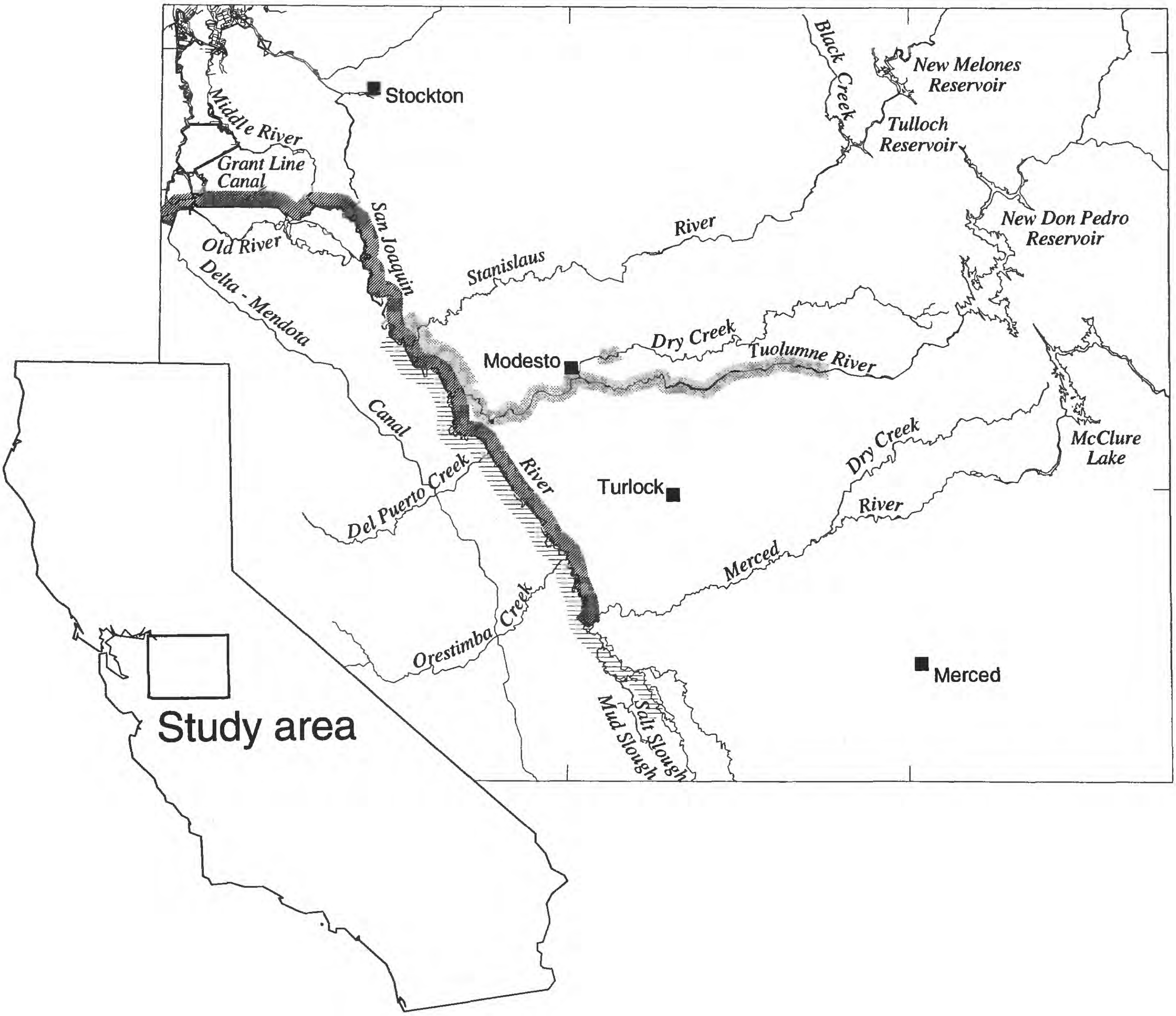
Determination of Traveltimes in the Lower San Joaquin River Basin, California, from Dye-Tracer Studies during 1994–1995



U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 97-4018

National Water Quality Assessment Program

The shading patterns on the front cover refer to the extent of the dye-tracer studies:

- February 1994
- June 1994
- February 1995

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By Charles R. Kratzer *and* Rhodora N. Biagtan

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National Water Quality Assessment Program

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CONTENTS

FIGURES

TABLES

Conversion Factors, Water-Quality Information, and Abbreviations

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
gallon (gal)	3.7854	liter
mile (mi)	1.609	kilometer
pound, avoirdupois (lb)	0.4536	kilogram
square mile (mi^2)	2.590	square kilometer

Water-Quality Units

Dye concentrations in water samples are given in micrograms per liter. One thousand micrograms per liter is equivalent to 1 milligram per liter. Micrograms per liter is equivalent to "parts per billion."

Abbreviations and Acronyms

DMC, Delta-Mendota Canal
DWR, Department of Water Resources (California)
h, hour
kg, kilogram
kg/L, kilograms per liter
kg/lb, kilograms per pound
L, liter
mg/L, milligrams per liter
µg/L, micrograms per liter
µg/kg, micrograms per kilogram
NAWQA, National Water Quality Assessment
USGS, U.S. Geological Survey

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Abstract

Dye-tracer studies were done in the lower San Joaquin River Basin in February 1994, June 1994, and February 1995. Dye releases were made in the Merced River (February 1994), Salt Slough (June 1994), Tuolumne River (February 1995), and Dry Creek (February 1995). The traveltimes determined in the studies aided the interpretation of pesticide data collected during storm sampling and guided sample collection during a Lagrangian pesticide study. All three studies used rhodamine WT 20-percent dye solution, which was released as a slug in midstream. The mean traveltime determined in the dye studies were compared to estimates based on regression equations of mean stream velocity as a function of streamflow. Dye recovery, the ratio of the calculated dye load at downstream sites to the initial amount of dye released, was determined for the 1994 studies and a dye-dosage formula was evaluated for all studies.

In the February 1994 study, mean traveltime from the Merced River at River Road to the San Joaquin River near Vernalis (46.8 river miles) was 38.5 hours, and to the Delta-Mendota Canal at Tracy pumps (84.3 river miles) was 90.4 hours. In the June 1994 study, mean traveltime from Salt Slough at Highway 165 to Vernalis (64.0 river miles) was 80.1 hours. In the February 1995 study, the mean traveltime from the Tuolumne River at Roberts Ferry to Vernalis (51.5 river miles) was 35.8 hours. For the 1994 studies, the regression equations provided suitable estimates of traveltime, with ratios of estimated traveltime to mean dye traveltime of 0.94 to 1.08. However, for the 1995 dye studies, the equations considerably underestimated traveltime, with ratios of 0.49 to 0.73.

In the February 1994 study, 70 percent of the dye released was recovered at Vernalis and 35 percent was recovered at the Delta-Mendota Canal at Tracy pumps. In the June 1994 study, recovery was 61 percent at Patterson, 43 percent just upstream of the Tuolumne River confluence, and 37 percent at Vernalis. The dye-dosage formula overestimated the dye required for a given downstream concentration for the 1994 studies by ratios of 1.07 to 2.12. The ratios for the February 1995 studies were 0.67 to 0.95 for the Tuolumne River and 1.21 for Dry Creek. In all studies, the estimates improved with length of dye study.

INTRODUCTION

Dye-tracer studies are valuable for determining traveltimes, streamflow, dispersion, reaeration, flow patterns, and soluble waste transport in surface-water hydrologic and water-quality studies (Kilpatrick, 1993). Dye-tracer studies were done in the lower San Joaquin River Basin in February 1994, June 1994, and February 1995 as part of the San Joaquin–Tulare Basins National Water Quality Assessment (NAWQA) Program. The objective of the dye-tracer studies was to determine traveltimes in support of pesticide transport studies. Dye was released into the Merced River at site 4 (fig. 1, table 1), in Salt Slough at site 2, in the Tuolumne River at site 10, and in Dry Creek at site 15. The dye was sampled at 11 sites. The sites were chosen to provide information for the pesticide transport studies and not to provide the detail necessary for a complete description of dye recoveries. The February 1994 and February 1995 dye studies were done to help interpret the pesticide data collected during the storms.

The June 1994 dye study was done to guide sample collection during a Lagrangian pesticide study, where a single parcel of water was sampled from site 2 to site 18 along with inflows contributing to the parcel.

The location of the river reaches where the dye-tracer studies were done are shaded in figure 1. Descriptions of the dye release and sampling sites are listed in table 1. The June 1994 and February 1995 Tuolumne studies concluded at the San Joaquin River near Vernalis (site 18). The February 1994 study concluded at the Delta-Mendota Canal (DMC) at Tracy pumps (site 21). The February 1995 Dry Creek study concluded at El Vista Avenue (site 16) because of backwater conditions in Dry Creek caused by high streamflows in the Tuolumne River. Downstream flow in Dry Creek stopped shortly below site 16 during the dye study.

The DMC pumps—part of the Federal Central Valley Project—divert water from the Sacramento–San Joaquin Delta to the San Joaquin Valley primarily for agricultural use. The southern part of the delta begins at Vernalis and its tidal action affects streamflow downstream of Vernalis. The San Joaquin River streamflow splits downstream of Vernalis at Old River (fig. 1). Old River streamflow can take several routes to the DMC pumps depending on tidal effects, San Joaquin River streamflow, and pumping rates at the DMC pumps and the State Water Project pumps near

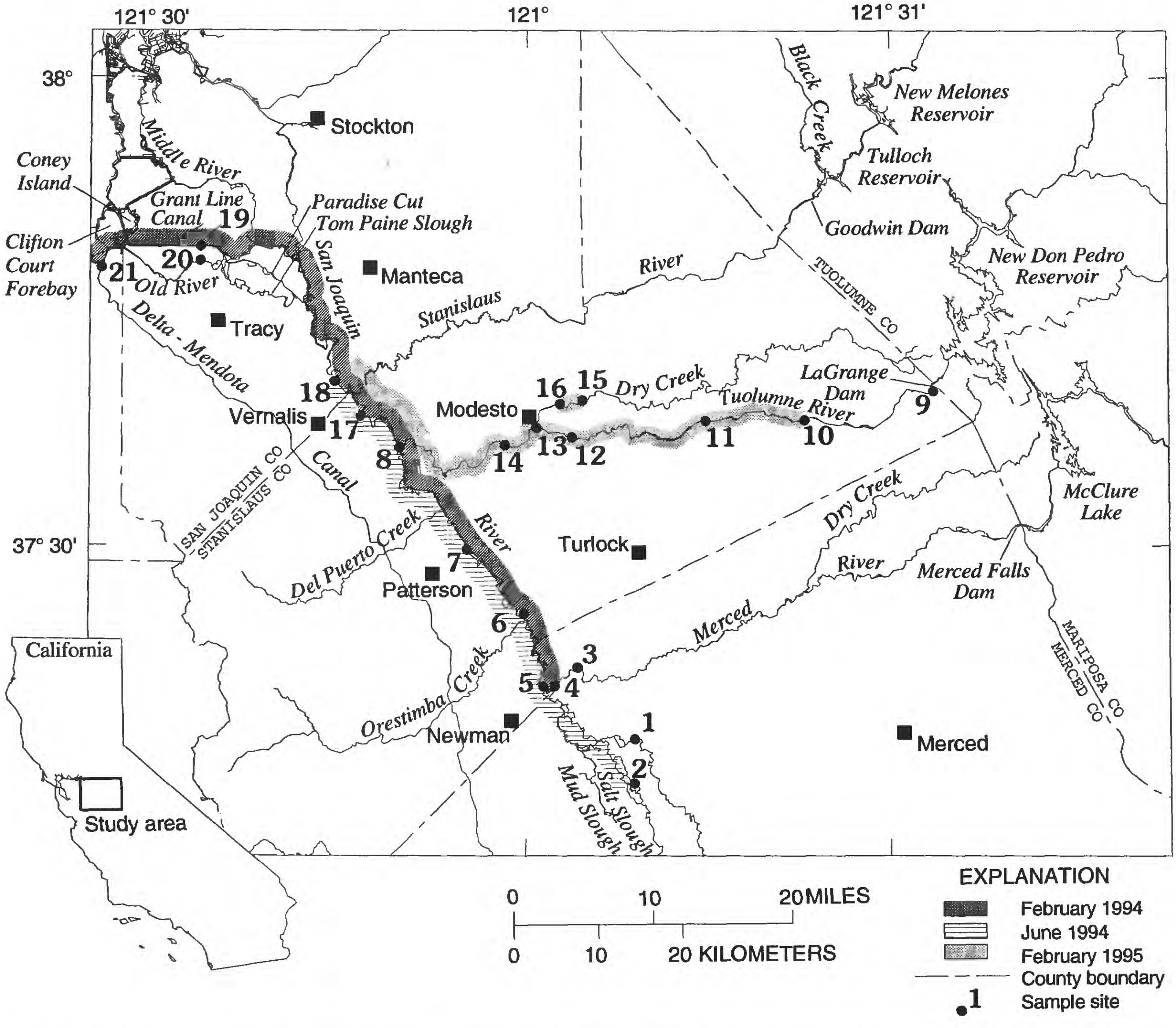

Figure 1. Locations of river reaches where dye-tracer studies were done (shading patterns), including dye sampling sites (sites 2, 4, 5, 6, 7, 8, 10, 12, 14, 15, 16, 18, 19, 20, 21), and sites for which regression equations of mean stream velocity as a function of streamflow have been developed (sites 1, 2, 3, 5, 7, 9, 11, 13, 15, 17, 18).

Clifton Court Forebay. The main route from the San Joaquin River to the DMC pumps is the Grant Line Canal (Oltmann, 1995).

Streamflows in the February 1994 study were unstable and rising because of storm runoff, and diversions were not significant. Streamflows during the June 1994 study were relatively low and stable. Diversions for agricultural use were probably very significant from the approximately 50 diversions along the dye route (Kratzer and others, 1987). However, the actual diversion amounts were not determined in the June 1994 study and daily diversion amounts are not reported. Streamflows in the February 1995 Tuolumne study were relatively high and stable, primarily due to the steady release of water from New Don Pedro Reservoir (fig. 1). Streamflows in the February 1995 Dry Creek study were relatively low and stable at the time of the dye study. Diversions were not significant in the 1995 studies.

Table 1. Dye release and sampling sites for 1994-95 tracer studies

Site no. (from fig. 1)	Station name	Station location	Date of dye study	Flow data available
2	Salt Slough at Highway 165	6.8 river miles upstream from San Joaquin River; 64.0 river miles upstream from Vernalis.	June 1994	Yes
4	Merced River at River Road	1.1 river miles upstream from San Joaquin River; 46.8 river miles upstream from Vernalis.	Feb 1994	Yes[1]
5	San Joaquin River near Newman	45.7 river miles upstream from Vernalis	June 1994	Yes
6	San Joaquin River at Crows Landing	35.5 river miles upstream from Vernalis	June 1994	No
7	San Joaquin River at Patterson	26.3 river miles upstream from Vernalis	June 1994	Yes
8	San Joaquin River above confluence of Tuolumne River.	11.6 river miles upstream from Vernalis	June 1994	Yes[2]
10	Tuolumne River at Roberts Ferry	40.3 river miles upstream from San Joaquin River; 51.5 river miles upstream from Vernalis.	Feb 1995	No
12	Tuolumne River at Mitchell Road	19.3 river miles upstream from San Joaquin River; 30.5 river miles upstream from Vernalis.	Feb 1995	No
14	Tuolumne River at Carpenter Road	12.7 river miles upstream from San Joaquin River; 23.9 river miles upstream from Vernalis.	Feb 1995	No
15	Dry Creek near Modesto at Claus Road	5.5 river miles upstream from Tuolumne River; 33.0 river miles upstream from Vernalis.	Feb 1995	Yes
16	Dry Creek at El Vista Avenue	2.9 river miles upstream from Tuolumne River; 30.4 river miles upstream from Vernalis.	Feb 1995	No
18	San Joaquin River near Vernalis	37.5 river miles upstream from Delta-Mendota Canal.	Feb 1994, June 1994, Feb 1995	Yes
19	Grant Line Canal at Tracy Boulevard	28.8 river miles downstream from Vernalis; 8.7 river miles upstream from Delta-Mendota Canal.	Feb 1994	No
20	Old River at Tracy Boulevard	29.5 river miles downstream from Vernalis; 10.5 river miles upstream from Delta-Mendota Canal.	Feb 1994	No
21	Delta-Mendota Canal at Tracy Pumps	37.5 river miles downstream from Vernalis	Feb 1994	Yes

[1] Gaging station is 3.6 river miles upstream at Merced River near Stevinson (site no. 3 shown in fig. 1).

[2] No gaging station; several streamflow measurements during dye study.

This report describes the sampling design used for the dye studies and discusses the results of each study in terms of dye-cloud location, traveltime, and time-concentration curves at sampling sites. Dye traveltime is compared with estimates of traveltime based on regression equations relating mean stream velocity to streamflow. Dye recoveries are calculated and a dye-dosage formula (Kilpatrick and Wilson, 1989) is evaluated.

The authors would like to thank the U. S. Geological Survey (USGS) personnel outside the NAWQA program who helped with dye sampling, especially Francis Huber, hydrologist with the California District, who put in many extra hours on all three dye studies. Cynthia Laguna, Mitchell Ryan, Patricia Saelao, and Leslie Grober of the Central Valley Regional Water Quality Control Board staff provided assistance in sampling. Ed Hagemann, landowner, kindly provided access to the San Joaquin River site above the confluence of the Tuolumne River. Larry Baxter of the California Department of Water Resources' (DWR) San Joaquin District office promptly provided streamflow data and velocity measurements for their stream gaging stations. Rick Oltmann, hydrologist with the USGS California District, provided helpful comments which greatly improved the discussion of dye movement in the Sacramento-San Joaquin Delta. Finally, we greatly appreciate the excellent job that Priscilla Hays, formerly a hydrologic assistant with the USGS California District, did on the illustrations for this report.

SAMPLING DESIGN AND METHODOLOGY

All dye-tracer studies used rhodamine WT 20-percent dye. Rhodamine WT is recommended for tracer studies because it is (1) water soluble, (2) highly detectable, (3) not susceptible to background fluorescence, (4) nontoxic in low concentrations, (5) relatively inexpensive, and (6) reasonably stable in a normal water environment (Wilson and others, 1986). In the February 1994 study, 15 lb of dye (75 lb of 20-percent dye solution, lot #086; specific gravity 1.12) was released into the Merced River at River Road (fig. 1, site 4). In the June 1994 study, 4.91 lb of dye (lot #04001; specific gravity 1.11) was released into Salt Slough at Highway 165 (fig. 1, site 2). In the February 1995 study, 9.46 lb of dye (lot #04007, specific gravity 1.11) was released into the Tuolumne River at Roberts Ferry (fig. 1, site 10) and 0.27 lb was released into Dry Creek near Modesto at Claus Road (fig. 1, site 15).

The 20-percent rhodamine WT dye solution was introduced midstream by lowering it in 5-gal plastic buckets from a bridge and releasing it all at once. The dye release sites were generally the farthest upstream sampling sites in the concurrent pesticide transport study. Downstream sampling sites were at bridges and pesticide sampling sites. In the 1994 dye studies, samples were collected throughout the passage of most of the dye cloud at all sampling sites except 19 and 20. Sampling was concluded when concentrations dropped to less than 10 percent of peak concentration, but prior to reaching background levels. At site 19, sampling concluded shortly after the peak concentration was measured. At site 20, concentrations remained at the background level for all samples. Except for sites 19 and 20, these concentration data and streamflow information permitted the mass of dye passing the sites to be calculated, in addition to dye traveltime. In the 1995 dye study, samples were collected near the time of the peak dye concentration only. This permitted the calculation of dye traveltime only.

Dye samples were collected by lowering a glass sample bottle, attached to a metal flange, into the streamflow. An aliquot of the sample was poured from the sample bottle into the fluorometer cuvette for analysis in the field. The rest of the sample was kept in the sample bottle and labeled for analysis later in the laboratory. At most sites, samples were collected only at midstream. However, at the San Joaquin River near Newman (fig. 1, site 5), samples were collected at the 10- and 25-percent points across the stream cross-section (from the west bank) and three samples were also collected at the 75-percent point. At the San Joaquin River near Vernalis (fig. 1, site 18), all samples were collected at midstream and three samples were also collected at the 25- and 75-percent points in the stream cross-section. Samples at the San Joaquin River site above the confluence of the Tuolumne River (fig. 1, site 8) were collected at about the 10-percent point by wading from the west bank; there is no bridge at this site.

Two Turner Designs model 10 fluorometers were used to analyze samples in the field. All samples were reanalyzed in the laboratory using one fluorometer at a constant temperature. A 0.45 lb aliquot of the 20-percent dye solution used in the June 1994 study was used to make standards for calibrating the fluorometer for analysis of the samples from the February 1994 and June 1994 studies. The dye used in the February 1995 study was used for analysis of the February 1995 samples. Dye standards were obtained by serial dilutions using equation (1) (Wilson and others, 1986). Initial fluorometer readings at a site determine the background fluorescence, which is caused primarily by turbidity. This background reading is subtracted from each fluorometer reading to determine dye concentrations.

$$C_f = C_i D_1 \times D_2 \times \ldots D_n \tag{1}$$

where

C_f = final concentration of dye standard obtained after dilutions (in µg/L);

C_i = initial concentration of dye solution obtained from manufacturer (20 percent by weight) (in µg/L); [$C_i = 0.2 \times W_s$ (in kg) $\times 10^9$ µg/kg / V_s (in L)];

where

W_s = weight of 20-percent dye solution (W_s = 0.45 lb x 0.454 kg/lb = 0.204 kg for June 1994 study);

V_s = volume of 20-percent dye solution ($V_s = W_s/\gamma_s$ where γ_s is the specific weight of the 20-percent dye solution, $\gamma_s = \gamma_w \times S_G$ where γ_w is the specific weight of water (γ_w = 1.00 kg/L) and S_G is the specific gravity of the 20-percent dye solution (S_G = 1.11 for June 1994 study) [V_s = 0.204 kg/(1.00 kg/L)(1.11) = 0.184 L];

[for June 1994 study,

C_i = 0.2 x 0.204 x 10^9 / 0.184 = 222,000,000 µg/L]; and

D_i = a dilution factor at step *i* equal to [$V_d/(V_w+V_d)$]; V_w is the volume of deionized water added as a diluent and V_d is the pipet volume of the 20-percent dye solution for each step.

TRAVELTIMES DETERMINED FROM DYE-TRACER STUDIES

For sites with almost complete time-concentration curves, mean dye traveltime is defined as the time to the centroid (center of gravity) of the area under the time-concentration curve. The tail of the time-concentration curves for the 1994 studies at sites 6, 7, 8, 18, and 21 were completed by extending the curves to a concentration of zero using an exponential fit to the last several raw data points. The raw data include the background readings of the fluorometer. When the exponential curve reaches the background reading, the actual dye concentration is zero and the centroid of the curve can be calculated. The centroids ($\bar{t}$, $\bar{c}$) were calculated using the trapezoidal rule approximation (Selby, 1973) to solve equations (Purcell, 1965):

$$\bar{t} = \frac{\int_0^t C(t)\,t\,dt}{\int_0^t C(t)\,dt} \quad \text{and} \quad \bar{c} = \frac{\frac{1}{2}\int_0^t C(t)\,C(t)\,dt}{\int_0^t C(t)\,dt} \tag{2}$$

For sites without complete time-concentration curves (site 19 in February 1994; all sites in February 1995), the mean dye traveltime is defined as the time to the peak dye concentration. For sites with complete time-concentration curves, the ratios of traveltime determined by peak concentration to traveltime determined by centroid were 0.94 to 1.02.

February 1994 Study

The dye was released into the Merced River at River Road (fig. 1, site 4) at 2315 h on February 8, 1994 at the early stages of the rising limb of the storm hydrograph (fig. 2). The subsequent presence of the dye cloud at downstream sites relative to streamflows is shown in figure 2. The time-concentration curves at downstream sampling sites are shown in figure 3. The concentrations shown are all for midstream samples. For the three cross-section samples at Vernalis, the midstream concentrations were within 5 percent of the cross-section average concentrations. The mean traveltime for the 46.8 river miles from the Merced River at River Road to the San Joaquin River near Vernalis was 38.5 h (average velocity of 1.79 ft/s). Streamflows in the San Joaquin River ranged from about 1,000 ft^3/s near Newman (fig. 1, site 5) to 2,800 ft^3/s near Vernalis (fig. 1, site 18). The mean traveltime determined from a dye study on this 45.7-mi stretch of San Joaquin River in July 1987 when streamflow ranged from 600 to 1,600 ft^3/s was 55.9 h (Clifton and Gilliom, 1989).

The effect of tidal action downstream of Vernalis is apparent in the slowing of the dye cloud (fig. 3). The mean traveltime for the 28.8 river miles from Vernalis to the Grant Line Canal at Tracy Boulevard (fig. 1, site 19) was 32.9 h (average velocity 1.29 ft/s), while the mean traveltime for the 8.7 river miles from the Grant Line Canal at Tracy Boulevard to the Delta-Mendota Canal (DMC) at Tracy pumps (fig. 1, site 21) was 19.0 h (average velocity 0.67 ft/s).

The time-concentration curve for the first dye cloud at the DMC pumps (figs. 2 and 3) represents the dye detected at Grant Line Canal. The steep tail on the time-concentration curve is probably due to the change from ebb to flood tide bringing in dilution water from the Coney Island area (fig. 1). The second dye cloud at

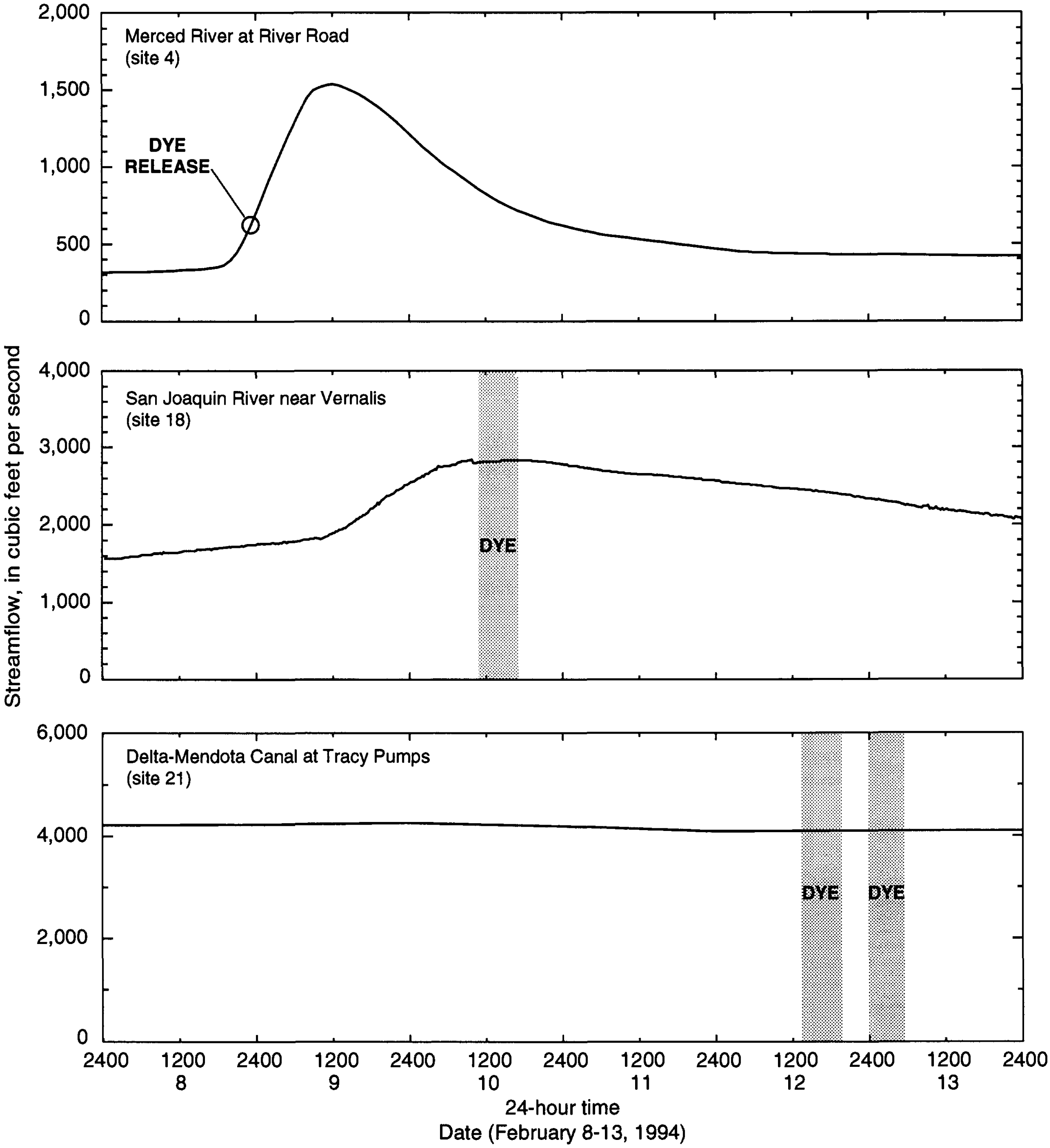

Figure 2. Presence of dye cloud relative to streamflow at dye release site and at sampling sites with streamflow data for the February 1994 study (site numbers refer to figure 1).

the DMC pumps could have taken several paths. The time-concentration curve is estimated from three points based on the shape of the first curve. Possible pathways include:

1. A second pulse of dye through Grant Line Canal that was delayed by a tidal cycle.
2. Dye that travelled through the meandering Old River channel. This channel was sampled (site 20) at the same time as Grant Line Canal (site 19) and dye was not detected.
3. Dye entering the pumps during flood tide after moving past the DMC intake channel and toward Coney Island during ebbtide.
4. Dye reentering Grant Line Canal or Old River during ebbtide after being temporarily contained in Paradise Cut or Tom Paine Slough during the previous tidal cycle.

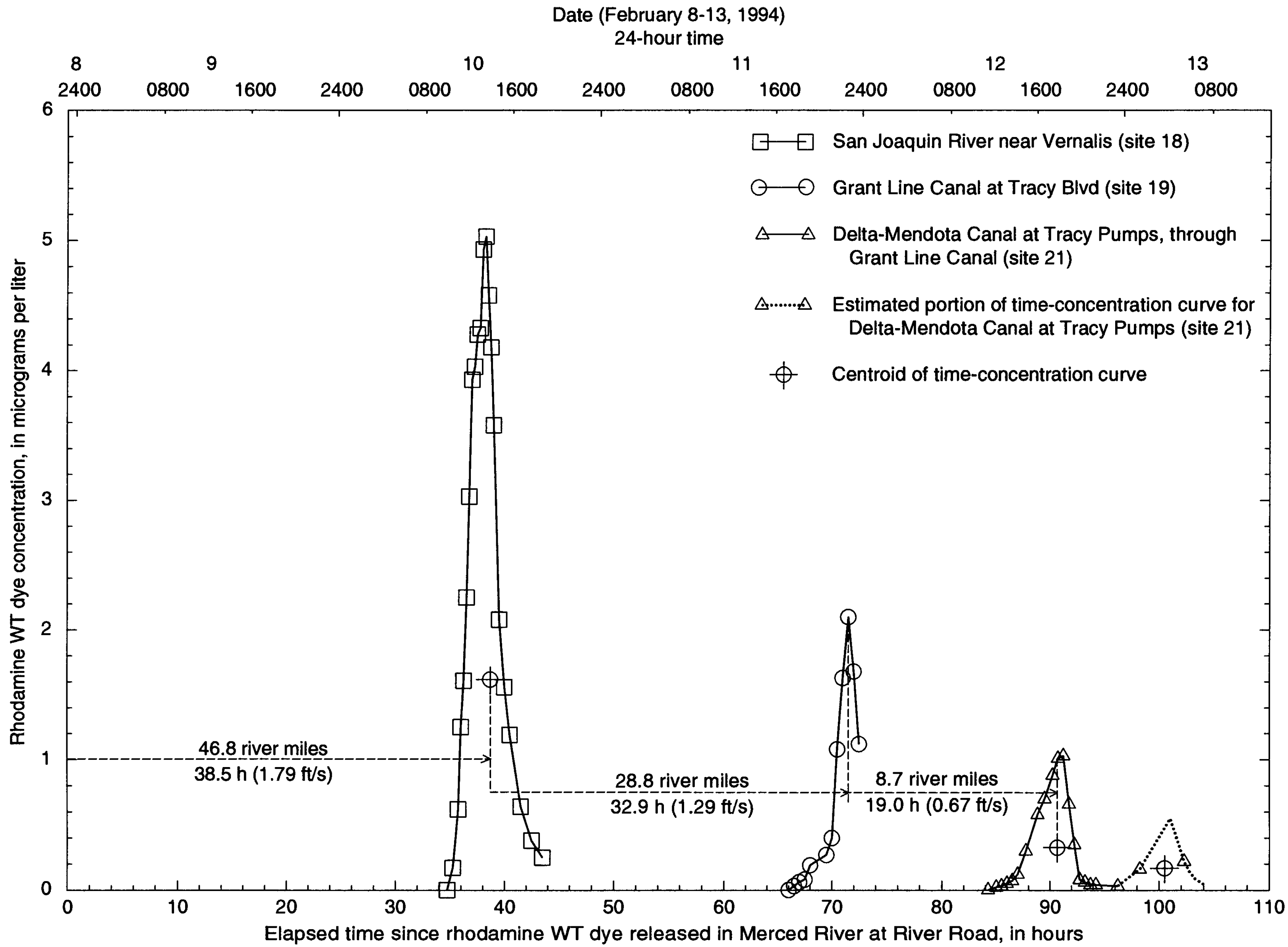

Figure 3. Time-concentration curves at sampling sites for February 1994 study. Dye traveltimes and average velocities (shown below horizontal dashed lines labeled with river miles) are based on centroid of time-concentration curves at sites 18 and 21; based on peak concentration at site 19 (site numbers refer to figure 1). ft/s, foot per second; h, hour.

June 1994 Study

The dye was released into Salt Slough at Highway 165 (fig. 1, site 2) at 0900 h on June 20, 1994 (fig. 4). The subsequent presence of the dye cloud at downstream sites relative to streamflows is shown in figure 4. The actual timing of the dye cloud at the Newman site is estimated because only the end of the dye cloud was sampled at this site. Also, the hydrograph for the San Joaquin River site above the confluence of the Tuolumne River is estimated for the period of the dye cloud based on daytime streamflow measurements and nighttime stage readings. A linear stage versus streamflow relation was developed from six streamflow measurements with stage readings (three during the dye cloud are shown on fig. 4). Eleven stage readings without streamflow measurements were converted to streamflows using the linear relation to approximate the hydrograph during the dye cloud.

The time-concentration curves at downstream sampling sites are shown in figure 5. The concentrations shown are all for midstream samples except at the San Joaquin River near Newman and above the confluence of the Tuolumne River, where the concentrations are shown for samples collected at 10-percent across the cross-section from the west bank. At the San Joaquin River near Newman, most of the streamflow occurred at this point because of the confluence of the Merced River about 0.1 river mile upstream and there were large variations in dye concentrations across the cross-section due to incomplete mixing. The data for this site was only used to determine the end of the dye cloud (fig. 4). At the San Joaquin River above the confluence of the Tuolumne River, mixing is assumed to be complete since the site is several river miles downstream of any major inflows. The mean traveltime for the 64.0 river miles from Salt Slough to Vernalis was 80.1 h (average velocity of 1.18 ft/s). Average velocities were fairly constant throughout the study, ranging from 1.14 ft/s for Salt Slough to Crows Landing, to 1.23 ft/s for Patterson to above the confluence of the Tuolumne River. On the basis of these average velocities, the mean traveltime for the 45.7-mi stretch of San Joaquin River from Newman to Vernalis was about 56.5 h with streamflows ranging from 340 to 1,120 ft^3/s; compared to 55.9 h and 600 to 1,600 ft^3/s in July 1987 (Clifton and Gilliom, 1989).

February 1995 Study

Dye was released into the Tuolumne River at Roberts Ferry (fig. 1, site 10) at 1045 h on February 14, 1995. A second dye release was made at Dry Creek near Modesto at Claus Road (fig. 1, site 15) at 1345 h on February 14, 1995. The subsequent presence of the Tuolumne River dye cloud at downstream gaging stations is shown in figure 6.

The limited time-concentration curves at downstream sampling sites are shown in figure 7. The concentrations shown are all for midstream samples. The mean traveltime for the 51.5 river miles from the Tuolumne River at Roberts Ferry to Vernalis was 35.8 h (average velocity of 2.12 ft/s). Average velocities increased downstream from 1.94 ft/s for Roberts Ferry to Mitchell Road to 2.31 ft/s for Carpenter Road to Vernalis. The mean traveltime for the 2.6 river miles of Dry Creek from Claus Road to El Vista Avenue was 5.1 h (average velocity of 0.75 ft/s).

TRAVELTIMES ESTIMATED BY REGRESSION EQUATIONS

Dye traveltime is determined by mean stream velocity, which can be correlated with streamflow. Mean stream velocity and associated streamflow data for USGS and DWR gaging stations were obtained from the USGS' National Water Information System and from DWR (Larry Baxter, California Department of Water Resources, San Joaquin District, written commun., 1995), respectively. First-, second-, and third-order regressions, with and without log transformation of streamflow, were attempted at 11 sites.

Suitable relations between mean stream velocity and streamflow were found at nine sites (table 2; fig. 1). No suitable relation was found at two sites: the San Joaquin River near Stevinson and the Tuolumne River below La Grange sites (fig. 1, sites 1 and 9, respectively). Streamflow at the Stevinson gage is often pooled and the La Grange gage is directly below the La Grange Dam release. The relations were not very strong at the San Joaquin River near Newman and Dry Creek near Modesto sites. The relation at Newman was improved by considering the irrigation and non-irrigation seasons separately. This site is just below the Merced River confluence, and the ratio of Merced River flow to the total flow strongly influences mean stream velocities at the site. The Dry Creek site is often dry or has very low streamflow. Most of the 167 measurements of stream velocity with streamflow at this site were at low streamflows. For the other seven sites in table 2, the portion of the variance (R^2) in mean stream velocity explained by streamflow ranged from 0.65 to 0.89. The range of streamflows used in development of the regression equations is shown in table 2. The regression equations may not be applicable outside of this range.

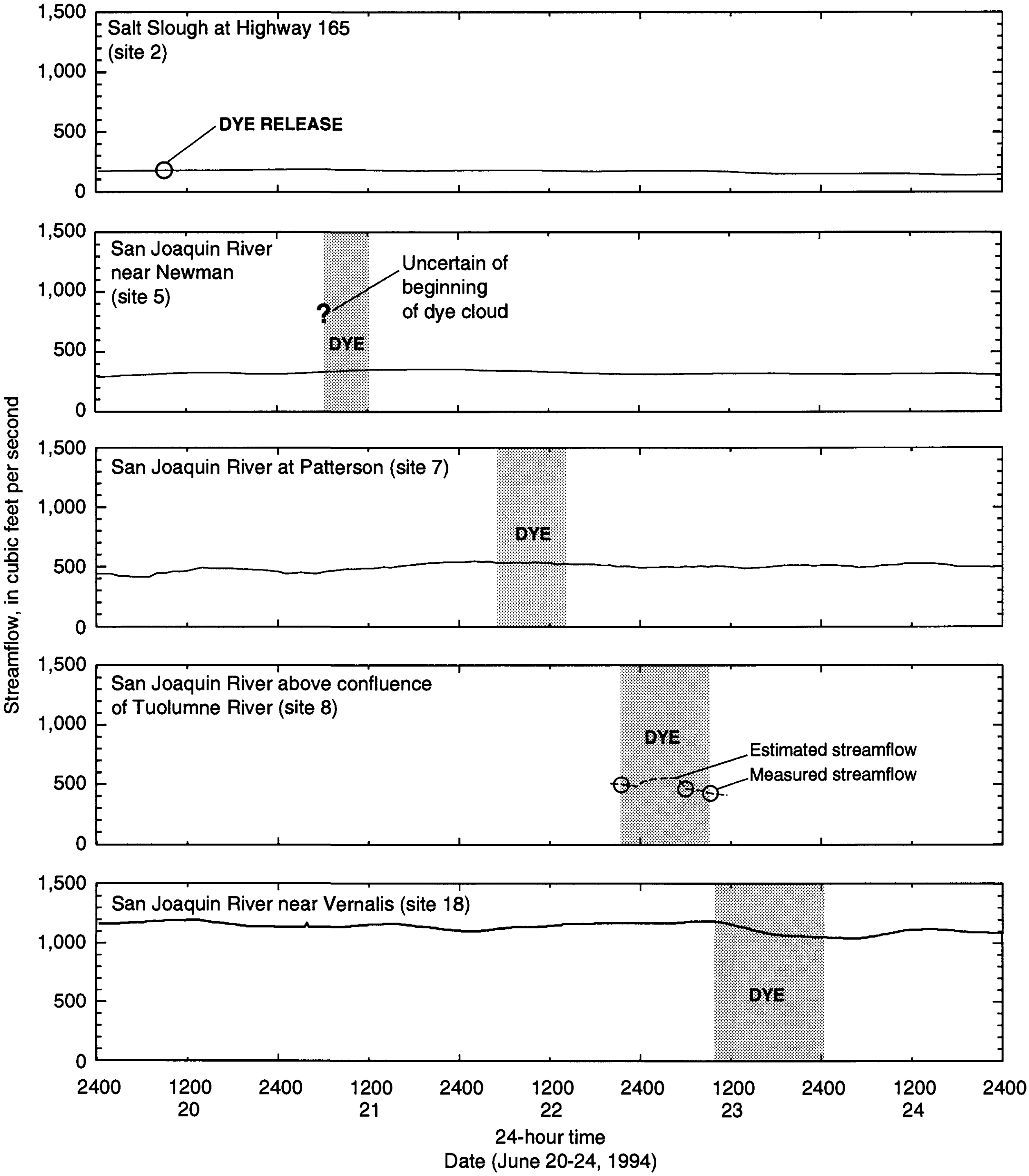

Figure 4. Presence of dye cloud relative to streamflow at dye release site and at sampling sites with streamflow data for the June 1994 study (site numbers refer to figure 1).

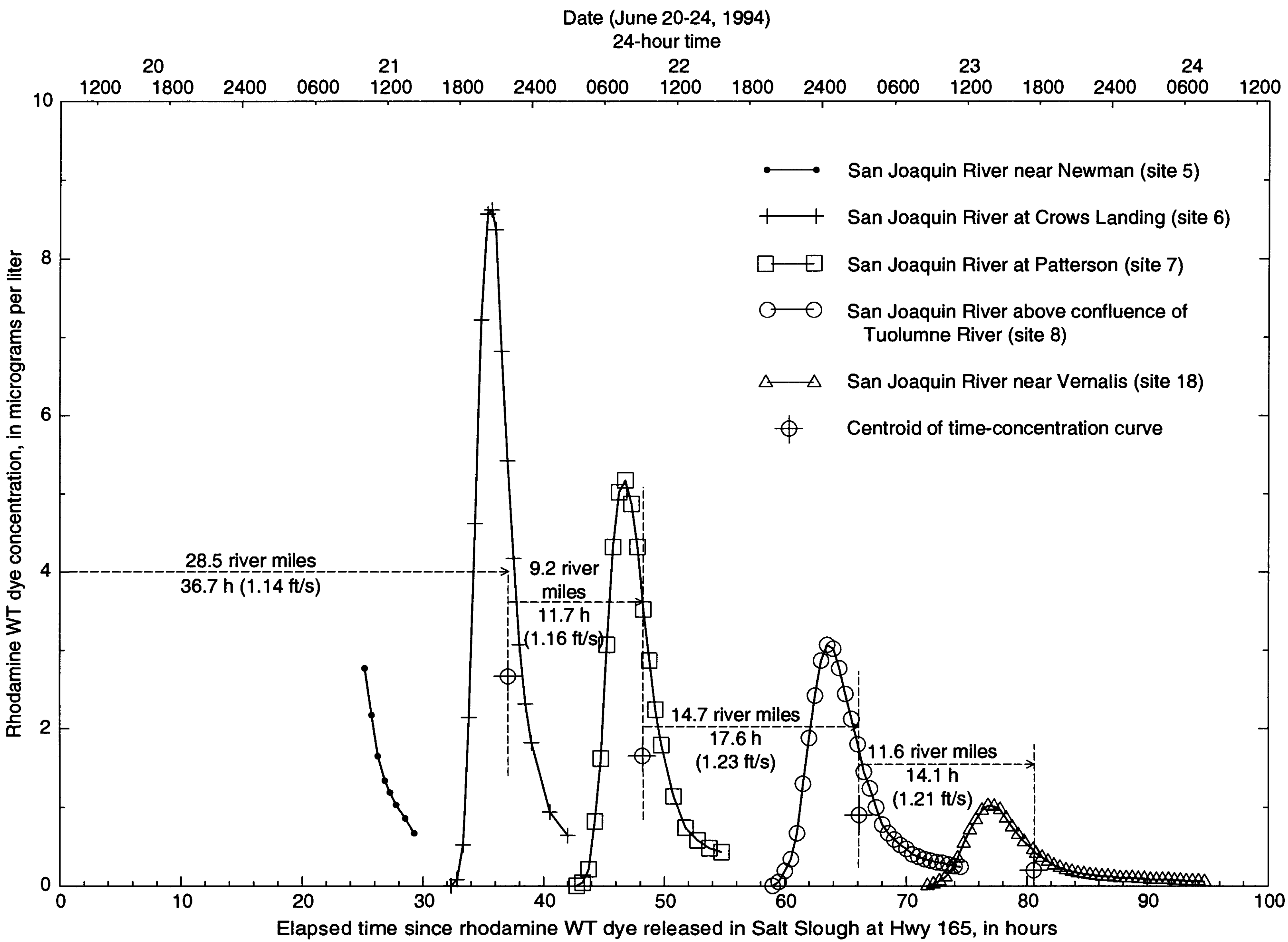

Figure 5. Time-concentration curves at sampling sites for June 1994 study. Dye traveltimes and average velocities (shown below horizontal dashed lines labeled with river miles) are based on centroid of time-concentration curves (site numbers refer to figure 1). ft/s, foot per second; h, hour.

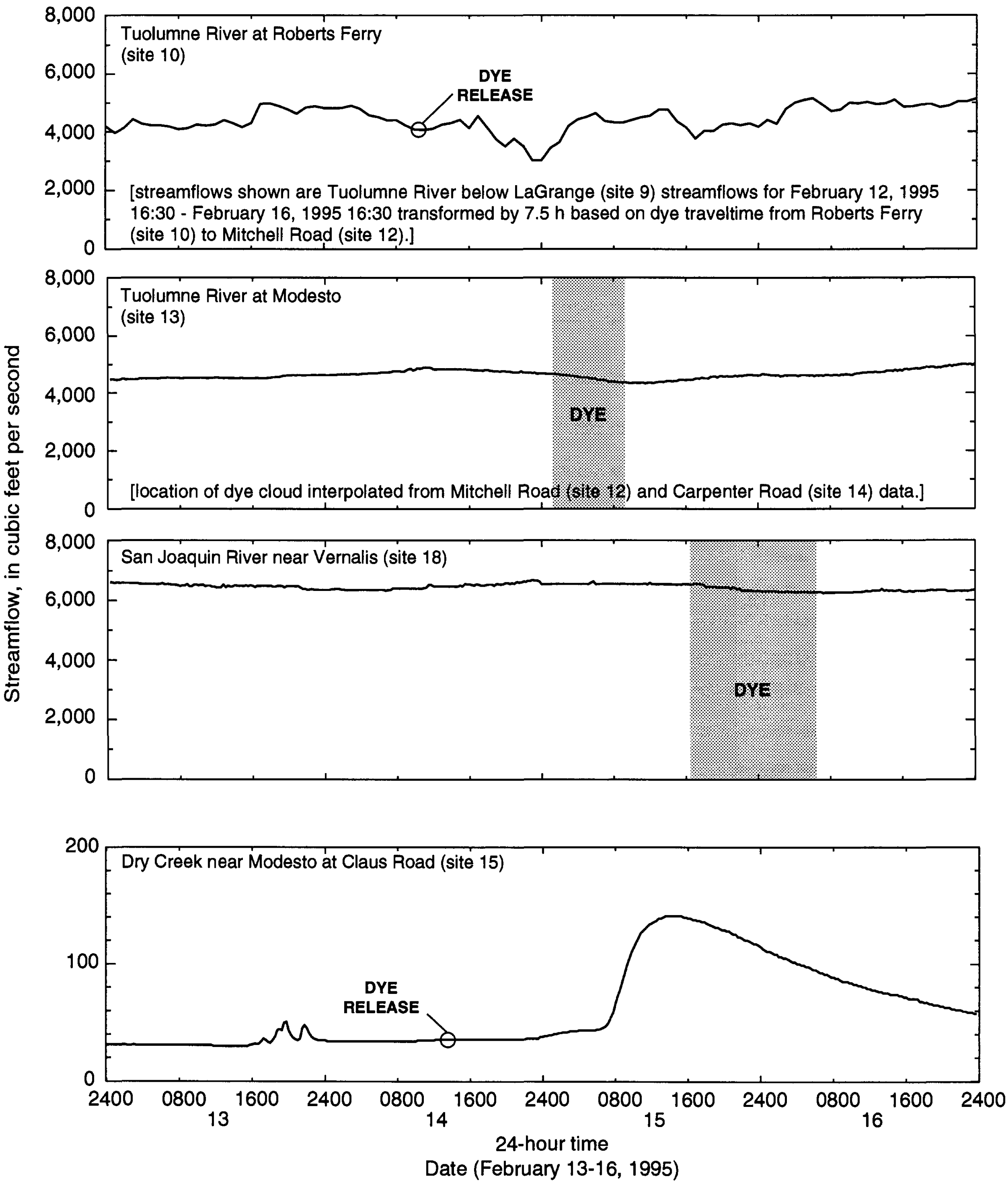

Figure 6. Presence of dye cloud relative to streamflow at dye release sites and at (or near) sampling sites with streamflow data for the February 1995 study (site numbers refer to figure 1).

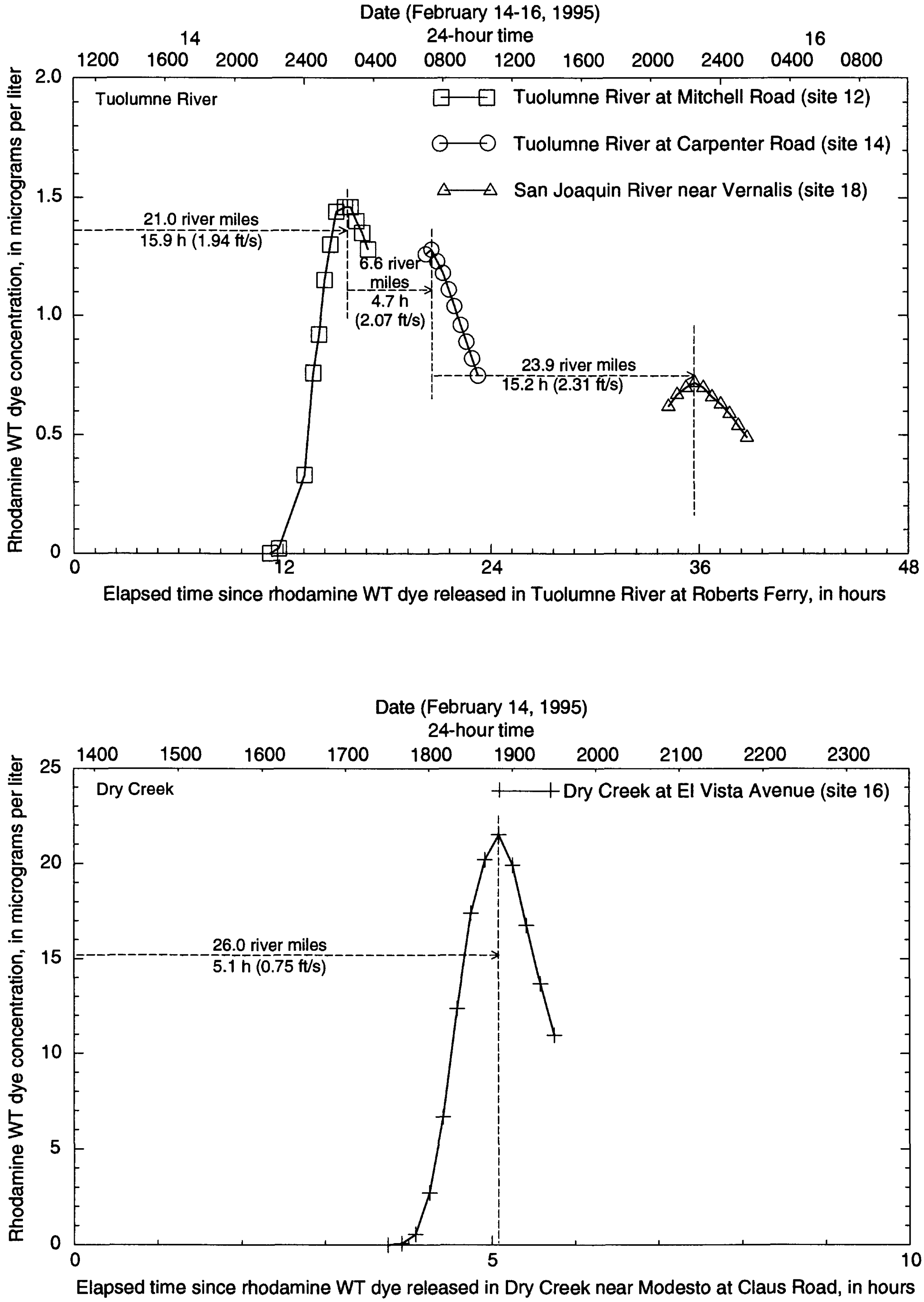

Figure 7. Time-concentration curves at sampling sites for February 1995 study: Tuolumne River and Dry Creek. Dye traveltimes and average velocities (shown below horizontal dashed lines labeled with river miles) are based on peak concentrations (site numbers refer to figure 1). ft/s, foot per second; h, hour.

Table 2. Regression equations for estimating mean stream velocity as a function of streamflow for relevant gaging stations in area of dye studies (based on 1988-95 measurements)

[USGS, U.S. Geological Survey; DWR, California Department of Water Resources; v, mean stream velocity in foot per second; Q, streamflow in cubic foot per second; n, number of data points; R^2, coefficient of determination; ft^3/s, cubic foot per second; log Q, base 10 logarithm of streamflow]

Site no.[1] (from fig. 1)	Station name	Agency	Station no.	Regression equation	n	R^2	Range of streamflow (ft^3/s)
2	Salt Slough at Highway 165	USGS	11261100	$v = 0.00244\,Q + 0.746$	76	0.82	26 – 452
3	Merced River near Stevinson	USGS	11272500	$v = 0.283(\log Q)^2 - 0.474(\log Q) + 0.577$	78	0.69	1.1 – 1,280
5	San Joaquin River near Newman (N)[2]	USGS	11274000	$v = 0.000844\,Q + 0.811$	33	0.21	91 – 1,030
	San Joaquin River near Newman (I)[2]			$v = 3.47 \times 10^{-6}\,Q^2 - 0.00332\,Q + 1.77$	34	0.36	106 – 976
7	San Joaquin River at Patterson	DWR	B0-7200	$v = 0.318(\log Q)^2 - 0.871(\log Q) + 1.16$	173	0.71	174 – 4,626
11	Tuolumne River at Hickman Bridge	DWR	B0-4152	$v = 1.29(\log Q) - 0.745$	174	0.65	33 – 4,426
13	Tuolumne River at Modesto	USGS	11290000	$v = 1.09(\log Q)^2 - 4.56(\log Q) + 5.98$	59	0.87	80 – 2,820
15	Dry Creek near Modesto at Claus Road	DWR	B0-4130	$v = 0.397(\log Q) + 0.906$	167	0.39	0.02 – 286
17	San Joaquin River at Maze Road	DWR	B0-7040	$v = 0.499(\log Q)^2 - 1.88(\log Q) + 2.64$	172	0.82	217 – 12,149
18	San Joaquin River near Vernalis	USGS	11303500	$v = 0.681(\log Q)^2 - 3.34(\log Q) + 5.31$	79	0.89	461 – 6,390

[1]No suitable equations were found for sites 1 and 9.

[2]Regression equation labeled “N” is for non-irrigation season (October–March) data only; “I” is for irrigation season (April–September).

Traveltimes determined in the dye studies are compared to traveltimes determined from the regression equations in table 3. The regression equations provide suitable estimates of traveltimes for the 1994 dye studies, with ratios of estimated traveltime to mean dye traveltime of 0.94 to 1.08. However, for the 1995 dye studies, the equations considerably underestimated traveltime with ratios of 0.49 to 0.73. For the Tuolumne study, this underestimation was probably due to the streamflows being outside the range used in developing the equations (4,685 ft^3/s versus maximum of 4,426 ft^3/s for Hickman and 4,670 ft^3/s versus maximum of 2,820 ft^3/s for Modesto). The San Joaquin River near Vernalis streamflow of 6,330 ft^3/s was also close to the maximum of 6,390 ft^3/s. For the Dry Creek study, downstream backwater conditions were probably the main cause of the poor estimates.

DYE RECOVERIES

Dye tracers, such as rhodamine WT, are water soluble and dilute solutions of dye tracers have virtually the same physical characteristics as water. When introduced into a flowing stream they undergo the same movement, dispersion, and dilution as does the element of water tagged. The dispersion and mixing of the dye tracer in a receiving stream takes place in all three dimensions of the channel. Vertical mixing normally is completed first and lateral later, depending on the stream characteristics. Longitudinal dispersion continues downstream indefinitely. The calculation of dye recoveries, which is the ratio of the calculated dye load at downstream sites to the initial amount of dye released, in this section assumes that vertical and lateral mixing is complete.

Dye losses have a direct effect on dye recovery and applications based on dye recovery (for example, streamflow measurements), but are rarely serious enough to affect the results of time-of-travel measurements (Wilson and others, 1986). The main pathways of dye loss are photochemical decay, adhesion to suspended material, chemical quenching, and diversions of water (Smart and Laidlaw, 1977; Wilson and others, 1986; McCutcheon, 1989; Kilpatrick, 1993). Photochemical decay depends upon many factors, including intensity and duration of sunlight, stream depth, shading of the stream channel, and turbidity. Kilpatrick (1993) has noted average photochemical decay rates for rhodamine WT dye in rivers to be about 5 percent per day. In the three dye studies reported here, photochemical decay would be greatest in the June 1994 study, especially upstream of the Merced River.

Rhodamine WT dye is moderately susceptible to adhesion to suspended material and to aquatic vegetation relative to other dye tracers (Wilson and others, 1986; McCutcheon, 1989). Smart and Laidlaw (1977) reported on laboratory tests using known weights of adsorbent and dye solutions of selected concentration sealed in a flask and shaken for 2 h. After sitting for several days, the samples were centrifuged and the equilibrium dye concentrations determined. Percentage recoveries of rhodamine WT mixed with clays were 89 to 92 percent at 2,000 mg/L suspended-sediment concentration. Recoveries of dye mixed with organic adsorbents were 81 to 82 percent at 2,000 mg/L suspended-sediment concentration. However, at suspended-sediment concentrations less than 100 mg/L, these sorption losses of rhodamine WT were insignificant (Smart and Laidlaw, 1977; McCutcheon, 1989). Mean daily suspended-sediment concentrations in the San Joaquin River near Vernalis during the dye studies were 168 mg/L in February 1994, 102 mg/L in June 1994, and 72 mg/L in February 1995 (Anderson and others, 1995; Hayes and others, 1996). Because of these relatively low suspended-sediment concentrations, dye loss caused by adhesion to suspended material was probably not a major loss pathway for the dye studies in the lower San Joaquin River Basin.

Chemical quenching results from the action of other chemicals that affect the fluorescence of the dye tracer. The most common quenching problems occur with high levels of chlorine or oxygen (Wilson and others, 1986; McCutcheon, 1989). The chlorine or oxygen levels during these dye studies were not high enough to be of concern.

Dye recovery is represented by the area under a complete time-concentration curve. The time-concentration curves for the 1994 studies at sites 6, 7, 8, 18, and 21 were completed with exponential curve fits, and dye recoveries were calculated using the trapezoidal rule approximation [Selby, 1973 (table 4)]. The 1995 studies did not have sufficient data to calculate dye recoveries. For the February 1994 study, 70 percent of the dye was recovered at Vernalis. This study was done following a winter storm with no significant diversions and with primarily sunny weather. The calculated recovery dropped to 35 percent at the DMC pumps, though some additional dye may have reached the pumps after sampling because of delay caused by tidal action.

In addition to photochemical decay, there are several possible explanations for the dye loss from

Table 3. Traveltimes from dye studies compared to estimates from regression equations

[Mean Dye Traveltime: Based on centroid of time-concentration curve for 1994 dye-tracer studies and on peak concentrations for 1995 dye study. h, hour; ft^3/s, cubic feet per second; ft/s, feet per second. SJR, San Joaquin River. T_d, dye traveltimes; T_{de}, estimated traveltimes]

Dye Studies				Estimates from Regression Equations							
River reach	River miles	Dye travel-time to dye peak (h)	Mean dye travel-time, T_d (h)	Gaging station	Dis-charge at dye peak (ft^3/s)	Velocity from table 2 equation (ft/s)	Relevant river reach	River miles	Estimated travel-times, T_{de} (h)	Estimated travel-time for dye reaches, T_{de} (h)	T_{de}/T_d for dye reaches
FEBRUARY 1994 DYE STUDY											
Merced River at River Road to San Joaquin River near Vernalis.	46.8	38.3	38.5	Merced River near Stevinson	630	1.47	Merced River at River Road to SJR.	1.1	1.1		
				San Joaquin River near Newman	1,050	1.70	SJR (at Merced River) to SJR halfway between Newman and Patterson.	9.7	8.4		
				San Joaquin River at Patterson	1,270	1.52	SJR halfway between Newman and Patterson to SJR (at Tuolumne River).	24.8	24.0		
				San Joaquin River at Maze Road	2,565	2.03	SJR (at Tuolumne River) to SJR (at Stanislaus River).	8.7	6.3		
				San Joaquin River near Vernalis	2,820	1.89	SJR (at Stanislaus River) to SJR near Vernalis.	2.5	1.9	41.7	1.08
JUNE 1994 DYE STUDY											
Salt Slough at Highway 165 to San Joaquin River at Crows Landing.	28.5	35.7	36.7	Salt Slough at Highway 165	178	1.18	Salt Slough at Highway 165 to SJR (at Salt Slough).	6.8	8.5		
				San Joaquin River near Newman	340	1.04	SJR (at Salt Slough) to SJR halfway between Newman and Patterson.	21.2	30.0		
				San Joaquin River at Patterson	530	1.15	SJR halfway between Newman and Patterson to SJR at Crows Landing.	0.5	0.6	39.1	1.07
SJR at Crows Landing to SJR at Patterson.	9.2	11.1	11.7	San Joaquin River at Patterson	530	1.15	SJR at Crows Landing to SJR at Patterson.	9.2	11.8	11.8	1.01
SJR at Patterson to SJR above confluence of Tuolumne River.	14.7	16.8	17.6	San Joaquin River at Patterson	530	1.15	SJR at Patterson to SJR above confluence of Tuolumne River.	14.7	18.8	18.8	1.07
SJR above confluence of Tuolumne River to SJR near Vernalis.	11.6	13.3	14.1	San Joaquin River at Patterson	530	1.15	SJR above confluence of Tuolumne River to SJR (at Tuolumne River).	0.4	0.5		
				San Joaquin River at Maze Road	570	1.25	SJR (at Tuolumne River) to SJR (at Stanislaus River).	8.7	10.2		
				San Joaquin River near Vernalis	1,110	1.45	SJR (at Stanislaus River) to SJR near Vernalis.	2.5	2.5	13.2	0.94

Table 3. Traveltimes from dye studies compared to estimates from regression equations—Continued

Dye Studies				Estimates from Regression Equations							
River reach	River miles	Dye travel-time to dye peak (h)	Mean dye travel-time, T_d (h)	Gaging station	Dis-charge at dye peak (ft^3/s)	Velocity from table 2 equation (ft/s)	Relevant river reach	River miles	Estimated travel-times, T_{de} (h)	Estimated travel-time for dye reaches, T_{de} (h)	T_{de}/T_d for dye reaches
FEBRUARY 1995 DYE STUDY											
Tuolumne River at Roberts Ferry to Tuolumne River at Mitchell Road.	21.0	15.9	15.9	Tuolumne River at Hickman Bridge.	4,685	3.99	Tuolumne River at Roberts Ferry to Tuolumne River halfway between Hickman and Modesto.	16.3	6.0		
				Tuolumne River at Modesto	4,670	3.92	Tuolumne River halfway between Hickman and Modesto to Tuolumne River at Mitchell Road.	4.7	1.8	7.8	0.49
Tuolumne River at Mitchell Road to Tuolumne River at Carpenter Road.	6.6	4.7	4.7	Tuolumne River at Modesto	4,670	3.92	Tuolumne River at Mitchell Road to Tuolumne River at Carpenter Road.	6.6	2.5	2.5	0.53
Tuolumne River at Carpenter Road to SJR near Vernalis.	23.9	15.2	15.2	Tuolumne River at Modesto	4,670	3.92	Tuolumne River at Carpenter Road to Tuolumne River (at SJR).	12.7	4.8		
				San Joaquin River at Maze Road	6,205	2.69	SJR (at Tuolumne River) to SJR (at Stanislaus River).	8.7	4.8		
				San Joaquin River near Vernalis	6,330	2.45	SJR (at Stanislaus River) to SJR near Vernalis.	2.5	1.5	11.1	0.73
Dry Creek at Claus Road to Dry Creek at El Vista Avenue.	2.6	5.1	5.1	Dry Creek near Modesto at Claus Road.	35	1.52	Dry Creek at Claus Road to Dry Creek at El Vista Avenue.	2.6	2.5	2.5	0.49

Table 4. Dye recoveries and comparison of dye usage with Kilpatrick and Wilson (1989) dye-dosage formula

[D_u, dye released upstream; D_d, dye recovered downstream; W_s, weight of 20-percent dye solution; L, distance to the downstream site, in miles; V_s, volume of 20-percent dye solution; kg/L, kilogram per liter; lb, pounds; lb/kg, pounds per kilogram; L, liter; mi, miles; v, mean stream velocity; ft/s, feet per second; ft^3/s, cubic feet per second; µg/L, micrograms per liter]

River reach (identifier for fig. 8)	Dye recoveries: Amount of dye released upstream, D_u (lb)	Dye recoveries: Amount of dye recovered downstream D_d (lb)	D_d/D_u	Comparison of dye usage with dosage formula[1]: Amount of 20-percent dye solution released at upstream sites[2] W_s (lb)	Amount of 20-percent dye solution released at upstream sites[2] V_s (L)	Reach length, L (mi)	Average reach velocity[3], v (ft/s)	Discharge at downstream site at Time of C_p, Q_m (ft^3/s)	Peak dye concentration at downstream site, C_p, (µg/L)	Estimated dosage of 20-percent dye solution required for C_p, V_{se} (L)	V_{se}/V_s
FEBRUARY 1994 DYE STUDY											
Merced River at River Road to San Joaquin River near Vernalis. (A1)	15.0	10.5	0.70	75.0	30.4	46.8	1.79	2,820	5.03	64.4	2.12
Merced River at River Road to Delta-Mendota Canal at Tracy Pumps. (A2)	15.0	5.2	0.35	75.0	30.4	84.3	1.37	4,090	1.03	41.8	1.38
JUNE 1994 DYE STUDY											
Salt Slough at Highway 165 to San Joaquin River at Patterson. (B1)	4.91	3.0	0.61	24.6	10.1	37.7	1.15	530	5.17	17.0	1.68
Salt Slough at Highway 165 to San Joaquin River above confluence of Tuolumne River. (B2)	4.91	2.1	0.43	24.6	10.1	52.4	1.17	525	3.07	13.4	1.33
Salt Slough at Highway 165 to San Joaquin River near Vernalis. (B3)	4.91	1.8	0.37	24.6	10.1	64.0	1.18	1,110	1.02	10.8	1.07
FEBRUARY 1995 DYE STUDY											
Tuolumne River at Roberts Ferry to Mitchell Road. (C1)	9.46	(4)	(4)	47.3	19.4	21.0	1.94	[5]4,670	1.46	13.1	0.67
Tuolumne River at Roberts Ferry to Carpenter Road. (C2)	9.46	(4)	(4)	47.3	19.4	27.6	1.97	[5]4,670	1.28	14.6	0.75
Tuolumne River at Roberts Ferry to San Joaquin River near Vernalis. (C3)	9.46	(4)	(4)	47.3	19.4	51.5	2.12	6,330	0.72	18.4	0.95
Dry Creek at Claus Road to El Vista Avenue. (C4)	0.27	(4)	(4)	1.4	0.55	2.6	0.75	[6]35	21.5	0.67	1.21

[1]Dosage Formula for rhodamine WT (Kilpatrick and Wilson, 1989): $V_s = 3.4\times10^{-4}\left(\frac{Q_m L}{v}\right)^{0.94} C_p$.

[2]W_s=2.2×γ_w×S_G×V_s; [2.2 lb/kg; γ_w (specific weight of water)=1.00 kg/L; S_G (specific gravity)=1.12 for February 1994; S_G=1.11 for June 1994 and February 1995; V_s in liters].

[3]Based on traveltime to centroid of time-concentration curves for 1994 dye studies and traveltime to peak concentrations for 1995 dye study.

[4]Insufficient dye concentration data to determine downstream dye recovery.

[5]Used Tuolumne River at Modesto gage flows.

[6]Used Claus Road flows for El Vista; assumed no inflows (stormdrains stopped about 6 hours prior to dye release).

Vernalis to the DMC pumps (Rick Oltmann, U.S. Geological Survey, personal commun., 1996):

1. On the basis of analysis of delta streamflow data for similar San Joaquin River streamflow and delta pumping rates, about 20 percent of the San Joaquin River streamflow (and, therefore, dye) would continue downstream past the Old River split.
2. Some dye was probably lost during ebbtide to Middle River (fig. 1). This dye might have eventually travelled to either the DMC pumps or the State Water Project pumps near Clifton Court Forebay (fig. 1).
3. Some dye might have travelled past Coney Island during ebbtide.
4. Some dye might have been trapped in Old River, Paradise Cut, or Tom Paine Slough.

The June 1994 dye study was done during a period of hot, sunny weather and very significant agricultural diversions. Dye recovery was 61 percent at the Patterson site and 43 percent at the San Joaquin River site above the confluence of the Tuolumne River. Little additional loss occurred between this site and Vernalis, as 37 percent of the dye was recovered at Vernalis.

EVALUATION OF THE DYE-DOSAGE FORMULA

Dye volumes required for a specific downstream dye concentration were estimated using the following dye-dosage formula from Kilpatrick and Wilson (1989):

$$V_s = 3.4\times10^{-4}\left(\frac{Q_m L}{v}\right)^{0.94} C_p \ , \qquad (3)$$

where

V_s = volume of stock rhodamine WT 20-percent dye solution, in liters;

Q_m = maximum stream discharge at the downstream site, in cubic feet per second;

L = distance to the downstream site, in miles;

v = mean stream velocity, in feet per second; and

C_p = desired peak concentration at the downstream sampling site, in micrograms per liter.

Equation (3) assumes that there are no major diversions in the reach being studied and that streamflows are stable. This equation takes into account other dye losses, since it is based on results from 85 dye studies on rivers (Kilpatrick, 1970).

Comparisons of estimated dye volumes with actual dye volumes used in the dye studies show that estimated dye volumes were high for the 1994 dye studies and the 1995 Dry Creek study and were low for the 1995 Tuolumne study (table 4). The ratios of estimated to actual dye volumes for a given downstream concentration ranged from 1.38 to 2.12 for the February 1994 study; 1.07 to 1.68 for the June 1994 study; 0.67 to 0.95 for the 1995 Tuolumne study; and was 1.21 for the 1995 Dry Creek study. Streamflows during the February 1994 dye study were unstable and the San Joaquin River split below Vernalis, with a portion flowing toward the DMC at Tracy pumps and a portion continuing downstream toward Stockton (Oltmann, 1995). Although streamflows were stable during the June 1994 dye study, there were several diversions unaccounted for by equation (3). Streamflows were stable and there were no significant diversions during the 1995 studies. Regardless of the conditions during the dye studies, the actual dye volumes required for a downstream peak concentration of 1 µg/L generally fell within the range of the data used by Kilpatrick (1970) to develop the dye-dosage formula (fig. 8).

In all dye studies, estimates of required dye volumes improved with length of dye study. For the 1994 studies, these improvements probably were caused by downstream diversions and flow splits unaccounted for by the dye-dosage formula; for the 1995 Tuolumne study, they probably were caused by the increased mean stream velocity as the dye reached the San Joaquin River.

SUMMARY AND CONCLUSIONS

In the February 1994 dye study, the mean traveltime for the 46.8 river miles from the Merced River at River Road to the San Joaquin River near Vernalis was 38.5 h (average velocity of 1.79 ft/s). The dye cloud slowed greatly downstream of Vernalis, in the Sacramento-San Joaquin Delta, with an average velocity of 1.29 ft/s from Vernalis to Grant Line Canal at Tracy Boulevard and 0.67 ft/s from there to the DMC at Tracy pumps. In the June 1994 dye study, mean traveltime for the 64.0 river miles from Salt Slough to Vernalis was 80.1 h (average velocity of 1.18 ft/s). In the February 1995 dye studies, mean traveltime for the 51.5 river miles from the Tuolumne River at Roberts Ferry to Vernalis was 35.8 h (average velocity of 2.12 ft/s) and mean traveltime for the 2.6 river miles of Dry Creek from Claus Road to El Vista Avenue was 5.1 h (average velocity of 0.75 ft/s).

For the 1994 dye studies, regression equations of mean stream velocity as a function of streamflow

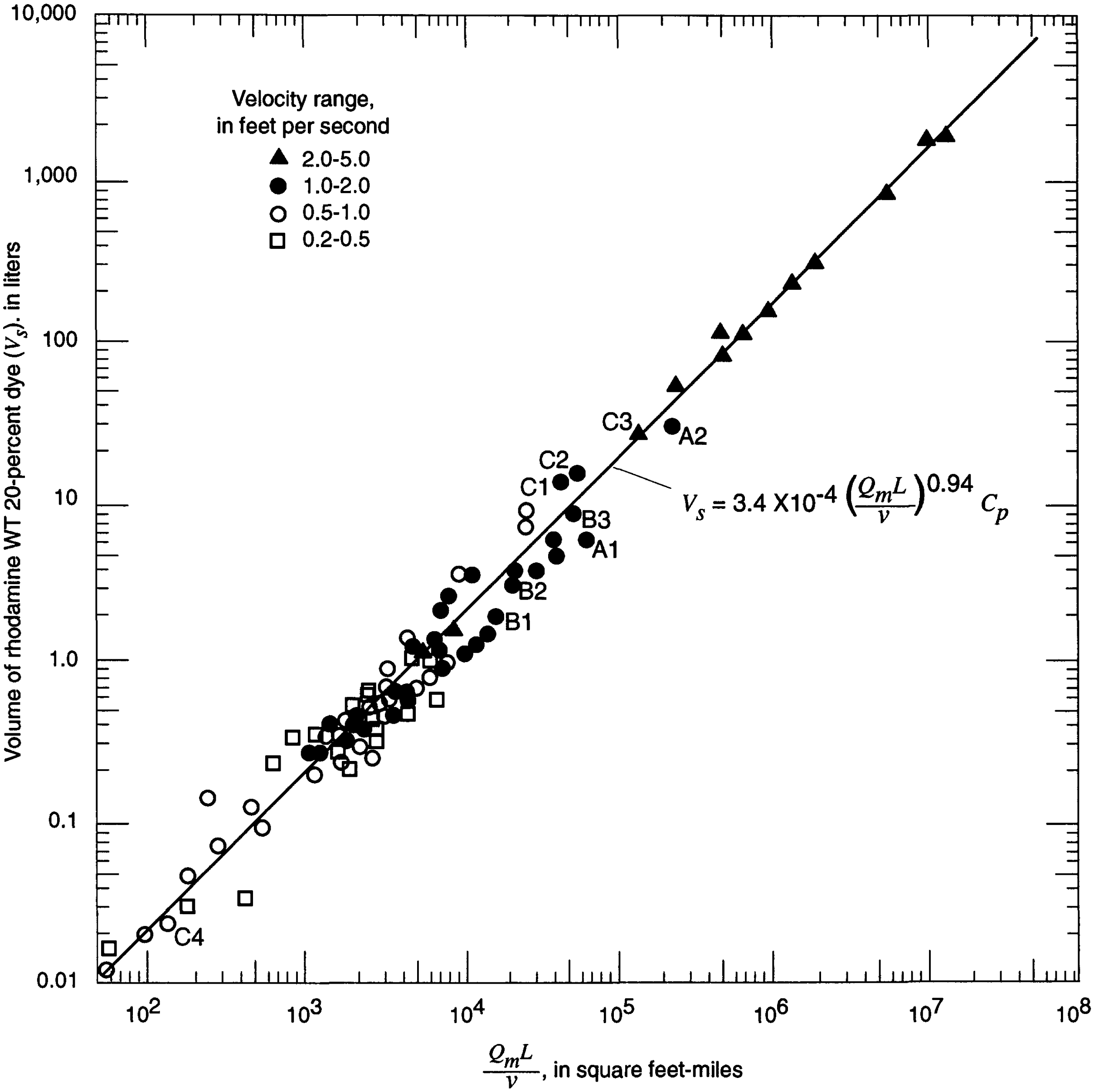

Figure 8. Dye studies in the lower San Joaquin River Basin relative to the 85 dye studies used to develop the dye-dosage formula (best fit line) for a peak concentration of 1 microgram per liter (from Kilpatrick, 1970). Identifiers (for example, A1) on lower San Joaquin River Basin dye studies refer to the river reaches in table 4. Explanation for equation: Q_m = maximum stream discharge at the downstream site, in cubic feet per second; L = distance to the downstream site, in miles; v = mean stream velocity, in feet per second; and C_p = desired peak concentration at the downstream sampling site, in micrograms per liter.

provided suitable estimates of traveltime, with ratios of estimated traveltime to mean dye traveltime of 0.94 to 1.08. However, for the 1995 dye studies, the equations considerably underestimated traveltime, with ratios of 0.49 to 0.73. For the Tuolumne study, this underestimation was probably attributable to some streamflows being outside the range used for developing the equations. For the Dry Creek study, downstream backwater conditions were probably the main cause of the underestimation.

For the February 1994 dye study, 70 percent of the dye released was recovered at Vernalis. The calculated recovery dropped to 35 percent at the DMC at Tracy pumps, although some additional dye may have reached the pumps after sampling because of delay caused by tidal action. For the June 1994 dye study, 61 percent of the dye was recovered at Patterson and 43 percent at the San Joaquin River site above the confluence of the Tuolumne River. Little additional loss occurred between this site and Vernalis, where 37 percent was recovered.

The required dye volumes estimated by the Kilpatrick and Wilson (1989) dye-dosage formula were high for the 1994 studies and the 1995 Dry Creek study and low for the 1995 Tuolumne study. In all studies, estimates of required dye volumes improved with length of dye study. For the 1994 studies, this improvement probably was caused by downstream diversions and flow splits unaccounted for by the dye-dosage formula. For the 1995 Tuolumne study, it probably was caused by the increased mean stream velocity as the dye reached the San Joaquin River.

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