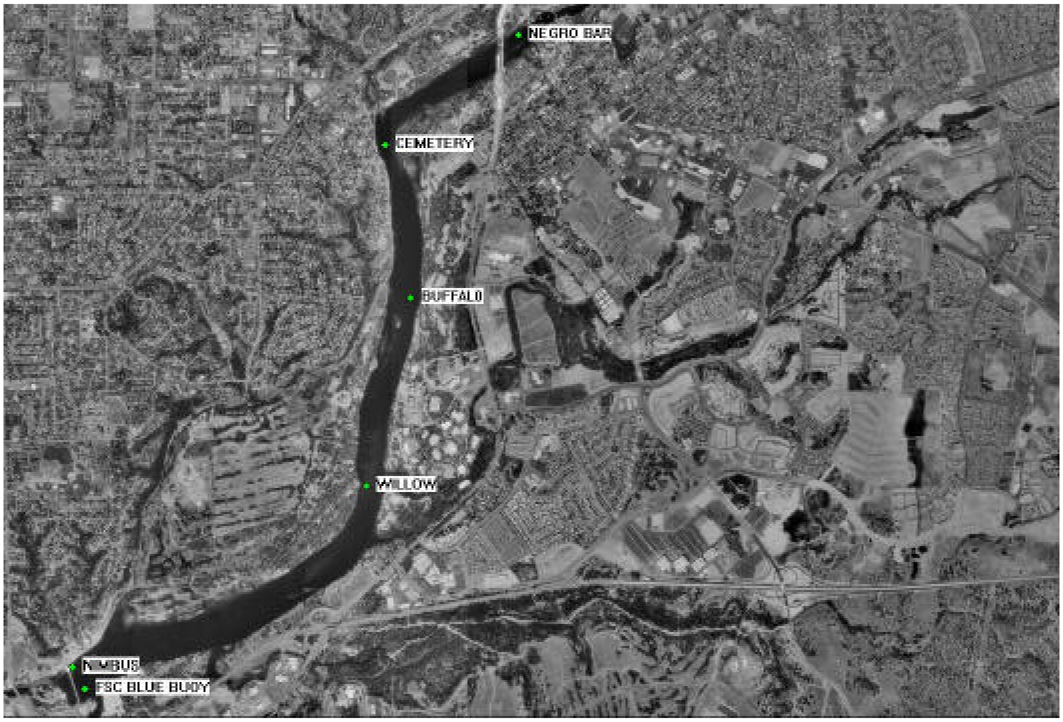

Figure 4. Aerial photograph with annotations of Lake Natoma temperature profiling sites.

Table 3. Vertical position of temperature loggers at each sampling site shown in figure 4

	Negro Bar	Cemetery	Buffalo Avenue	Willow	FSC[1] Blue Buoy	Nimbus Dam
Depth (ft)	0.5	0.5	0.5	0.5	0.5	0.5
	5	5	5	5	5	5
	10	10	10	10	10	10
		15	15	15	15	15
		20	20	20	20	20
		25	25	25	25	25
			30		30	30
						35

FSC = Folsom South Canal

Table 4. Lake Natoma Temperature Profiling Deployments

Profiling Site	Deployment No. 1	Deployment No. 2	Comments
Negro Bar	May 09 - July 17, 2001	July 17 - Feb. 28, 2002	226 days, 21,715 data points
Cemetery	May 09 - July 17, 2001	July 17 - Feb. 28, 2002	226 days, 21,715 data points
Buffalo	May 09 - July 17, 2001	July 17 - Feb. 28, 2002	226 days, 21,715 data points
Willow	May 09 - July 17, 2001	July 17 - Oct 08, 2001	82 days, 7940 data points
FSC Blue Buoy	May 09 - July 17, 2001	July 17 - Oct 08, 2001	82 days, 7940 data points
Nimbus Dam	May 09 - July 17, 2001	July 17 - Oct 08, 2001	82 days, 7940 data points

Reservoir Operations Data

Reclamation's reservoir operations data are stored in the California Data Exchange Center (CDEC) database and can be accessed through the internet at http://cdec.water.ca.gov/ . Hourly reservoir operations data were retrieved from the database for the period of analysis. Operations data available for Folsom and Nimbus Dams include: reservoir elevation (feet), reservoir storage (acre-feet), inflow and outflow discharges (cubic feet per second [ft^3/s]). Figure 5 is a plot of Lake Natoma inflows and outflows, along with annotations of Folsom shutter changes. Operations data plotted in figure 5 clearly show the base load and peaking power operations at Nimbus and Folsom Powerplants, respectively. Table 5 summarizes the meta data for the Folsom and Nimbus Dam sites. Hourly operations data from the CDEC database are available from 1993 to present for Folsom and from 1994 to present for Nimbus Reservoir.

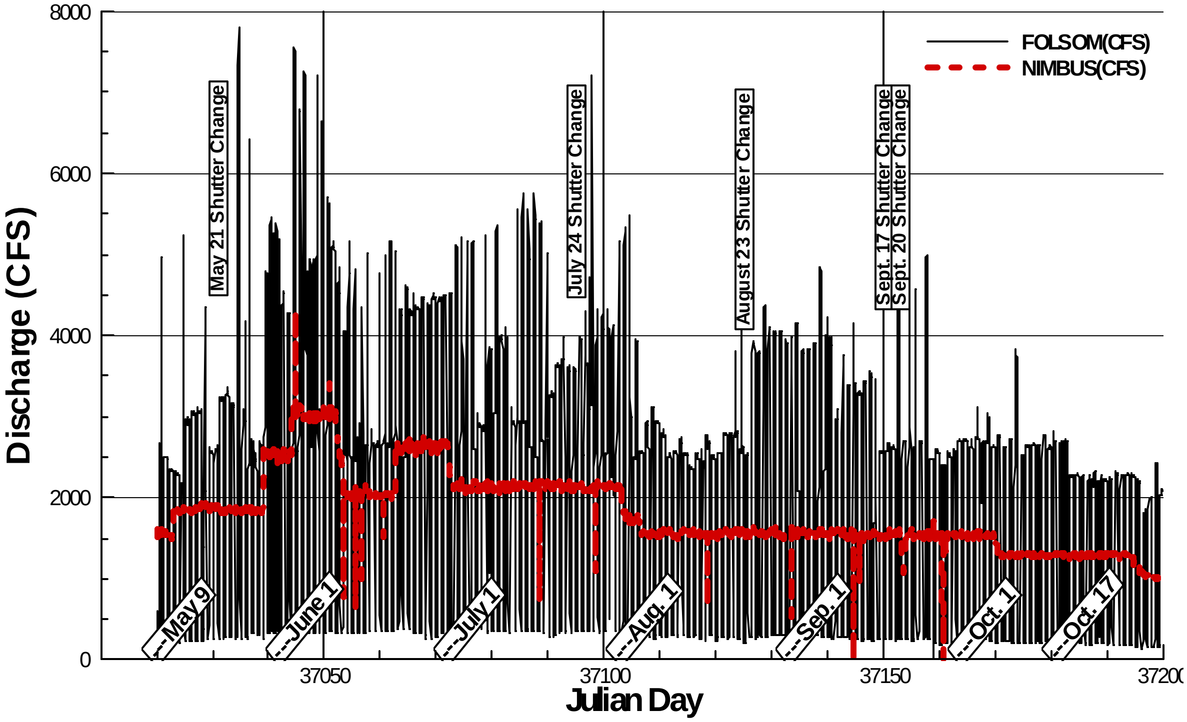

Figure 5. Summary of Lake Natoma Reservoir operations (inflows and outflows) and Folsom shutter changes for May through October 2001.

Table 5. CDEC meta data for Folsom and Lake Natoma Reservoir operations sites

Folsom Lake (Folsom Dam)			
Station ID	FOL	**Elevation**	466 feet
River basin	American River	**County**	Sacramento
Hydrologic area	Sacramento River	**Nearby city**	Folsom
Latitude	38.6830°N	**Longitude**	121.1830°W
Operator	US Bureau Of Reclamation	**Data collection**	Data exchange
Lake Natoma (Nimbus Dam)			
Station ID	NAT	**Elevation**	132 feet
River basin	American River	**County**	Sacramento
Hydrologic area	Sacramento River	**Nearby city**	Nimbus
Latitude	38.6500°N	**Longitude**	121.1830°W
Operator	Reclamation	**Data collection**	Data exchange

Reservoir Release Temperatures

Reservoir release temperatures from Folsom and Nimbus Dams are available from CDEC Sites: American River below Folsom Dam (AFD) and the American River at Hazel Avenue Bridge (AHZ), respectively. See table 6 for the meta data for the AFD and AHZ sites. Hourly operations data are available from 1998 to present for AFD and from 2001 to present for AHZ.

Table 6. CDEC meta data for AFD and AHZ temperature monitoring sites on the American River, California

American River below Folsom Dam			
Station ID	AFD	**Elevation**	220 feet
River basin	American River	**County**	Sacramento
Hydrologic area	Sacramento River	**Nearby city**	Folsom
Latitude	38.7040°N	**Longitude**	121.1630°W
Operator	U.S. Geological Survey	**Data collection**	Satellite
American River at Hazel Avenue Bridge (below Nimbus Dam)			
Station ID	AHZ	**Elevation**	100 feet
River basin	American River	**County**	Sacramento
Hydrologic area	Sacramento River	**Nearby city**	Sacramento
Latitude	38.6360°N	**Longitude**	121.2240°W
Operator	U.S. Geological Survey	**Data collection**	Satellite

Meteorological Data

Meteorological data at Folsom Dam are available from CDEC site FLD. The FLD site collects the following parameters: atmospheric pressure, precipitation (tipping bucket), relative humidity, air temperature, and wind speed and direction. The CDEC database contains data from October 1995 to present. Analyses of meteorological data were limited to a qualitative analysis of the relationship between reservoir surface temperatures and air temperature. Detailed analyses of meteorological data were beyond the scope of this project but will likely be necessary for future studies.

Penstock Flowmeter Data

As part of this project, flow and temperature data from the Accusonic flowmeters on the Folsom penstocks were collected and entered into a database. Accusonic flowmeter data provide the individual penstock release temperature and flow rate. Data were collected every 15 minutes; however, only units No. 2 and No. 3 had flowmeters installed during this study. Subsequent to this study, a flowmeters were installed on unit No. 1 at Folsom and on both units at Nimbus Powerplant.

Reservoir Currents

In an effort to understand the current patterns in Lake Natoma an Acoustic Doppler Current Profiler (ADCP) was used to measure several sets of current profiles at the temperature profiling sites in Lake Natoma.

On June 27, 2002, a Rio Grande 1,200-kilohertz broadband ADCP made by RD Instruments was used to measure currents in Lake Natoma. ADCP system configuration settings used at Lake Natoma are listed below:

Depth of sensor (below surface): 0.5 feet
Compass correction: 0°
Firmware: v10.14 Beam angle: 20°
Orientation: Down Pattern: Convex
Water mode: 1 Bottom mode: 5
Pings/ensemble: 1 water, 1 bottom
Intensity scaling factor: 0.43 decibels/count

Blanking distance: 1.64 feet
Magnetic variation: 14.8° E
Frequency: 1,200 kilohertz
Bin size: 0.82 feet
No. of bins: 60
Sound adsorption: 0.04 decibels/foot
Salinity: 0.00 parts per million

Profiles were collected upstream from Nimbus Powerplant, at Willow, at Buffalo, at a proposed curtain site (between Buffalo and Cemetery), at Cemetery, at Negro Bar, and under the Rainbow Bridge.

In an effort to minimize boat speed, the boat was anchored at each site. Minimizing the boat speed was critical to achieve good bottom-tracking and velocity measurements. During ADCP data collection, Nimbus Powerplant was discharging a constant 2,900 ft^3/s. Hourly releases from Folsom Dam were relatively constant at 4,600 ft^3/s during ADCP measurements on June 27, 2002. Weather conditions during ADCP data collection were clear and calm. Weather conditions are an important consideration when trying to measure small currents in a reservoir where anchoring is not practical.

A laptop computer was used to configure the ADCP, control data collection, and store data. ADCP profiling sites were located in earth coordinates using a

Garmin GPS. The GPS receiver was connected to the computer so that GPS data were recorded simultaneously within the ADCP data file.

ADCP data were not analyzed for this study because they did not coincide with the selected modeling periods. However, these data are available for subsequent studies, if needed.

Results

Summary of Shutter Operations at Folsom Dam

2001 Shutter Operations

In 2001, the Folsom temperature shutter system was used to manage temperatures in the lower American River. Table 7 contains a summary of the shutter change schedule for 2001. Shutter changes involved raising the shutter panels 39 feet using three 13-feet-long lifting stems. In an effort to conserve the cold water in Folsom Reservoir, project operators implemented a blending technique that involved making shutter adjustments on one penstock intake at a time. Then, flows through the operating units were blended to release the desired water temperature. Later in the fall, blending operations included the use of low-level river outlets to access the remaining cold water in Folsom Lake. Plots like figure 6 clearly show the effects of shutter changes on the inflow temperatures to Lake Natoma.

Shutter changes chosen for data analysis were: July 24 (from UUU to MMM), August 23 (from MMM to OML), September 17 (from MOL to OOL), and November 10 (from OLO to OLO + lower river bypass open at 500 ft^3/s). These operations are summarized in table 7, where A = all shutters lowered, U = upper shutters raised, M = middle shutters raised, L = lower shutters raised, and O = offline. Three letters are used to represent the shutter position for generating units 1, 2, and 3.

Table 7. Summary of Folsom shutter operations for 2001

Date	Shutter operations	Shutter crest elevation (feet)
Before 5/21/01	All shutters lowered (AAA)	401
5/21/01	All upper shutters raised (UUU)	362
7/24/01	All middle shutters raised (MMM)	331
8/23/01	Bottom shutters raised on Unit 3 (OML)	Blending with 331 and 284
9/17/01	Bottom shutters raised on Unit 2 (OOL)	Blending with 331 and 284
9/20/01	Bottom shutters raised on Unit 1 (LOL)	All set at 284
11/10/01	Start low-level outlet bypasses (500 ft^3/s)	50/50 blending with 284 and 210
11/26/01	End low-level outlet bypasses (500 ft^3/s)	284
12/19/01	Lower shutters lowered (MMM)	331

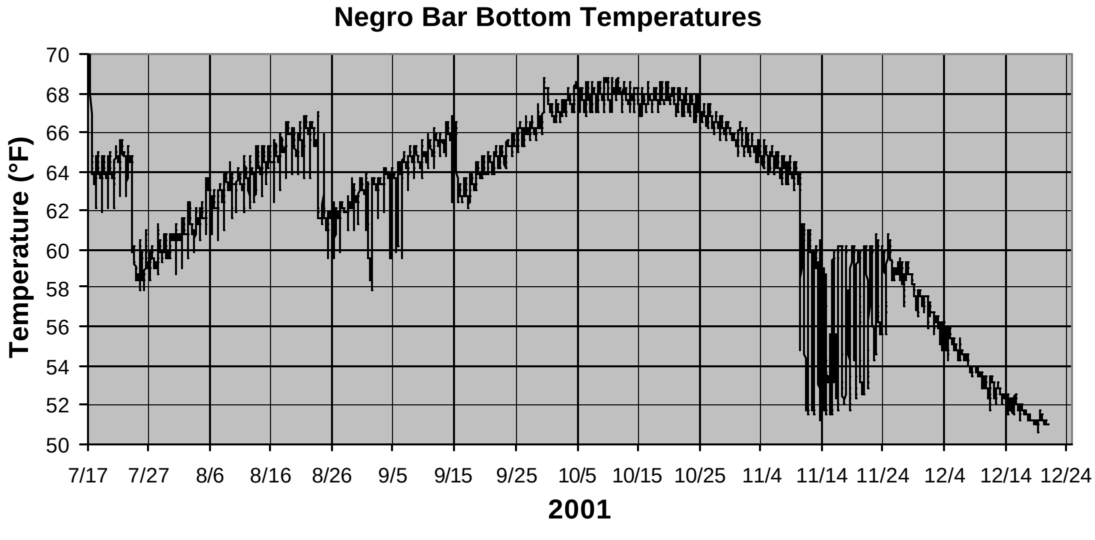

Figure 6. Plot of Folsom release temperatures measured at Negro Bar profiling site, July to December 2001. The large changes in temperature indicate shutter and bypass operations.

Folsom Lake Stratification

Folsom forebay temperature profiles that were collected from May 8 to December 1, 2001, were analyzed in support of this study. Over this period, profiles were collected at a 15-minute interval; each profile was comprised of 14 temperature readings positioned throughout the water column. Over 19,600 temperature profiles (over 250,000 individual temperature readings) were compiled to create the temperature contour plot in figure 7. Figure 8 illustrates how stratification in Folsom Lake develops and progresses through the summer and fall. The contour plot shows how shutter operations influence cold water storage in the reservoir. For example, in September and October, when all the shutters have been raised, there comes a time when no additional cold water can be accessed by the penstock intakes. This is illustrated by a near constant elevation for the cold water pool (or upper limit of the hypolimnion). On November 10, 2001, when low-level river outlets (El. 210 feet) were opened to access the remaining cold water, the cold water pool immediately began to shrink. This draining of the cold water pool continued until November 26, when low-level bypasses were stopped. It is important to note that low-level river outlet releases bypass the powerplant and result in reduced power revenues. In early December 2001, a storm caused the reservoir to mix, which effectively ended the selective withdrawal season. On December 19, 2001, the lower and middle shutters were lowered into position to begin storing cold water for next year.

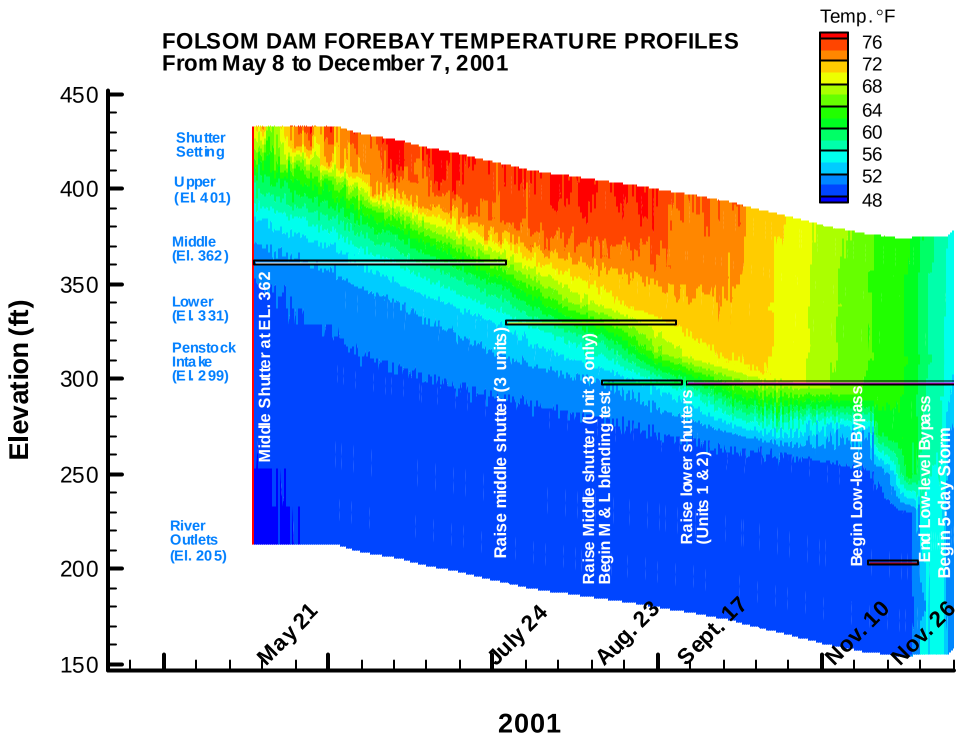

Figure 7. Contour plot of Folsom forebay temperature profiles from May 8 through December 7, 2001. The annotations show the shutter changes and the color bars show the period and elevation of shutter operations.

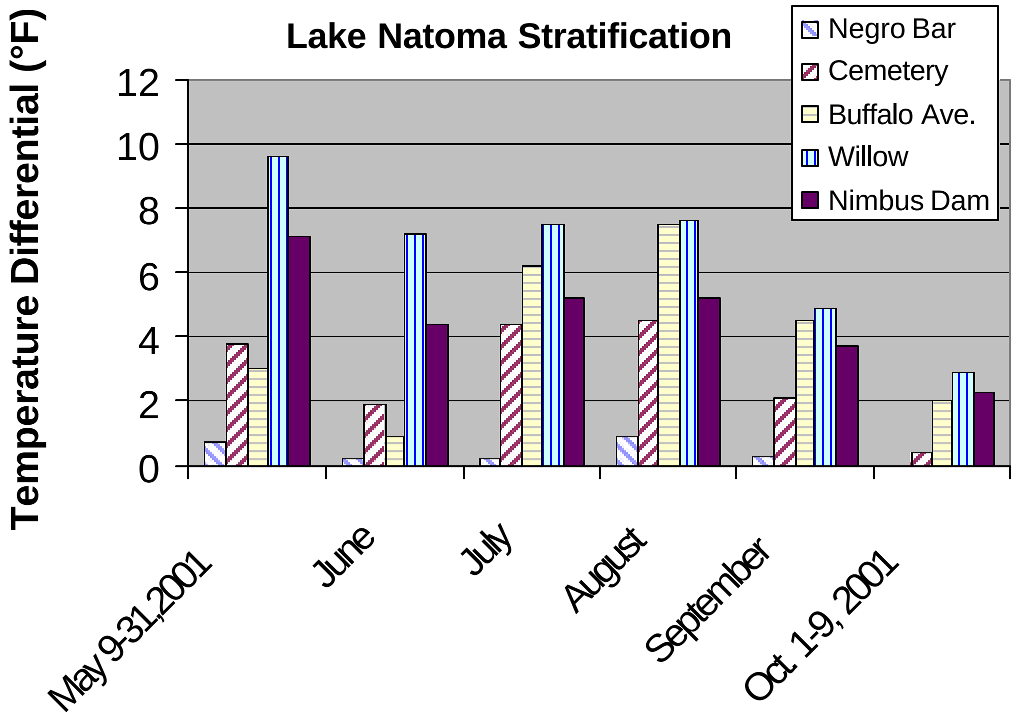

Figure 8. Plot of monthly average surface to bottom temperature differentials in Lake Natoma for the period from May 9 to October 9, 2001. This plot shows the Willow Creek profiling site consistently has the strongest stratification.

Temperature Gain within Lake Natoma, 2001

One of the main objectives of this study was to develop an understanding of the magnitude of temperature gain as water moves through Lake Natoma and to determine where the temperature gains are occurring.

Temperature Gain between Sampling Sites

Surface and bottom temperature logger data were analyzed on a monthly basis to determine strength of thermal stratification, inflow water temperature gain between sites, and thermal characteristics of Lake Natoma. Table 8 contains the average monthly surface and bottom temperatures in Lake Natoma for the period May 9 through October 9, 2001. Figure 8 shows the average monthly surface to bottom temperature differential at five Lake Natoma profiling sites. Figure 8 shows the Willow profiling site consistently had the strongest stratification and the Negro Bar site had the weakest. Willow also had the warmest surface temperatures and the thickest epilimnion (mixed surface layer). In most reservoirs, the surface temperatures are warmest near the dam. However, surface withdrawals through the Nimbus Powerplant act to reduce the surface temperatures when compared to temperatures measured at the Willow site.

Reservoir stratification would increase for several days after a shutter change because cold water from Folsom displaced warmer water and increased the temperature differential between surface and bottom temperatures. For example, at the Willow site, the average daily temperature differential between surface and bottom water was 6.7 °F before the July 24 shutter change and was 10.2 °F after the shutter change. With time, the stratification slowly weakens as inflows from Folsom gradually warm up.

Analysis of the surface and bottom temperatures showed that there were several occasions when warm surface water extended all the way to the Negro Bar. Conversely, there were several occasions when the stratification broke down at all sites in Lake Natoma. Temperature profiles showed that stratification in Lake Natoma varies diurnally. The strongest stratification occurred in the mid-afternoon. The intermittent presence of stratification at the Buffalo Avenue and Cemetery sites was highly dependent on Folsom Powerplant operations. During high Folsom Powerplant releases, inflows pushed warm surface water downstream and stratification broke down. Conversely, when powerplant releases were reduced, warm surface water in Lake Natoma moved upstream and stratification was re-established. Table 9 contains the average monthly temperature gain for Folsom releases that pass through Lake Natoma.

Table 8. Summary of average surface and bottom temperatures (°F) for Lake Natoma profiling sites for 2001 data

Month	Negro Bar	Cemetery	Buffalo Avenue	Willow	Nimbus Dam
May 9-31, 2001	56.2 (surface) 55.5 (bottom)	59.7 55.9	59.1 56.1	66.4 56.8	64.4 57.3
June	56.7 56.5	58.6 56.7	57.8 56.9	64.5 57.3	62.1 57.7
July	62.1 61.8	64.2 59.9	66.3 60.1	68.2 60.7	68.5 63.4
August	64.2 63.3	67.9 63.4	71.3 63.8	71.8 64.2	69.4 64.2
September	65.0 64.7	66.6 64.5	68.8 64.3	69.7 64.8	68.5 64.8
October 1-9, 2001	67.4 67.5	67.7 67.3	68.9 66.9	70.0 67.1	69.5 67.2

Figure 9 presents a time-series temperature contour plot for the Willow profiling site for May 20-31, 2001. This plot shows the effects of raising the upper shutters on May 21, 2001. The plot also shows how a strong stratification persists because of near 100 °F air temperatures as recorded at the Folsom Dam weather station (CDEC site: FLD). The temperature difference between the surface and bottom water was about 19 °F and the thermocline was located between 5 and 10 feet below the water surface. On May 26, 2001, air temperatures dropped into the 80s and the surface water cooled significantly.

Table 9. Average monthly temperature gain of Folsom releases in Lake Natoma

Month	Inflow temperature gain (°F)
May 9-31, 2001	1.8
June	1.2
July	1.3
August	0.9
September	0.1
Oct 1-9, 2001	-0.35 (cooling)

In figure 10, the top plot shows the powerplant releases from Folsom and Nimbus Dams. The lower plot shows a time-series temperature contour plot for the Cemetery profiling site for May 20-27, 2001. This plot shows that peaking operations at Folsom move warm surface water downstream. The contour plot also illustrates the typical variation in reservoir elevation.

Travel Times between Sampling Sites

Lake Natoma temperature profile data were used to study the speeds and travel times at which Folsom releases move through Lake Natoma. Time-series data from near-bottom temperature loggers were used at each profiling site to determine the speed of the cold water wave generated by a Folsom shutter change. This analysis was complicated by Folsom's peaking powerplant operations. For example, the travel time for a mid-day shutter change when Folsom releases are small can take 11 hours to reach the Negro Bar site; whereas travel time for a afternoon shutter change when Folsom releases are high takes 2.5 hours to reach Negro Bar. The dependence of travel times on Folsom releases will diminish with distance downstream as Nimbus releases begin to control the current speed. The location of this transition zone would be difficult to determine because of its transient nature and was not attempted for this study.

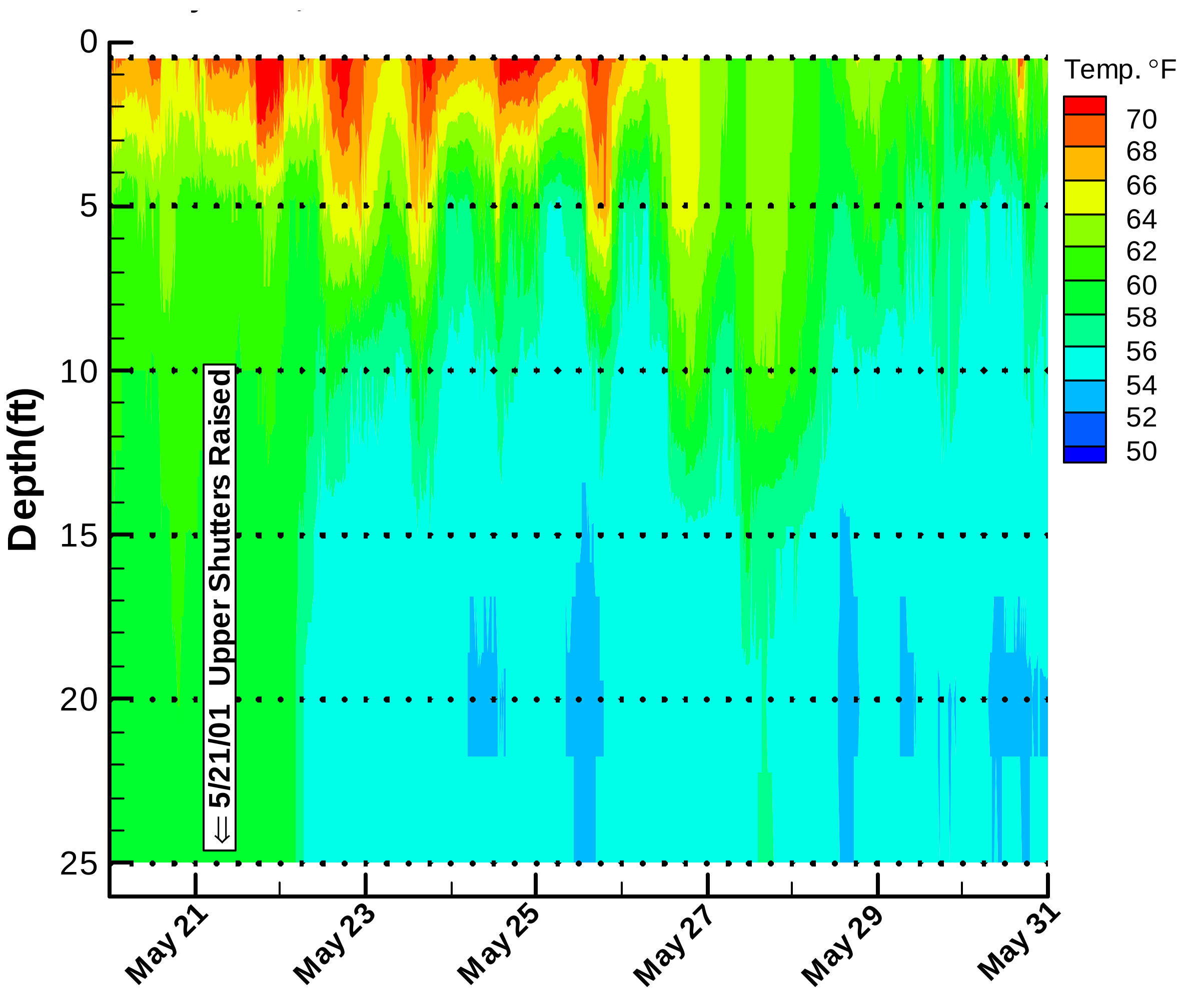

Figure 9. Time-series temperature contour plot for the Willow site for May 20-31, 2001. This plot shows the effects of raising the upper shutters on May 21, 2001, and how a strong stratification persisted because of 90+ °F air temperatures. Air temperatures dropped into the 80s on May 26, and the surface water began to cool. Note: Black dots on the plot represent the temperature logger locations in the water column.

Tables 10 through 14 summarize the travel times and temperature gains between profiling sites for the shutter changes that occurred from July to November 2001. Each table also includes the total temperature gain in Lake Natoma for conditions before and after each shutter change.

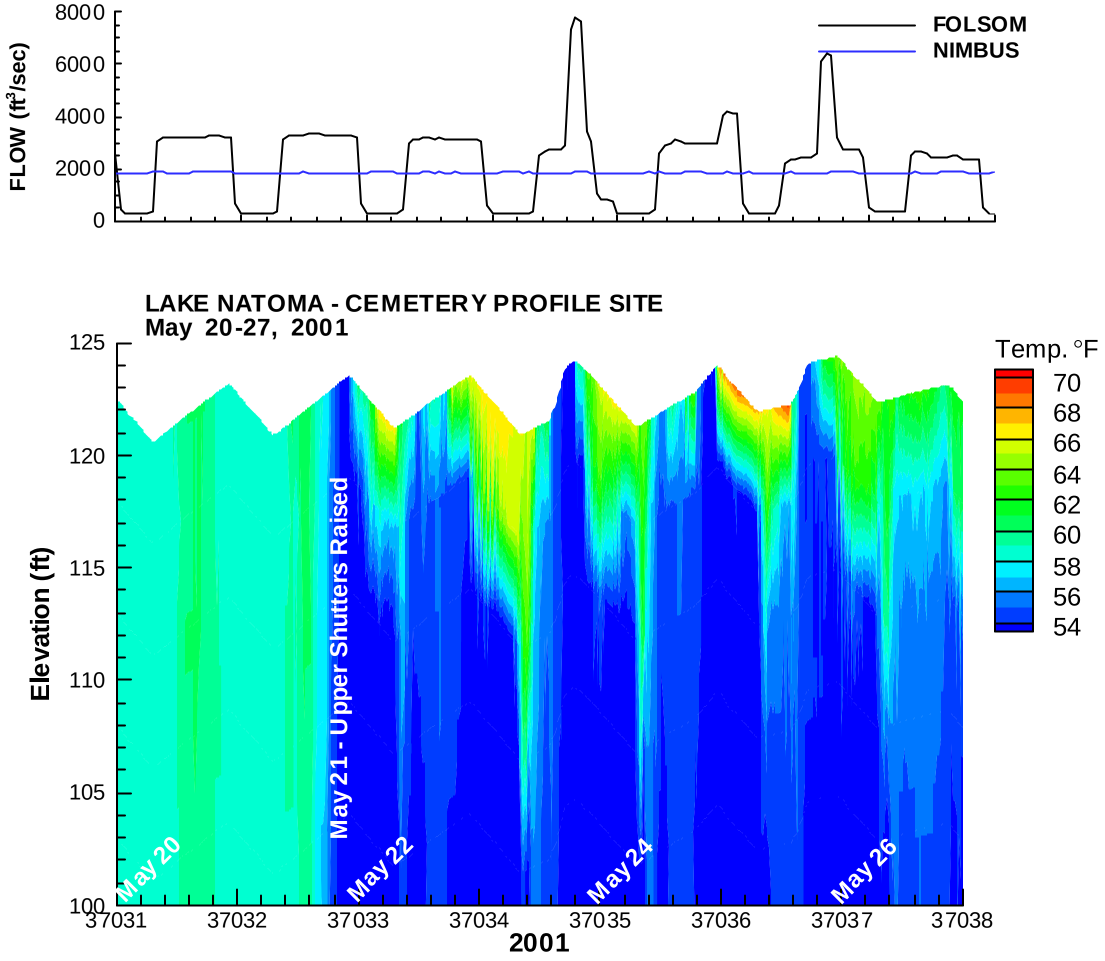

Figure 10. The top plot shows the releases from Folsom and Nimbus Dams. The lower plot shows a time-series temperature contour plot for the Cemetery profiling site for May 20-27, 2001. Peaking inflows from Folsom displaces the warm surface water at the Cemetery site. Note: The varied water surface elevation illustrates the daily fluctuations in Lake Natoma storage volume.

Table 10. Summary travel times and temperature gains for July 24, 2001, Folsom shutter change. The middle shutters were raised on all three units.

			Shutter change on July 24, 2001 From UUU to MMM			
Profile site [logger #]	**Mile marker (miles)**	**River reach (miles)**	**Travel time (hours)**	**Velocity (miles/ hour)**	**Temp (°F) before change**	**Temp (°F) after change**
NB [02]	2.5				64.7	58.7
		0.8	2:46	0.29		
CEM [05]	3.3				65.0	59.0
				ΔTemp=	0.3	0.3
CEM [05]	3.3				64.5	59.0
		0.8	3:36	0.22		
BUFAVE [06]	4.1				64.9	59.7
				ΔTemp =	0.4	0.7
BUFAVE [06]	4.1				65.2	59.7
		0.9	3:19	0.27		
WILLOW [05]	5				65.6	60.5
				ΔTemp =	0.4	0.8
WILLOW [05]	5				65.6	60.5
		1.8	9:45	0.19		
DAM [07]	6.8				65.9	61.0
				ΔTemp =	0.3	0.5
Total temperature gain from NB to DAM				ΔTemp =	1.2	2.3

Table 11. Summary travel times and temperature gains for August 23, 2001, Folsom shutter change. The lower shutters were raised on unit 3.

			Shutter change on August 23, 2001 from MMM to OML			
Profile site [logger #]	**Mile marker (miles)**	**River reach (miles)**	**Travel time (hours)**	**Velocity (miles/hr)**	**Temp (°F) before change**	**Temp (°F) after change**
NB [02]	2.5				65.9	61.0
		0.8	2:00	0.40		
CEM [05]	3.3				66.2	61.3
				ΔTemp =	0.3	0.3
CEM [05]	3.3				66.2	61.6
		0.8	3:51	0.21		
BUFAVE [06]	4.1				66.3	62.3
				ΔTemp =	0.2	0.7
BUFAVE [06]	4.1				66.3	62.3
		0.9	4:34	0.20		
WILLOW[05]	5				66.8	62.7
				ΔTemp =	0.5	0.4
WILLOW [05]	5				66.8	62.7
		1.8	10:15	0.18		
DAM [07]	6.8				66.7	63.0
				ΔTemp =	-0.1	0.3
Total temperature gain from NB to DAM				ΔTemp =	0.8	2.0

Table 12. Summary travel times and temperature gains for September 20, 2001, Folsom shutter change. The lower shutters were raised on unit 1.

		Shutter change on September 20, 2001 From MOL to OOL				
Profile Site [logger #]	**Mile marker (miles)**	**River reach (miles)**	**Travel time (hours)**	**Velocity (miles/hour)**	**Temp (°F) before change**	**Temp (°F) after change**
NB [02]	2.5				65.6	62.7
		0.8	2:46	0.29		
CEM [05]	3.3				65.6	62.7
				Δ Temp =	0.0	0.0
CEM [05]	3.3				65.6	62.7
		0.8	5:27	0.15		
BUFAVE [06]	4.1				65.8	63.7
				Δ Temp =	0.2	1.0
BUFAVE [06]	4.1				65.8	63.7
		0.9	5:49	0.15		
WILLOW [05]	5				65.9	64.2
				Δ Temp =	0.1	0.5
WILLOW [05]	5				65.6	63.9
		1.8	9:30	0.19		
DAM [07]	6.8				65.9	64.1
				Δ Temp =	0.3	0.2
Total temperature gain from NB to DAM				ΔTemp =	0.3	1.4

Table 13. Summary travel times and temperature gains for November 10, 2001, Folsom shutter change. Unit 2 lower shutters raised and bypass releases.

		Shutter Change on November 10, 2001 From OLO to [OLO + Lower Bypass]				
Profile site [logger #]	**Mile marker (miles)**	**River reach (miles)**	**Travel time (hours)**	**Velocity (miles/hour)**	**Temp (°F) before change**	**Temp (°F) after change**
NB [02]	2.5				63.6	Fluctuates
		0.8	2:46	0.29		
CEM [05]	3.3				63.6	52.3
				ΔTemp =	0.8	n/a
CEM [05]	3.3				63.0	52.3
		0.8	4:51	0.17		
BUFAVE [06]	4.1				63.4	53.3
				ΔTemp =	0.4	1.0
BUFAVE [06]	4.1					
		0.9		Not available		
WILLOW[05]	5					
WILLOW [05]	5					
		1.8		Not available		
DAM [07]	6.8					
Total temperature gain from NB to BUFAVE				ΔTemp =	-0.2	~1.0

Table 14 contains a summary of cold water travel times between profiling sites. During this study period, the average travel time for Folsom releases to pass through Lake Natoma was 36 hours. Peaking power operations at the Folsom Powerplant result in large variations in travel times through the upper end of Lake Natoma. As expected, lower flow rates through Nimbus Powerplant generate longer travel times between sites closer to Nimbus Dam. The travel time from Folsom Dam to Negro Bar on August 23, 2001, was difficult to establish because the AFD temperature record did not detect an appreciable temperature drop in the hours after the shutter change. This observation indicates that the AFD monitoring site may not be located at a well-mixed cross section; thus, it may not be accurately monitoring Folsom Dam release temperatures. A review of Folsom flowmeter temperature readings showed that colder water was released from Unit No. 3 starting at about 11:25 a.m. on August 23, 2001. Data from the Willow and Dam profiling sites were not available for the November 10 bypass period because the temperature loggers ran out of data memory.

Table 14. Summary of cold water travel times in Lake Natoma after a Folsom shutter change

Shutter change	Nimbus release flow (ft^3/s)	AFD to Negro Bar[1]	Negro Bar to Cemetery	Cemetery to Buf Ave	Buf Ave to Willow	Willow to Dam	Total time
7/24/2001	2,200	11:35	2:46	3:36	3:19	9:45	31:00
8/23/2001	1,600	4:20	2:00	3:51	4:34	10:15	[1] 25:00
9/14/2001	1,600	15:50	2:46	5:27	5:49	9:30	39:22
11/10/2001	1,100	16:20	2:46	4:51	n/a	n/a	n/a
Average travel time (hours)	--	12:00	2:34	4:26	4:34	9:50	36:02
Average water speed (miles/hour)	--	0.208	0.316	0.185	.207	.183	--

[1] Travel times through this reach are highly dependent on peaking power operations at Folsom and, to a lesser degree, flow rates from Nimbus Powerplant.

Lake Natoma Stratification Animations

Lake Natoma temperature profile data were combined to create a 2D data set that represents a longitudinal cross section through the reservoir. A sample of a cross-sectional view of Lake Natoma's thermal structure is shown in figure 11. This figure shows the reservoir stratification on July 25, 2001 – 1 day after a Folsom shutter change. The light blue contours illustrate cold water from Folsom flowing as an underflow into Lake Natoma. Flow in figure 11 is from right to left, and the blue area represents the reservoir bottom (not a temperature contour). An animation is included in figure 11 to demonstrate the dynamic nature of thermal stratification in Lake Natoma. The animation can be viewed by double clicking on the figure.

Temperature profile data were combined with reservoir operations data to create animations that were studied to understand the dynamics of water movement through the reservoir. An example animation created for temperature profiles collect near Nimbus Dam is included in figure 12. The animation can be started by double clicking on the figure.

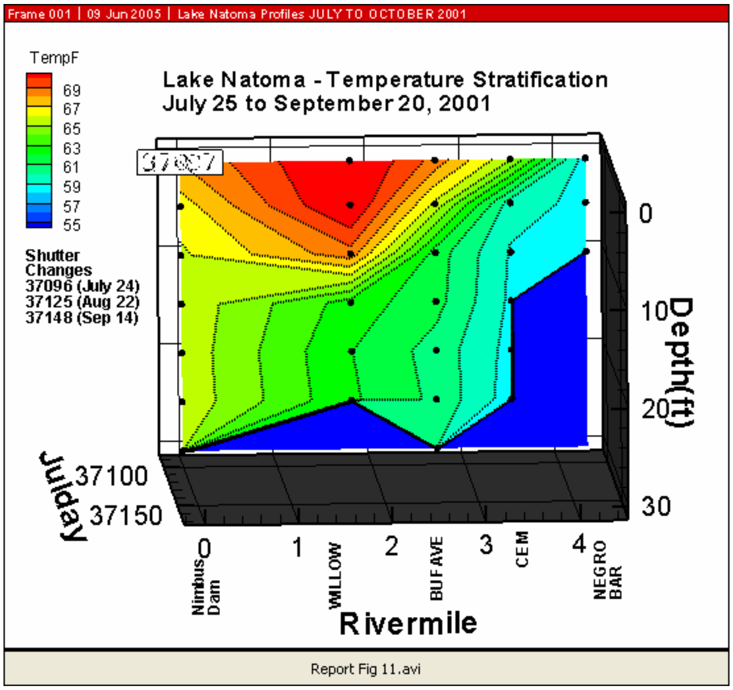

Figure 11. Plot of Lake Natoma stratification on July 25, 2001. The reservoir stratification is for 1 day after the middle shutters were raised at Folsom Dam. Double click on the plot to run a 57-day animation.

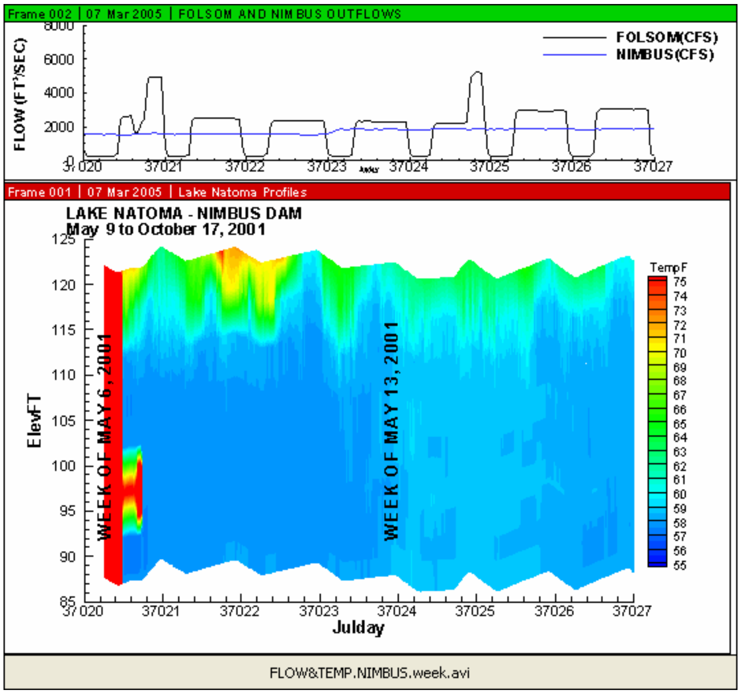

Figure 12. Animation of temperature profiles collected at Nimbus Dam for the period May 9 to October 17, 2001. To play the 147-day animation in weekly time steps, double-click your mouse on the figure. (NOTE: This animation will not work in a PDF version of this report.)

Lake Natoma CFD Modeling

In an effort to quantify the benefits of temperature curtains, powerplant intake modifications or channel modification (excavation), a CFD model of the existing powerplant intake at Nimbus Dam was assembled to compare three prospective alternatives to generate colder releases to the lower American River. To evaluate channel modifications, a separate CFD model was developed for the reservoir between the Willow and Cemetery profiling sites.

A list of potential temperature reduction alternatives to be modeled using FLOW-3D® is as follows:

1. Evaluate the removal or partial removal of a debris wall surrounding the Nimbus Powerplant intakes. Specifically, these two options were considered:
    a. Removing the south-facing debris wall.
    b. Lowering the debris wall to El. 90 from 105 feet.
2. Evaluate the effectiveness of a temperature curtain surrounding the Nimbus Powerplant intakes, which included these two curtain options:
    a. A temperature curtain that extends approximately 500 feet upstream from the dam and angles back to the northern shoreline
    b. A temperature curtain that spans the entire width of the reservoir and is located approximately 1000 feet upstream from Nimbus Dam
3. Evaluate the effectiveness of proposed channel dredging to remove piles of material that reduce the depth of the reservoir and may create mixing with warm surface water. Dredging was proposed for the reservoir area between the Buffalo Avenue and Cemetery profiling sites.
4. Evaluate the effectiveness of a plunge zone curtain located near the Cemetery profiling site.

Computational Hydraulic Model Preparation and Investigation

There are many steps required in developing a CFD model. These steps include developing, refining, and testing the meshed grid; establishing boundary conditions; selecting model extents; and inserting obstacles (structures) into the CFD modeling space.

CFD Program Description

The program FLOW-3D® by Flow Science, Inc. (1996), was used to model the alternatives identified in the scope of work. FLOW-3D® is a finite difference, free surface, transient flow modeling system that was developed to solve the governing Navier-Stokes equations, in three spatial dimensions.

The finite difference equations are based on a fixed Eulerian mesh of nonuniform, rectangular control volumes using the Fractional Area/Volume (FAVOR™) method (Sicilian, 1990). Free surfaces and material interfaces are defined by a fractional volume-of-fluid (VOF) function. FLOW-3D® uses an orthogonal coordinate system as opposed to a body-fitted system. A more detailed description of the FLOW-3D model can be found in a CFD primer available on Flow Science's website http://www.flow3d.com/Cfd-101/whatyou.htm.

The FLOW-3D code was modified for this project to add the following capabilities:

- Simulate the temperature-density relationship of water
- Apply a fixed temperature profile at the upstream model boundary
- Initialize the flow field to the profile of the upstream model boundary
- Summarize and output average release temperatures from the Nimbus Powerplant.

Meshed Grid Development

CFD models that employ finite-element methods require the generation of a solution grid that conforms to the geometry of the flow region. It is a nontrivial task to generate these grids with acceptable element sizes and shapes for accurate numerical approximations. For large or complicated models, this type of grid generation may consume days or even weeks of work. Some programs attempt to eliminate this generation problem by using simplified rectangular grids, but then they must deal with stair-step boundaries that can affect flow and heat-transfer properties. FLOW-3D solves these problems by using easy to generate, rectangular grids in which geometric features are smoothly embedded using the FAVOR™ method. A simple and powerful solids modeler is packaged with FLOW-3D, or users may import geometric data from AutoCAD or a similar computer-aided design (CAD) program. For this study, Lake Natoma bathymetry data were provided by Reclamation's Mid-Pacific Regional Office. The survey data were collected in June 2001. The bathymetry data were based on the

California State Plane Coordinate System, Zone 2. The horizontal and vertical datums were NAD 1927 and NGVD 1929, respectively. The elevation contour interval was 2 feet.

Most simulations in this study used grids constructed with 5 feet of spacing. The upstream face of the dam and penstock intake was modeled on the minimum X boundary, X = 0. The model had 300 cells in the X-direction and extended 1,500 feet upstream from Nimbus Dam. The model had 251 cells in the Y-direction and extended 1,500 feet parallel to the face of the dam, and the vertical extent of model ranged from El. 75 to El. 140 feet in the Z-direction. A total of 979,000 cells are included in this model space. Figure 13 contains a plot of the model extents for a horizontal slice through El. 102.5 feet.

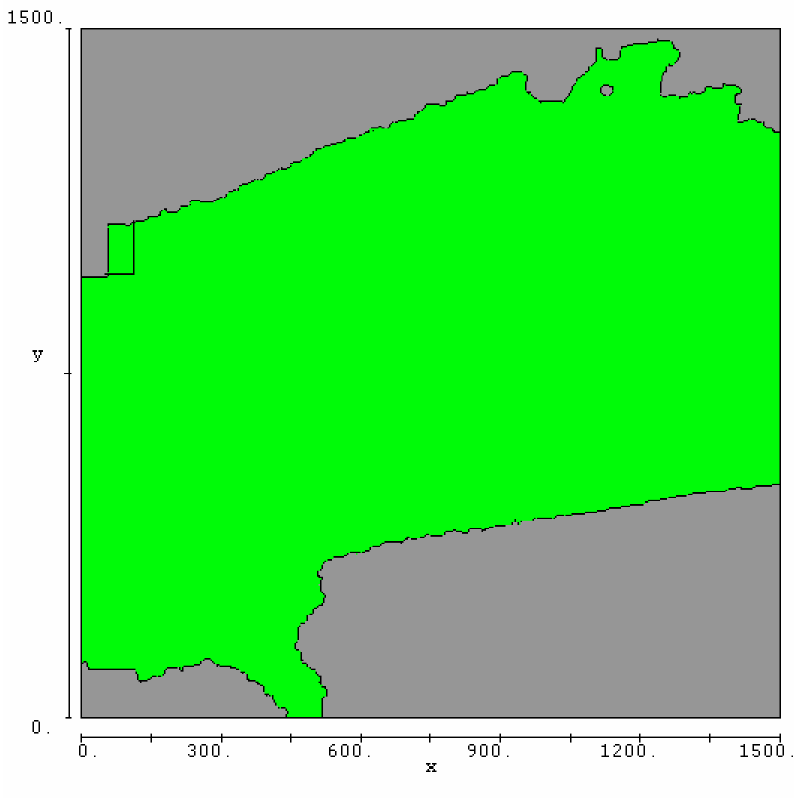

Figure 13. Extents for the Nimbus Dam CFD in the X-Y (horizontal) plane through El. 102.5 feet. The dam is located on the left side of the plot, and flow is from right to left. The Nimbus Powerplant debris wall is shown in the upper left corner. Note: The model grid spacing was too dense to display.

Boundary Conditions

The Lake Natoma CFD simulations used a temperature/density stratified inflow from the river at the maximum X boundary located 1,500 feet upstream from Nimbus Dam. A special subroutine was written for Flow-3D that assigns the temperature, computes the density of the water based on that temperature, and computes a hydrostatic pressure distribution for each cell on the upstream boundary. For model runs, temperature profile data collected at the Folsom South

Canal (Blue Buoy) temperature profiling site were used to simulate the boundary conditions.

Since the Nimbus Powerplant intakes were simulated using a “sink” object, the minimum X boundary was defined as a “wall.” A wall boundary condition was also modeled at the other four boundaries, both Y boundaries (sides) and both Z boundaries (top and bottom).

Obstacles and Baffles

Obstacles (structures in the flow field) used by the FLOW-3D solids modeler are defined by primitives (squares, cubes, blocks, planes, circles, spheres) and quadratic functions.[1] Imported computer-aided design data can also be used by FLOW-3D. This model was assembled using imported CAD data converted to stereolithography to describe Lake Natoma’s bathymetry (Figure 14). Figure 14 shows the three-dimensional (3D) coordinate system (X,Y,Z) that was used in the model development, where Z is in the vertical direction. Other primitives were used to model the dam, penstock intakes, debris wall, and concrete apron located upstream from the dam.

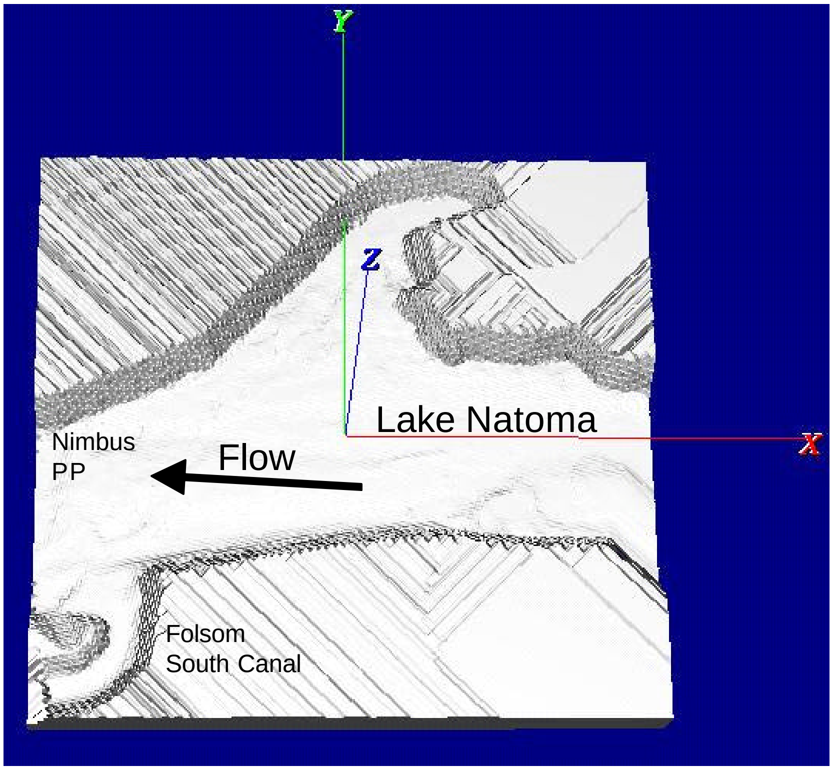

Figure 14. Bathymetry of Lake Natoma, extending 1,500 feet upstream of Nimbus Dam. In this figure, Nimbus Dam is on the left side and flow is from right to left. The upper surface of the object was well above the maximum water surface elevation so that the diagonal features seen on the upper surface were outside of the modeled domain.

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[1] Flow Science, Inc., Quick Reference Guide, 1995.

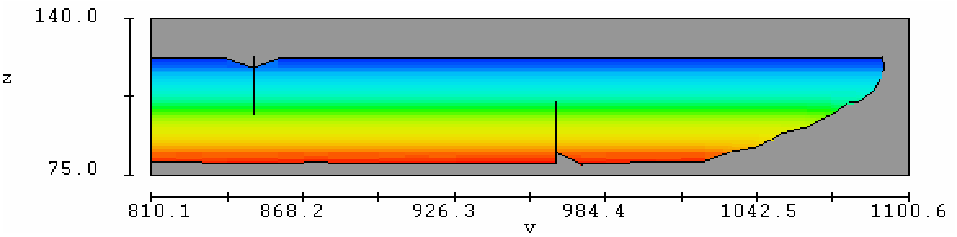

Figure 15. Typical reservoir cross section from left to right. The apron at El. 80 feet, a temperature curtain, the south debris wall, intake apron at El. 79 feet, sloping apron, and bathymetry. The “rigid lid” simulates the water surface at El. 123.56 feet. The color contours in this plot represent hydrostatic pressure distribution.

Similarly, temperature curtains and the debris wall were simulated using baffles in Flow-3D (figure 15). Baffles are simply barriers between two rows of cells. The baffles representing the curtain extended from the water surface to El. 100 feet. To avoid making modifications to the custom subroutines used in this study, and to reduce computational time involved with modeling a free surface, an object was placed at and above the elevation of the water surface to form a “rigid lid” boundary.

FLOW-3D Limitations

It is important to note that surface evaporation and solar heating were not modeled for this study. While with extensive effort, FLOW-3D could be modified to simulate the transient thermal processes (e.g., thermal input due to solar radiation) involved with this application, it has not been proposed because of the associated costs. Coding such flexibility into FLOW-3D would be a long-term investigation in itself. Furthermore, the computational time required to run simulations that are days or months in length would not be practical. Another limitation is that the upstream boundary has a fixed temperature profile and water surface elevation, while temperature profile animations clearly show that both reservoir elevation and temperature profiles are dynamic. For this model application, we selected a time period when the water surface elevation was constant so the rigid lid would not require adjustment.

Test Cases

The inflow temperature profiles that were simulated were based on two conditions measured in the field on July 29, 2001: one at 5:00 a.m., and a second at 12:00 p.m. (noon). Figure 16 compares the two different temperature profiles modeled. Note the large change in surface temperatures in 7 hours’ time and that the surface temperature was warmer in the early morning. These profiles were measured near the Folsom South Canal diversion and were applied as the boundary condition at the maximum X boundary. Unfortunately, temperature profiles could not be collected at the upstream model boundary because that area of Lake Natoma is part of a competitive rowing course.

Model runs included the existing conditions; a condition where the south debris wall was removed, the top of the debris wall was reduced to El. 90 feet from 105 feet, and temperature curtains were located 500 feet (figure 17); and

1,000 feet upstream (figure 18) from Nimbus Dam. While impractical to apply a curtain at this location, the temperature curtain located 1,000 feet upstream from the dam was considered an extreme test case, which might provide a significant reduction in the outflow temperature.

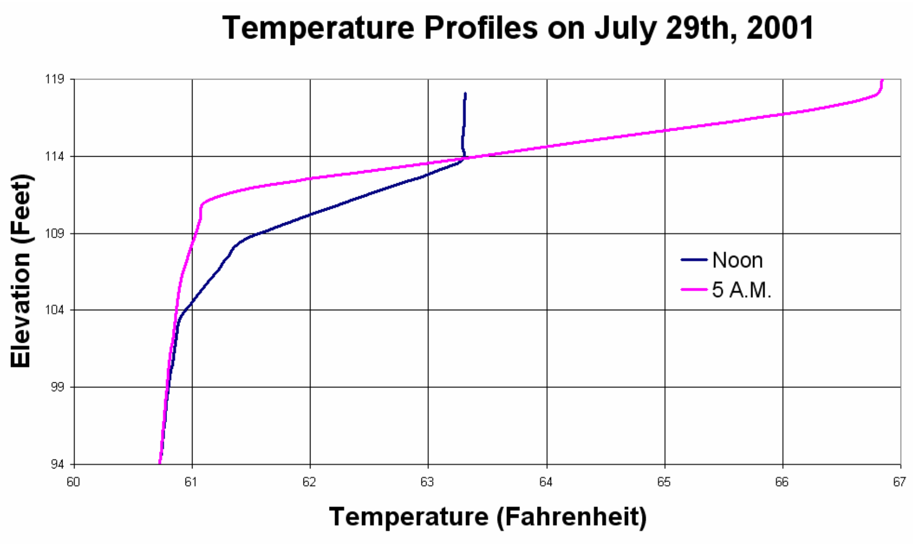

Figure 16. Lake Natoma forebay temperature profiles selected for model boundary conditions.

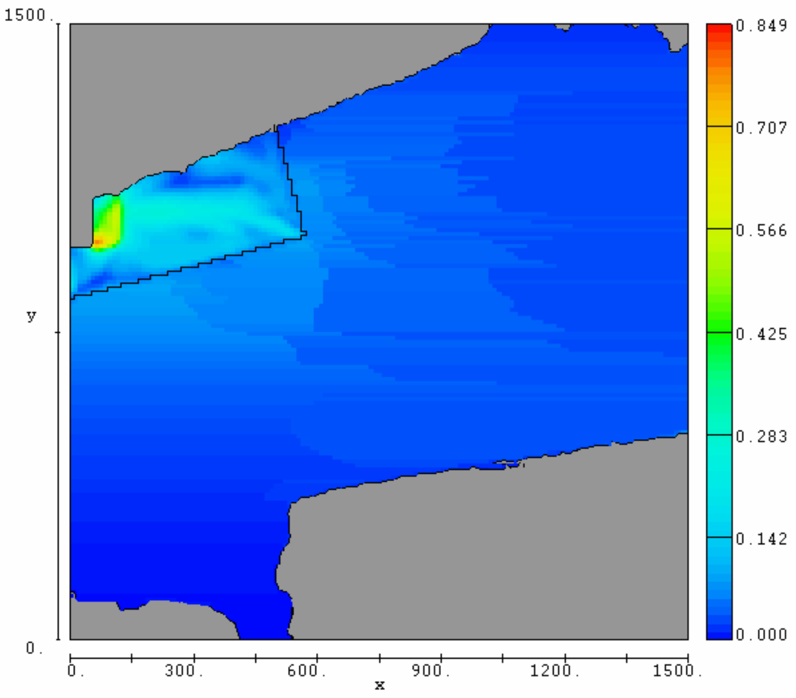

Figure 17. Layout and velocity contours for the 500-foot curtain model for a horizontal slice through El. 107.5 feet. The bottom of the curtain is at El. 100.0 feet. Variations in the velocity field inside the curtain result from variations in the bathymetry. Velocity contours are in ft/s.

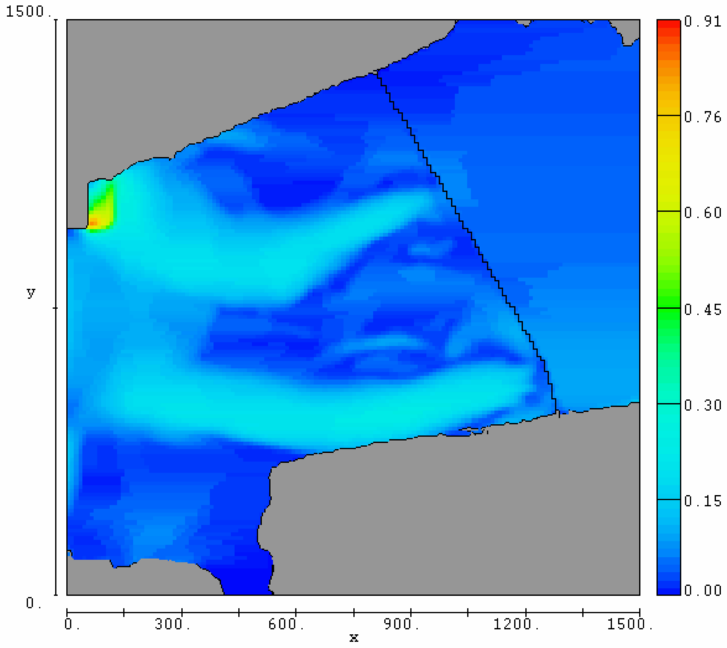

Figure 18. Layout and velocity contours for the 1,000-foot curtain model for a horizontal slice through El. 107.5 feet. The curtain bottom is at El. 100.0 feet. Variations in the velocity field inside the curtain result from channels in the bathymetry. Velocity contours are in ft/s.

CFD Modeling Results

July 29, 2001, 12:00 p.m. (Noon)

The simulated cases included the existing powerplant intake. The debris wall elevation was reduced from 105 to 90 feet, and the south side of the debris wall was completely removed. Model simulations determined that release temperatures were within 0.1 °F of the depth-averaged reservoir temperature of 62.1 °F. Modeled outflow temperatures for three alternatives are presented in table 15. The outflow temperature reported at the Hazel Avenue monitoring site (CDEC Site: AHZ) for this time period was 61.9 °F. Comparing model release temperatures to actual temperatures indicated that the alternatives modeled created no appreciable reduction in temperatures from Nimbus Powerplant. The reason for this may be explained using figures 19 through 23, which show the velocity fields generated by the three alternative intake configurations. The plots show that the velocity field approaching the powerplant was uniform from the surface to bottom, which means water was withdrawn uniformly throughout the water column. If the reservoir and intakes were deeper or if the stratification were stronger, a larger temperature reduction might be possible. It is important to note that the temperatures in table 15 and the temperature contours in figures 20, 22, and 23 do not appear to agree. The difference between the average release temperatures and the contours can be attributed to stratified temperatures (both vertically and horizontally) in the penstock that were not represented in the cross-sectional plot. The cross-sectional plots only show 3 of the 27 grid nodes that were used to compute the flow-weighted average temperatures shown in table 15.

Table 15. CFD model results using a Lake Natoma temperature profile collected at 12:00 p.m. (noon) on July 29, 2001. At this time, the depth-averaged lake temperature at the upstream boundary was 62.1°F.

Test case	Outflow temperature (°F)
Existing condition	62.1
Partial debris wall (El. 90)	62.0
Removed south side of debris wall	62.0

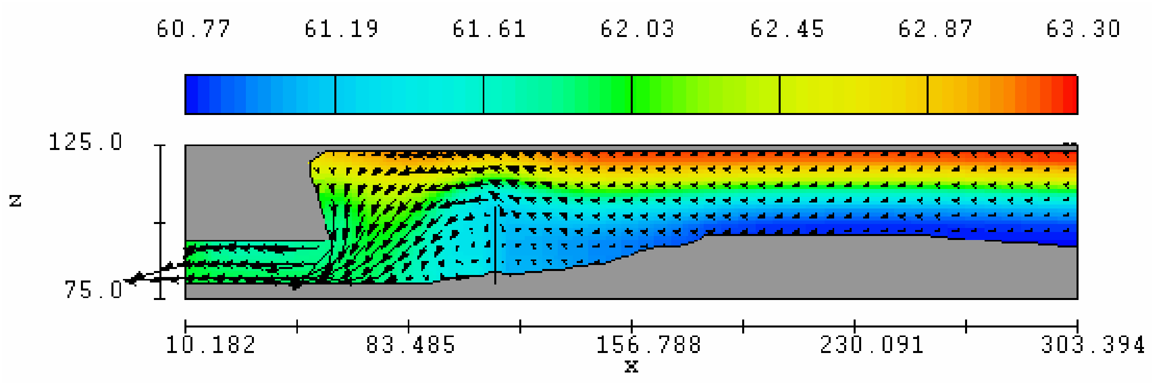

Figure 19. Existing condition, profile through penstock, debris wall, and upstream bathymetry. Velocity vectors at x = 230 show a uniform withdrawal throughout the water column. The largest velocity vector represents a maximum velocity equal to 3.5 ft/s. Color contours represent the reservoir water temperatures in °F.

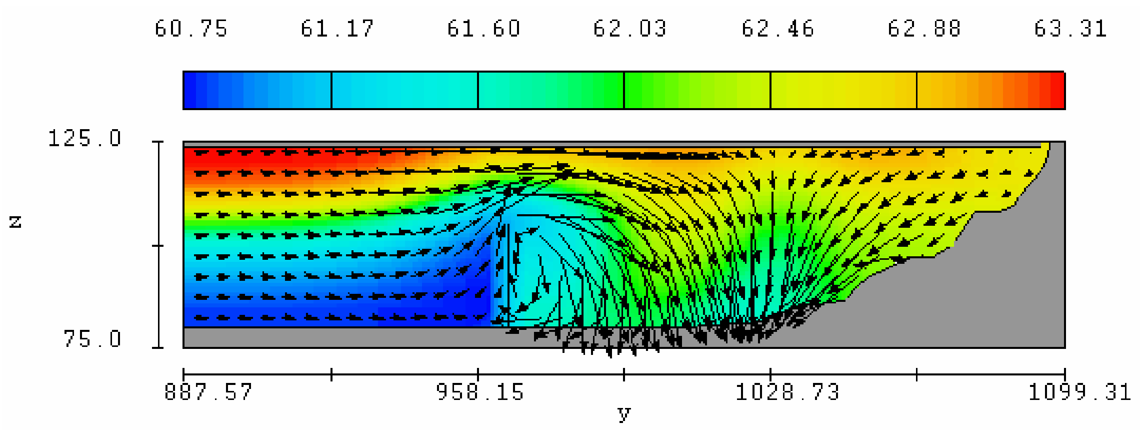

Figure 20. Existing condition, profile through the south debris wall, and bathymetry along the apron of Nimbus Dam. Velocity vectors show a uniform far-field velocity distribution. The largest velocity vector represents a maximum velocity equal to 1.4 ft/s. The color contours represent the reservoir water temperatures in °F.

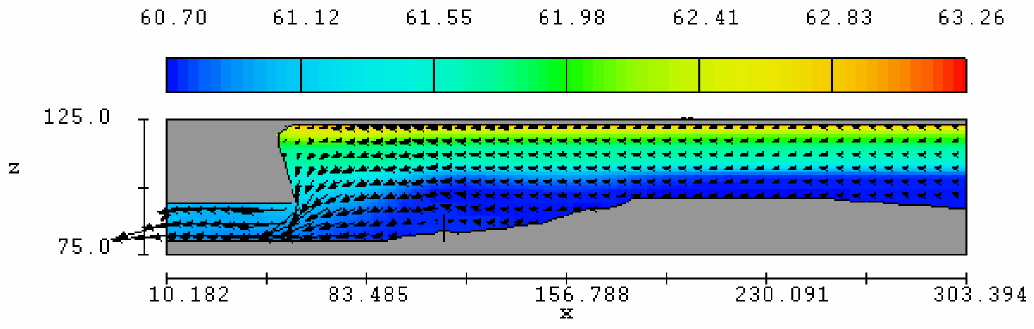

Figure 21. Partially removed debris wall (El. 90) - profile through penstock, debris wall, and upstream bathymetry. Velocity vectors show a uniform withdrawal throughout the water column. The largest velocity vector represents a maximum velocity equal to 3.6 ft/s. The color contours represent the reservoir water temperatures in °F.

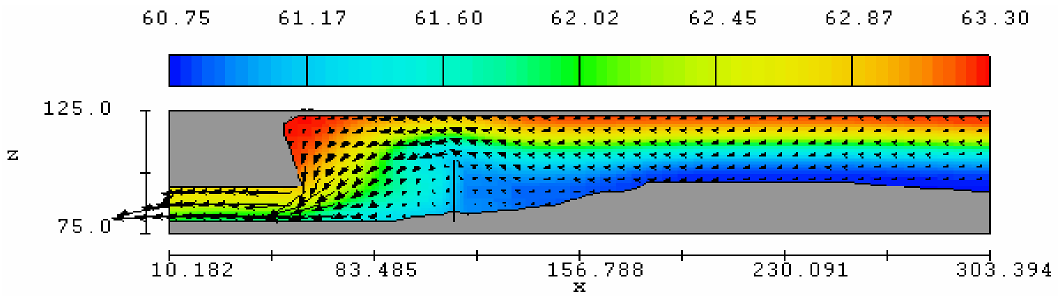

Figure 22. No south wall condition—profile through penstock, debris wall, and upstream bathymetry. Approach velocity vectors show a uniform velocity field. The largest velocity vector represents a maximum velocity equal to 3.6 ft/s. The color contours represent the reservoir water temperatures in °F.

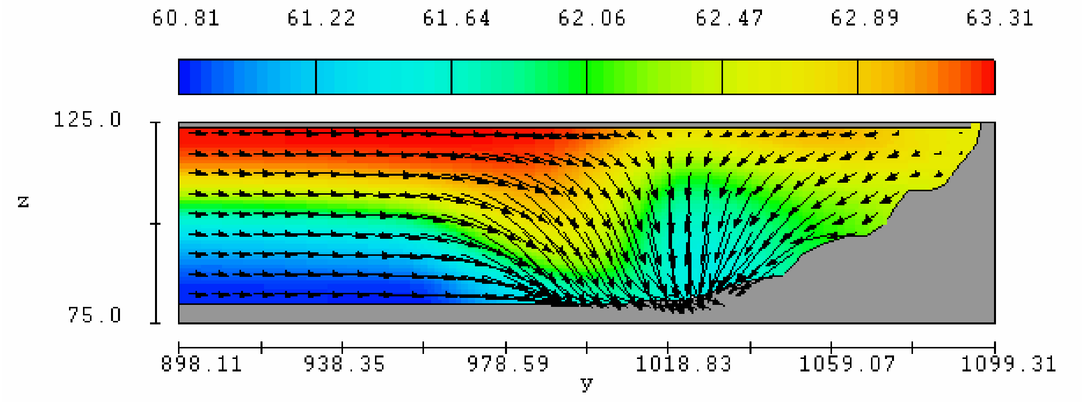

Figure 23. No south wall condition—profile along the apron of Nimbus Dam. Velocity vectors show uniform approach velocities and the near-field velocity field at the intake. The largest velocity vector represents a maximum velocity equal to 1.3 ft/s. The color contours represent the reservoir water temperatures in °F.

July 29, 2001, 5 a.m.

Model simulations for this time period included the existing powerplant intake, complete removal of the south debris wall, a curtain located 500 feet upstream, and a curtain located 1,000 feet upstream from Nimbus Dam. CFD modeling results showed a slight change in outflow temperatures as indicated in Table 16.

Table 16. Simulations using a Lake Natoma temperature profile collected at 5:00 a.m. on July 29, 2001. At this time, the depth-averaged lake temperature at the upstream boundary was 63.5 °F.

Case	Outflow temperature (°F)
Existing configuration	63.4
No south wall	63.3
500-foot upstream curtain	63.4
1,000-foot upstream curtain	63.2

The outflow temperature reported at the Hazel Avenue monitoring site (CDEC Site: AHZ) for this time period was 62.8 °F. At this point in time, the depth-averaged lake temperature at the upstream boundary was 63.5 °F. Comparing model to actual release temperatures showed a 0.6 °F differential, which might indicate a problem with the model prediction or that the AHZ temperature probe was out of calibration or that there is a time lag between the powerplant and the AHZ sampling site. A comparison of the alternatives modeled showed they generated no appreciable reduction in release temperature from Nimbus Powerplant. Again, for each case modeled (figures 24 through 29), it appears that water was withdrawn nearly evenly throughout the water column at the upstream boundary, which is consistent with the withdrawal temperatures being similar to the depth-averaged lake temperature. The uniform velocity profiles are shown in the near-field plots of the velocity fields for the two curtain alternatives (see figures 30 and 31). If the reservoir and intakes were deeper or if the stratification were stronger, a larger temperature reduction might be possible.

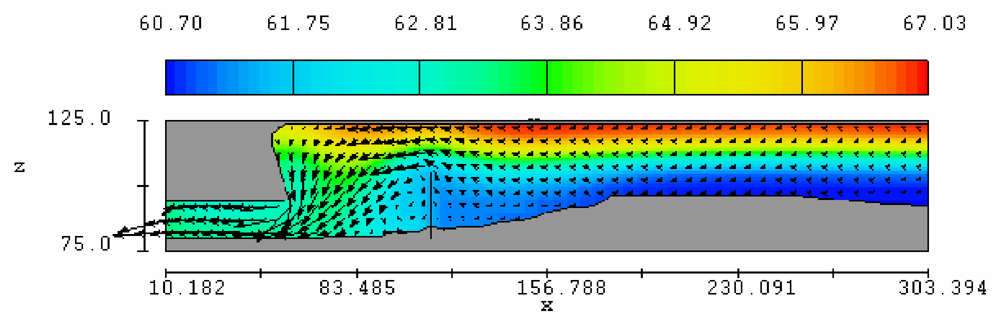

Figure 24. Existing condition section through the centerline of the left-most penstock and debris wall (y = 994 feet). The largest velocity vector represents a maximum velocity equal to 2.2 ft/s. The contours represent the reservoir water temperature in °F.

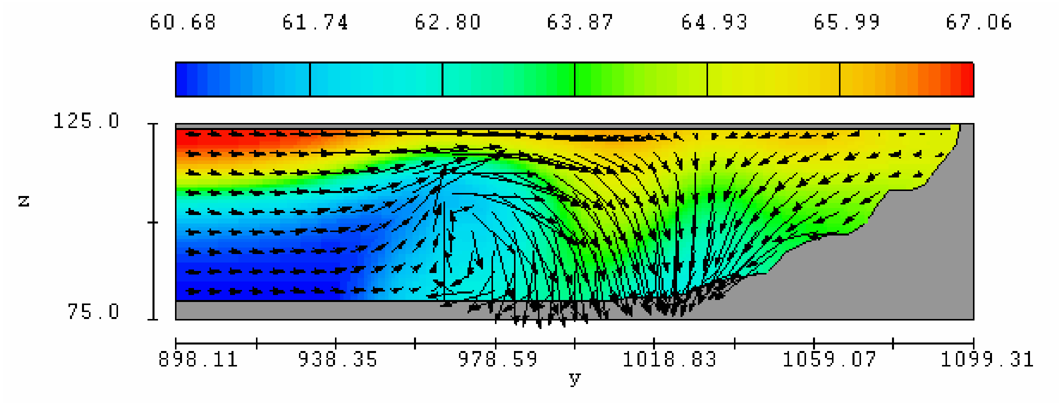

Figure 25. Existing condition section taken parallel to the dam face and through the south debris wall (x = 68 feet). The largest velocity vector represents a maximum velocity equal to 0.9 ft/s. The contours represent the reservoir water temperature in °F.

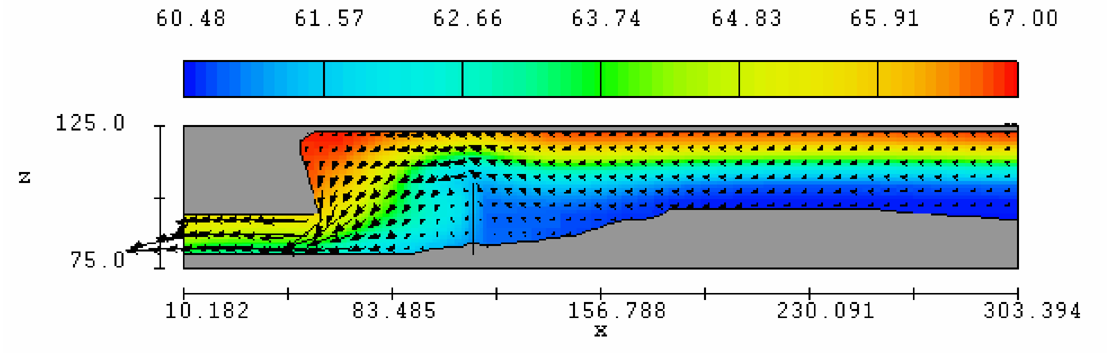

Figure 26. Section through the centerline of the left-most penstock, with the south debris wall removed (y = 994 feet). The largest velocity vector represents a maximum velocity equal to 2.3 ft/s. The color contours represent the reservoir water temperature in °F.

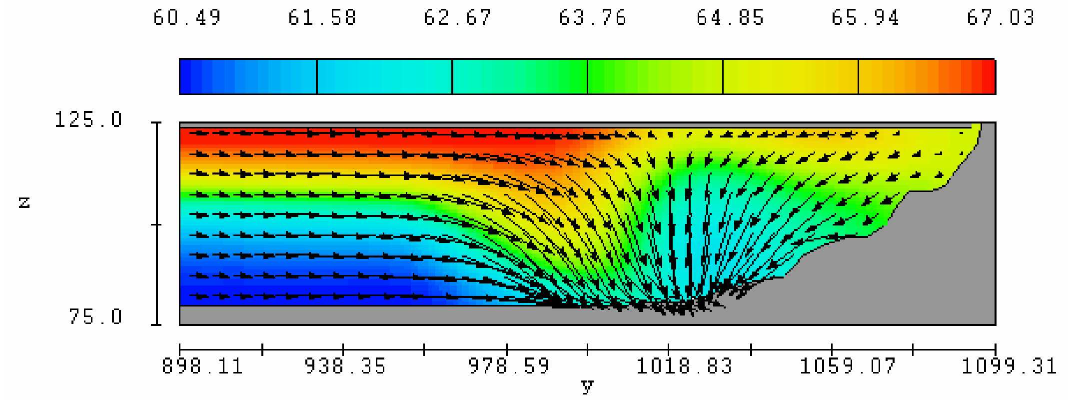

Figure 27. Section along the dam face, with the south debris wall removed (x = 68 feet). The largest velocity vector represents a maximum velocity equal to 0.8 ft/s. The contours represent the reservoir water temperature in °F.

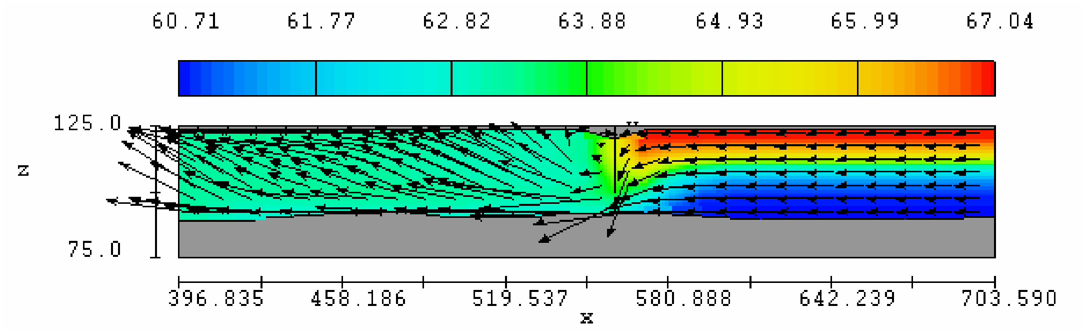

Figure 28. Section through the 500-foot curtain upstream from Nimbus Dam (y = 1,000 feet, and this plot does not extend to debris wall). Notice the well-mixed condition that develops downstream from the curtain. The largest velocity vector represents a maximum velocity equal to 0.3 ft/s. The color contours represent the reservoir water temperature in °F.

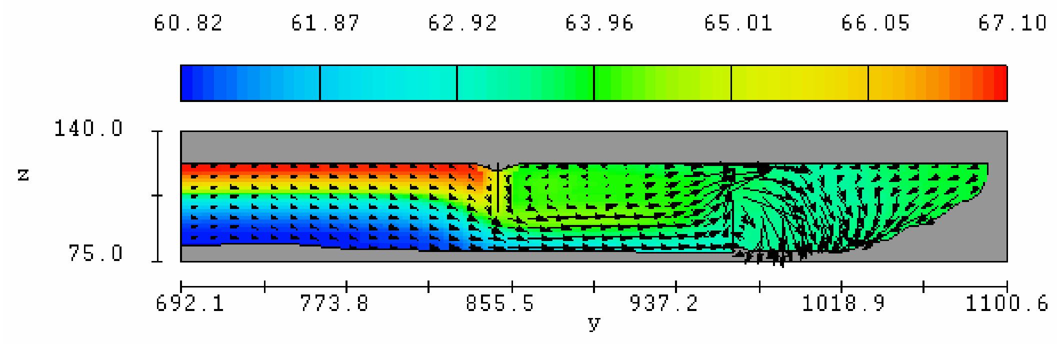

Figure 29. Section through the 500-foot curtain and the debris wall upstream from Nimbus Dam (x = 87 feet). The largest velocity vector represents a maximum velocity equal to 0.7 ft/s, which occurred as water moved over the debris wall. The color contours represent the reservoir water temperature in °F.

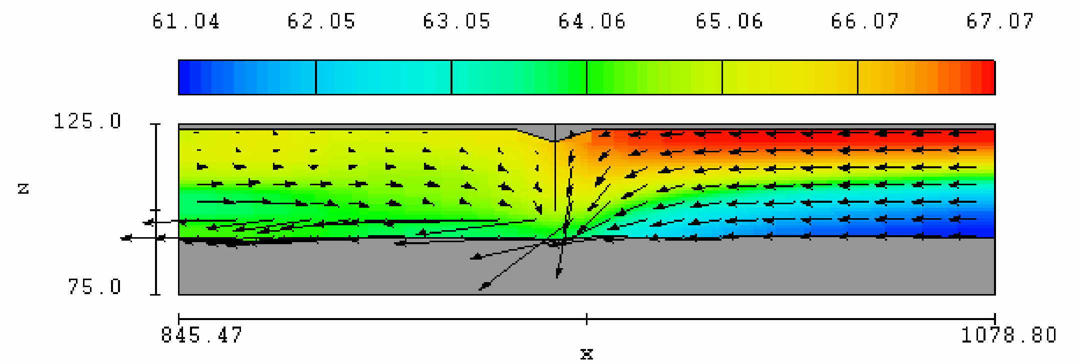

Figure 30. Near-field velocities at the 1,000-foot curtain (y = 1,106 feet). The velocity distribution at the upstream boundary was uniform. The largest velocity vector occurred beneath the curtain and represents a maximum velocity equal to 0.3 ft/s. Notice the shear layer that occurs between the jet exiting the curtain and the ambient water above. This shear zone will cause mixing that will entrain the surface water, which will warm the underflow. The color contours represent the reservoir water temperature in °F.

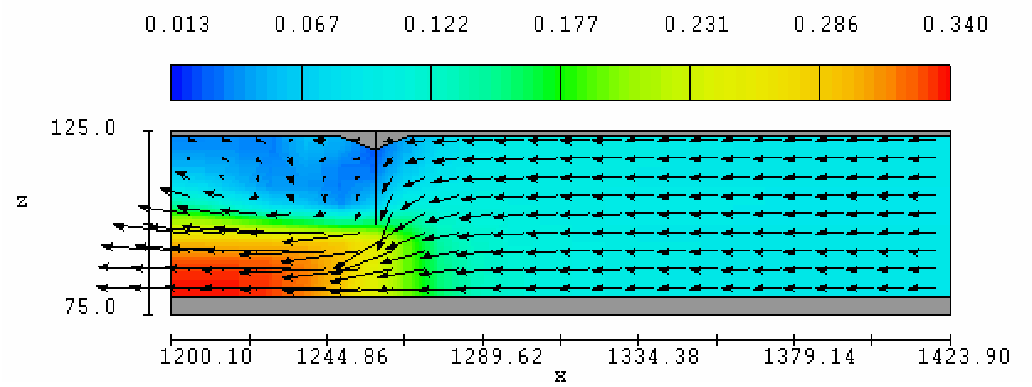

Figure 31. Near-field velocities at the 1,000-foot curtain site (y = 578 feet). The largest velocity vector represents a maximum velocity equal to 0.34 ft/s. At the upstream boundary, the approach velocities are very uniform. The color contours represent velocity magnitudes in ft/s.

Channel Modification Modeling

For the channel modification model, Lake Natoma bathymetry data provided by Reclamation's Mid-Pacific Regional Office were used to develop the model. A relatively large modeling space was constructed. The horizontal dimensions of the model were 11,220 by 2,080 feet. The vertical dimension extended from El. 90 up to El. 130 feet. Meshed grids developed for this study used a 7.5-foot horizontal spacing and a 5-foot vertical spacing. This model space contains about 2.15 million cells. The upstream model extent was near the Cemetery profiling location, and the downstream extent was near the Willow profiling site (see figure 32).

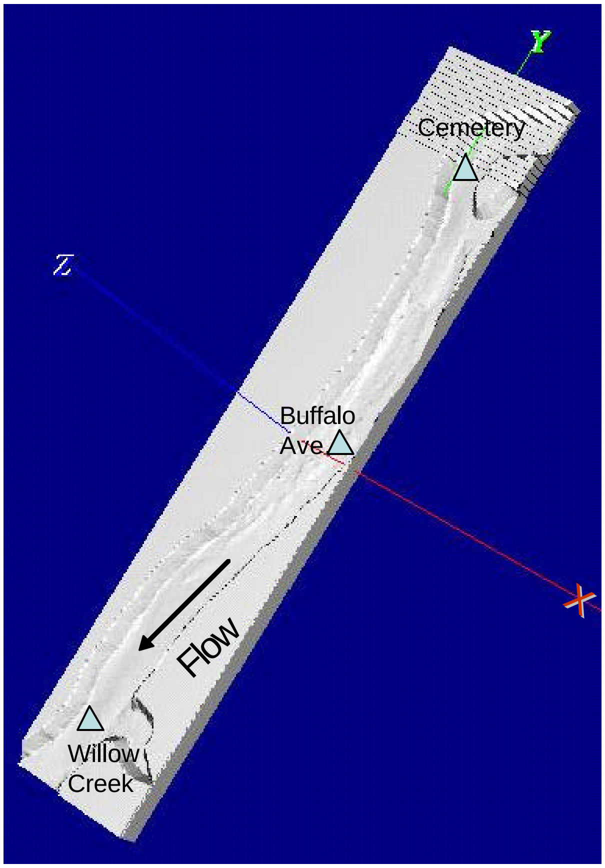

Figure 32. Bathymetry of Lake Natoma for the channel modification model. The 3D (X,Y,Z) coordinate system is also shown.

Boundary Condition Data Needs

This model was difficult to set up because there were no fixed hydraulic controls to use for a boundary, such as Nimbus Dam and Powerplant in the downstream model. As a result, assumptions would have to been made to simplify the highly dynamic flow conditions in this part of Lake Natoma. The dynamic flow conditions were generated by peaking power operations at Folsom Powerplant. Likewise, there are dynamic temperature conditions at both the upstream and downstream boundaries caused by diurnal and flow-related temperature fluctuations. Because of these limitations, along with budget constraints, the project manager decided to postpone modeling this region of Lake Natoma until more field data could be collected. This decision postponed the modeling of channel modifications and/or temperature curtain alternatives and failed temperature profiling deployments prevented this modeling from being completed.

Boundary Condition Data Limitations

Ideally, it would have been useful to have a temperature profiling site near the curtain location to compare to model results. Therefore, a temperature profiling site was established at Folsom Junction, which is between the Buffalo Avenue and Cemetery sites. The Folsom Junction site was identified as a good potential curtain site using the 2001 bathymetry data. Unfortunately, this temperature profiling deployment did not produce useful data until after the project was scheduled for completion. It would also be useful to have velocity profile data at the boundary conditions to verify 3D model velocity profiles.

Discussion

A substantial amount of reservoir operations, temperature profile data, and modeling results has been produced during this study. An analysis of the data and modeling results have revealed that Lake Natoma is too large and too dynamic to be effectively modeled using the FLOW-3D model on a personal computer system. Hourly temperature and water surface fluctuations, along with lengthy travel times, make it difficult to run meaningful FLOW-3D simulations because of all the simplifying assumptions that were made. FLOW-3D was used to describe two brief snapshots of hydraulic and thermal conditions in Lake Natoma. While the FLOW-3D model runs indicated there was little to no reduction in Nimbus Powerplant release temperatures, there may be other combinations of alternatives that could reduce the temperature gain in Lake Natoma. Likewise, modifying Folsom Powerplant operations from peaking to baseload could significantly change the performance of the temperature modification alternatives.

After a review of the modeling results, it was apparent that too many simplifying assumptions were made to make this model a practical tool for evaluating the long-term impacts of structural and operational modifications proposed to deliver cooler water to the lower American River. As a result, all FLOW-3D modeling results should be considered provisional, and additional model development will be required to improve the model performance. Furthermore, it became apparent during the course of this study that a 2D reservoir water quality model would be necessary to identify the most beneficial alternative(s) for the time period when Lake Natoma is thermally stratified. The 2D model selected should be able to handle the complex reservoir operations and to model an entire year of reservoir operations. Furthermore, a 2D model should be able to model the upstream curtain concept, modifications to the Nimbus Powerplant intake, and various levels of channel modification. Lake Natoma appears to be well suited for 2D modeling because it is a long, narrow water body.

It is likely that a 2D reservoir model would not have the spatial resolution necessary to adequately design and locate an intake curtain or resolve the effects of near-field power intake modifications associated with dredging or removal of the existing debris wall surrounding Nimbus Powerplant. To help answer these questions, FLOW-3D can be used, in a similar manner as it was used in this study, to fine tune the design and effectiveness of the proposed alternatives or a combination thereof. It is envisioned that the 2D model would generate the boundary condition data needed to initialize the FLOW-3D model.

A substantial amount of reservoir operations and temperature profile data have been collected and archived as part of this study. This data is available for future analysis or modeling efforts. However, additional data collection may be required or collection sites may have to be relocated to support the development of future models. Collecting flow and temperature data from the penstock flowmeters at Folsom and Nimbus dams should be continued because it is the most accurate (and, likely, the most reliable) method to collect data.

Conclusions and Recommendations

- The complexity of the Folsom/Natoma reservoir system will require a combination of 2D and 3D reservoir modeling to fully describe the hydrodynamic and water quality characteristics necessary to evaluate the proposed temperature modification alternatives. Models of both reservoirs will be useful for an extension of this study and for future studies involving raising Folsom Dam, upgrading the Folsom shutters, adding selective withdrawal capability to other diversion structures, and conducting operational studies related to the proposed modifications to the Folsom spillway outlets.

- Based on a very limited number of Flow-3D model runs using several simplifying assumptions to the boundary conditions, it appears that none of the proposed temperature modification alternatives will provide significantly colder water to the lower American River. However, this result should be considered provisional.

- Difficulties with CFD model development, calibration, and budget constraints prevented an evaluation of the channel modification/upstream curtain alternatives. However, analysis of near-bottom temperature data showed that there was typically less than 1 °F of temperature gain between the Cemetery and Willow profiling sites where dredging would be warranted.

- Temperature profile data analyses showed that the maximum potential for temperature modification in Lake Natoma was 1.8 °F. It is important to note that these results are applicable to powerplant operations and meteorological conditions for the period of analysis. It is possible that changing Folsom Powerplant from peaking to baseload operations would significantly change the dynamics of Lake Natoma and create a entirely different response.

- Temperature profiling sites were very useful for understanding the hydrodynamics and thermal characteristics of Lake Natoma. It is recommended that temperature profiling sites remain in operation to collect calibration data for future modeling projects. However, it is recommended that the profiling locations be reevaluated and relocated if doing so will produce better data for model calibration.

- Collecting flow and temperature data from the penstock flowmeters at Folsom and Nimbus Dams should be continued because it is the most accurate (and, likely, the most reliable) method to obtain inflow and outflow temperature data. Furthermore, these data will be an important component to the calibration data set for any future reservoir models.

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