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Final

Measured and Simulated Temperatures in Putah Creek, Yolo and Solano Counties, California

Prepared for:

University of California, Davis
Davis, CA 95616
Contact: Sid England
916/752-2432

Prepared by:

Jones & Stokes Associates, Inc.
2600 V Street, Suite 100
Sacramento, CA 95818-1914
Contact: Gus Yates
916/737-3000

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EXECUTIVE SUMMARY

The temperature regime in Putah Creek between Monticello Dam and the Yolo Bypass is an important factor affecting the distribution of fish species along the creek. During the summer months, cold water (about 11°C) released to the creek from Lake Berryessa warms rapidly as it flows downstream and can reach temperatures too high (over 30°C) for some native and game fish species.

Historical temperature data compiled for this study included 3 years of weekly temperature measurements at the University of California, Davis (UC Davis) wastewater treatment plant outfall and the results of temperature surveys conducted on three dates during 1990-1992. For this study, data loggers were used to record hourly water temperatures at three locations during June through September in 1993 and 1994. Temperatures were manually measured at five additional locations on eight occasions during April through October 1993 and five occasions during June through September 1994.

The data revealed consistent temporal and spatial patterns in the temperature regime. Temperatures at Solano Dam were generally less than 2°C warmer than at Monticello Dam because of the high flow between the dams during summer. The daily average temperature typically increased by about 10-11°C along the first 4 miles below Solano Dam, although much smaller increases occurred in spring and fall and during rainy weather. Maximum afternoon water temperatures downstream of Winters commonly reached 25-30°C. Diurnal temperatures generally fluctuated ±1-2°C around the daily average temperature.

There was a decrease in the rate of warming along the reach upstream of Stevenson Bridge, probably because of groundwater entering the creek. Temperatures continued to increase downstream of Stevenson Bridge. Thermal stratification in the creek occurs in large pools when flow and velocity are low.

A spreadsheet model of creek temperatures was developed for this study using Lotus 1-2-3. The model simulates temperatures on an hourly basis by calculating the mass balance and energy balance for water in the creek as it flows down a series of reaches. The creek between Monticello Dam and the Yolo Bypass was divided into 25 reaches averaging about 1 mile in length. The mass balance calculations accounted for Solano Project operations, irrigation diversions and return flow, evaporation, riparian vegetation evapotranspiration, spills from Willow Canal, discharges from UC Davis facilities, and seepage of water through the creekbed. The energy balance equations accounted for solar and atmospheric radiation, shading by riparian vegetation, longwave radiation from the water surface, evaporation, conduction, and convection. The energy balance equations are similar to those used in the QUAL2E and SNTEMP models.

Model parameters were calibrated to obtain a satisfactory simulation of measured temperatures during June through September 1993 and 1994. The model was able to simulate downstream warming patterns, diurnal temperature fluctuations, and weather-related daily temperature variations reasonably accurately. Simulated temperatures at Interstate 505 (I-505) and

Stevenson Bridge (where data loggers were located) were almost always within 1°C of measured temperatures.

Sensitivity analysis indicated that simulated temperatures are fairly sensitive to wind speed and streamflow and less sensitive to air temperature and dew point temperature. The amplitude of the diurnal temperature fluctuations is strongly affected by local water depth, and the downstream rate of warming is fairly sensitive to stream width and shading.

The model was used to simulate three hypothetical temperature management strategies. Increasing the release from Solano Dam by 20 cubic feet per second (cfs) caused a decrease in water temperature of about 2.5°C along most of the distance from the dam to the Yolo Bypass. Eliminating irrigation diversions decreased water temperatures by 0.2-0.5°C, mostly between Stevenson Bridge and the Yolo Bypass. Removing selected beaver dams decreased temperatures by up to 3°C near Winters, but the effect gradually diminished to a decrease of only 0.5 C at the Yolo Bypass.

INTRODUCTION

Putah Creek flows from Lake Berryessa to the Yolo Bypass generally along the boundary between Yolo and Solano Counties (Figure 1). The aquatic and riparian habitats along the creek are remnants of much more extensive habitat areas that existed in the Central Valley of California before European settlement. The Putah Creek stream corridor supports a great diversity of vegetation and wildlife, including 26 species of fish. The fisheries in Putah Creek are valuable for recreational fishing, biological research, and protection of native species.

The distribution and condition of fish species in Putah Creek depend strongly on water temperature, especially in summer. Temperatures in the creek vary greatly in summer because the creek is supplied by cold water from Lake Berryessa, and the water warms rapidly as it flows downstream. Water temperatures along the lower part of the creek usually exceed optimal or maximum temperatures for trout and sometimes exceed maximum temperatures for most other native species and smallmouth bass.

Local, state, and federal agencies and public interest groups have been considering ways to improve and manage conditions for fisheries in Putah Creek. Because fish are highly sensitive to water temperature, considerable attention has been focused on ways to regulate temperatures in the creek, and in particular, on ways to avoid high temperatures in summer. These efforts have been hampered by the lack of information regarding the existing temperature regime in the creek. Evaluation of alternative strategies for changing the temperature regime has been difficult without a quantitative tool for simulating temperatures in the creek.

This report describes the results of a study designed to document the existing temperature regime in Putah Creek and develop a temperature model capable of simulating existing and managed temperature regimes. The study investigated only the reach of Putah Creek between Lake Berryessa

(Monticello Dam) and the Yolo Bypass; the reach upstream of Lake Berryessa was not considered. The scope of the study included the following tasks:

- monitoring hourly water temperatures using data loggers at three locations during June through September 1993 and June through September 1994,
- manually measuring water temperatures periodically at five additional locations,
- compiling available historical temperature data,
- documenting creek width and shading characteristics with low-altitude aerial photography,
- developing assumptions and data regarding stream-aquifer interactions consistent with those used in a concurrent groundwater study by Luhdorff and Scalmanini Consulting Engineers.
- developing and calibrating a computer model to simulate temperatures in the creek, and
- simulating selected alternatives for managing temperatures in the creek.

MEASURED TEMPERATURE REGIME

The existing temperature regime in Putah Creek can be described in terms of temporal and spatial variations. Temporal variations include daily and seasonal cycles that are generally regular but are affected by transient weather conditions. Spatial variations include temperature changes as the water flows downstream below Monticello Dam. Also, vertical temperature stratification can occur in pools under low-flow conditions.

Temperature data were obtained from several sources. Weekly temperature measurements at the UC Davis wastewater treatment plant outfall during 1990-1993 were transcribed from field notes on file at the treatment plant. The outfall is located about 200 feet upstream of the Old Davis Road bridge (Figures 1a and 1b). Measurements of temperature, dissolved oxygen (DO), and turbidity for both the creek and the outfall were obtained. The U.S. Geological Survey (USGS) recorded daily water temperature at the gaging station "Putah Creek near Winters" during 1966-1981. The gage is located 1.3 miles below Monticello Dam (Figure 1a). Temperatures at selected locations along the creek were measured during three reconnaissance surveys in 1991 and 1992. Two of the surveys were conducted by Jones & Stokes Associates hydrologists Gus Yates and Bill O'Leary, and one survey was conducted by Tom Harvey of the U.S. Fish and Wildlife Service. Vertical temperature profiles were measured during one of the surveys.

For this study, dual-channel data loggers were installed at three locations (sites 1 and 3 in Figure 1a and site 5 in Figure 1b), and they recorded water temperature hourly during June through September 1993 and June through September 1994. Both channels recorded water temperature, although one probe at site 3 was accidentally pulled out of the water and recorded air temperature for several weeks in August and September 1993. Water temperatures were measured at those sites and five additional sites (sites 2, 4, 6, 7, and 8) on eight dates during April through October 1993 and five dates during June through September 1994. At most sites water temperatures were recorded at a depth of 1-2 feet in locations where the current was swift enough to prevent thermal stratification. Surface and bottom temperatures were measured at sites where thermal stratification was present.

Temporal Temperature Variations

Seasonal and Annual

The temperature of Putah Creek upstream of the UC Davis wastewater outfall during 1990-1993 is shown in Figure 2. There were several periods of no flow during 1990-1993. During some of these periods, the creek water quality was not measured, and during other periods, the quality of standing water in pools upstream of the outfall was measured. The maximum creek temperatures usually occurred in June and July and were as high as 29°C in 1991. In 1993, the maximum recorded temperature was only 25°C. This decrease probably resulted from a change in the time of day when temperature was measured. Water temperatures in the creek also undergo diurnal (i.e., daily) cycle as heat is gained during the day and lost at night. Before March 1993, temperature was measured around 1 p.m., when temperatures approach the high point of the diurnal cycle. Since then, temperatures generally have been measured around 9 a.m., which is only about an hour after the low point of the cycle. The two highest creek temperatures recorded during summer 1993 were on the 2 days when measurements were made at 1 p.m. instead of 9 a.m. The temperature of the UC Davis wastewater discharge also is shown in Figure 2 and is discussed below under "Input Data".

During winter, minimum creek temperatures above the outfall were often lower than typical temperatures at depth in Lake Berryessa and reflected net cooling along the creek during cold weather. The minimum recorded temperature was less than 6°C in all 3 years with complete winter records and was as low as 2°C during winter 1993.

The DO concentration in the creek upstream of the wastewater outfall during 1990-1993 is shown in Figure 3. High water temperatures are less stressful for most fish species if DO levels remain high. The recorded DO levels in the creek generally ranged between 6 and 12 milligrams per liter, with the high values usually occurring in winter. DO also follows a diurnal cycle. Before March 1993, DO was measured at approximately 1 p.m., when DO would be near its peak concentration for the day. Since then, measurements have generally been made at approximately 9 a.m. This may explain why DO appears to have been slightly lower in spring and summer 1993 than in 1992.

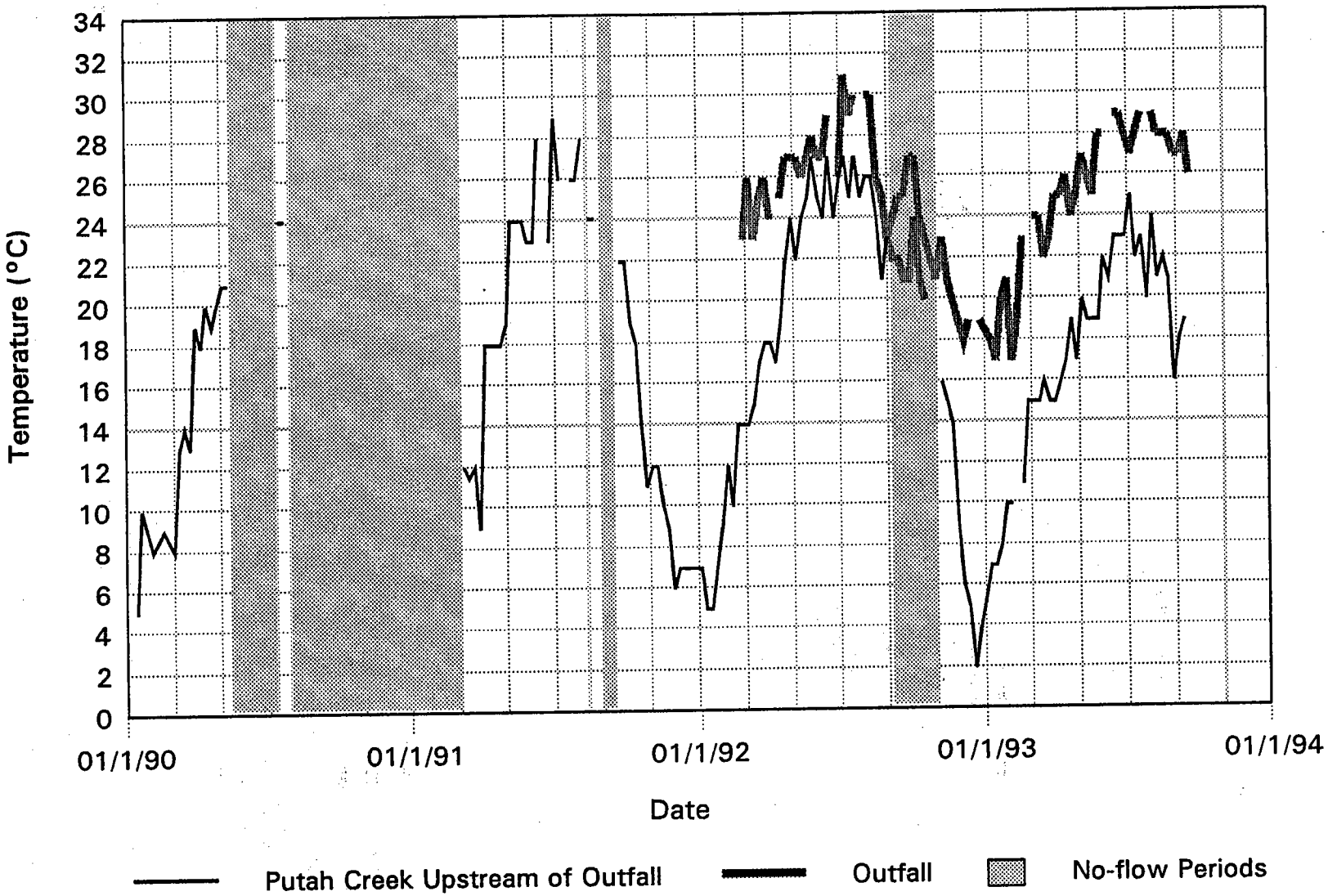

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Figure 2
Water Temperatures of Outfall from UC Davis Wastewater Treatment Plant and Putah Creek Upstream of Outfall for 1990–1993

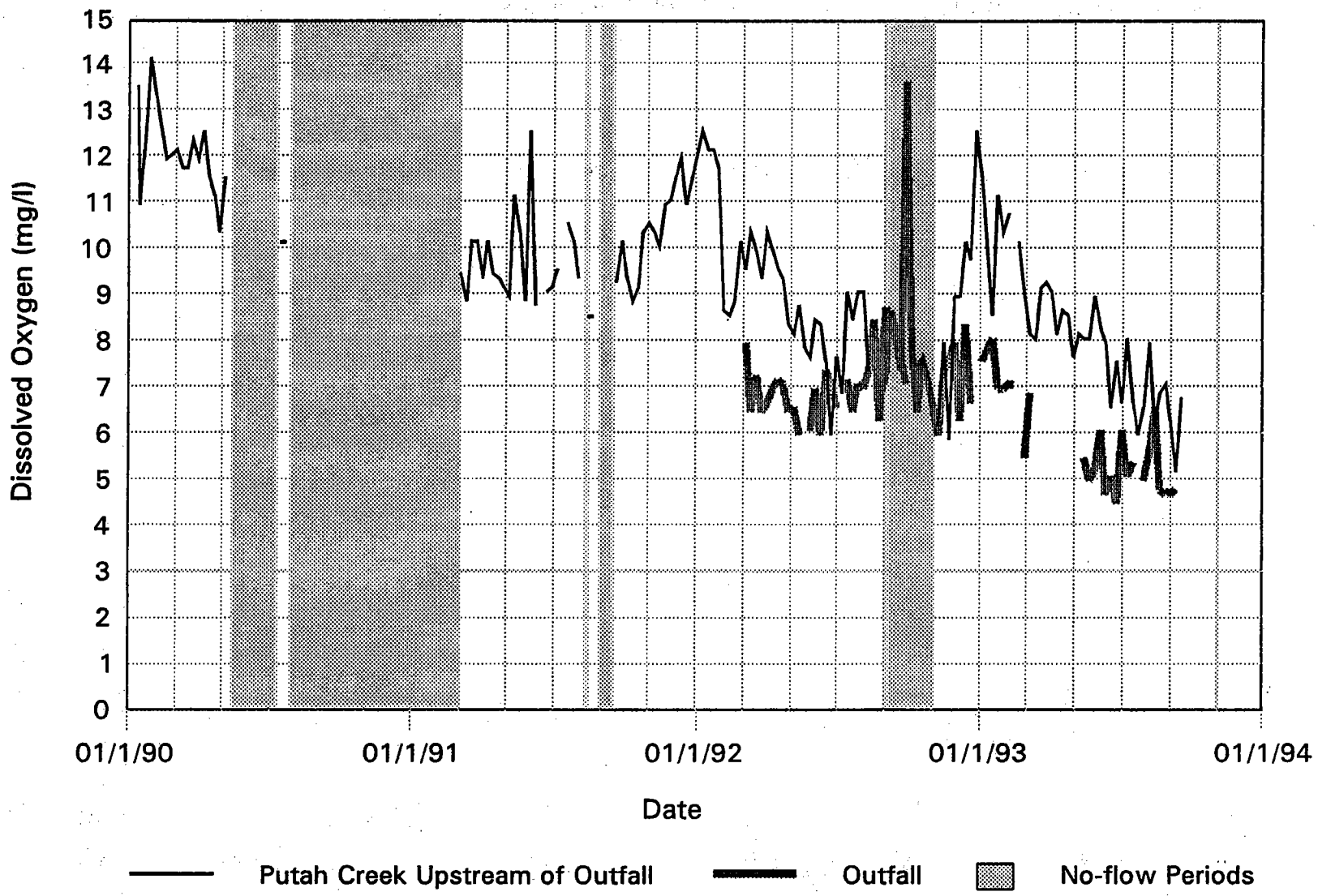

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Figure 3
Dissolved Oxygen Content of Outfall from UC Davis Wastewater Treatment Plant and Putah Creek Upstream of Outfall for 1990–1993

The turbidity of the creek upstream of the wastewater outfall is shown in Figure 4. The turbidity of the creek water increases substantially during storm events when runoff enters the creek.

Daily water temperatures in Putah Creek at the USGS gaging station below Monticello Dam during 1980-1981 are shown in Figure 5. Water temperature in winter is lower and more variable than in summer. The variability probably results from sporadic runoff from Cold Canyon. The temperature of the runoff is strongly affected by ambient weather conditions, whereas the temperature of the release from Lake Berryessa remains relatively stable. The temperature in winter typically was 10-11°C in 1980 and approximately 12°C in 1981. During spring and summer 1981, the temperature increased steadily from 12.2°C to 13.3° C. During summer 1993, temperatures measured for this study were lower than in 1981. The water temperature at the outlet of Monticello Dam was 10.8°C and 10.3°C on July 31 and August 27, 1993, respectively.

Temperature variations in lower Putah Creek over periods of days to weeks during June through September 1993 and 1994 are evident in the measured hourly temperature data shown in Figures 6a and 6b. The temperature at Solano Dam usually remained between 11°C and 15° C. Because of the high rates of flow between Monticello Dam and Solano Dam, the average daily water temperature increased by only about 2°C along this reach.

The temperatures at sites 3 and 5 showed some variations in response to weather conditions. Most notably, temperatures were 6-7°C cooler during an unusual period of rainy weather in early June 1993 than during most of the rest of the summer. Average daily temperatures remained fairly constant during July and August at about 22°C at site 3 and 24.5 C at site 5. Average daily temperature at the UC Davis wastewater plant outfall was probably about 24-25°C, if the measured data are adjusted for the time of day of the measurement.

Diurnal

The hourly data (Figures 6a and 6b) indicate that the amplitude of the diurnal temperature cycle tends to remain fairly constant at each site as long as the weather remains clear. Cloud cover tends to decrease the amplitude in addition to decreasing the average daily temperature. The amplitude under typical clear weather conditions usually is about 2-4°C. The amplitude is strongly affected by water depth in the reach immediately upstream of the measuring point.

Diurnal temperature fluctuations vary with depth in pools where the water column is thermally stratified. At site 7 upstream of Old Davis Road in 1994, for example, diurnal temperature fluctuations had an amplitude of 6-7°C near the surface and about 2°C near the bottom.

Figure 7 shows the diurnal temperature variations at site 1 during June 6-8, 1993, in detail. Hourly air temperature at the California Irrigation Management Information System (CIMIS) weather station near Davis is also shown for comparison. The CIMIS station is located about 1 mile north of the creek and 0.2 mile west of State Route 113 (SR 113) (Figure 1b). Figures 8 and 9 show similar sets of data for sites 3 and 5. The diurnal temperature cycle is not symmetrical. The minimum water temperature typically occurs at approximately 8 a.m. and the maximum occurs at

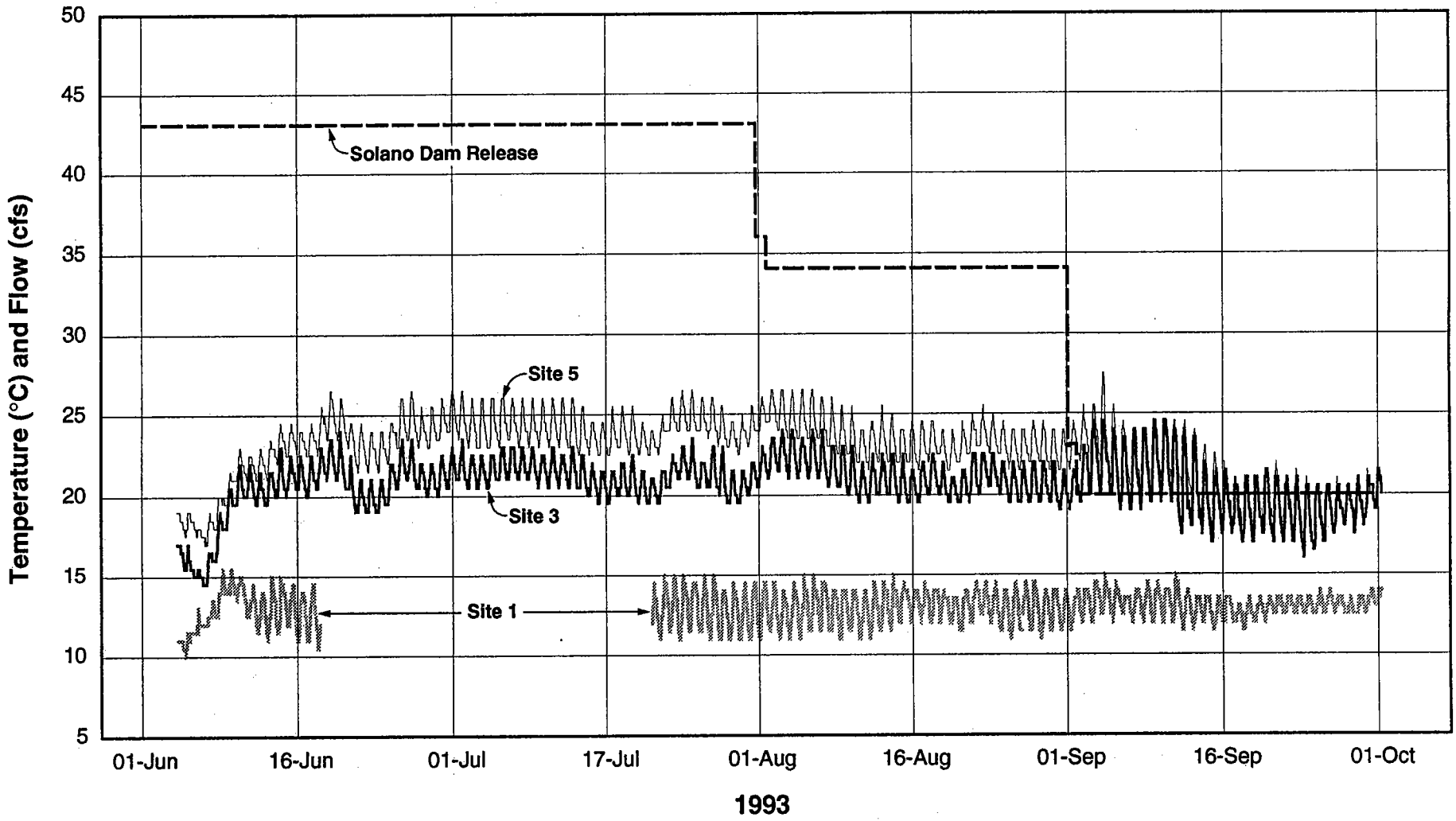

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Figure 6a
Hourly Water Temperatures at Sites 1, 3, and 5 along Lower Putah Creek during June through September 1993

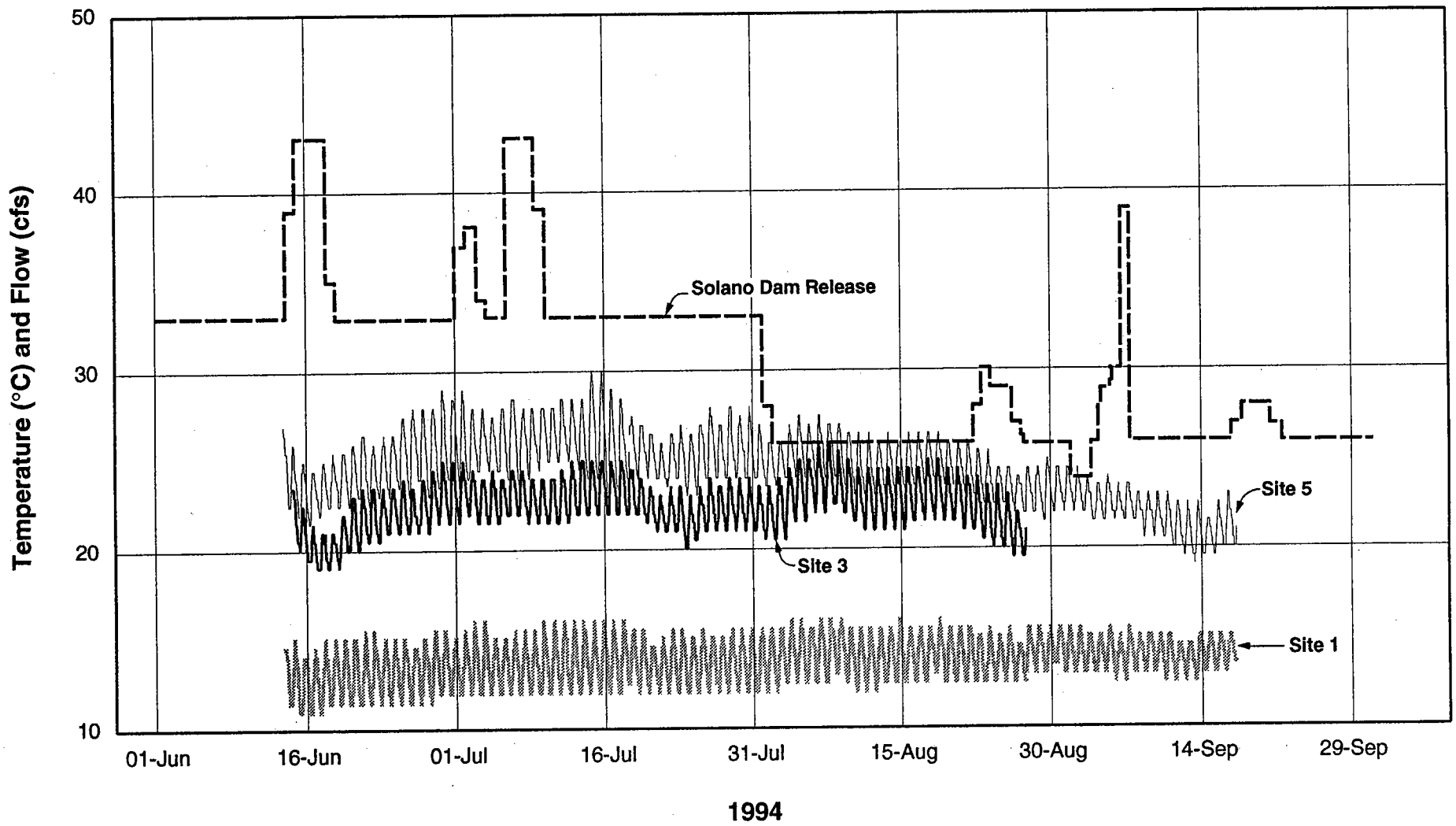

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Figure 6b
Hourly Water Temperatures at Sites 1, 3, and 5 along Lower Putah Creek during June through September 1994

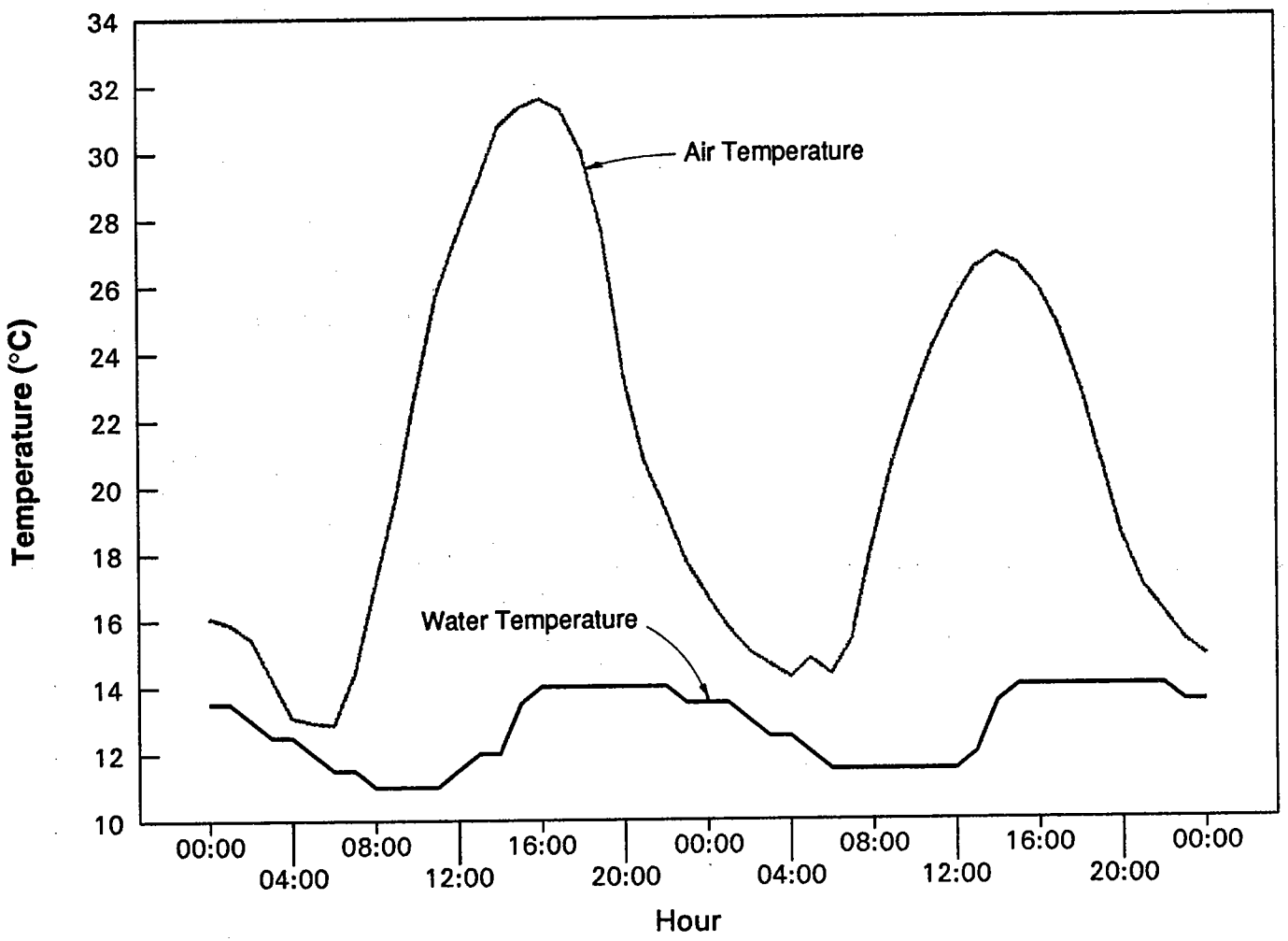

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Figure 7
Hourly CIMIS Air Temperatures and Hourly Datalogger Water Temperatures at Site 1 Downstream of Solano Dam for August 9-10, 1993

approximately 4 p.m. The warming phase is driven largely by solar radiation, which becomes significant when the sun first shines directly on the water surface. Although solar radiation peaks at midday, the water continues to warm up as long as solar radiation is larger than the rate of heat loss by evaporation, conduction, and longwave radiation. The heat loss fluxes are small compared to the rate of heat gain from solar radiation, so water temperatures cool gradually overnight until the sun rises again the following morning.

The data in Figures 7 through 9 also illustrate that air temperature is not the principal factor regulating water temperature. At site 1, the daily average water temperature is consistently less than the daily average air temperature. At site 3, the average temperatures are about equal, and at site 5, the daily average water temperature is greater than the daily average air temperature.

Spatial Temperature Variations

Downstream Warming Rate

Longitudinal profiles of water temperature along Putah Creek between Solano Dam and the Yolo Bypass on 12 dates are shown in Figures 10 and 11. Temperatures increase rapidly in the first 4 miles below the dam and much more gradually below that. The temperature increase in the first 4 miles is often 10-11°C during periods of warm, sunny weather, and this amounts to about two-thirds of the total temperature increase downstream of Solano Dam.

On almost every sampling date there was a dip in the temperature profile near Stevenson Bridge. There are no significant surface water inflows in that vicinity, and the temperature drop almost certainly results from groundwater seepage into the creek along the 2-mile reach upstream of the bridge. Groundwater inflow of about 2 cfs along this reach is common, and ambient groundwater temperatures are cooler (17.5°C) than creek temperatures in summer (California Division of Water Resources 1955, Thomasson et al. 1960). Temperatures at Pedrick Road in 1994 appear to be lower than at Stevenson Bridge because flow was low enough that the large pool at Pedrick Road stratified. The data plotted in Figure 11 are the relatively cool bottom temperatures.

Vertical Temperature Profiles

Thermal stratification develops in large pools when flow is low and water velocities are small. For example, when surface and bottom temperatures were measured at 10 locations below Solano Dam on July 26, 1992, the water column was found to be well mixed at most locations, with surface temperatures within 1°C of bottom temperatures. In two large pools with very slow water velocities, a surface layer about 1 foot thick was 3-4°C warmer than the bottom temperature, as shown in Figure 12. The trend of the temperature profile along the creek indicated that stratification resulted from additional warming of the surface layer, rather than cooling of the bottom layer. Stratification also was found consistently at stations 6 and 7 (at Pedrick Road and upstream of Old Davis Road) during summer 1994, when flow at those locations was less than about 2 cfs. Surface temperatures commonly reached 26-30°C in the afternoon, whereas bottom temperatures generally

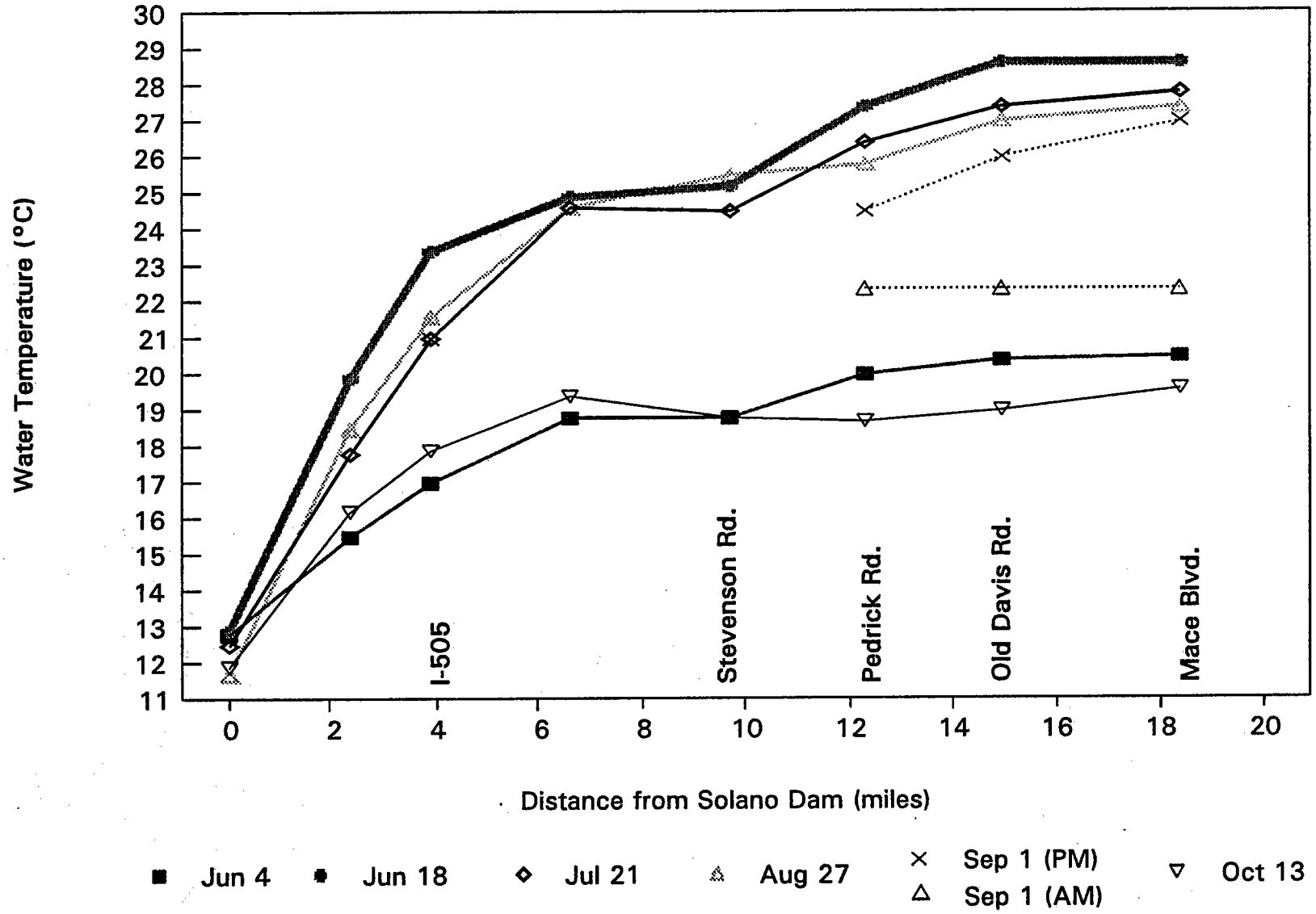

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Figure 10
Water Temperature Profiles of Putah Creek from Solano Dam to Mace Boulevard Bridge for June through October 1993

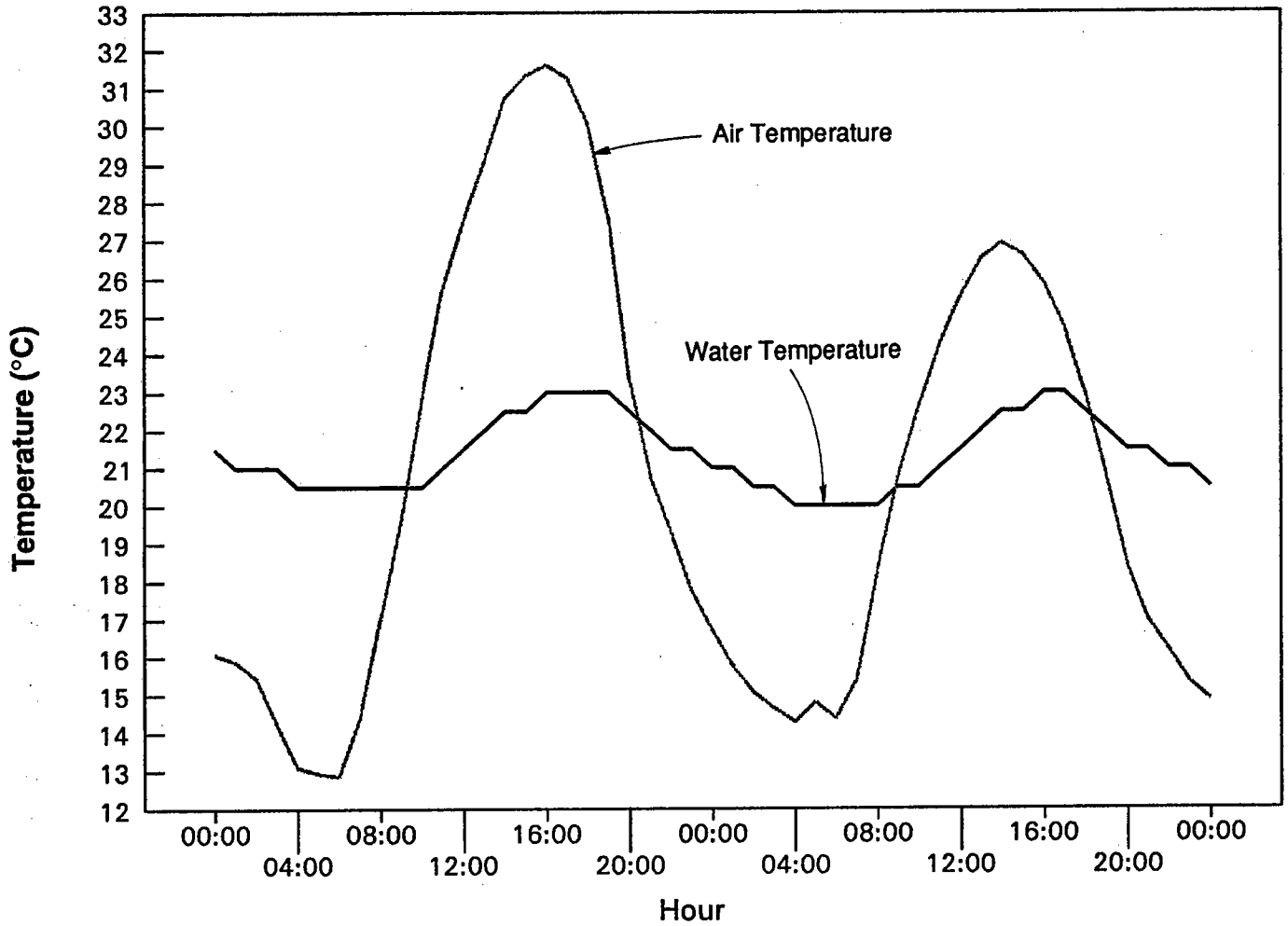

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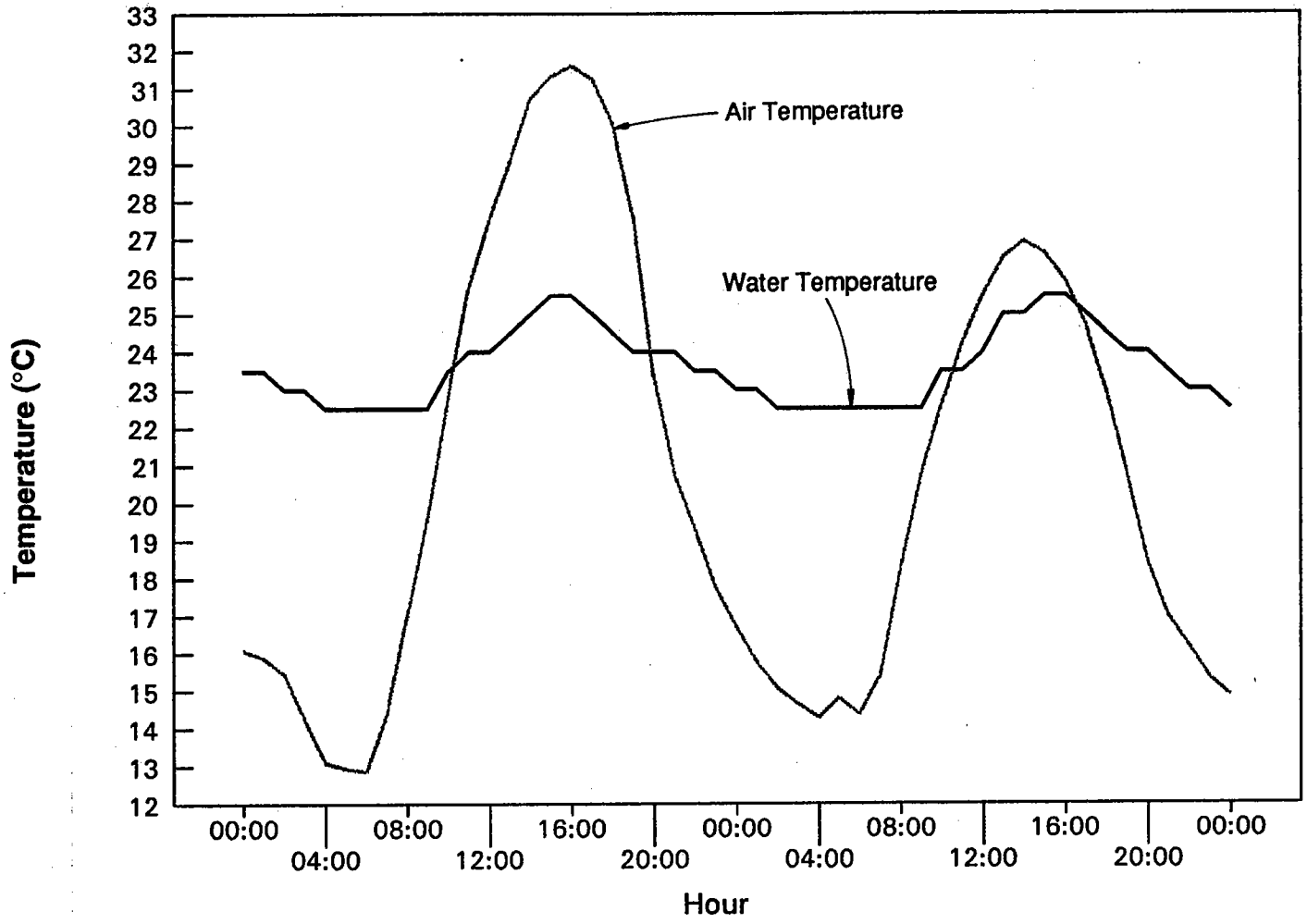
Figure 8
Hourly CIMIS Air Temperatures and Hourly Datalogger Water Temperatures at Site 3 near I-505 for August 9–10, 1993



Jones & Stokes Associates, Inc.

Figure 9
Hourly CIMIS Air Temperatures and Hourly Datalogger Water Temperatures at Site 5 at Stevenson Bridge for August 9–10, 1993

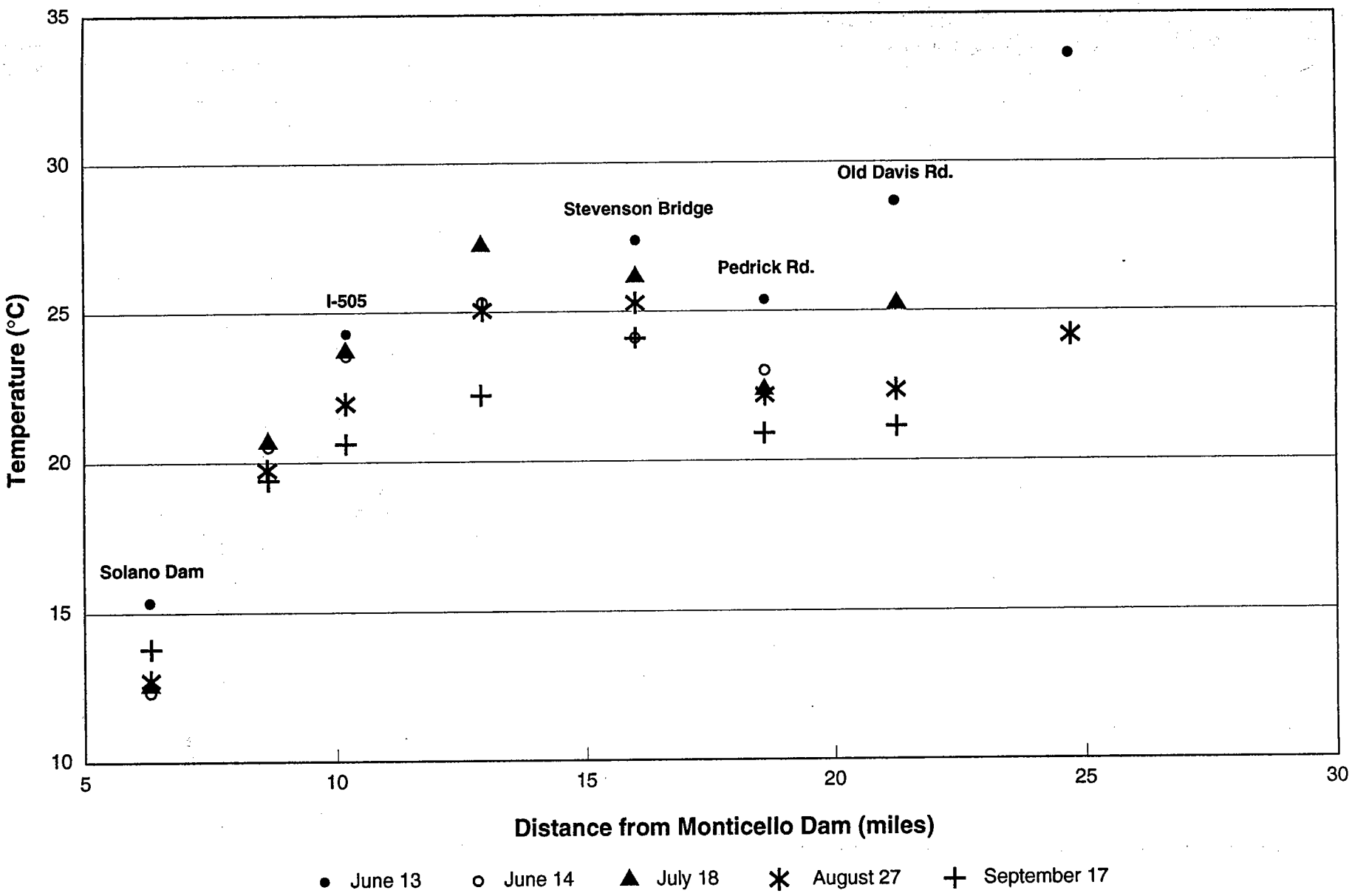


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Figure 11
Water Temperature Profiles of Putah Creek from Solano Dam to Mace Boulevard Bridge for June through September 1994

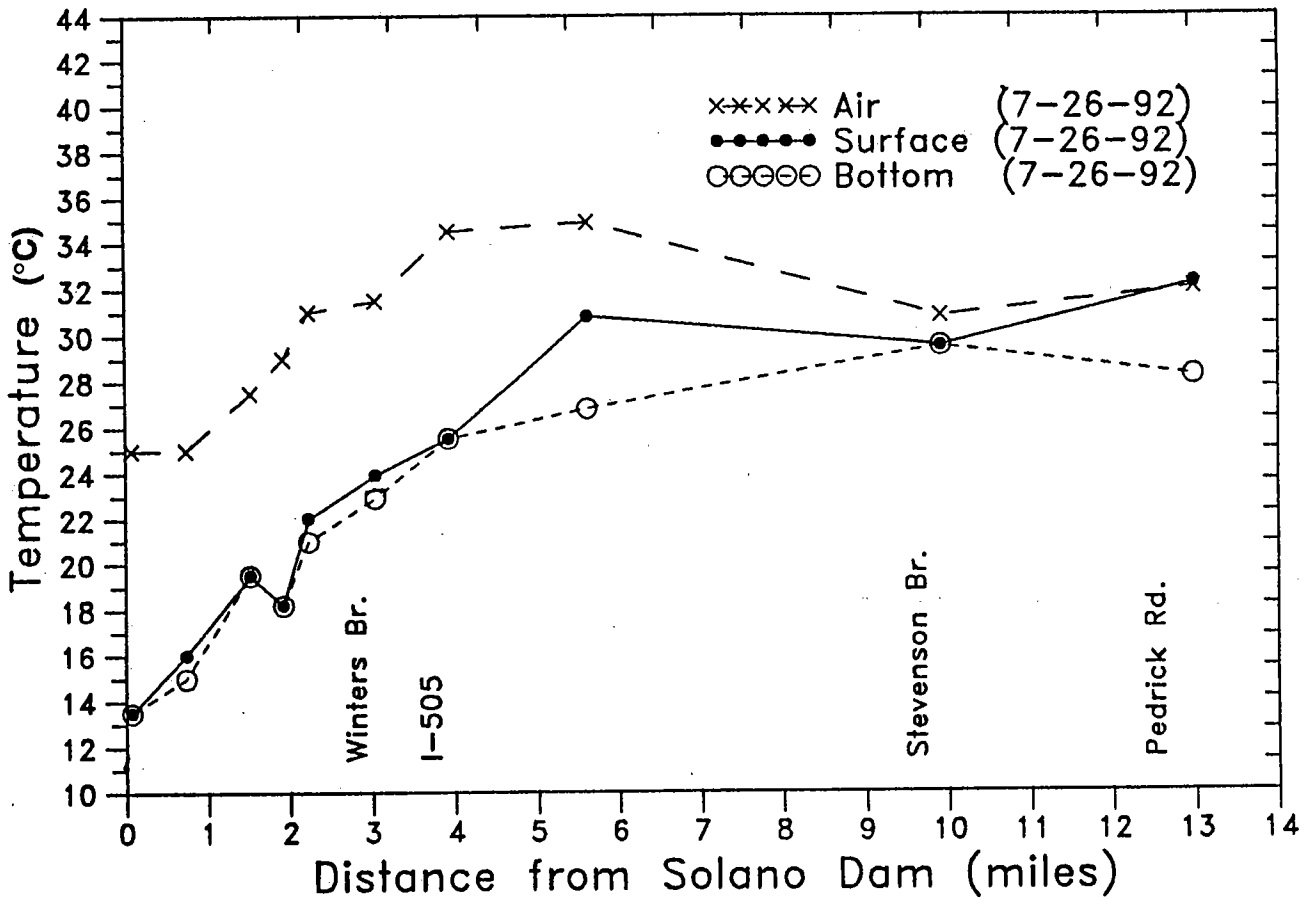

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Figure 12
Profiles of Putah Creek Air Temperatures and Surface and Bottom Water Temperatures from Solano Dam to Pedrick Road Bridge on July 26, 1992

were 21-24°C. The highest temperature recorded was 33.6°C at the surface of an isolated pool at Mace Boulevard (site 8). The differences between midafternoon surface and bottom temperatures at sites 7 and 8 generally were between 3.5°C and 6.5°C and averaged approximately 4.0°C.

TEMPERATURE SIMULATION MODEL

A spreadsheet model of creek temperatures was developed for this study using Lotus 1-2-3. The model calculates the mass balance and energy balance for water in the creek as it flows down a series of reaches. Daily mass balances and hourly energy budgets are calculated for a 1-month period. Putah Creek between Monticello Dam and the Yolo Bypass was divided into 25 reaches as shown in Figures 1a and 1b. Reach boundaries were located at temperature measurement sites, transitions in channel or vegetation characteristics, or easily identified cultural features. Table 1 is a printout of part of the spreadsheet and shows the results of the mass and energy balance equations by reach for a selected hourly time step.

The Putah Creek model was adapted from a model developed to simulate temperatures in the Owens River (Jones & Stokes Associates 1992). The most significant modifications made for this study are:

- use of measured hourly meteorological data instead of assumed hourly distributions of daily average data,
- addition of an algorithm to calculate the shading effects of tall riparian vegetation along the streambank,
- inclusion of seepage to and from groundwater as a spatially variable flow, and
- use of width and depth functions that reflect the presence of pools along much of lower Putah Creek.

Algorithms for Mass and Energy Balance

Mass Balance

The outflow from each reach is calculated in the model by adjusting the inflow from the adjacent upstream reach for local inflows and outflows. Inflows and outflows included in the model are releases from Monticello Dam, diversions to Putah South Canal, irrigation diversions by riparian landowners, irrigation return flow, spills from the end of Willow Canal, discharges from facilities at UC Davis, evapotranspiration by riparian vegetation, evaporation from the creek surface, and seepage through the creekbed to and from groundwater. Estimates for all but the last two of these inflows and outflows are input to the model directly as data, as described below under "Input Data".

Evaporation affects both the energy balance and the mass balance. The amount of water lost from the creek surface due to evaporation is calculated after the energy balance has been estimated

Table 1. Excerpt of Model Worksheet Showing Flow and Energy Budget Calculations by Reach at Noon on July 15, 1994.

Model Segment Number (Reach)	Mile Below Lake Berryessa (mi)	Location	Local Inflow (cfs)	Local Outflow (cfs)	Stream Flow (cfs)	Mean Depth (ft)	Surface Width (ft)	Mean Velocity (ft/sec)	Total Travel Time (hours)	Surface Area (acres)	Segment Volume (AF)	Local Inflow Temp (°C)	Initial Water Temp (°C)	Ending Water Temp (°C)
0	0.00	Monticello Dam			636.0							11.5	11.5	
1	2.10				636.0	4.1	52	3.00	1.0	13.3	54.0		11.5	11.5
2	4.25				636.0	4.1	52	3.00	1.1	13.6	55.3		11.5	11.5
3	5.15	Lake Solano			636.0	8.0	300	0.26	5.0	32.7	261.8		12.0	12.3
4	6.31	Site 1– Solano Dam		603.00	33.0	4.5	300	0.02	3.6	42.2	189.8		12.7	13.2
5	7.05		0.0	3.75	29.2	4.2	56	0.13	7.7	5.0	20.9		14.4	14.7
6	7.75	Wetland	0.0	3.58	25.7	4.1	204	0.03	29.6	17.3	71.5		19.2	19.6
7	8.65	Site 2	0.0	4.56	21.2	4.1	42	0.12	8.7	4.6	18.5		20.1	20.4
8	9.35	Perc. Dam	0.0	3.54	17.6	4.0	40	0.11	7.8	3.4	13.6		20.8	21.2
9	10.20	Site 3– I–505	0.0	4.30	13.3	3.9	38	0.09	10.4	3.9	15.2		21.8	22.2
10	11.25		0.0	3.13	10.2	3.8	36	0.07	16.0	4.6	17.6		22.8	23.2
11	12.00		0.0	1.23	9.0	3.8	36	0.07	14.6	3.3	12.4		23.8	24.3
12	12.90	Site 4	0.0	0.68	8.4	3.8	36	0.06	19.7	3.9	14.7		25.0	25.5
13	14.20		0.8	0.40	8.8	2.8	26	0.12	16.4	4.0	11.3	17.5	25.0	25.5
14	15.00		0.5	6.30	2.9	2.6	24	0.05	7.7	2.3	6.1	17.5	24.7	25.2
15	16.00	Site 5– Stevenson's Bridge	0.6	0.31	3.3	2.1	24	0.06	21.9	2.9	6.2	17.5	24.6	25.3
16	16.75		0.0	1.10	2.2	3.6	23	0.03	24.1	2.1	7.7		24.8	25.1
17	17.65		0.0	1.33	0.9	3.6	23	0.01	49.4	2.5	8.8		24.3	24.6
18	18.60	Site 6: Pedrick Rd.	0.4	1.40	0.0	3.5	32	0.00	183.6	3.7	12.9	25.0	25.0	25.5
19	20.20		0.0	3.92	0.0	3.5	32	0.00	657.4	6.2	21.7		25.1	25.2
20	21.25	Site 7– U/S UCD WW	0.0	1.55	0.0	1.5	12	0.00	ERR	1.5	2.3		23.8	ERR
21	22.10		2.5	1.24	1.3	3.6	33	0.01	ERR	3.4	12.1	27.9	27.1	ERR
22	23.33		0.0	1.80	0.0	2.5	32	0.00	38.2	4.8	11.9		27.8	28.4
23	24.70	Site 8– Mace Blvd.	0.0	2.00	0.0	3.5	32	0.00	ERR	5.3	18.6		26.0	ERR
24	26.50		0.0	2.63	0.0	3.5	32	0.00	ERR	7.0	24.4		26.0	ERR
25	28.50	Yolo Bypass	0.0	2.93	0.0	3.5	32	0.00	ERR	7.8	27.2		26.0	ERR

Table 1. Continued.

Model Segment Number (Reach)	Mile Below Lake Berryessa (mi)	Air Temp (°C)	Dew Temp (°C)	Wind (m/sec)	Heat Transfer Terms, Positive Into Water (100 ly will heat a 1m deep pond 1 deg C) Solar (ly/hr)	Sky (ly/hr)	Sat Vapor (mb)	Water (ly/hr)	Vapor Diff (mb)	Evap–Cond (ly/hr)	Convect (ly/hr)	Total Heat Transfer (ly/hr)	Evap Rate (mm/hr)	Evap Rate (cfs)	Evap Rate Previous Hour (cfs)
0	0.00	27.1	15.8	2.9	74.8	36.5	17.93	−31.0	−4.36	3.9	8.4	92.5			
1	2.10	26.0		2.9	67.1	35.8		−31.0	−4.36	3.9	7.8	83.6	0.06	0.034	0.009
2	4.25	26.0		2.9	67.1	35.8		−31.0	−4.36	3.9	7.8	83.6	0.06	0.035	0.009
3	5.15	26.0		2.9	73.4	35.8		−31.2	−3.92	3.5	7.6	89.0	0.06	0.075	0.008
4	6.31	26.0		2.9	73.4	35.8		−31.6	−3.20	2.8	7.2	87.6	0.05	0.079	−0.016
5	7.05	26.0		1.4	60.4	35.8		−32.3	−1.58	0.7	3.0	67.5	0.01	0.002	−0.003
6	7.75	26.0		1.4	71.8	35.8		−34.5	4.34	−1.8	1.7	73.0	−0.03	−0.021	−0.042
7	8.65	26.0		1.4	60.4	35.8		−34.9	5.53	−2.3	1.5	60.5	−0.04	−0.007	−0.013
8	9.35	26.0		1.4	64.8	35.8		−35.2	6.59	−2.7	1.3	63.9	−0.05	−0.006	−0.010
9	10.20	26.0		1.4	64.2	35.8		−35.7	8.20	−3.4	1.1	61.8	−0.06	−0.009	−0.014
10	11.25	26.0		1.4	58.1	35.8		−36.2	9.78	−4.1	0.8	54.4	−0.07	−0.012	−0.019
11	12.00	26.0		1.4	63.6	35.8		−36.7	11.59	−4.8	0.6	58.3	−0.08	−0.010	−0.015
12	12.90	26.0		1.4	63.5	35.8		−37.3	13.80	−5.7	0.3	56.5	−0.10	−0.015	−0.020
13	14.20	26.0		1.4	59.2	35.8		−37.3	13.70	−5.7	0.3	52.2	−0.10	−0.015	−0.021
14	15.00	26.0		1.4	49.4	35.8		−37.2	13.22	−5.5	0.3	42.9	−0.09	−0.008	−0.013
15	16.00	26.0		1.4	58.0	35.8		−37.1	12.96	−5.4	0.4	51.6	−0.09	−0.010	−0.016
16	16.75	26.0		1.4	40.5	35.8		−37.2	13.32	−5.5	0.3	33.9	−0.09	−0.008	−0.012
17	17.65	26.0		1.4	39.5	35.8		−37.0	12.41	−5.1	0.4	33.6	−0.09	−0.008	−0.013
18	18.60	26.0		1.4	56.0	35.8		−37.3	13.81	−5.7	0.3	48.9	−0.10	−0.014	−0.021
19	20.20	26.0		1.4	49.7	35.8		−37.4	13.99	−5.8	0.2	42.5	−0.10	−0.024	−0.035
20	21.25	26.0		1.4	24.7	35.8		−36.7	11.60	−4.8	0.6	19.5	−0.08	−0.005	−0.008
21	22.10	26.0		1.4	62.6	35.8		−38.4	18.03	−7.5	−0.3	52.2	−0.13	−0.017	−0.023
22	23.33	26.0		1.4	62.3	35.8		−38.8	19.50	−8.1	−0.5	50.7	−0.14	−0.026	−0.035
23	24.70	26.0		1.4	62.3	35.8		−37.8	15.65	−6.5	0.0	53.7	−0.11	−0.023	−0.031
24	26.50	26.0		1.4	56.0	35.8		−37.8	15.65	−6.5	0.0	47.5	−0.11	−0.030	−0.041
25	28.50	26.0		1.4	62.3	35.8		−37.8	15.65	−6.5	0.0	53.7	−0.11	−0.034	−0.045

and the amount of energy expended in vaporizing the water is known. The mass flux equals the heat flux divided by the latent heat of vaporization of water.

Seepage of groundwater to and from the creek is entered as input data, except that the distribution of seepage along the creek segment between I-505 and Stevenson Bridge is modified. The net seepage loss along that segment is decomposed into a loss along the upper half of the segment and a compensating gain along the lower half. Specifically, the loss rate per mile is assumed to gradually decrease in model reaches 10, 11, and 12 from the constant loss rate per mile used for reaches 5 through 9. A constant gain rate per mile is then calculated for reaches 13 through 15 so that the net gain or loss for the entire segment equals the amount estimated from the input data. This method of prorating gains and losses along the segment is consistent with the measured distribution of gains and losses (California Division of Water Resources 1955, Thomasson et al. 1960). The method was also necessary to achieve a match between simulated and measured creek temperatures. Groundwater is significantly cooler than creek water during summer, so a flow loss followed by a flow gain results in a lower simulated water temperature at Stevenson Bridge than does a constant small loss along the entire segment. As an illustration, seepage gains and losses for all model reaches during June through September 1993 (wet year conditions) are shown in Table 2.

Energy Balance

Shading by Riparian Vegetation. The amount of solar radiation striking the creek surface is adjusted hourly to account for shadows cast by tall riparian vegetation growing along the creek bank. The shading algorithm is simpler than the one used in the SNTEMP model (Theurer et al. 1984) but is adequate for an east-west-trending stream, such as Putah Creek. Two components of shading are included in the model. First, riverbank vegetation is assumed to overhang the water surface by an amount equal to 20% of the vegetation height. This component remains constant at all times. Second, the vegetation is assumed to project a shadow that varies by time of day and season. The sun is assumed always to be due south so that shadows are cast perpendicular to the orientation of the creek. The angle of the sun above the horizon each hour is calculated by combining terms that reflect the latitude, the time of day, and the time of year. If the earth's axis were not tilted, the maximum sun angle above the horizon would equal 90° minus the latitude, or 51.5° (0.899 radians) and the hourly angle would follow a simple sinusoidal pattern. The seasonal adjustment is made by adding an angular component (declination) on a monthly basis that reflects the 23° (0.401-radian) tilt of the earth's axis.

For the projected component of vegetation shading, riparian vegetation is assumed to be equivalent to a solid vertical wall at the edge of the overhanging canopy. The length of the projected shadow is:

$$\text{LENGTH} = \text{HEIGHT} / \tan(\text{TOTAL ANGLE})$$

Gaps between trees and partial penetration of light through vegetation with a sparse canopy is accounted for by adjusting the effective average height of the vegetation. Shading is accounted for in the energy budget by multiplying solar radiation by the ratio of the unshaded width to the total width of the creek.

Table 2. Groundwater Seepage To and From Putah Creek in 1993 and Riparian Vegetation Height

Model Reach Number	Distance from Monticello Dam (miles)	Groundwater Seepage To and From Putah Creek (cfs)								Height of South Bank Riparian Vegetation (feet)
		June		July		August		September		
		To Creek	From Creek	To Creek	From Creek	To Creek	From Creek	To Creek	From Creek	
1	2.10									10
2	4.25									10
3	5.15									10
4	6.31									10
5	7.05		2.03		2.19		1.87		1.59	20
6	7.75		1.92		2.07		1.77		1.50	15
7	8.65		2.47		2.66		2.28		1.93	15
8	9.35		1.92		2.07		1.77		1.50	10
9	10.20		2.33		2.51		2.15		1.83	10
10	11.25		2.02		1.86		1.33		0.90	15
11	12.00		0.82		0.67		0.38		0.16	10
12	12.90		0.49		0.27		0.00		0.00	10
13	14.20	1.23	0.00	0.90	0.00	0.34	0.00	0.00	0.01	10
14	15.00	0.76	0.00	0.55	0.00	0.21	0.00	0.00	0.01	15
15	16.00	0.95	0.00	0.69	0.00	0.26	0.00	0.00	0.01	10
16	16.75		0.45		0.38		0.50		0.62	20
17	17.65		0.54		0.46		0.60		0.74	20
18	18.60		0.57		0.49		0.64		0.78	15
19	20.20		0.97		0.82		1.07		1.32	20
20	21.25		0.63		0.54		0.70		0.87	15
21	22.10		0.63		0.73		0.66		0.47	10
22	23.33		0.91		1.05		0.95		0.68	10
23	24.70		1.02		1.17		1.06		0.76	10
24	26.50		1.34		1.54		1.39		1.00	15
25	28.50		1.49		1.71		1.54		1.11	10
	Total:	2.94	22.57	2.14	23.20	0.81	20.66	0.00	17.79	n.a.

Radiation from the Sky. Longwave radiation from the sky is assumed to strike the entire width of the creek. The intensity of the radiation in langleys per hour (ly/hr) equals:

$$SKY = 1.2 * 10^{-12} * (Ta + 273)^6 / 24$$

where Ta is the dry-bulb air temperature in °C. With different units and a slightly different assumed value for atmospheric emissivity, this is the same equation used for atmospheric radiation in the SNTEMP model (Theurer et al. 1984).

Radiation from the Water. The creek loses heat by longwave radiation. The intensity of the radiation (ly/hr) equals:

$$LONGWAVE = E * B * (Tw + 273)^4 / 24$$

where

E = emissivity of water = 0.97 (dimensionless)
B = Stefan-Boltzmann constant = $1.17 * 10^{-7}$ (ly/day/°K^4)
Tw = Water temperature (°C)

Again, with different units and a slightly different assumed value of emissivity, this equation is the same as the one used in the SNTEMP model (Theurer et al. 1984).

Evaporation and Advection. Evaporative and advective heat losses (ly/hr) from the creek are both functions of wind speed and the vapor pressure difference between the water surface and the air mass over the creek. They reflect the heat transfer that occurs when liquid water vaporizes during evaporation. They are combined in the model using the following equation:

$$EVADV = -0.3 * WIND * (e_s - e_a)$$

where

EVADV = combined evaporative and advective heat loss (ly/hr)
WIND = wind speed (meters per second)
e_s = saturated vapor pressure of the water surface (millibars)
e_a = vapor pressure of the air over the creek (millibars)

This equation is of the same form as the equation in the QUAL2E model (Brown and Barnwell 1987). The SNTEMP model uses an alternative equation based on relative humidity (Theurer et al. 1984). Vapor pressure is calculated as:

$$e = 6.1078 * \exp(17.27*T/[T+237.3])$$

where T is the water temperature or the dew point temperature of the air in °C.

Convection. The final component of the energy budget is convective heat transfer between the air and the water because of their temperature difference. It is independent of the vaporization process that occurs during evaporation. Convective heat transfer equals:

$$CONVEC = EVADV * Bf * (Tw-Ta)/(e_s - e_a)$$

where

Bf = Bowen ratio between convective and evaporative heat fluxes = 0.61
Tw = water temperature (°C)
Ta = dry-bulb air temperature (°C)

This equation is the same as the one used in the SNTEMP model, assuming atmospheric pressure remains constant (Theurer et al. 1984).

Input Data

Input data sets were prepared for the months of June, July, August, and September 1993 and 1994.

Flows

The input data requirements for flows in the temperature model are similar to the requirements for a water budget model of lower Putah Creek developed by the Putah Creek Council (PCC). Input values for each variable in the water budget model were obtained from actual measurements during 1993 and 1994, if available. If no measurements were available, estimates were developed for wet, normal, and dry conditions, and appropriate values were used for simulations of 1993 (wet) and 1994 (normal). The resulting estimates are shown in Table 3 and are described in the following paragraphs.

Solano Project Operations. Daily operations data for Lake Berryessa and Lake Solano were obtained from the U.S. Bureau of Reclamation. The measured release from Monticello Dam was used as the inflow to the uppermost model reach. The calculated inflow to lake Solano was within 10 cfs of the release from Monticello Dam on 78% of the days during June through September 1993, and the average inflow was 1.2 cfs less than the release from Monticello Dam. This indicates that tributary inflow and seepage losses were negligible during that period. The discrepancies amounted to only a small percentage of flow along the reaches between Monticello and Solano Dams but a large percentage of flow below Solano Dam. The model calculates the flow below Solano Dam by subtracting the diversion to Putah South Canal from the inflow to the reach at Solano Dam. The diversions were adjusted slightly as needed so that the flow below Solano Dam calculated by the model exactly equaled the measured release. During the summer of 1993, releases from Solano Dam followed the normal-year release schedule of 43 cfs in June and July, 34 cfs in August, and 20 cfs in September. During 1994, releases generally followed the dry year release schedule of 33 cfs in June and July, 26 cfs in August, and 15 cfs in September. Flows exceeded the scheduled releases on several occasions, when Solano County Water Agency released water that had been "banked" earlier in the year (Figures 6a and 6b). Of particular interest for this temperature study were an increase of 10 cfs (from 33 to 43 cfs) on July 7-9 and an increase of 4 cfs (from 26 to 30 cfs) on August 22-27.

Table 3. Local Inflows and Outflows Along Lower Putah Creek During Water Years 1993 and 1994 (All Values Are in Cubic Feet per Second)

	1993											
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Irrigation Diversions												
Solano Dam to I–505	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.04	0.03	0.01
I–505 to Stevenson Br.	0.00	0.00	0.00	0.00	0.00	0.00	0.20	1.95	2.52	2.83	1.95	0.40
Stevenson Br. to I–80	0.00	0.00	0.00	0.00	0.00	0.00	0.12	1.17	1.51	1.70	1.17	0.24
I–80 to Yolo Bypass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Irrigation Return Flows												
Solano Dam to I–505	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I–505 to Stevenson Br.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stevenson Br. to I–80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I–80 to Yolo Bypass	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.09	0.18	0.18	0.18	0.09
Willow Canal Spills												
Solano Dam to I–505	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I–505 to Stevenson Br.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stevenson Br. to I–80	0.00	0.00	0.00	0.00	0.00	0.00	1.00	2.00	3.00	3.00	3.00	3.00
I–80 to Yolo Bypass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UC Davis Wastewater												
I–80 to Yolo Bypass	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Riparian Vegetation ET												
Solano Dam to I–505	0.75	0.00	0.00	0.00	0.00	0.03	0.89	1.47	2.00	2.14	1.85	1.38
I–505 to Stevenson Br.	0.57	0.00	0.00	0.00	0.00	0.02	0.67	1.11	1.51	1.62	1.40	1.05
Stevenson Br. to I–80	0.43	0.00	0.00	0.00	0.00	0.02	0.51	0.85	1.15	1.24	1.07	0.80
I–80 to Yolo Bypass	0.65	0.00	0.00	0.00	0.00	0.03	0.76	1.26	1.72	1.84	1.59	1.19
Seepage Losses												
Solano Dam to I–505	6.09	4.93	4.96	4.96	4.94	5.85	6.93	9.26	10.67	11.50	9.84	8.36
I–505 to Stevenson Br.	1.69	1.77	0.96	0.96	0.92	0.56	0.54	0.09	0.39	0.66	0.90	1.09
Stevenson Br. to I–80	1.43	2.20	2.33	2.33	2.30	2.06	2.31	1.68	3.17	2.69	3.51	4.33
I–80 to Yolo Bypass	4.65	5.26	5.39	3.85	4.03	3.91	4.19	4.75	5.39	6.20	5.60	4.01

Table 3. Continued

	1994											
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Irrigation Diversions												
Solano Dam to I-505	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.03	0.04	0.02	0.02
I-505 to Stevenson Br.	0.22	0.06	0.00	0.00	0.00	2.73	7.69	3.33	8.49	6.06	0.95	0.63
Stevenson Br. to I-80	0.26	0.07	0.00	0.00	0.00	0.13	0.27	1.17	1.28	1.56	1.11	0.74
I-80 to Yolo Bypass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Irrigation Return Flows												
Solano Dam to I-505	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-505 to Stevenson Br.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stevenson Br. to I-80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-80 to Yolo Bypass	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.20	0.20	0.20	0.10
Willow Canal Spills												
Solano Dam to I-505	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-505 to Stevenson Br.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stevenson Br. to I-80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.40	0.50	1.20
I-80 to Yolo Bypass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UC Davis Wastewater												
I-80 to Yolo Bypass	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Riparian Vegetation ET												
Solano Dam to I-505	0.93	0.00	0.00	0.00	0.00	0.30	1.13	1.70	2.24	2.38	2.06	1.57
I-505 to Stevenson Br.	0.71	0.00	0.00	0.00	0.00	0.23	0.86	1.28	1.69	1.80	1.56	1.18
Stevenson Br. to I-80	0.54	0.00	0.00	0.00	0.00	0.18	0.66	0.98	1.29	1.38	1.19	0.91
I-80 to Yolo Bypass	0.80	0.00	0.00	0.00	0.00	0.26	0.97	1.46	1.92	2.05	1.77	1.35
Seepage Losses												
Solano Dam to I-505	12.25	13.22	12.31	11.36	10.38	10.99	12.03	12.35	14.62	17.31	14.82	11.54
I-505 to Stevenson Br.	2.26	3.53	3.75	2.80	1.82	3.10	3.95	2.04	2.25	2.34	1.91	1.38
Stevenson Br. to I-80	5.72	4.61	3.76	3.76	3.73	3.39	6.52	8.13	7.67	6.36	7.01	7.68
I-80 to Yolo Bypass	6.99	6.90	6.61	6.10	6.06	6.74	7.12	7.50	8.85	8.56	7.92	7.37

The release from Monticello Dam was assumed to remain at a constant temperature of 10.0°C during summer 1993, which was the average of two measurements made during that period. Temperatures below the dam were not measured in 1994. Based on model calibration, the estimated temperature was 11.5°C throughout the summer. Reservoir storage in 1994 reached the lowest level since Monticello Dam was constructed, and this could have resulted in a higher release temperature.

Irrigation Diversions and Return Flows. Irrigation diversions along Putah Creek were estimated from electric power records and recent statements and legal declarations by several riparian landowners. The following estimated annual diversions were included in the model:

- 9 acre-feet (af) by Mr. Pontius for 7 acres of walnuts upstream of Winters (model reach 6), plus 10% in dry years and minus 10% in wet years;
- 950 af by Mr. Borchard for 260 acres of tomatoes and walnuts east of I-505 (model reach 11), plus 10% in dry years and minus 10% in wet years;
- 291 af by UC Davis at the Russell Ranch upstream of Stevenson Bridge (model reach 14) in 1993 and 1,357 af in 1994; and
- 400 af by Mr. Olmo for approximately 200 acres of vineyard and tomatoes near Pedrick Road (model reach 19), plus 10% in dry years and minus 10% in wet years.

Wet and dry years are based on annual rainfall; 1993 and 1994 were classified as wet and normal, respectively.

The monthly distribution of irrigation diversions in normal and dry years was assumed to equal the monthly distribution of irrigation pumpage measured in the 1950s (Thomasson et al. 1960). The irrigation season extends from March through November, with 89% of total use occurring between May and September. In wet years, including 1993, the irrigation season extends from April through September because spring and fall rains decrease the need for irrigation during the early and late parts of the growing season.

The only commonly observed irrigation return flow entering the creek is a discharge of about 0.2 cfs at Mace Boulevard.

Willow Canal Discharge. During the irrigation season, a small amount of water spills from the end of Willow Canal and enters Putah Creek about 1,000 feet upstream of Pedrick Road. The average spill on 16 dates in 1991 and one date in 1993 was approximately 3 cfs, and this rate was used in the model during the summer months. Estimated spills during 1994 were 0.25 cfs in June, 0.40 cfs in July, 0.50 cfs in August, and 1.2 cfs in September, based on operational policies and data of the Yolo County Flood Control and Water Conservation District (Barton pers. comm.).

The temperature of the discharge was assumed to equal the temperature of the creek at the point of discharge. The temperature of the canal water was measured twice during the study and was usually 2-4°C warmer than the creek water. It is likely, however, that the canal temperature is cooler than the creek at night and that the daily average temperature is approximately the same.

University of California, Davis Wastewater Discharge. The temperature of the UC Davis wastewater discharge during 1992-1993 was generally higher and less variable than the temperature of the creek at the discharge point, as shown in Figure 2. It ranged from about 17°C in winter to as high as 31°C in summer. During the summer months when high temperatures can be a problem for fish, the discharge was often 2-6°C warmer than the creek. The increase in ambient water temperature downstream of the outfall is usually less because the discharge mixes with the water in the creek. Metered monthly discharge from the UC Davis wastewater treatment plant during 1984-1993 ranged from an average of 2.05 cfs in December to an average of 2.90 cfs in June. A constant average rate of 2.5 cfs was used for all months in the temperature model. Daily average discharge temperatures during the summer of 1993 were obtained by linear interpolation of the measured weekly temperature. These temperatures may be 1-2°C higher than the true daily average temperature if the discharge has a diurnal temperature cycle. The discharge temperature is usually measured in the early afternoon, when the temperature would be near the apogee of the daily cycle. Discharge temperatures were not needed for 1994 because flow in the creek above the discharge point declined to near zero, and the model is unable to simulate temperatures accurately under extreme low-flow conditions.

The DO concentration and turbidity of the wastewater discharge during 1992-1993 are shown in Figures 3 and 4. Although these constituents are not simulated by the model, they affect the suitability of the water for fish. The DO concentration was 0-3 milligrams per liter (mg/l) less than the ambient concentration in the creek, but was never less than 4.5 mg/l. Measurements were generally made in the morning or early afternoon, so the data probably represent the middle to high end of the range of diurnal DO fluctuation. The turbidity of the wastewater discharge was always less than or equal to the turbidity of the creek water.

Riparian Vegetation Evapotranspiration. Evapotranspiration (ET) by riparian vegetation along the low-flow channel can diminish flow in the creek. Estimates of ET for normal, dry, and wet climatic conditions were obtained from PCC's water budget model. Estimates for wet climatic conditions were used for simulations of 1993, and estimates of normal climatic conditions were used for simulations of 1994, reflecting the amount of rainfall in those years. Estimated total riparian vegetation ET between Solano Dam and the Yolo Bypass for June, July, August, and September 1993 were 6.38, 6.83, 5.91, and 4.42 cfs, respectively. Losses for the same months in 1994 were 7.14, 7.61, 6.58, and 5.01 cfs, respectively. These losses were allocated to reaches in the temperature model according to the distribution of vegetation along the creek.

Groundwater Seepage. Estimates of the rate of seepage into and out of the creek under existing conditions were calculated by PCC's monthly water budget model. The water budget model calculated seepage gains and losses by adjusting measured changes in total flow to account for other known inflows and outflows. Separate estimates were calculated for normal, wet, and dry climatic conditions. The estimates for wet conditions were used in the temperature model to simulate 1993. Based on model calibration to match observed flows, groundwater seepage rates in 1994 were estimated to equal 85% of the rates for normal climatic conditions.

The water budget model calculated seepage gains and losses along four long reaches covering the creek between Solano Dam and the Yolo Bypass. The seepage rates per mile for each of those reaches was used for all the temperature model reaches along the same segment of creek. As

described above under "Algorithms for Mass and Energy Balance", the average loss rate between I-505 and Stevenson Bridge was subdivided into a loss in the upper part of that segment, followed by a compensating gain in the lower part (Table 2). The temperature of groundwater seeping into the creek was assumed to be 17.5°C.

Other Flows. Two facilities associated with the Aquaculture and Fisheries Program at UC Davis discharge water to lower Putah Creek. During the summers of 1993 and 1994, the Aquatic Center discharged water at a monthly-average rate of 0.43-0.74 cfs at a location due south of the university airport, downstream of Pedrick Road. During the same months, the Putah Creek facility (fish hatchery) discharged at a rate of 0.31-0.65 cfs at a location about 1,000 feet upstream of Pedrick Road. These discharges were not included in the model because they were considered too small to significantly affect flow and temperature in the creek. Rainfall runoff from tributaries downstream of Monticello Dam was also not included in the model because the principal use of the model for this study was to simulate water temperatures in summer, when runoff rarely occurs.

Channel Geometry, Hydraulics, and Shading

During summer, water in Putah Creek is somewhat ponded along most of the reach from Solano Dam to the Yolo Bypass. The pools are commonly hundreds of feet long, 30-60 feet wide, and up to 8 feet deep. Pools are often separated by a beaver dam or gravel bar. In some areas, the low-flow channel is narrower (less than 10 feet wide) and shallower (less than 3 feet deep), and water velocities are much higher than in the pools. The latter conditions occur, for example, where Dry Creek enters Putah Creek upstream of Winters and along the reach upstream of Stevenson Bridge where the creek cuts through dense clayey bed material.

Summer flows are confined to the low-flow channel, which is usually rectangular in cross section. In most areas, the steep banks rise 1-2 feet above the normal water surface. Because of the shape of the low-flow channel, the width of the creek in most locations varies only slightly with changes in flow as long as flows are small enough to be contained within the low-flow channel. Total stream width is calculated each day in the model as a fixed base width plus a flow-dependent incremental width, as follows:

$$W = Wo + a\,Q^b$$

where:

W	=	total flow width for current day (feet),
Wo	=	base width (feet),
Q	=	flow (cfs),
a	=	coefficient of power function, and
b	=	coefficient of power function.

The initial estimates of base widths were estimated from detailed vegetation maps (U.S. Fish and Wildlife Service 1992); low-altitude aerial photographs taken on September 16, 1993; and visual estimates made during numerous canoe trips. During model calibration, base widths were decreased substantially and the power function components of width were made more responsive to flow as a means of reproducing the observed lack of temperature response to changes in flow. This

adjustment is discussed more thoroughly under "Model Calibration and Sensitivity Analysis" below. Calibrated base widths ranged from 12 feet to 32 feet except for the wetlands area upstream of Dry Creek (187 feet) and Lake Solano (300 feet). The power function coefficient was 1.76 from Solano Dam to I-505 and 0.807 below I-505. An exponent of 0.7 was used in all reaches. Table 3 shows the calculated width for each reach on July 15, 1993, when flow was 600 cfs from Monticello Dam to Solano Dam and 43 cfs below Solano Dam.

A similar function was used for stream depth because of the common occurrence of pools along the creek. These pools are often 4-8 feet deep even at very low flows, and additional flow increases the total water depth by a relatively small amount. The following function is used in the model to calculate water depth:

$$D = Do + 0.441\ Q^{0.4}$$

where:

D = water depth (feet),
Do = base depth (feet), and
Q = flow (cfs).

Base depths ranged from 1 to 3 feet. The incremental depth increases from about 1 foot at 10 cfs to almost 3 feet at 100 cfs. Base depths were obtained from visual estimates made during canoe trips and measurements at selected locations when the creek was dry in 1990. These depths were adjusted during model calibration. Flow velocity is calculated in the model by dividing the flow rate by the cross sectional area. Calculated depths on July 15, 1993, are shown in Table 1.

The shading algorithm in the model requires estimates of the average height of the riparian vegetation growing along the south bank of the low-flow channel. Estimates for each reach were obtained from a videotape made during the aerial survey in 1993. Although some trees are over 100 feet tall, there are gaps between trees and between stands of trees. Estimated average vegetation heights ranged from 10 feet to 20 feet. These were adjusted during model calibration to obtain the values shown in Table 1.

Meteorology

The model requires hourly data for air temperature, dew point temperature, solar radiation, and wind speed. Values of the first three variables measured at the CIMIS station near Davis were used without modification in the model. Measured windspeeds at the CIMIS station were raised to the 0.4 power before using them in the model, as explained under "Model Calibration and Sensitivity Analysis" below. Figures 13 through 15 show the raw hourly data during June through September 1993 and 1994 for each of these variables.

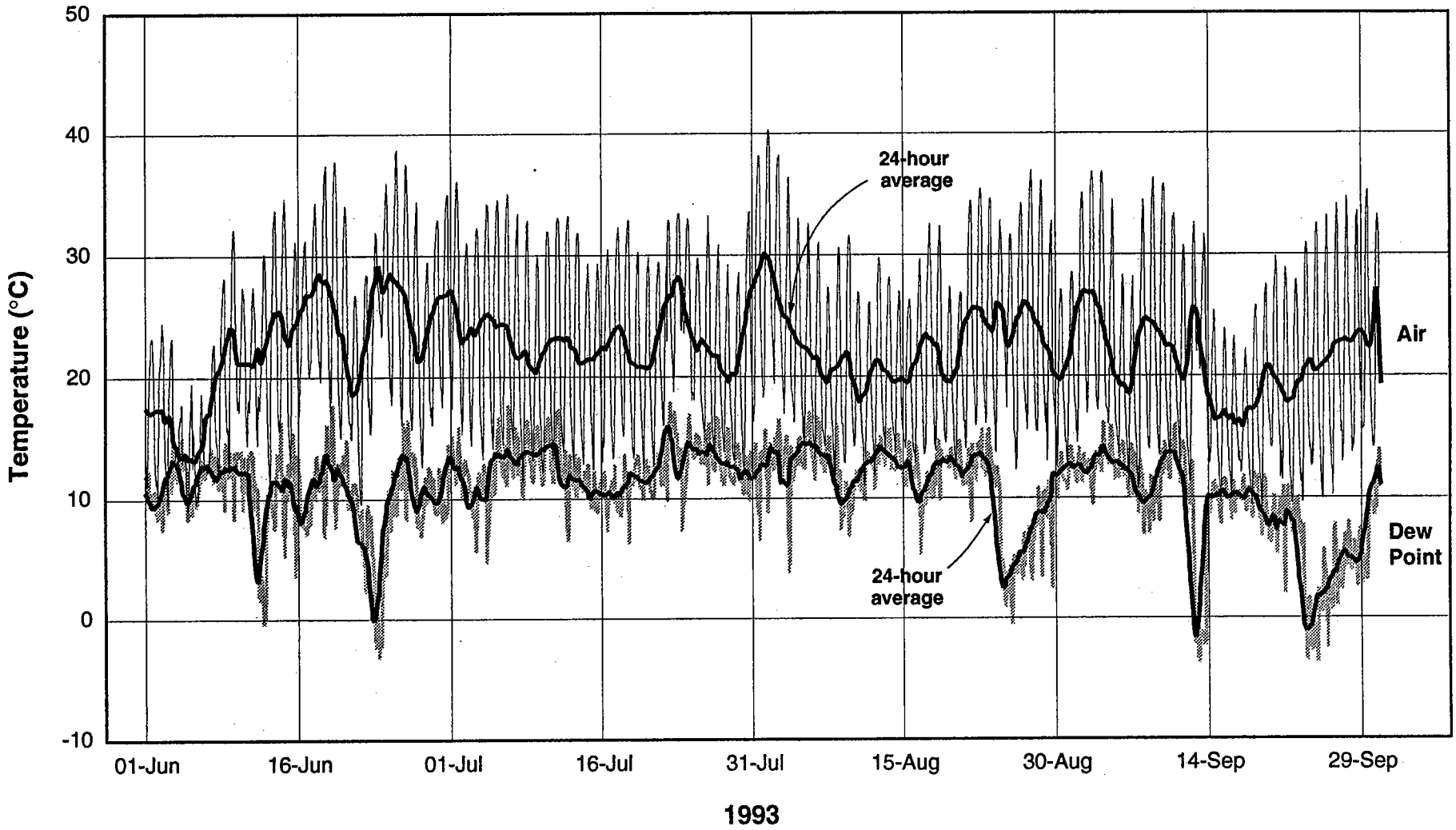

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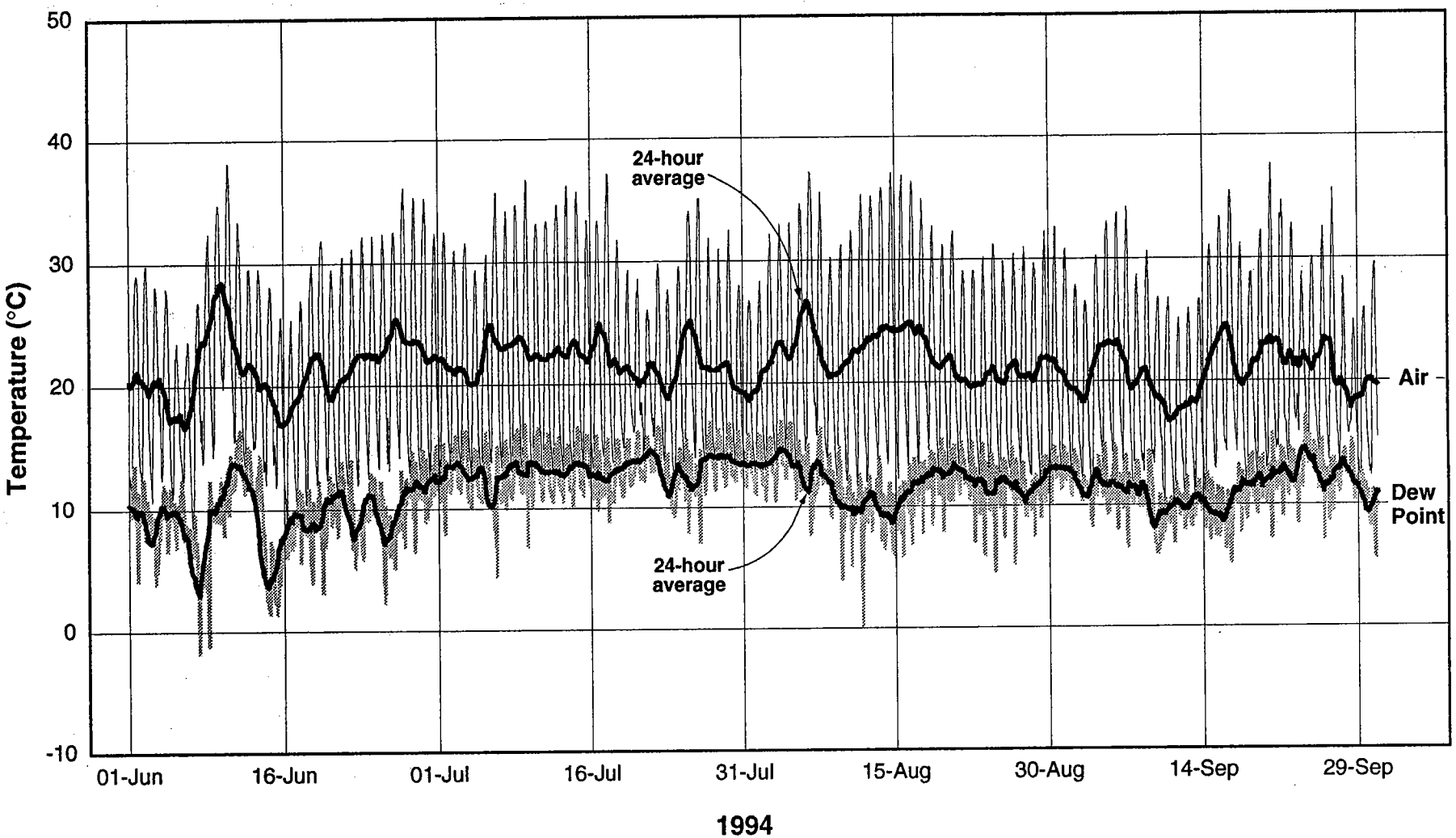
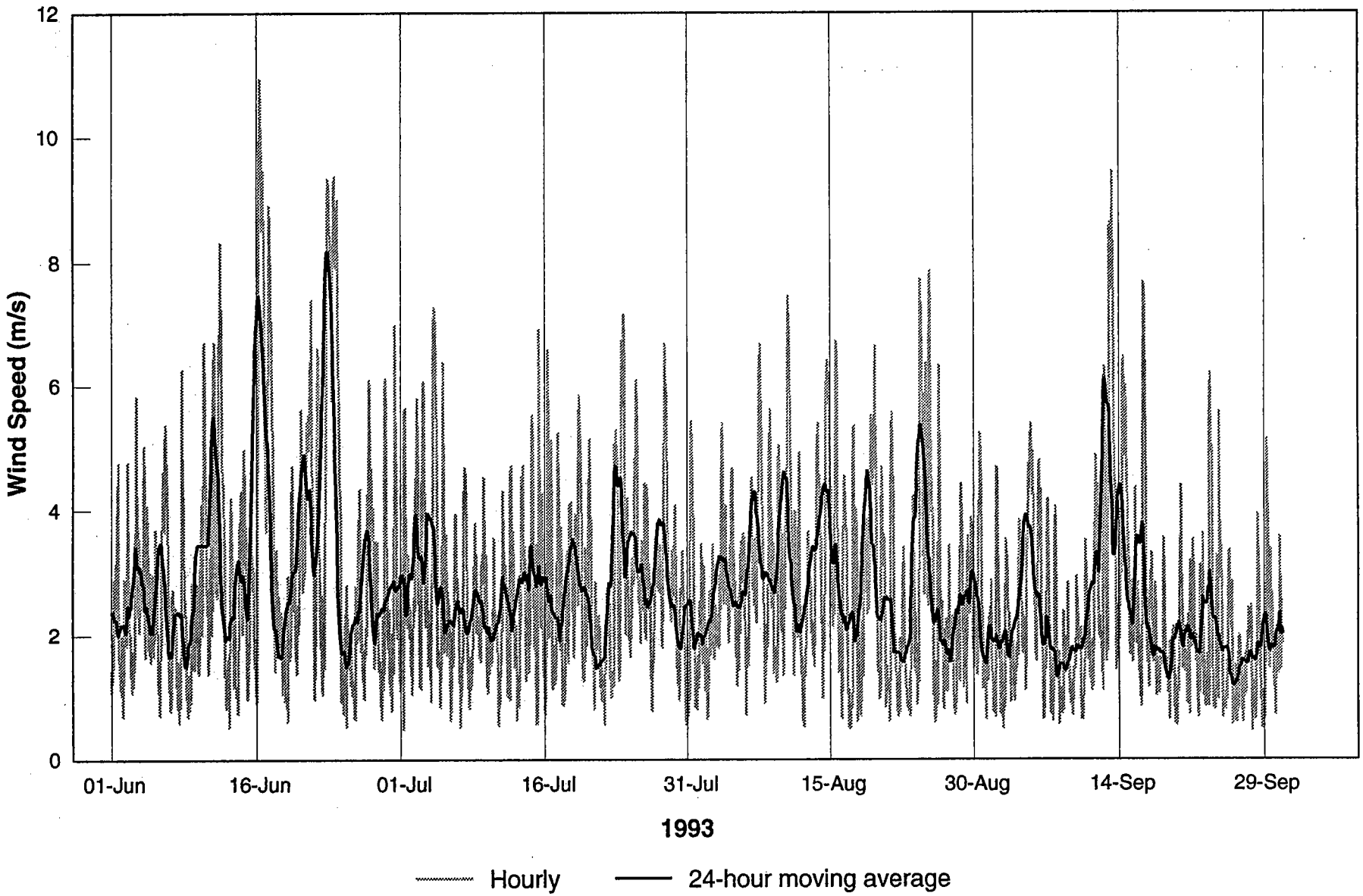
Figure 13a
Hourly Mean Air and Dew Point Temperatures at Davis for June through September 1993



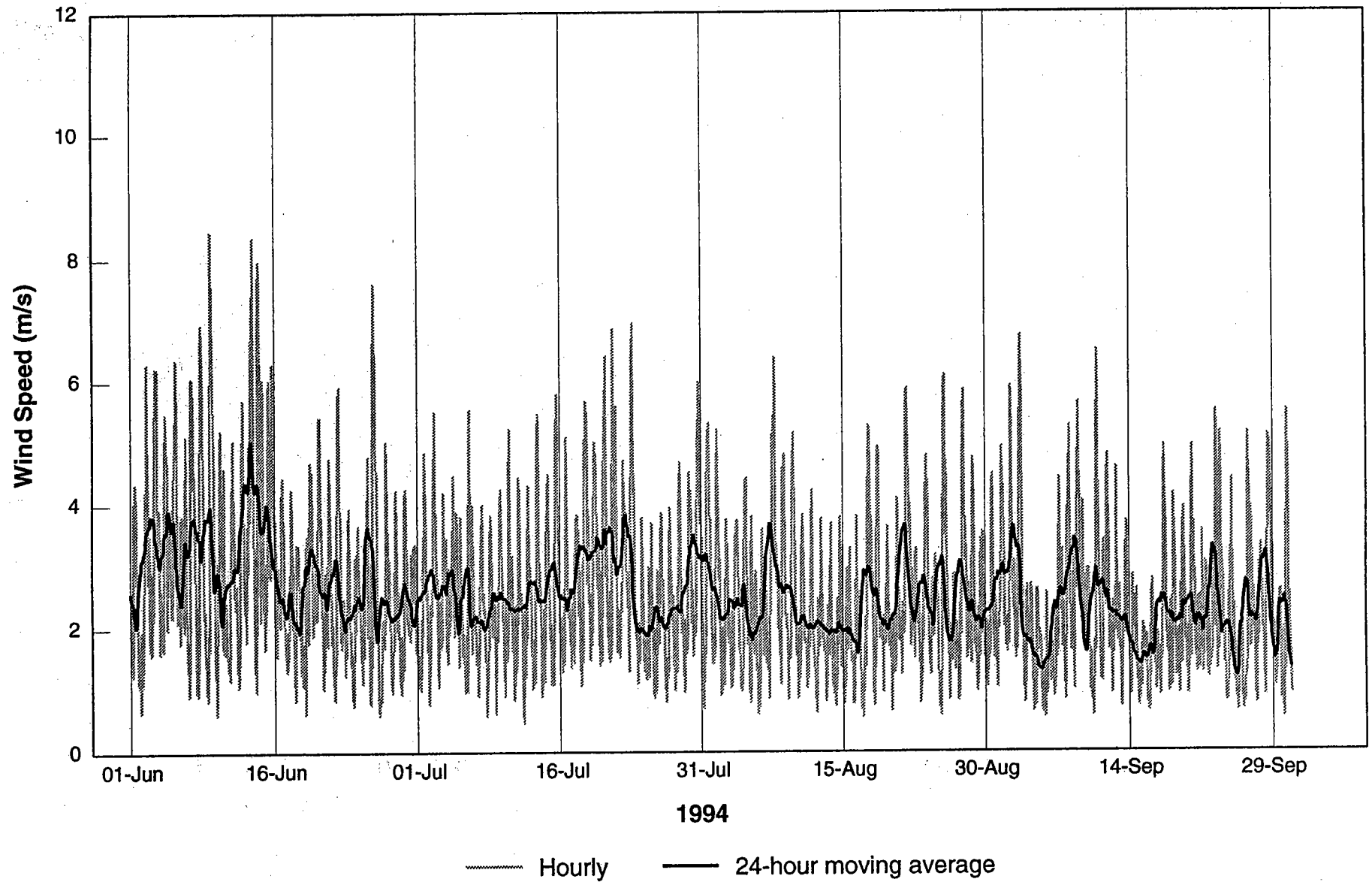
Jones & Stokes Associates, Inc.

Figure 13b
Hourly Mean Air and Dew Point Temperatures at Davis for June through September 1994



Jones & Stokes Associates, Inc.

Figure 14a
Hourly Wind Speed at Davis for June through September 1993 (Raw CIMIS Data)



Jones & Stokes Associates, Inc.

Figure 14b
Hourly Wind Speed at Davis for June through September 1994 (Raw CIMIS Data)

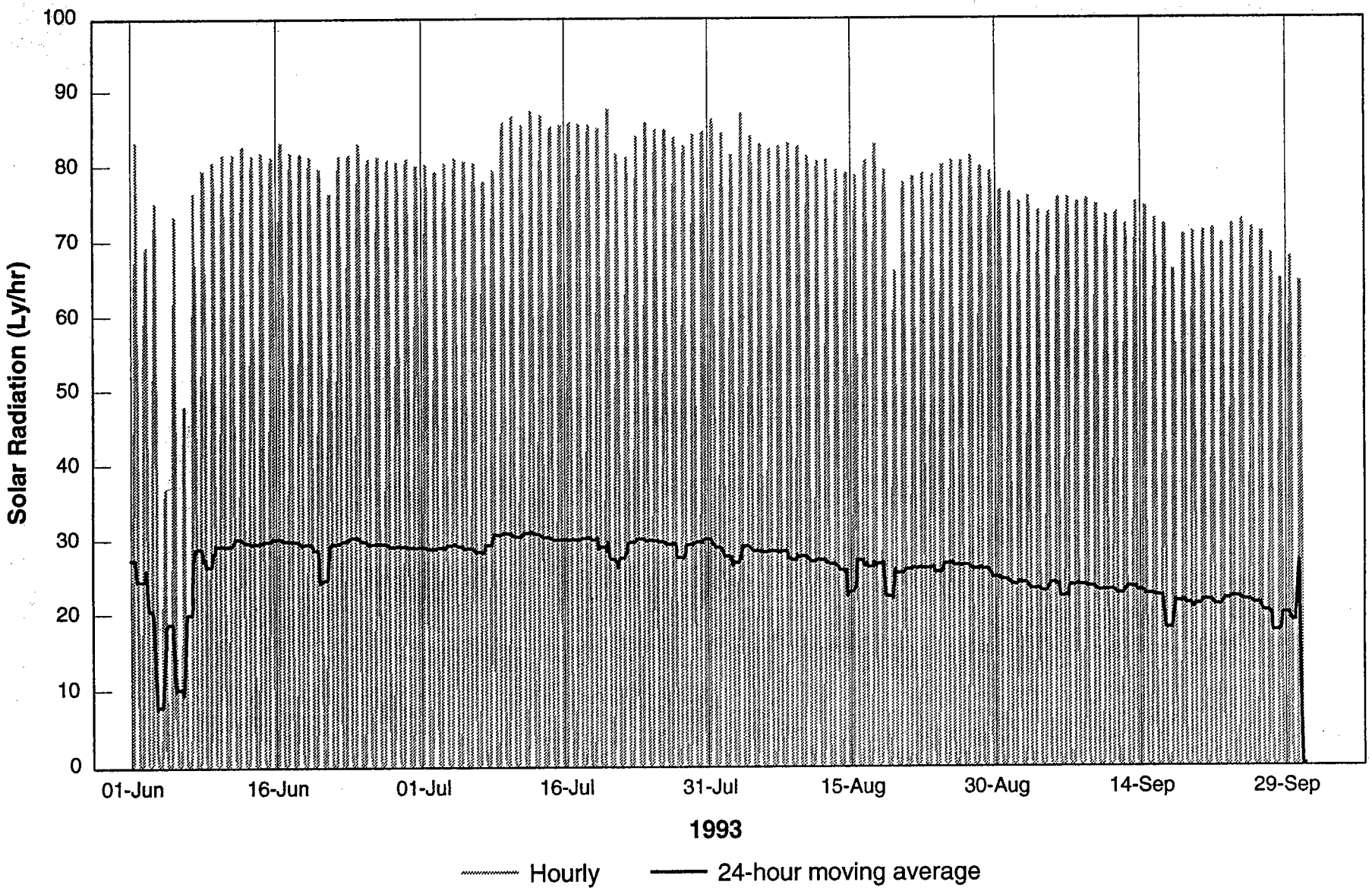


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Figure 15a
Hourly Total Solar Radiation at Davis for June through September 1993 (CIMIS Data)

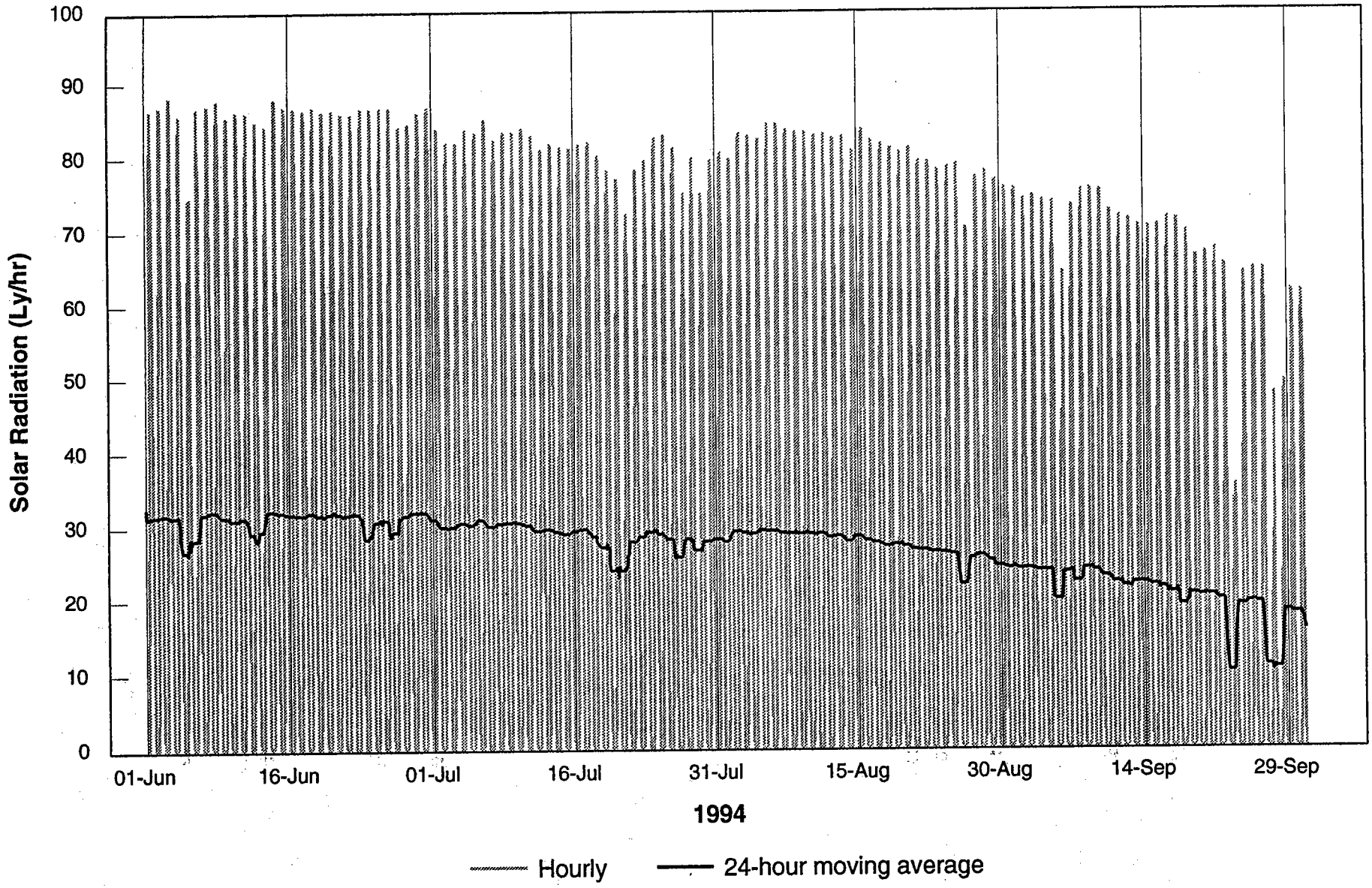

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Figure 15b
Hourly Total Solar Radiation at Davis for June through September 1994 (CIMIS Data)

Model Calibration and Sensitivity Analysis

Calibrated Results

Measured and simulated water temperatures at the data logger locations (sites 1, 3, and 5) during June through September 1993 are shown in Figures 16 through 19. Similar graphs for June through September 1994 are shown in Figures 20 through 23. In general, the average daily simulated temperatures and the simulated amplitude of the diurnal temperature cycles match the measured averages and amplitudes reasonably well. Longitudinal profiles of measured and simulated temperatures along the creek on five dates during summer 1993 and summer 1994 are shown in Figures 24a and 24b.

The goal of model calibration was to achieve a reasonably accurate simulation of the eight summer months using a constant set of channel characteristics and physical parameters (width and depth functions, vegetation height, and wind adjustment factor) and the measured daily or hourly flow and meteorological conditions. It would have been possible to simulate measured water temperatures more accurately by changing the channel and vegetation characteristics from month to month, but this was considered unrealistic.

A comparison of measured and simulated hourly temperatures at sites 3 and 5 revealed no bias in monthly average temperatures (average simulated temperatures were within 0.48°C of average measured temperatures except for 1 month at site 5). The difference between simulated and measured temperatures was less than 1°C for 50-95% of the simulated hours in each month and less than 2°C for 85-100% of the simulated hours. The largest discrepancy (3.18°C) occurred in August 1994.

The longitudinal profile of simulated flows along Putah Creek in July 1993 and July 1994 are shown in Figure 25.

Sensitivity to Individual Variables

Flow. A comparison of the time series of measured hourly temperatures at sites 1, 3, and 5 with the time series of releases from Solano Dam during June through September 1994 (Figure 6b) indicates that temperatures at I-505 (site 3) and further downstream are not sensitive to small or moderate changes in flow. The brief pulses of higher flow (43 cfs versus 33 cfs at Solano Dam) in June and July caused a slight cooling at I-505 relative to the temperature at Stevenson Bridge. The effect is evident in the slightly greater separation between the temperature hydrographs for those two stations beginning about 1 day after the onset of each flow pulse. The effect of the additional 10 cfs was to retard the downstream warming rate and thereby decrease the temperature at I-505 by about 1°C relative to the temperature at Stevenson Bridge. The water temperature at Stevenson Bridge is more fully equilibrated with ambient meteorological conditions. Similarly, the decrease in flow at Solano Dam from 33 cfs to 26 cfs beginning on August 1 caused temperatures at sites 3 and 5 to become more similar, decreasing the temperature difference between those stations by slightly less than 1°C.

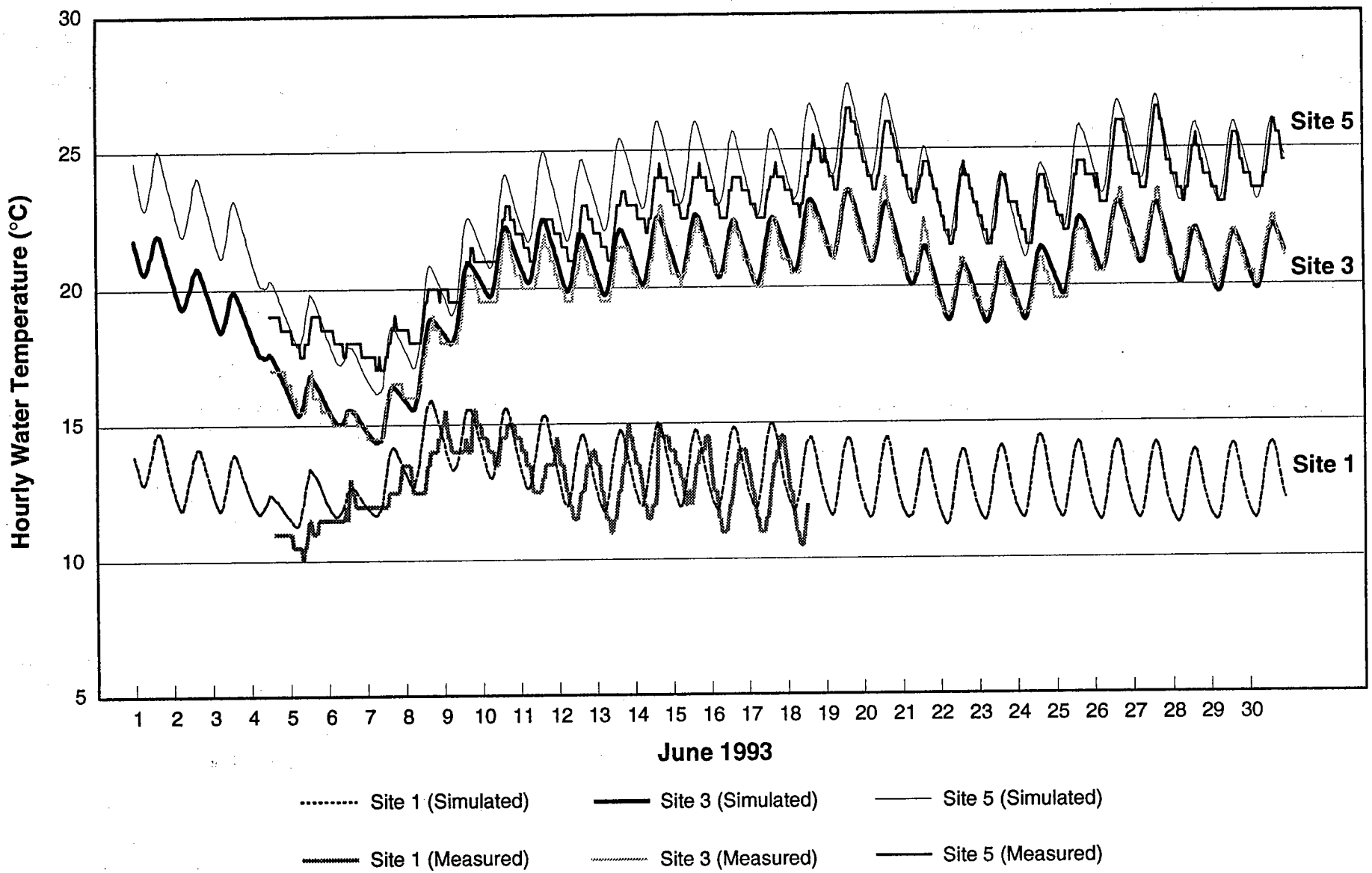

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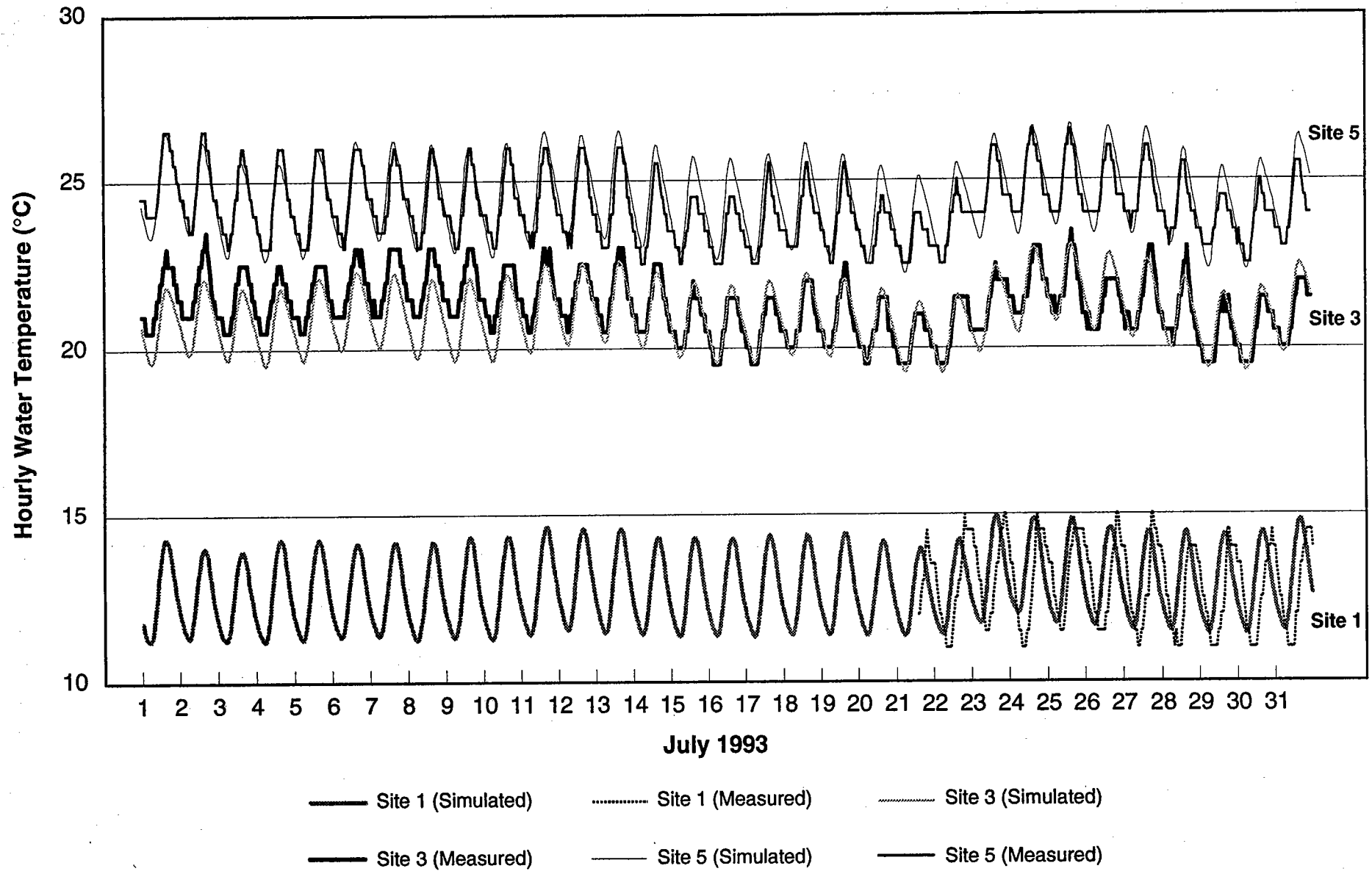
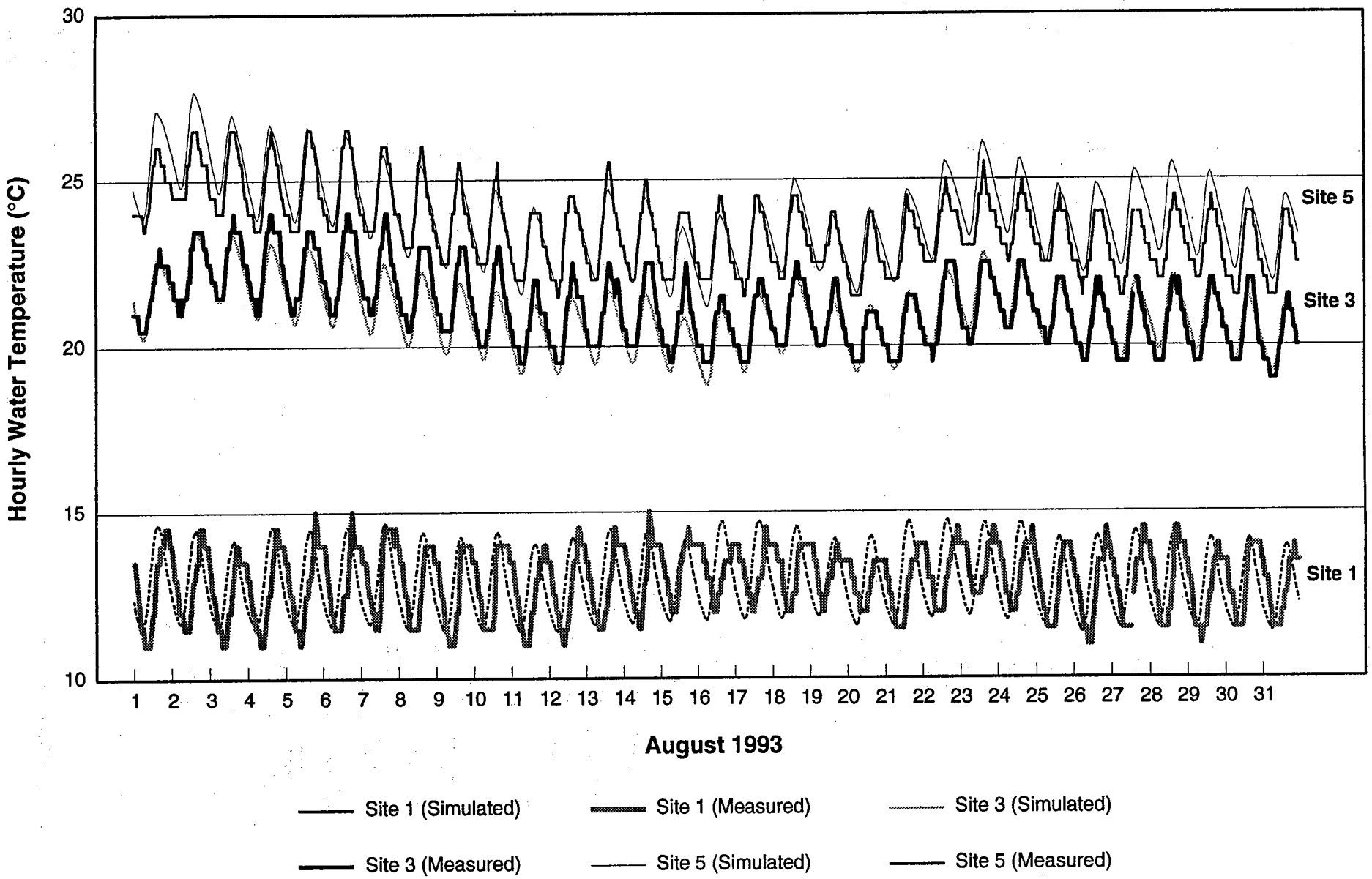
Figure 16
Simulated and Measured Hourly Water Temperatures at Sites 1, 3, and 5 during July 1993



Jones & Stokes Associates, Inc.

Figure 17
Simulated and Measured Hourly Water Temperatures at Sites 1, 3, and 5 during July 1993



Jones & Stokes Associates, Inc.

Figure 18
Simulated and Measured Hourly Water Temperatures at Sites 1, 3, and 5 during August 1993

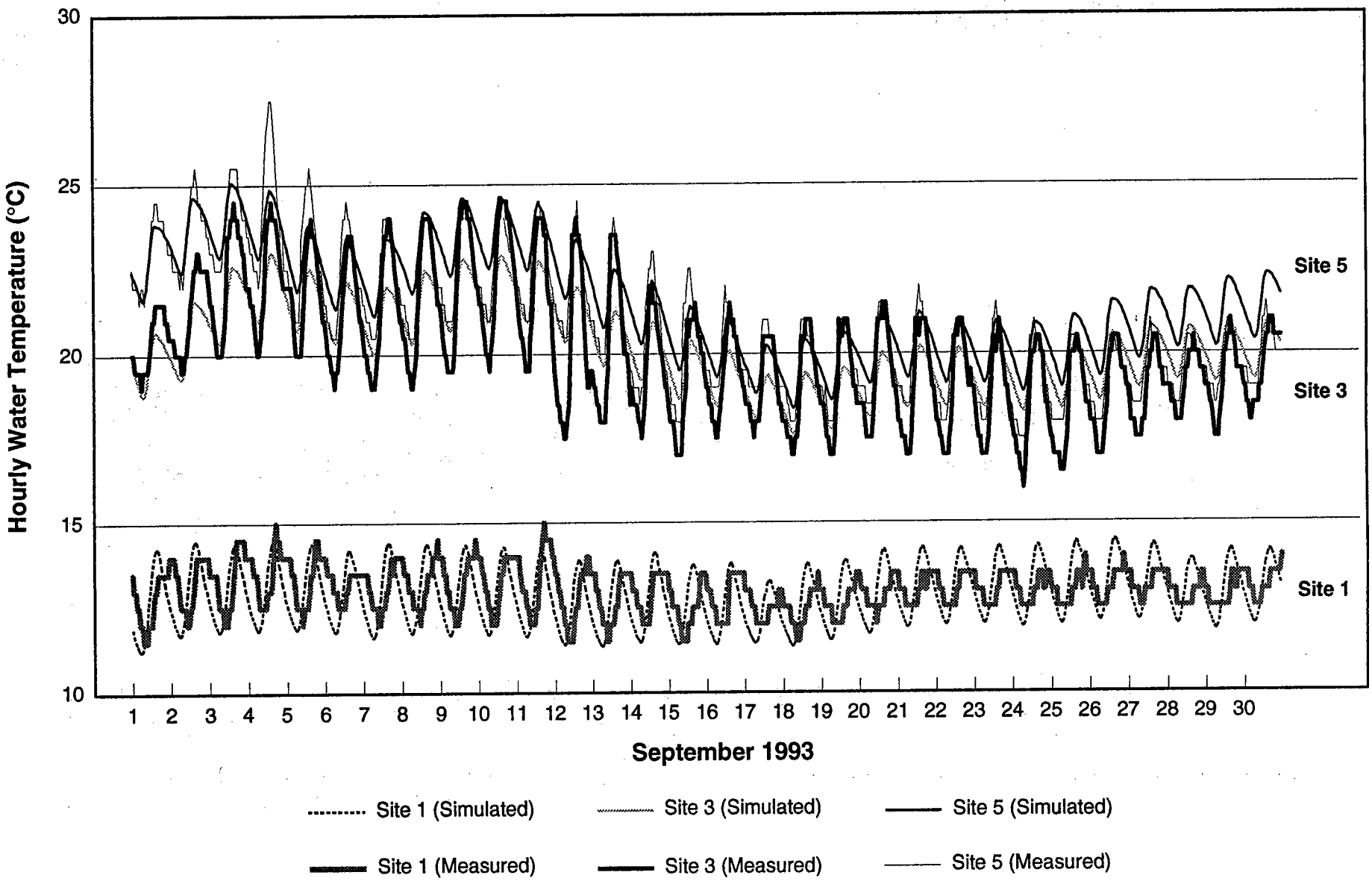


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Figure 19
Simulated and Measured Hourly Water Temperatures at Sites 1, 3, and 5 during September 1993

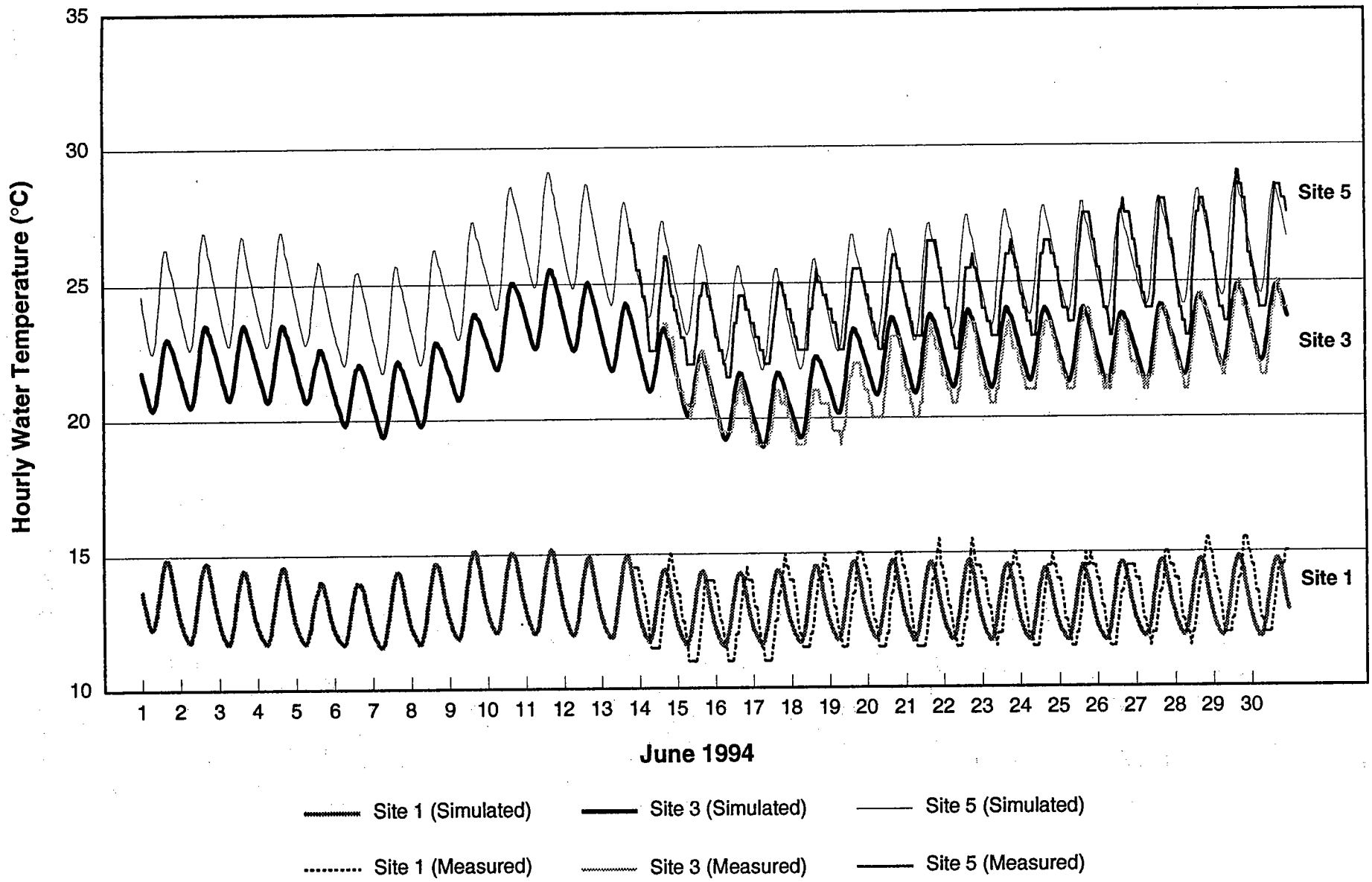

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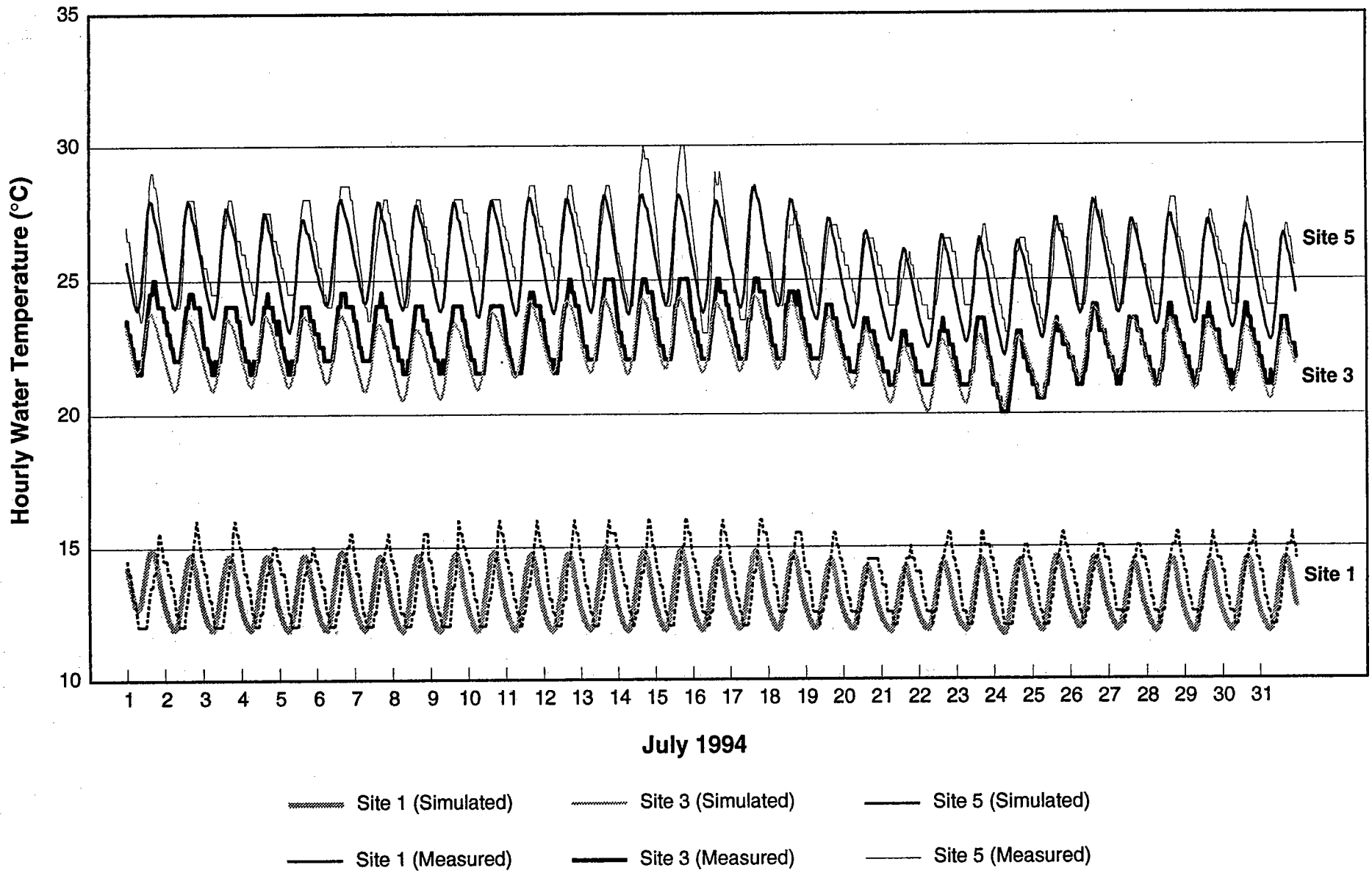
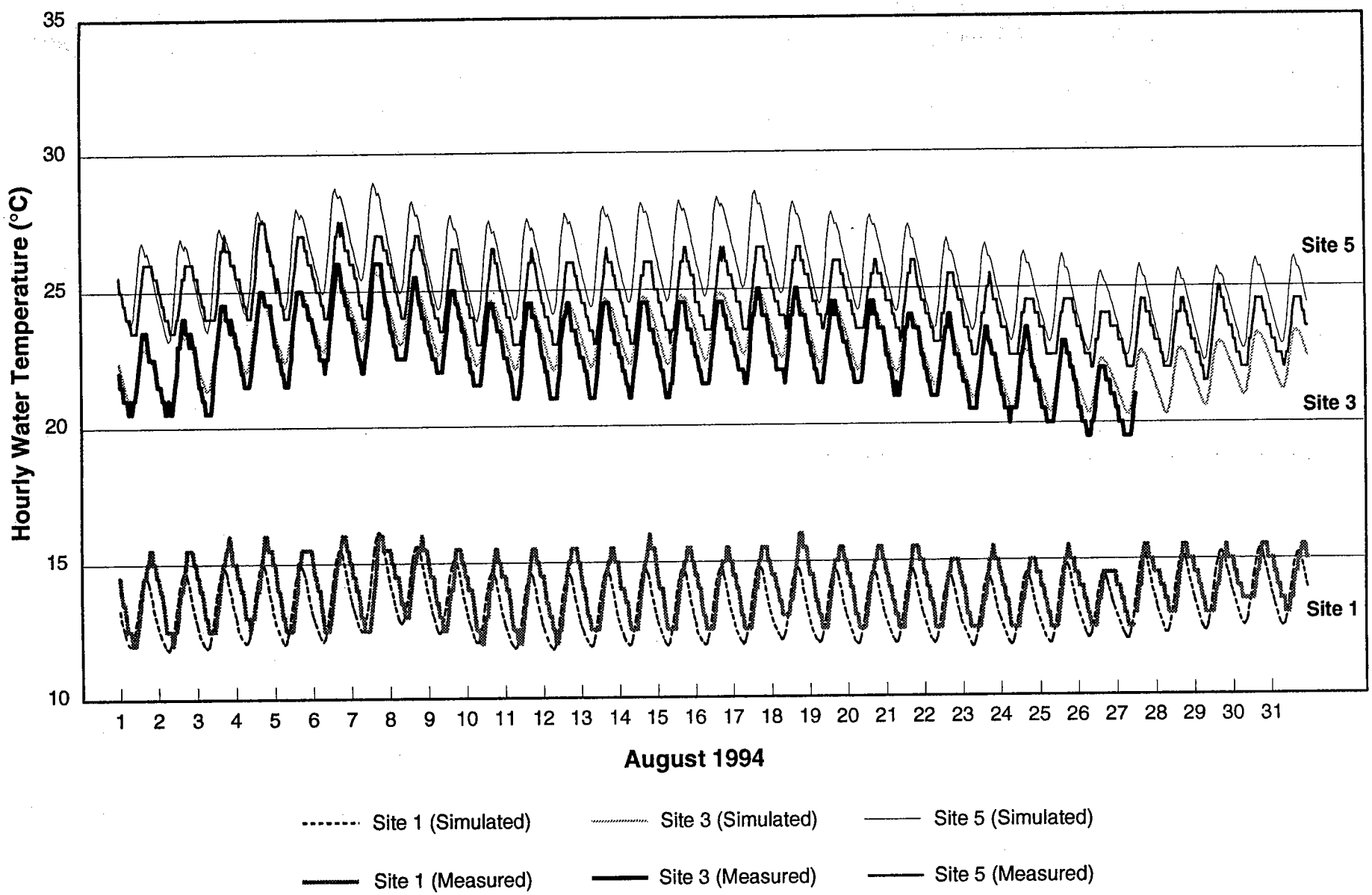
Figure 20
Simulated and Measured Hourly Water Temperatures at Sites 1, 3, and 5 during June 1994



Jones & Stokes Associates, Inc.

Figure 21
Simulated and Measured Hourly Water Temperatures at Sites 1, 3, and 5 during July 1994



Jones & Stokes Associates, Inc.

Figure 22
Simulated and Measured Hourly Water Temperatures at Sites 1, 3, and 5 during August 1994

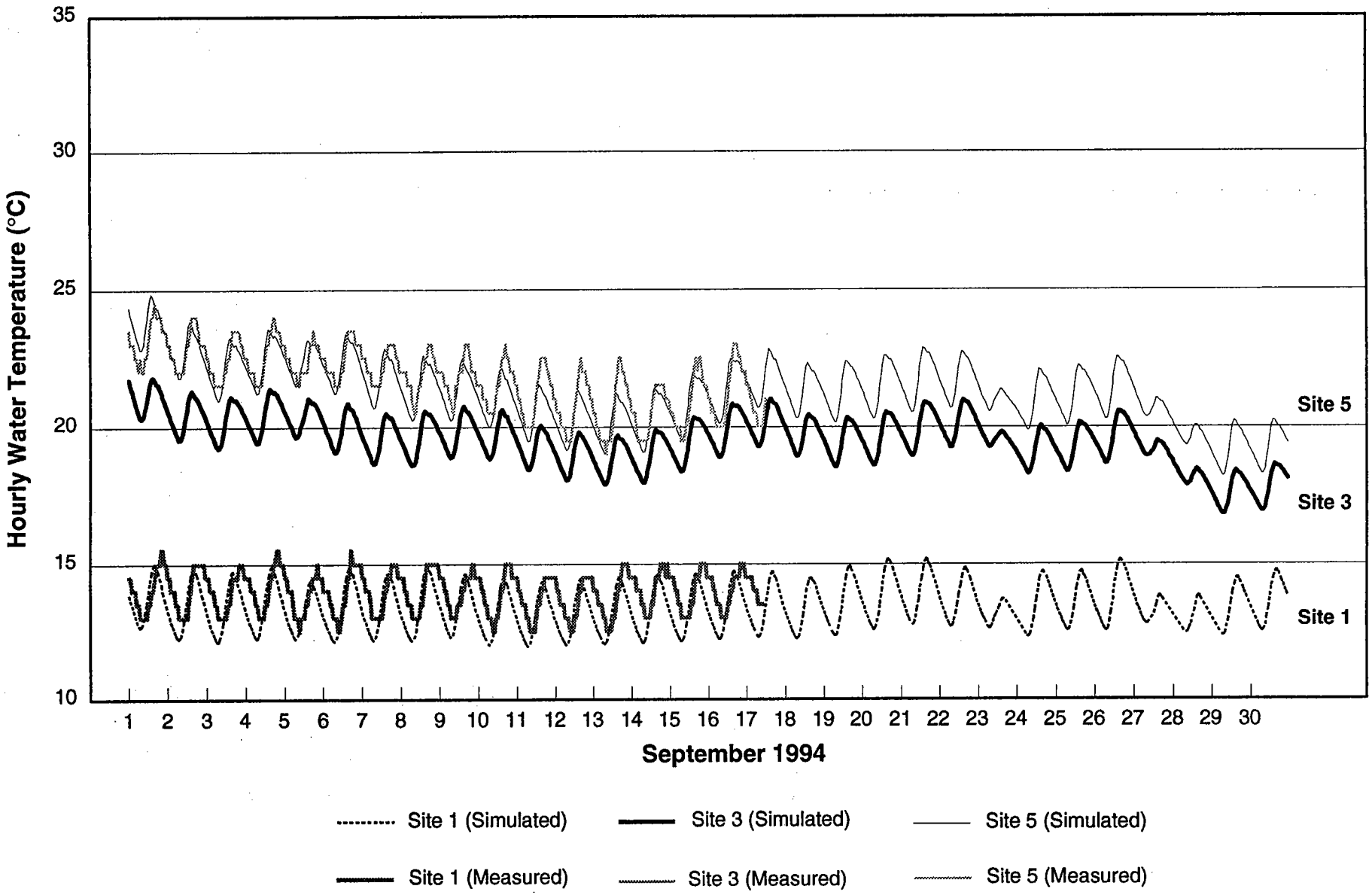


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Figure 23
Simulated and Measured Hourly Water Temperatures at Sites 1, 3, and 5 during September 1994

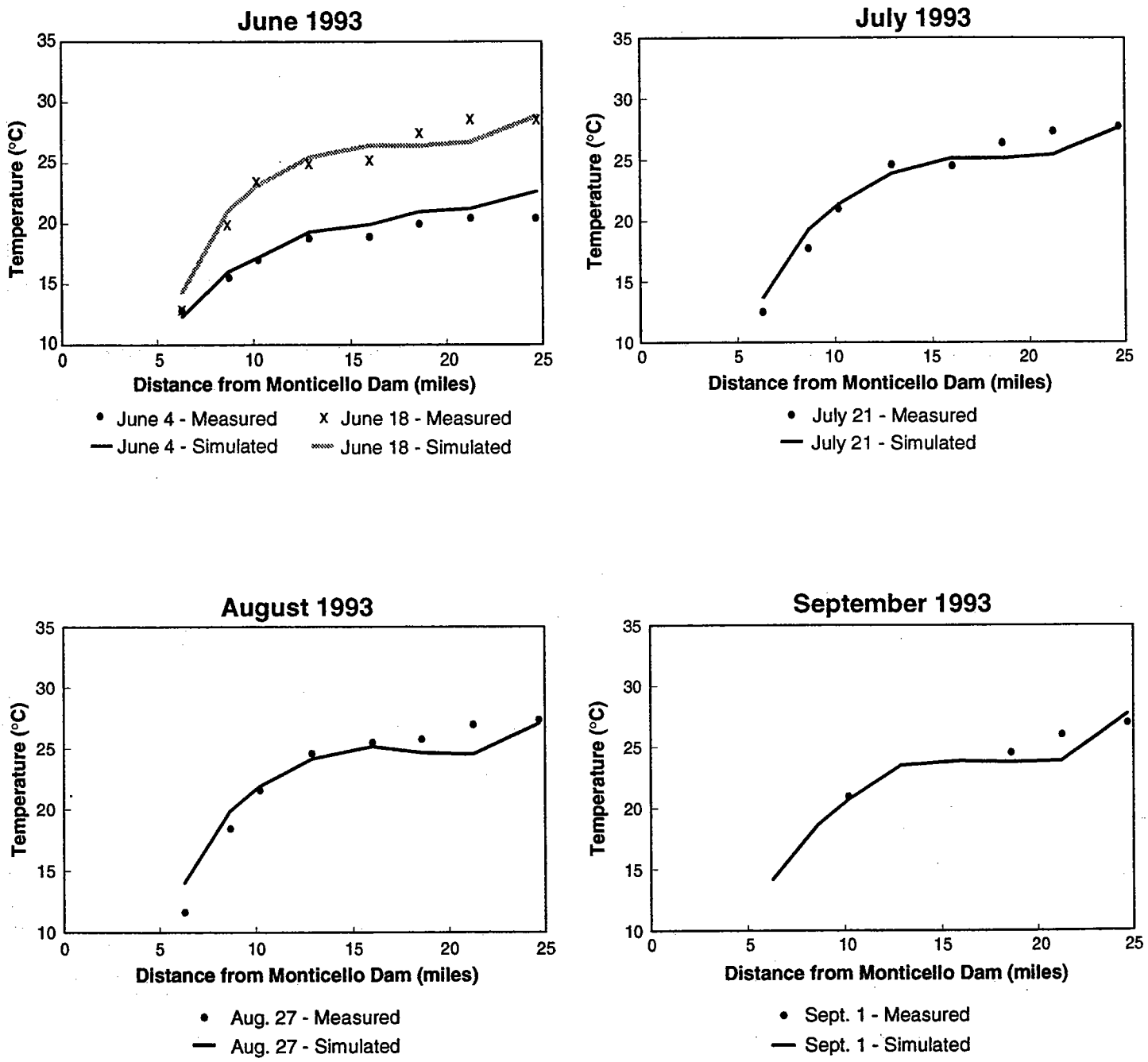

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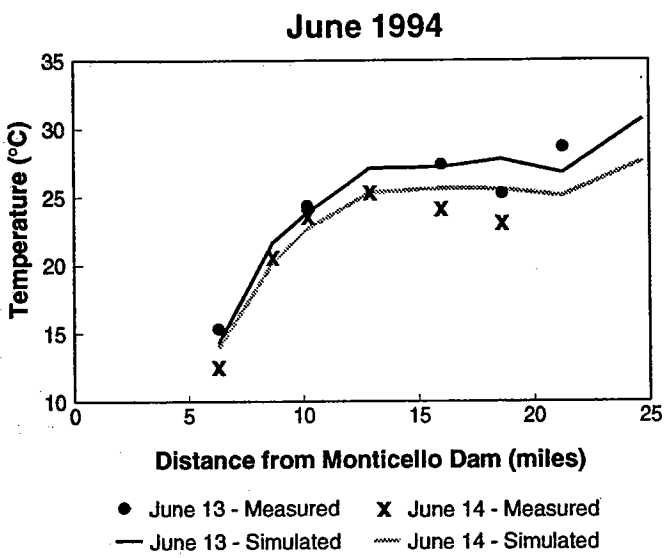
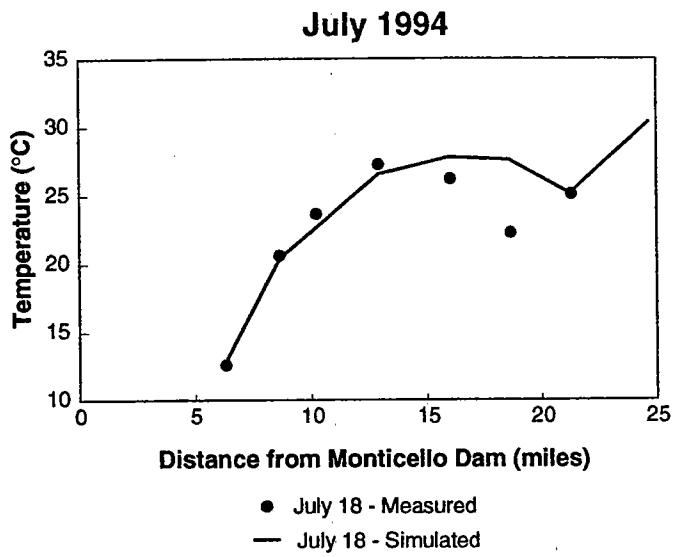
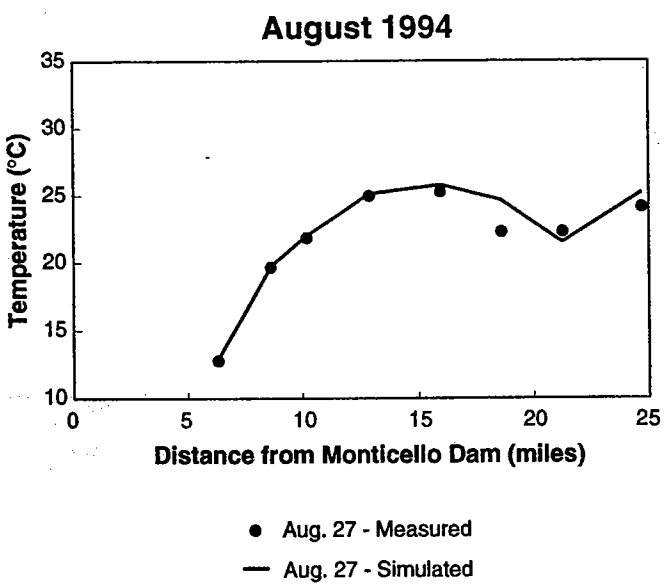
Figure 24a
Longitudinal Profiles of Measured and Simulated Temperatures along Lower Putah Creek during Summer 1993







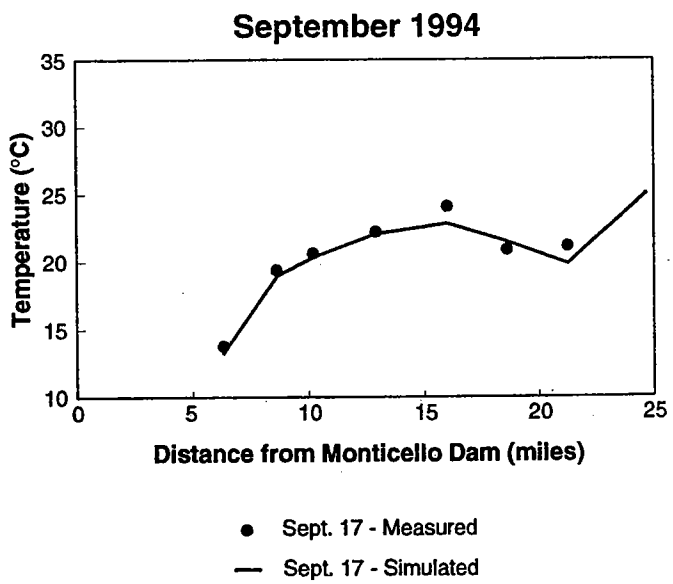


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Figure 24b
Longitudinal Profiles of Measured and Simulated Temperatures along Lower Putah Creek during Summer 1994

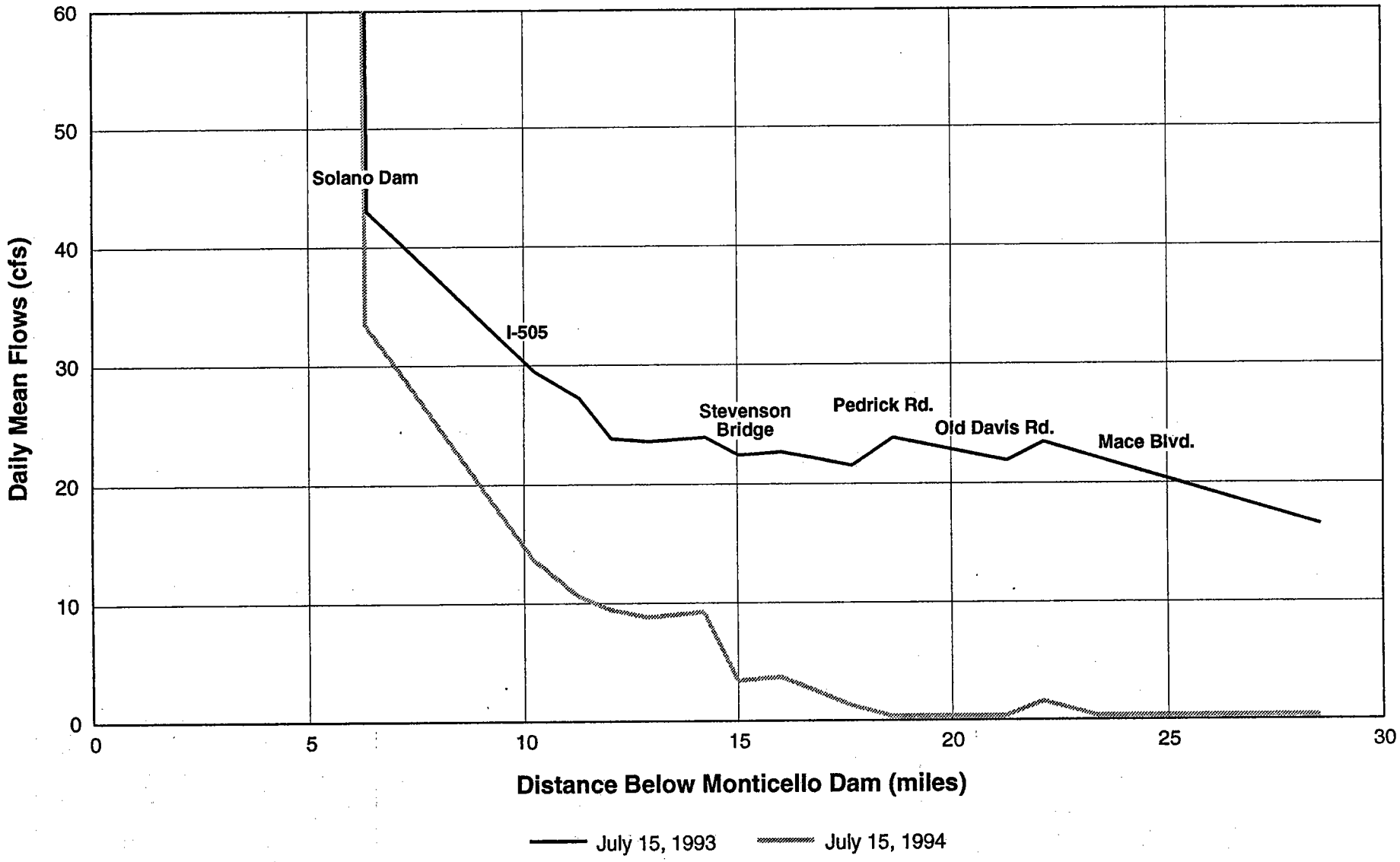

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Figure 25
Longitudinal Profiles of Simulated Flows along Lower Putah Creek in July 1993 and July 1994

Initially, the model was too sensitive to changes in flow. The simulated temperature responses to the flow pulses and to the decrease in the Solano Dam release in August were too large. There appears to be a thermal buffering mechanism operating at least in the reach between Solano Dam and I-505. Although this mechanism was not positively identified, an equivalent effect was created by altering the stream width functions so that flow width was more responsive to flow. Following this adjustment, the decrease in travel time associated with higher releases (which tends to cause relative cooling at I-505) is partially offset by an increase in flow width and solar heat gain (which tend to cause relative warming at I-505).

Flow Depth. Flow depth strongly affects the amplitude of the diurnal temperature cycle. Decreasing the depth by 2-3 feet (about 50%) increased the amplitude from 2°C to 3°C in many cases. The effects are somewhat localized so that amplitudes will be larger in shallow reaches than in deeper ponded reaches farther downstream. If changes in flow depth are not compensated by changes in flow width, the flow velocity also changes, which can change the rate of downstream warming. In most cases, this latter effect was small compared to the effect on amplitude.

A very shallow depth in Lake Solano was necessary to accurately simulate the large amplitude (2.5°C) of the diurnal temperature fluctuation at site 1 near Solano Dam. Depths of 6 and 5 feet were selected for reaches 3 and 4, which represent Lake Solano. Aerial photographs reveal large areas of shallow water near the downstream end of the lake, including shoals with vegetation. The rate of sediment influx to the lake is probably large enough to have filled in much of the lake volume since Solano Dam was built in 1959.

The proximity of the Putah South Canal diversion gate to the outlet on Solano Dam used to make releases to lower Putah Creek may also influence the amplitude of the diurnal temperature fluctuation. The two outlets are less than 100 feet apart. When diversions to Putah South Canal decreased rapidly from about 430 to about 280 cfs during the third week of September 1993, the amplitude of the diurnal temperature fluctuation decreased from about 2.5°C to about 1.5°C. This suggests that high diversion rates to Putah South Canal generate local currents strong enough to alter the temperature profile at the nearby outlet to lower Putah Creek. For example, strong currents could prevent or alter the occurrence of thermal stratification in Lake Solano near Solano Dam.

Flow Width and Shading. The rate of warming downstream of Solano Dam is strongly affected by the width of the creek and the fraction of the creek surface that is shaded by vegetation. Decreasing the base width decreases the solar heat gain because a larger fraction of the creek surface is shaded. It also increases flow velocity and delays the rate of downstream warming. For example, decreasing the base width in all reaches by 10 feet (generally 15-40% of total width) consistently decreased the temperature at sites 3 and 5 by about 1°C; however, the temperature at the Yolo Bypass remained unchanged.

Adjusting the height of the riparian vegetation has a similar effect on water temperatures. Decreasing the estimated vegetation height by a factor of 2 in all reaches resulted in temperatures 0.5-1°C higher at sites 3 and 5 but no change in the final temperature at the Yolo Bypass.

The separate effects of flow width and shading on water temperatures were differentiated by comparing simulation results for June with results for September. In any single month, the decrease

in sunlit width of flow that would result from increasing vegetation height could be achieved equally well by simply decreasing the total flow width. However, shadow length varies with time of year, whereas flow width does not. Vegetation height and flow width were adjusted during model calibration so that simulated temperatures match measured temperatures in June and September equally well. The same set of calibrated base widths and vegetation heights was then used to simulate all 4 months.

Channel width and vegetation height can have localized effects. By decreasing the base width by 10-20 feet and increasing the vegetation height by 5-10 feet along several reaches in a row, it was possible to decrease temperatures at the next downstream reach by 2°C. Reasonable adjustments of this type were done during calibration to match measured temperatures at sites 5 and 8.

Air Temperature and Solar Radiation. The effects of meteorological variables are easily distinguishable from the effects of channel geometry and shading because they change with time. During initial simulations, daily average simulated water temperatures tended to vary much more than measured temperatures during the month. Solar radiation was constant during most of these fluctuations. Many of the variations correlated with variations in air temperature. However, they also correlated with wind speed because hot days tend to occur when there is little wind to bring in cool air from the Delta. Through sensitivity analysis, however, it was discovered that adjustments in air temperature have a minor effect on water temperatures. For example, when the hourly excursions from the daily average temperature were decreased to 70% of the excursions in the raw CIMIS data, the change in simulated water temperatures was negligible. The excursions of the measured hourly air temperatures 0.2 foot above the water surface at site 3 in August 1993 were about 37% as large as the excursions in the CIMIS data, as shown in Figure 26.

Water temperatures are also relatively insensitive to adjustments in the dew point temperature. For example, on June 9, 1993, at noon, the air temperature was 29.2°C and the dew point temperature was 9.3°C. Increasing the dew point temperature by 10°C increased the total heat transfer to the water by only 10%. When all dew point temperatures were increased by an amount equal to 30% of the difference between the dew point and dry-bulb air temperatures, the effect on simulated temperatures was negligible.

Wind. Water temperatures are strongly affected by wind speed, which affects evaporative and convective cooling. Initial simulations with the raw wind speed data from the CIMIS station resulted in large day-to-day variations in simulated water temperatures. The wind speed at the creek surface is noticeably lower than in open agricultural fields in surrounding areas (including the CIMIS station site) because the creek channel is incised 30 feet below the valley floor along much of its length and is also shrouded by tall, dense vegetation in many areas. Decreasing all wind speeds by a constant percentage tended to elevate simulated water temperatures without greatly decreasing the magnitude of day-to-day fluctuations.

Better results were obtained when the CIMIS wind speeds were adjusted by a fractional exponent. For example, the square root of the wind speed corresponds to an exponent of 0.5. This method has the advantage of decreasing high wind speeds proportionately more than low wind speeds. This assumes that sheltered environment at the creek surface excludes gusts of winds more

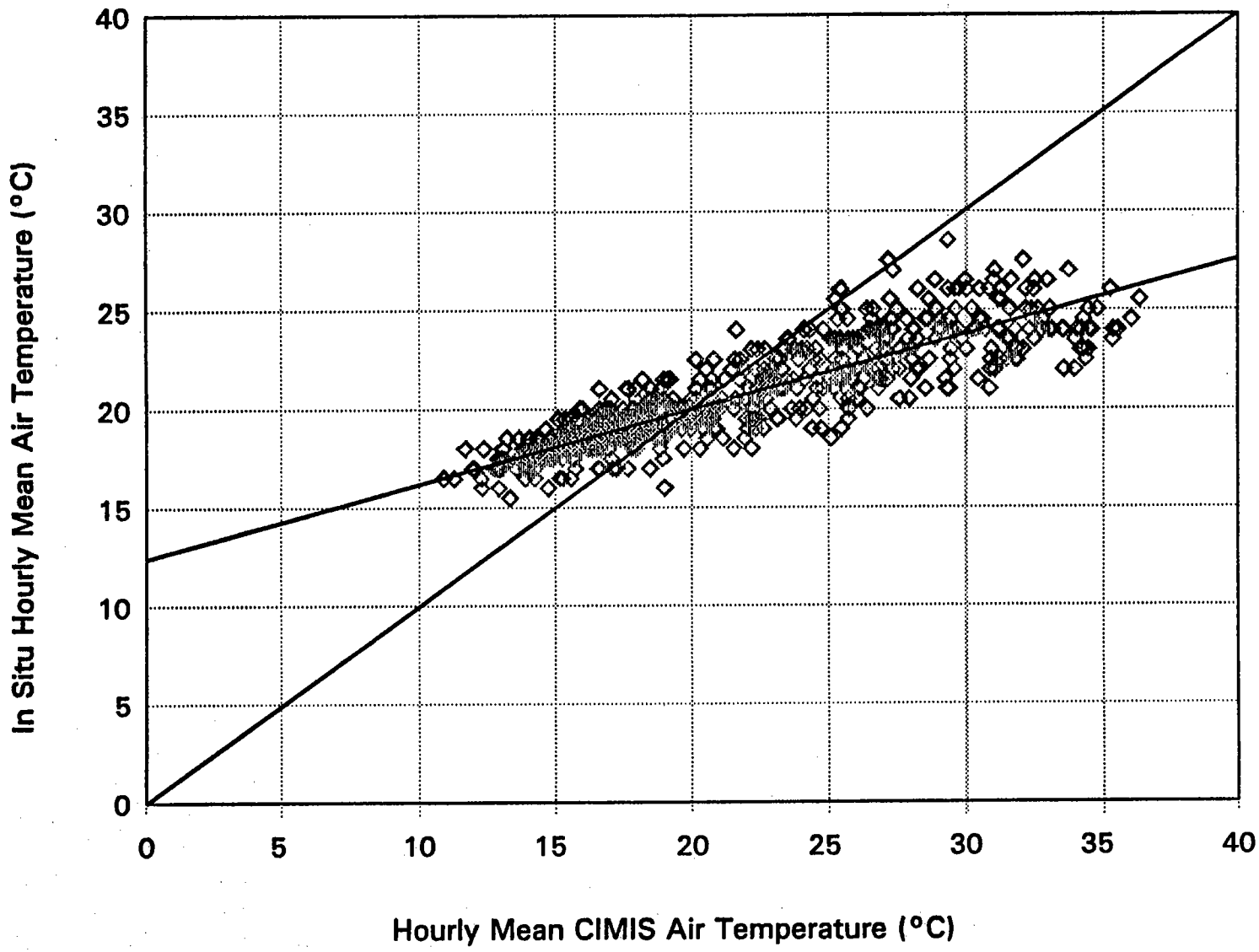

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Figure 26
Air Temperatures Measured Downstream of Highway I-505 Bridge Correlated to Air Temperatures Measured at Davis CIMIS Station in August 1993

than light breezes. In the final calibration, an exponent of 0.4 was selected. This decreased maximum wind speeds (about 10 meters per second) by a factor of 4, while minimum wind speeds (consistently about 1 meter per second) remained unchanged.

Model Limitations

The principal limitations of the model stem from limitations in the range of data used for model calibration. The model was calibrated for flow and meteorological conditions in summer. Similarly, the temperature data used for model calibration were collected when flows were less than or equal to 43 cfs. The accuracy of the calibration for simulating temperatures in winter or under higher flow conditions has not been tested.

The model is incapable of simulating temperatures correctly when flows are very low (less than perhaps 1 or 2 cfs). The model assumes complete mixing of water within each reach of the creek and does not simulate the thermal stratification that often develops under low-flow conditions. Also, the model works best when advective heat transport (downstream flow) is a significant component of the energy budget. Results become erratic if flow approaches or reaches zero.

SIMULATION OF MANAGEMENT ALTERNATIVES

The temperature model was used to simulate several possible alternative strategies for manipulating the temperature regime of the creek. The choice of alternatives and the extent to which they were implemented in the simulations were based on their physical feasibility and likelihood of having a significant effect. Practical, legal, and economic aspects of the alternatives were not considered. The alternatives were chosen primarily to illustrate the ability of the model to evaluate temperature management strategies. Their inclusion in this report should not be interpreted as an endorsement of implementing them.

Increase Releases from Solano Dam

The effect of increased releases from Solano Dam on water temperatures was investigated by increasing the release from Monticello Dam by 20 cfs while leaving the diversion to Putah South Canal unchanged. In June 1993, for example, the flow below Solano Dam would increase from 43 to 63 cfs. This simulation also constitutes a sensitivity analysis of the effect of flow on temperature.

The effect on simulated hourly water temperatures during July 1994 is shown in Figure 27, and the effect on the longitudinal temperature profiles on July 7 and 18, 1994, is shown in Figure 28. Temperatures at sites 3 and 5 were consistently lower by 2.0-2.5°C throughout the month. The longitudinal profiles indicate that the temperature difference gradually increases

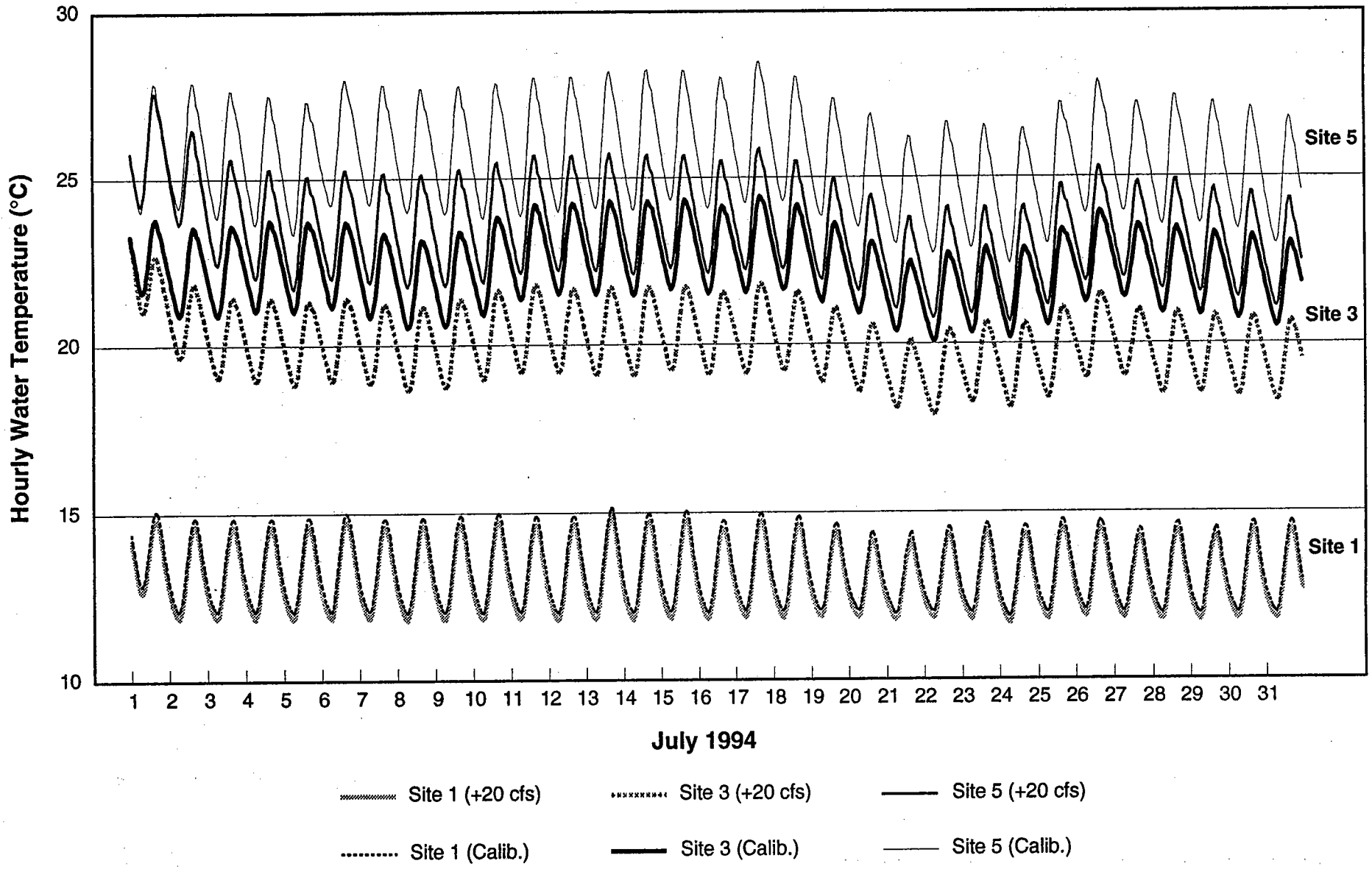

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Figure 27
Effect of Increasing Flow Below Solano Dam by 20 cfs on Simulated Hourly Water Temperatures at Sites 1, 3, and 5 during July 1994

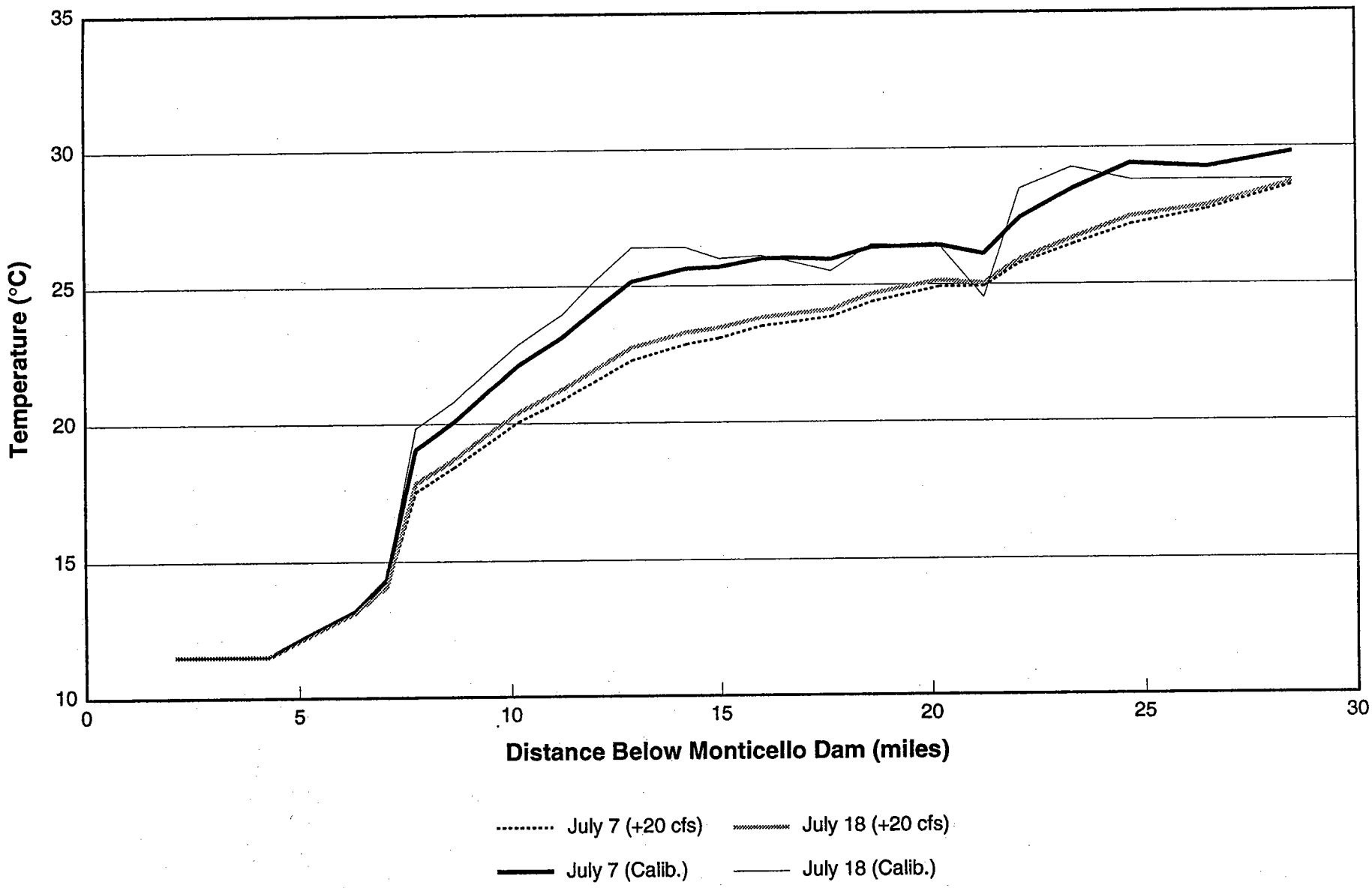

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Figure 28
Effect of Increasing Flow Below Solano Dam by 20 cfs on Simulated Hourly Water Temperature Profiles along Putah Creek on July 7 and 18, 1994

between Solano Dam and I-505 and remains fairly constant from there to the Yolo Bypass. A similar simulation for July 1993 yielded similar results.

Eliminate Irrigation Diversions

Diversions for irrigation withdraw water from the creek at a combined rate of about 5.9 cfs during July in normal years, principally along the reaches between I-505 and I-80. Eliminating the diversions had a small effect on simulated water temperatures at site 5 and essentially no effect at sites 1 and 3. Daily average temperatures at site 5 were about 0.1°C higher. Maximum afternoon temperatures remained essentially the same, but the amplitude of the diurnal temperature fluctuations decreased by about 0.2°C. The effect of irrigation diversions on temperature is small because the water temperature has largely equilibrated with ambient meteorological conditions by the time the water reaches the points of diversion.

Remove Selected Beaver Dams

In several locations along Putah Creek, the ponded conditions in the channel are created by beaver dams. If the dams were removed, flow depth and width would decrease and flow velocity would increase. These changes would all tend to delay the rate of warming below Solano Dam and allow cold water to travel farther downstream. To simulate this possibility, the base depths of reaches 5, 8, 10, and 19 were decreased from 3 feet to 1 foot, and the base widths were decreased from 40 or 60 feet to 20 feet. In addition, the base width of reach 6, which includes a large wetland adjacent to the channel, was decreased from 160 to 40 feet. This represents implementation of a measure to allow only a small fraction of streamflow to circulate through the wetland.

The height of the riparian vegetation along the altered reaches was not changed. In practice, removal of beaver dams would initially create wide, unvegetated bank areas along the new, narrower low-flow channel. Tall vegetation would not become established in these areas for possibly 5-15 years following removal of the beaver dams.

The results of the simulation for July 1994 are shown in Figures 29 and 30. Average daily water temperatures at site 3 were consistently 4°C cooler throughout the month. The temperatures at site 5 were about 1°C cooler most of the time and slightly more than 2°C cooler during the pulse of higher flow on July 7-9. The effect on the longitudinal temperature profile (Figure 30) is different than the effect of increasing the release from Solano Dam (Figure 28). In this case, the decrease in temperature relative to the calibration simulation gradually diminishes downstream from about 4°C near Winters to 1°C near Pedrick Road.

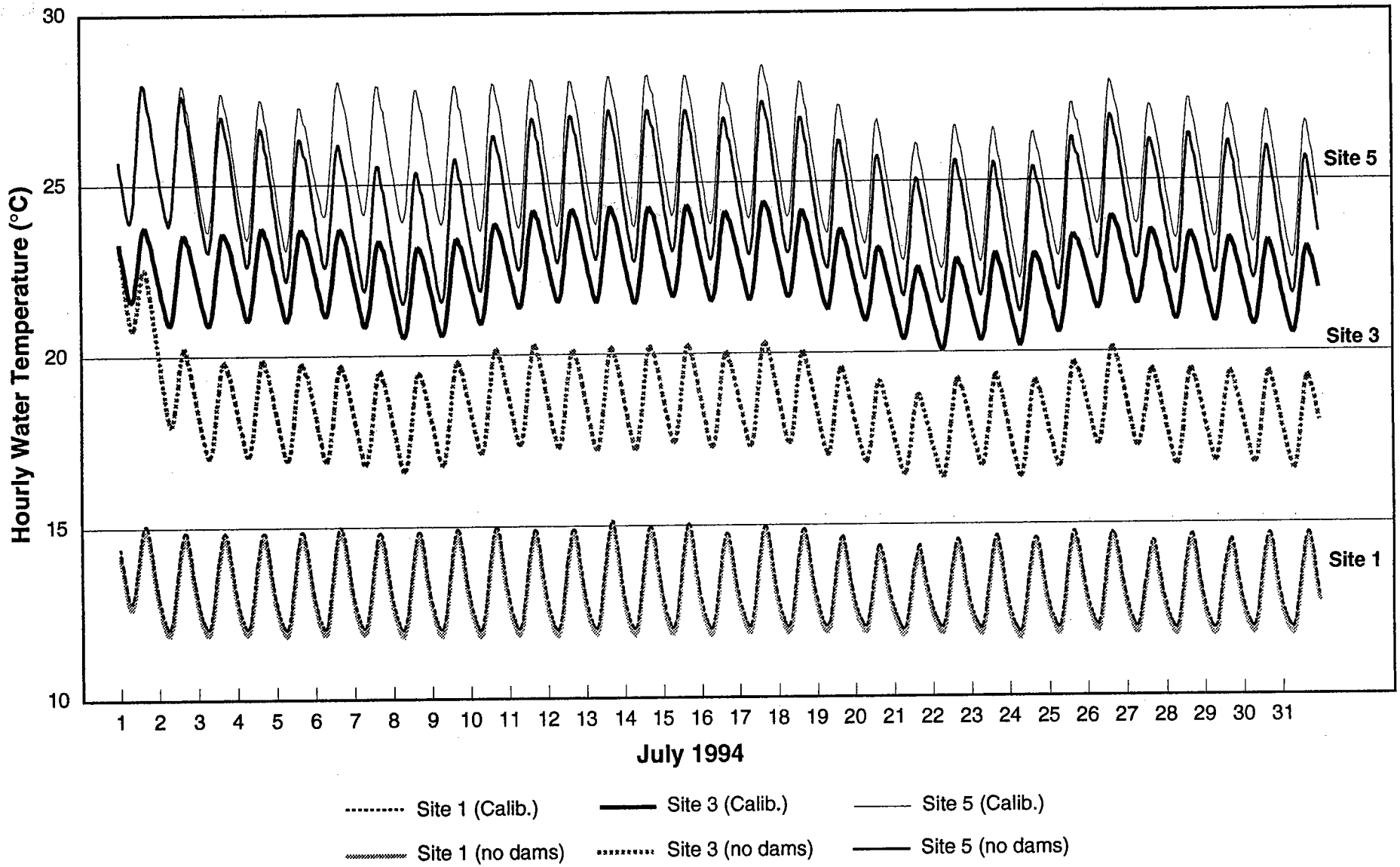

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Figure 29
Effect of Removing Selected Beaver Dams on Simulated Hourly Water Temperatures at Sites 1, 3, and 5 during July 1994

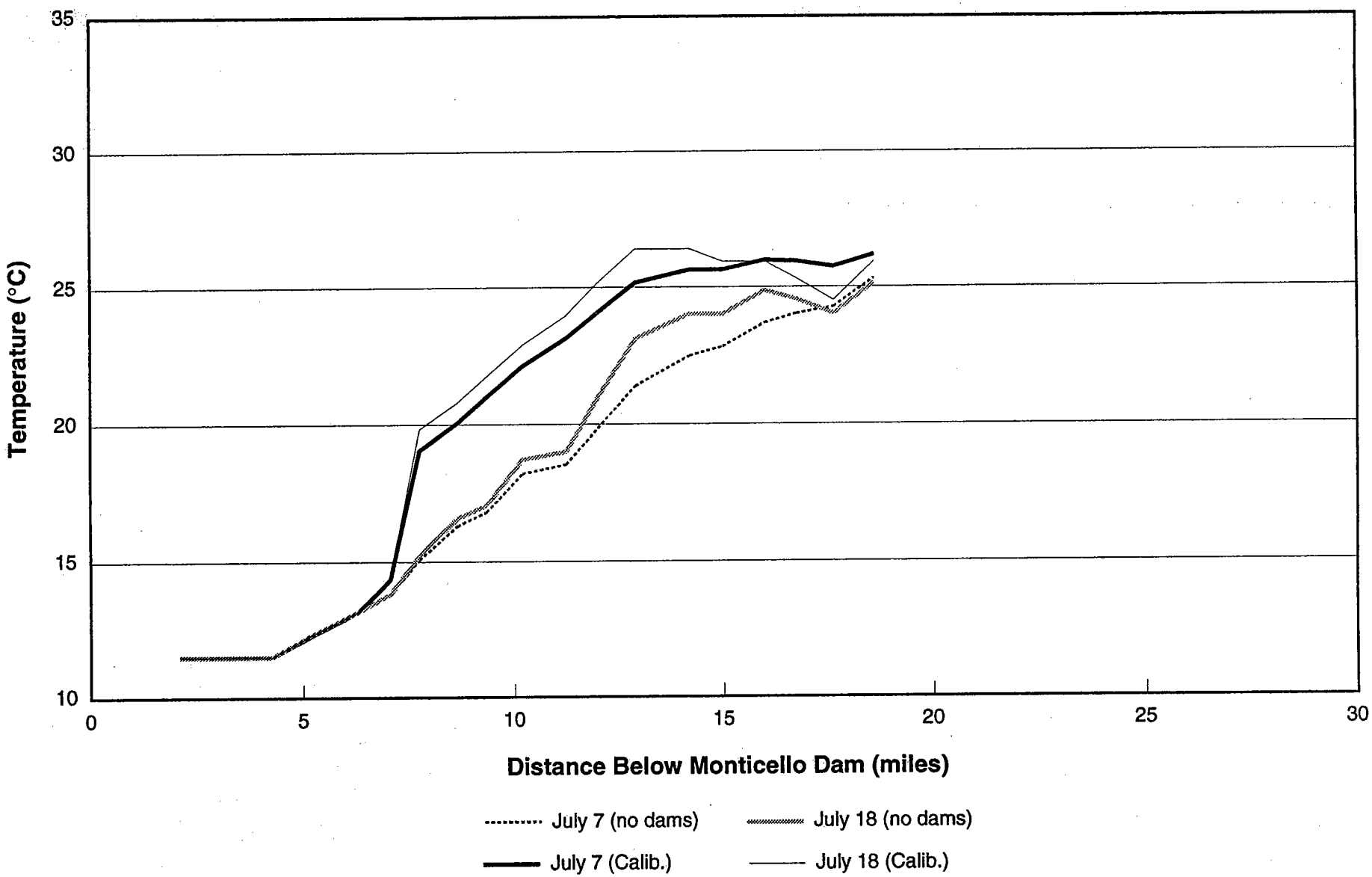

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Figure 30
Effect of Removing Selected Beaver Dams on Simulated Hourly Water Temperature Profiles along Putah Creek on July 7 and 18, 1994

Conclusions

The key conclusions derived from analysis of measured and simulated temperatures in Putah Creek are as follows:

- Water temperatures in summer warm up rapidly from about 12°C at Solano Dam to about 22-23°C at I-505 and 24-26°C at Stevenson Bridge. Most of the warming occurs upstream of I-505. Downstream of I-505, the creek temperature generally is in equilibrium with ambient meteorological conditions.

- A slight temperature depression was measured consistently near Stevenson Bridge in 1993. This depression probably resulted from seepage of relatively cool (17.5°C) groundwater into the creek.

- Daily average water temperatures from Solano Dam to Stevenson Bridge rarely exceeded 26°C during 1993-1994 and consequently were within the tolerance range of smallmouth bass and probably most native fish (except trout).

- Thermal stratification occurs in pools in the creek when flows are very low. Afternoon temperatures within about 1 foot of the water surface (26-34°C) are too hot for most species. Bottom temperatures (21-24°C) are consistently in a tolerable range for most native fish.

- When flows are very low, water temperature becomes locally variable. At any given location, the thermal effects of local shading, air temperature, and turbulence are larger than the effect of the inflow temperature from upstream reaches.

- The model does not simulate temperature accurately when flows are very low. Flows from site 6 (Pedrick Road) to the Yolo Bypass in 1994 were too low to simulate accurately.

- Increased releases from Solano Dam in summer delay the warming rate of the creek and allow cool water to reach farther downstream. The effect is not large, however. At I-505, increasing the release by 10 cfs decreases the temperature at I-505 by about 1°C.

- The rate of warming of the creek downstream of Solano Dam is affected strongly by the width of stream surface exposed to the sun. Consequently, factors that affect stream width or shading from vegetation (such as removal of beaver dams) had a relatively large effect on simulated temperatures.

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Personal Communications

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