

# **Summary of Suspended-Sediment Concentration Data, San Francisco Bay, California, Water Year 2003**

By Paul A. Buchanan and Neil K. Ganju

In cooperation with the CALFED Bay-Delta Program, and the U.S. Army Corps of  
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## Conversion Factors, Datum, Abbreviations, and Acronyms

Multiply	By	To obtain
inch (in.)	25.40	millimeter
foot (ft)	.3048	meter
foot per second (ft/s)	.3048	meter per second

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Mean lower low water (MLLW): The average of the lower low water height above the bottom, in feet, of each tidal day observed during the National Tidal Datum Epoch. The National Tidal Datum Epoch is the specific 19-year period (1960–78 for values given in this report) adopted by the National Ocean Service as the official time segment during which tide observations are taken and reduced to obtain mean values.

### Abbreviations and Acronyms

ADAPS	automated data-processing system
DWR	California Department of Water Resources
mg/L	milligram per liter
mV	millivolt
NTU	nephelometric turbidity units
PI <sub>np</sub>	nonparametric prediction interval
RMS	root-mean-squared (error)
SSC	suspended-sediment concentration
USCG	U.S. Coast Guard
USGS	U.S. Geological Survey
WY	water year (October 1–September 30)

# Summary of Suspended-Sediment Concentration Data, San Francisco Bay, California, Water Year 2003

By Paul A. Buchanan and Neil K. Ganju

## Abstract

Suspended-sediment concentration data were collected in San Francisco Bay during water year 2003 (October 1, 2002–September 30, 2003). Optical sensors and water samples were used to monitor suspended-sediment concentration at two sites in Suisun Bay, three sites in San Pablo Bay, one site in Central San Francisco Bay, and three sites in South San Francisco Bay. Sensors were positioned at two depths at most sites. Water samples were collected periodically and analyzed for concentrations of suspended sediment. The results of the analyses were used to calibrate the output of the optical sensors so that a record of suspended-sediment concentrations could be derived. This report presents the data-collection methods used and summarizes the suspended-sediment concentration data collected from October 2002 through September 2003. Calibration curves and plots of edited data for each sensor also are presented.

## Introduction

Sediments are an important component of the San Francisco Bay estuarine system. Bottom sediments provide habitat for benthic organisms and are a reservoir for nutrients that contribute to estuarine productivity (Hammond and others, 1985). Potentially toxic substances, such as metals and pesticides, adsorb to sediment particles (Kuwabara and others, 1989; Domagalski and Kuivila, 1993; Flegal and others, 1996). Benthic organisms can ingest these substances and introduce them into the food web (Luoma and others, 1985; Brown and Luoma, 1995; Luoma, 1996). Large tidal-induced velocities and wind waves in shallow water are capable of resuspending bottom sediments (Powell and others, 1989; Schoellhamer, 1996).

The transport and fate of suspended sediments are important factors in determining the transport and fate of sediment-associated contaminants. In Suisun Bay, the maximum suspended-sediment concentration (SSC) usually marks the position of the turbidity maximum—a crucial ecological zone where suspended sediments, nutrients, phytoplankton, zooplankton, larvae, and juvenile fish accumulate (Peterson and others, 1975; Arthur and Ball, 1979; Kimmerer, 1992; Jassby and Powell, 1994; Schoellhamer and Burau, 1998; Schoellhamer, 2001).

Suspended sediments limit the penetration of light into San Francisco Bay, which affects photosynthesis and primary photosynthetic carbon production (Cole and Cloern, 1987; Cloern, 1987, 1996). Sediments also deposit in ports and shipping channels, which then require dredging to maintain navigation (U.S. Environmental Protection Agency, 1992). The U.S. Geological Survey (USGS), in cooperation with the CALFED Bay-Delta Program, and the U.S. Army Corps of Engineers, is studying the factors that affect SSC in San Francisco Bay.

## Purpose and Scope

This report summarizes SSC data collected by the USGS in San Francisco Bay during water year (WY) 2003 and is the latest in a series based on data collected beginning in WY 1992 (Buchanan and Schoellhamer, 1995, 1996, 1998, 1999; Buchanan and others, 1996; Buchanan and Ruhl, 2000, 2001; and Buchanan and Ganju, 2002, 2003, 2004). Collection of SSC data in San Francisco Bay required development of monitoring methods and calibration techniques which are presented in this report. SSC were monitored at two sites in Suisun Bay, three sites in San Pablo Bay, one site in Central San Francisco Bay, and three sites in South San Francisco Bay. These data were used to help determine the factors that affect SSC in San Francisco Bay (U.S. Geological Survey, accessed July 14, 2004). SSC data for WY 1992 through 2003 are available from the U.S. Geological Survey (accessed July 15, 2004).

### Study Area

San Francisco Bay (*fig. 1*) comprises several major subembayments; Suisun Bay, San Pablo Bay, Central San Francisco Bay (Central Bay), and South San Francisco Bay (South Bay). In San Francisco Bay, tides are semidiurnal (two high and two low tides per day) with a range of about 5.5 feet (ft) in Suisun Bay, 6.5 ft at the Golden Gate and Central Bay, and about 10 ft in South Bay. The tides also follow a 14-day spring-neap cycle. Typical tidal currents range from 0.6 feet per second (ft/s) in shallow water to more than 3 ft/s in deep channels (Cheng and Gartner, 1984; Smith, 1987). Winds typically are strongest in summer during afternoon, onshore sea breezes. Most precipitation occurs from late autumn to early spring, and freshwater discharge into San Francisco Bay is greatest in the spring due to runoff from snowmelt. About 90 percent of the discharge into the Bay is from the Sacramento-San Joaquin River Delta, which drains the Central Valley of California (Smith, 1987).

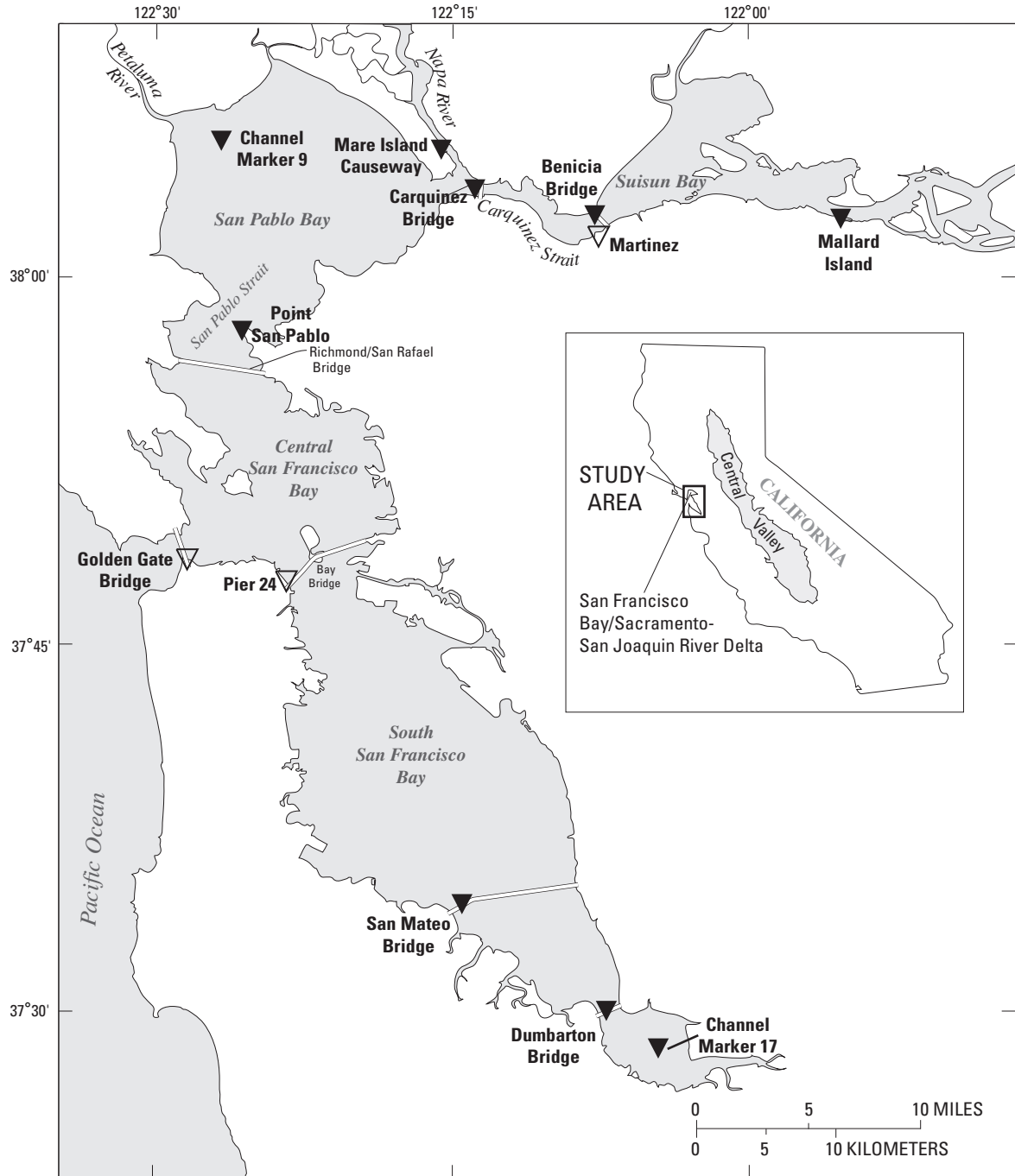
Typically, discharge from the Delta contains over 60 percent of the fluvial sediments that enter the Bay (McKee and others, 2002), though this percentage varies from year to year. During wet winters, turbid plumes of water from the Delta have extended into South Bay (Carlson and McCulloch, 1974). The bottom sediments in South Bay and in the shallow water areas (about 12 ft or less) of Central, San Pablo, and Suisun Bays are composed mostly of silts and clays. Silts and sands are present in the deeper parts of Central, San Pablo, and Suisun Bays and in Carquinez Strait (Conomos and Peterson, 1977).

### Acknowledgments

The authors gratefully acknowledge the U.S. Coast Guard (USCG), California Department of Transportation, California Department of Water Resources (DWR), EAI International, and the City of Vallejo for their permission and assistance in establishing the monitoring sites used in this study.

The CALFED Bay/Delta Program, USGS Priority Ecosystem Science Program, and the U.S. Army Corps of Engineers, as part of the San Francisco Estuary Regional Monitoring Program for Trace Substances, supported collection of these data.





**EXPLANATION**

- ▼ Continuous suspended-sediment concentration monitoring site
- ▽ Discontinued monitoring site

**Figure 1.** San Francisco Bay study area, California.

## Methods

### Instrument Description and Operation

Three different types of optical sensors were used to monitor SSC during WY 2003. The first type of sensor is manufactured by D & A Instrument Company and is a cylinder approximately 7 inches (in.) long and 1 in. in diameter with an optical window at one end, a cable connection at the other end, and an encased circuit board. A high-intensity infrared emitting diode produces a beam through the optical window that is scattered, or reflected, by particles that are about 0.2–12 in. in front of the window. A detector (four photodiodes) receives backscatter from a field of 140–165 degrees which is converted to a voltage output and recorded on a separate data logger. The second type of sensor, manufactured by BTG, is self-cleaning and differs from the D & A Instrument Company sensor in that it measures the intensity of light scattered at 90 degrees between a light-emitting diode and a high-sensitivity photodiode detector. The BTG sensor has a separate electronic unit that sets the resolution and maximum reading, expressed in nephelometric turbidity units (NTU). The output from the electronic unit is recorded on a separate data logger. The third type of sensor, versions of which are used by both Hydrolab and YSI instruments, measures the intensity of light scattered at 90 degrees between a light-emitting diode and a high-sensitivity photodiode detector, and the output is processed by internal software to read in NTU. The Hydrolab and YSI instruments are self-contained, including a power source and data logger.

Optical sensors were positioned in the water column using polyvinyl chloride (PVC) pipe carriages coated with an antifoulant paint to impede biological growth. Carriages were designed to align with the direction of flow and to ride along a stainless steel or Kevlar-reinforced nylon suspension line attached to an anchor weight, which allowed sensors to be easily raised and lowered for servicing (*fig. 2*). The plane of the optical window maintained a position parallel to the direction of flow as the carriage and sensor aligned itself with the changing direction of flow. Optical sensor depths in the water column are listed in table 1. Data acquisition was controlled by electronic data loggers. The loggers used with the D & A Instrument Company and BTG sensors were programmed to power the optical sensor every 15 minutes, collect data each second for 1 minute, then average and store the output voltage for that 1-minute period. The Hydrolab and YSI internal data loggers collect instantaneous values every 15 minutes. Power was supplied by 12-volt batteries.

Biological growth (fouling) interferes with the collection of accurate optical sensor data. Fouling generally was greatest on the sensor closest to the water surface. However, at shallower sites where the upper sensor was set 10 ft above the lower sensor, fouling was similar on both sensors. Self-cleaning optical sensors were used where conditions allowed. Due to the difficulty in servicing some of the monitoring stations, sensors were cleaned manually every 1–5 (usually 3) weeks. Fouling would begin to affect sensor output from 2 days to several weeks after cleaning, depending on the level of biological activity in the Bay. Generally, biological fouling was greatest during spring and summer.

On-site checks of sensor accuracy were performed using turbidity solutions prepared from a 4,000-nephelometric turbidity unit formazin standard. Formazin is an aqueous suspension of an insoluble polymer and is the primary turbidity standard (Greenberg and others, 1992). The turbidity solutions were prepared by diluting a 4,000-nephelometric turbidity unit stock standard with de-ionized water in a clean, sealable bucket. Prepared solutions ranged from 50 to 200 NTU. At the field site, the cleaned sensors were immersed in the solution and the output was recorded on the station log. Monitoring a period of sensor performance in a known standard helps to identify output drift or sensor malfunction.

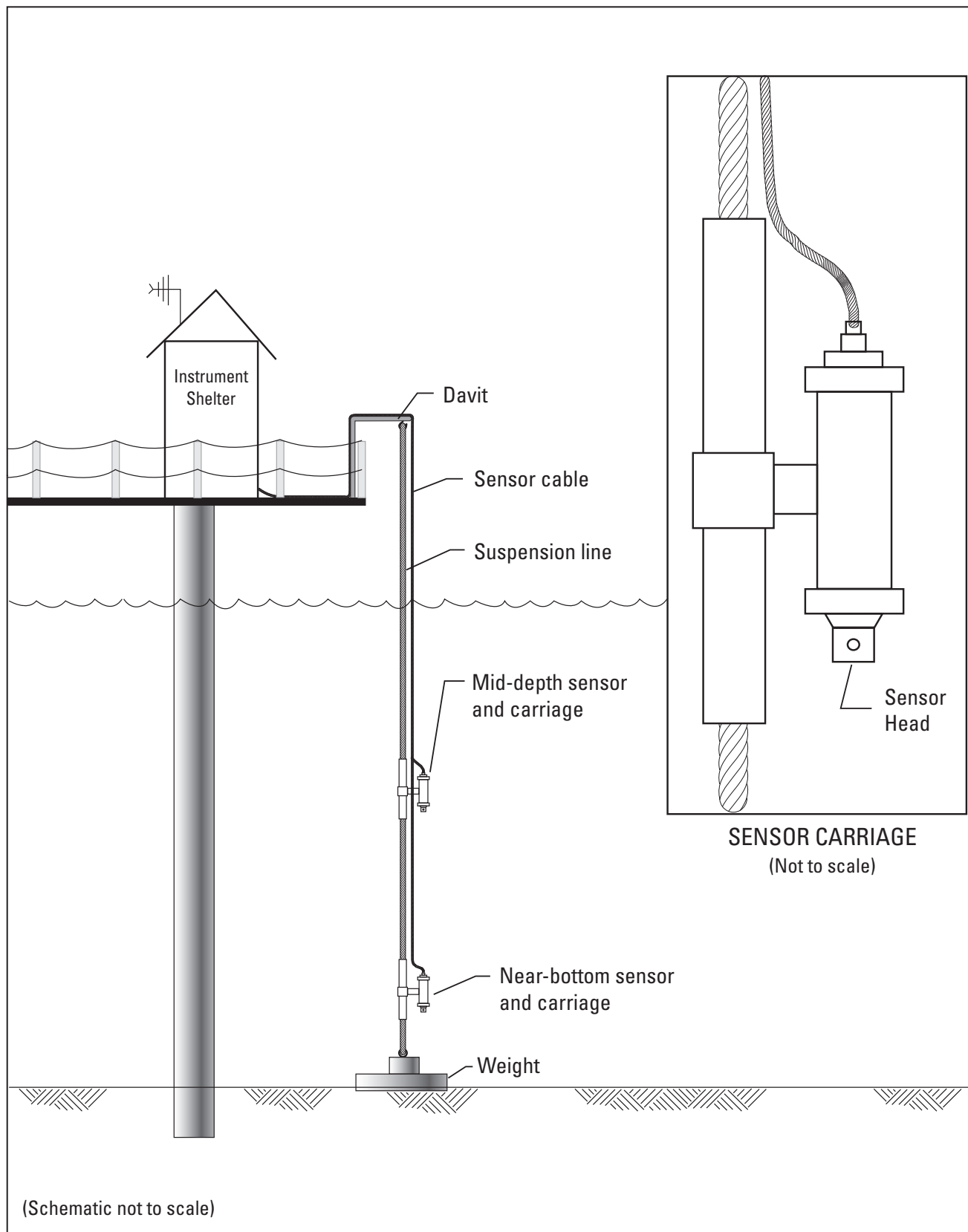


Figure 2. Typical monitoring installation, San Francisco Bay study.

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**Table 1.** Optical sensor depths (in feet) below mean lower low water (MLLW), Suisun Bay, San Pablo Bay, and Central and South San Francisco Bays, California, water year 2003

[For definition of MLLW, see Conversion Factors, Datum, Abbreviations, and Acronyms entry at front of this report]

Site	Station No.	Latitude	Longitude	Sensor depth	Depth below MLLW	Water depth at MLLW
Mallard Island	11185185	38°02'34"	121°55'09"	Near-surface	3.3 <sup>1</sup>	25
				Near-bottom	20	
Benicia Bridge	11455780	38°02'42"	122°07'32"	Near-surface	6	80
				Near-bottom	55	
Carquinez Bridge	11455820	38°03'41"	122°13'23"	Mid-depth	40	88
				Near-bottom	83	
Mare Island Causeway	11458370	38°06'40"	122°16'25"	Mid-depth	15	30
				Near-bottom	25	
Channel Marker 9	380519122262901	38°05'19"	122°26'29"	Near-bottom	4	6
Point San Pablo	11181360	37°57'53"	122°25'42"	Mid-depth	13	26
				Near-bottom	23	
San Mateo Bridge	11162765	37°35'04"	122°14'59"	Mid-depth	19	48
				Near-bottom	40	
Dumbarton Bridge	373015122071000	37°30'15"	122°07'10"	Mid-depth	22	45
				Near-bottom	41	
Channel Marker 17	372844122043800	37°28'44"	122°04'38"	Mid-depth	12	25
				Near-bottom	22	

<sup>1</sup>Depth below water surface.

## Monitoring Sites

### Suisun Bay Installations

SSC data were collected in Suisun Bay at Mallard Island and Benicia Bridge (*fig. 1, table 1*). Optical sensors were installed at the DWR Mallard Island Compliance Monitoring Station on February 8, 1994. Optical sensors were positioned to coincide with DWR near-bottom electrical conductance and temperature sensors and near-surface pump intake. The pump intake is attached to a float and draws water from about 3 ft below the surface. The near-surface optical sensor is attached to a separate float and positioned at the same depth as the pump intake.

Optical sensors were deployed off of Pier 7 on the Benicia Bridge on March 15, 1996. The Benicia Bridge site was shut down in WY 1998 for seismic retrofitting of the bridge and was reestablished with sondes equipped with optical, conductance, and temperature sensors on May 1, 2001. A monitoring site at the Martinez Marina fishing pier was discontinued in WY 1996 because data from the Benicia Bridge site were considered more representative of SSC in the Carquinez Strait area of Suisun Bay (Buchanan and Schoellhamer, 1998).

### San Pablo Bay Installations

SSC data were collected in Carquinez Strait at Carquinez Bridge, Napa River at Mare Island Causeway, and San Pablo Bay at Channel Marker 9 (*fig. 1, table 1*). Sondes with optical, conductance, and temperature sensors were deployed off the center pier structure at Carquinez Bridge on April 21, 1998. Optical sensors were deployed off a catwalk beneath Mare Island Causeway on October 1, 1998. A sonde with optical, conductance, and temperature sensors was deployed off of USCG Channel Marker 9 on November 12, 1998.

### Central San Francisco Bay Installations

SSC data were collected in San Pablo Strait at Point San Pablo (*fig. 1, table 1*). Optical sensors were deployed at San Pablo Strait on the northern end of the Richmond Terminal no. 4 pier on the western side of Point San Pablo on December 1, 1992. The station at Point San Pablo was shut down on January 2, 2001, and reestablished on December 11, 2001, off a pier-adjacent structure approximately 25 ft from the previous deployment site. A monitoring station at San Francisco Bay at Pier 24 was discontinued on January 3, 2002. The USGS assumed operation of these stations from DWR in October 1989 (collection of conductivity and temperature data was cooperatively funded by DWR and the USGS). A monitoring station at the south tower of the Golden Gate Bridge was operational during water years 1996 and 1997. Conductivity and temperature data collected at Point San Pablo and Pier 24 prior to October 1, 1989, can be obtained from DWR.

### South San Francisco Bay Installations

SSC data were collected in South San Francisco Bay at San Mateo Bridge, Dumbarton Bridge, and USCG Channel Marker 17 (*fig. 1, table 1*). Optical sensors were deployed off of Pier 20 on the San Mateo Bridge, on the east side of the ship channel, on December 23, 1991. In addition to SSC, specific conductance and temperature (cooperatively funded by DWR and the USGS) were monitored at near-bottom and near-surface depths at San Mateo Bridge. The USGS assumed operation of this station from DWR in October 1989. Conductivity and temperature data collected at San Mateo Bridge prior to October 1, 1989, can be obtained from DWR. Optical sensors were deployed off of Pier 23 on the Dumbarton Bridge on the west side of the ship channel on October 21, 1992. Optical sensors were deployed at USCG Channel Marker 17 on February 26, 1992.

## Water-Sample Collection

Water samples, used to calibrate the voltage output of the optical sensors to SSC, were collected using a horizontally positioned modified Van Dorn sampler before and after the sensors were cleaned. The Van Dorn sampler is a plastic tube with rubber stoppers at each end that snap shut when triggered by a small weight dropped down a suspension cable. The Van Dorn sampler was lowered to the depth of the sensor by a reel and crane assembly and triggered while the sensor was collecting data. After collection, the water sample was marked for identification and placed in a container for transport. The SSC of water samples collected with a modified Van Dorn sampler and a P-72 point sampler, used until WY 1994, were virtually identical (Buchanan and others, 1996).

Samples were sent to the USGS Sediment Laboratory in Marina, California, for analysis of SSC. Suspended sediment includes all particles in the sample that do not pass through a 0.45-micrometer membrane filter. Suspended-sediment concentrations were referred to as suspended-solids concentration in previous reports (Buchanan and Schoellhamer, 1995, 1996, 1998, 1999; Buchanan and others, 1996; and Buchanan and Ruhl, 2000, 2001). The analytical method used to quantify concentrations of suspended solid-phase material did not change but the nomenclature used to describe sediment data did change (Gray and others, 2000). Water samples collected for this study were analyzed for suspended-sediment concentration by filtering samples through a pretared 0.45-micrometer membrane filter. The filtrate was rinsed with de-ionized water to remove salts, and the insoluble material and filter were dried at 103°C and weighed (Fishman and Friedman, 1989).

## Data Processing

Data loggers stored the voltage outputs from the optical sensors at 15-minute intervals (96 data points per day). Recorded data were downloaded from the data loggers onto either a storage module or laptop computer during site visits. Raw data from the storage modules or laptop computer were loaded into the USGS automated data-processing system (ADAPS).

The time-series data were retrieved from ADAPS and edited using MATLAB software to remove invalid data. Invalid data included rapidly increasing voltage outputs and unusually high voltage outputs of short duration. As biological growth accumulated on the optical sensors, the voltage output of the sensors increased (except for the Hydrolab's optical sensor output, which decreased). An example time series of raw and edited optical sensor data is presented in *figure 3*. After sensors were cleaned, sensor output immediately decreased (*fig. 3A*: May 6, 30, June 17, and July 8). Efforts to correct for biofouling proved to be unsuccessful because the signal often was highly variable. Thus, data affected by biofouling often were unusable and were removed from the record (*fig. 3B*). Identifying the point at which fouling begins to affect optical sensor data is somewhat subjective. Indicators are used to help define the point at which fouling begins to take place such as an elevated baseline, increasingly variable signal, and comparisons with the other sensor at the site. Spikes in the data, which are anomalously high voltages probably caused by debris temporarily wrapped around the sensor or by large marine organisms (fish, crabs) on or near the sensor, also were removed from the raw data record (*fig. 3B*). Sometimes, incomplete cleaning of a sensor would cause a small, constant shift in sensor output that could be corrected using water-sample data.

## Sensor Calibration and Suspended-Sediment Concentration Data

The output for the three types of sensors used for this study are proportional to the SSC in the water column at the depth of the sensor. SSC calculated from the output of side-by-side sensors with different instrument designs (BTG and D & A Instrument Company) were virtually identical (Buchanan and Schoellhamer, 1998). Calibration of the sensor output to SSC will vary according to the size and optical properties of the suspended sediment; therefore, the sensors must be calibrated using suspended material from the field (Levesque and Schoellhamer, 1995).

The output from the optical sensors was converted to SSC by linear regression using the robust, nonparametric, repeated median method (Siegel, 1982). In addition, the prediction interval and the 95-percent confidence interval were calculated and presented for each calibration equation.

The repeated median method calculates the slope in a two-part process. First, for each point ( $X, Y$ ), the median of all possible "point  $i$ " to "point  $j$ " slopes was calculated

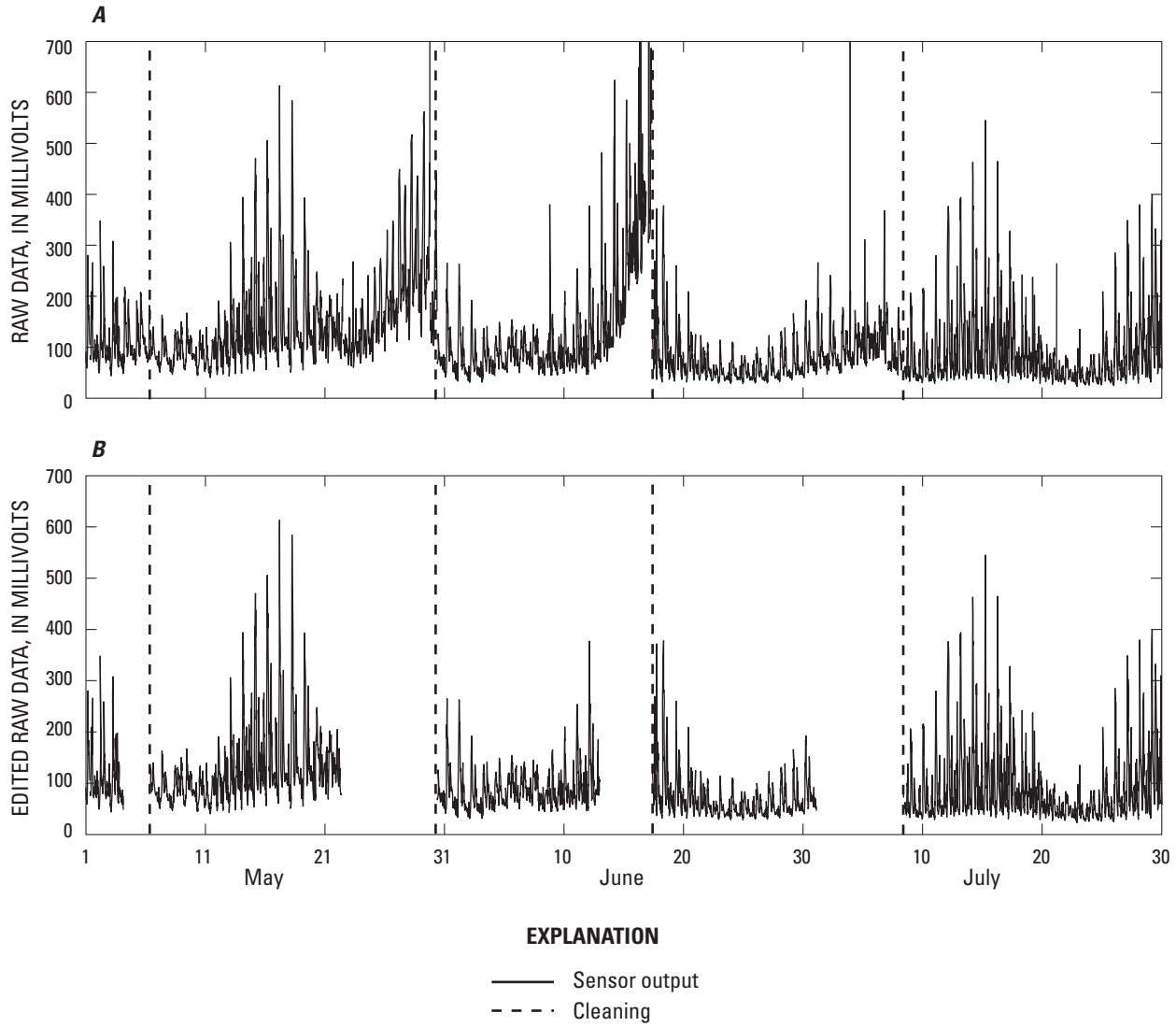
$$\beta_i = \text{median} \frac{(Y_j - Y_i)}{(X_j - X_i)} \text{ for all } j \neq i \quad (1)$$

The calibration slope was calculated as the median of  $i$

$$\text{slope} = \hat{\beta}_1 = \text{median}(\beta_i) \quad (2)$$

Finally, the calibration intercept was calculated as the median of all possible intercepts using the slope calculated above

$$\text{intercept} = \hat{\beta}_0 = \text{median}(Y_i - \hat{\beta}_1 X_i) \quad (3)$$



**Figure 3.** Example of (A) raw and (B) edited optical data, near-bottom sensor, Mare Island Causeway, San Pablo Bay, California, water year 2003.

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The final linear calibration equation is

$$Y = \hat{\beta}_1 X + \hat{\beta}_0 \quad (4)$$

The nonparametric prediction interval ( $PI_{np}$ ) (Helsel and Hirsch, 1992, p. 76) is a constant-width error band that contains about 68 percent, or one standard deviation, of the calibration data set. The 68-percent value was selected because essentially it has the same error prediction limits as the root-mean-squared (RMS) error of prediction in ordinary least squared regression; the latter was used in previous data reports (Buchanan and Schoellhamer, 1995, 1996, 1998, 1999; Buchanan and others, 1996) to analyze random sets of normally distributed data. The prediction interval describes the likelihood that a new observation comes from the same distribution as the previously collected data set.

The  $PI_{np}$ , unlike the RMS error of prediction, frequently is not symmetrical about the regression line. For example, the  $PI_{np}$  may be reported as +10 milligrams per liter (mg/L) and -7 mg/L. This asymmetry about the regression line is a result of the distribution of the data set. The  $PI_{np}$  is calculated by computing and sorting, from least to greatest, the residuals for each point. Then, based on the sorted list of residuals:

$$\text{nonparametric prediction interval} = PI_{np} = \hat{Y}_{\left(\frac{\alpha}{2}\right)(n+1)} \text{ to } \hat{Y}_{\left(1-\frac{\alpha}{2}\right)(n+1)} \quad (5)$$

where

- $\hat{Y}$  is the residual value,
- $n$  is the number of data points, and
- $\alpha$  is the confidence level of 0.68.

To calculate the confidence interval, all possible point-to-point slopes must be sorted in ascending order. Based on the confidence interval desired, 95-percent for the purposes of this report, the ranks of the upper and lower bounds are calculated as follows:

$$Ru = \frac{\frac{n(n-1)}{2} + 1.96 \sqrt{\frac{n(n-1)(2n+5)}{18}}}{2} + 1, \text{ and} \quad (6)$$

$$Rl = \frac{\frac{n(n-1)}{2} - 1.96 \sqrt{\frac{n(n-1)(2n+5)}{18}}}{2} \quad (7)$$

where

- $Ru$  is the rank of the upper bound slope,
- $Rl$  is the rank of the lower bound slope, and
- $n$  is the number of samples.

To establish the 95-percent confidence interval, the ranks calculated above are rounded to the nearest integer and the slope associated with each rank in the sorted list is identified. This is a large-sample approximation and was used for each of the confidence intervals presented in this report. However, in the event that fewer than 10 samples had been collected, a direct calculation could be performed using the methodology presented in Helsel and Hirsch (1992, p. 273–274).

A statistical summary of the SSC, calculated from optical sensor data, is presented in [table 2](#). The usable percentage of a complete year of valid data (96 data points per day  $\times$  365 days) for each site is presented in [table 2](#).

This section of the report also includes the robust regression (calibration) figures for optical sensor output versus SSC (in milligrams per liter). The calibration figures include the number of water samples (all water samples used to develop calibration, including those from previous water years), the calculated linear correlation equation, the nonparametric prediction interval (shown on the calibration figures as a grey band), and the 95-percent confidence interval (shown on the calibration figures as a dash-dot line). In addition, the time-series plots of calculated SSC data are shown for each site.



**Table 2.** Statistical summary of calculated suspended-sediment concentration data and usable percentage of a complete year of valid data (96 data points per day x 365 days) collected using optical sensors, Suisun Bay, San Pablo Bay, and Central and South San Francisco Bays, California, water year 2003

[All values are in milligrams per liter except percent valid data. Lower quartile is 25th percentile; upper quartile is 75th percentile]

Site	Depth	Mean	Median	Lower quartile	Upper quartile	Percent valid data
Mallard Island	Near-surface	38	33	28	42	56
	Near-bottom	48	41	31	56	58
Benicia Bridge	Near-surface	40	29	17	52	60
	Near-bottom	86	74	46	112	61
Carquinez Bridge	Mid-depth	31	21	13	38	86
	Near-bottom	81	59	29	107	62
Mare Island Causeway	Mid-depth	70	53	29	89	59
	Near-bottom	114	86	52	147	71
Channel Marker 9	Near-bottom	132	63	32	160	73
Point San Pablo	Mid-depth	27	20	14	31	40
	Near-bottom	62	44	30	74	52
San Mateo Bridge	Mid-depth	44	36	27	50	26
	Near-bottom	51	40	28	62	31
Dumbarton Bridge	Mid-depth	56	45	31	64	33
	Near-bottom	76	59	36	91	47
Channel Marker 17	Mid-depth	72	53	29	91	32
	Near-bottom	83	55	31	102	32

## Suisun Bay

### Mallard Island

PERIOD OF CALIBRATION.—

NEAR-SURFACE SENSOR: WY 2003 (*fig. 4*).

NEAR-BOTTOM SENSOR (A): October 1, 2002, to February 5, 2003 (*fig. 5A*).

NEAR-BOTTOM SENSOR (B): February 5, 2003, through WY 2003 (*fig. 5B*).

NUMBER OF DATA POINTS (WATER SAMPLES) USED FOR CALIBRATION.—

NEAR-SURFACE SENSOR: 18 (18 from WY 2003).

NEAR-BOTTOM SENSOR(A): 181 (5 from WY 2003).

NEAR-BOTTOM SENSOR(B): 7 (5 from WY 2003).

CALCULATED LINEAR CORRELATION EQUATION.—

NEAR-SURFACE SENSOR:  $SSC = 0.317 \times \text{millivolt (mV)} + 5.2$ .

NEAR-BOTTOM SENSOR(A):  $SSC = 0.499 \times \text{mV} - 8.6$ .

NEAR-BOTTOM SENSOR(B):  $SSC = 0.423 \times \text{mV} + 51.1$ .

NONPARAMETRIC PREDICTION INTERVAL.—

NEAR-SURFACE SENSOR: +10 to -4 mg/L.

NEAR-BOTTOM SENSOR(A): +9 to -8 mg/L.

NEAR-BOTTOM SENSOR(B): +24 to -14 mg/L.

REMARKS.—Interruptions in record were caused by fouling or malfunction of the sensing and(or) recording instruments. Sensors were positioned at near-surface (attached to float assembly) and near-bottom depths to coincide with DWR near-surface pump intake and the near-bottom electrical conductance and temperature sensors. The near-bottom sensor malfunctioned and was replaced on February 5, 2003. The calibration developed for the replacement sensor included two water samples collected in WY 2004 to help define the calibration. A -90-millivolt shift to the near-bottom sensor calibration, calculated from five water samples not shown on figure 5B (not used to develop calibration), was applied from February 5, 2003, through May 8, 2003, when the gain setting on the sensor was changed. The calculated SSC time-series data collected during WY 2003 are presented in *figure 6*.

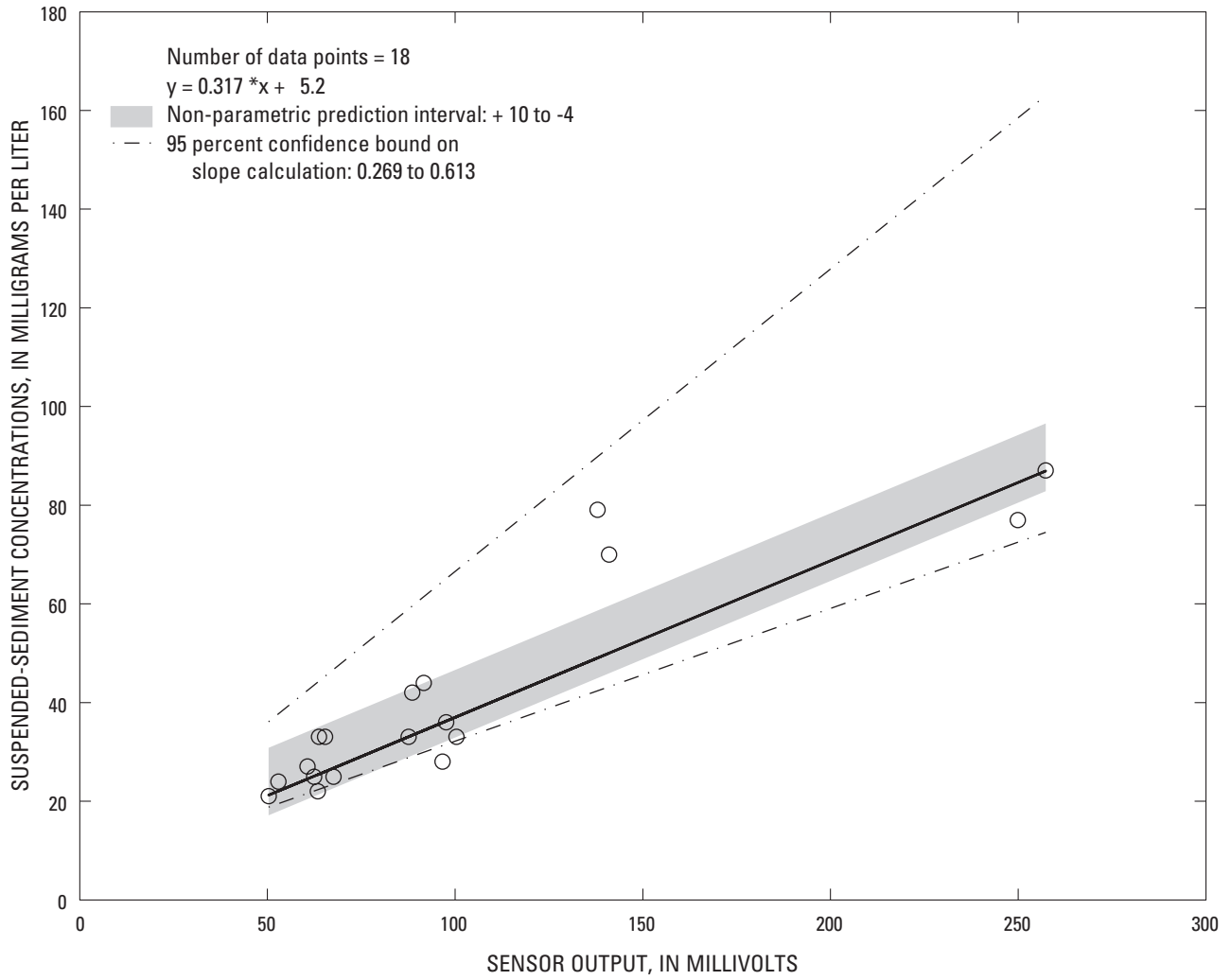


Figure 4. Calibration of near-surface optical sensor at Mallard Island, Suisun Bay, California, water year 2003.

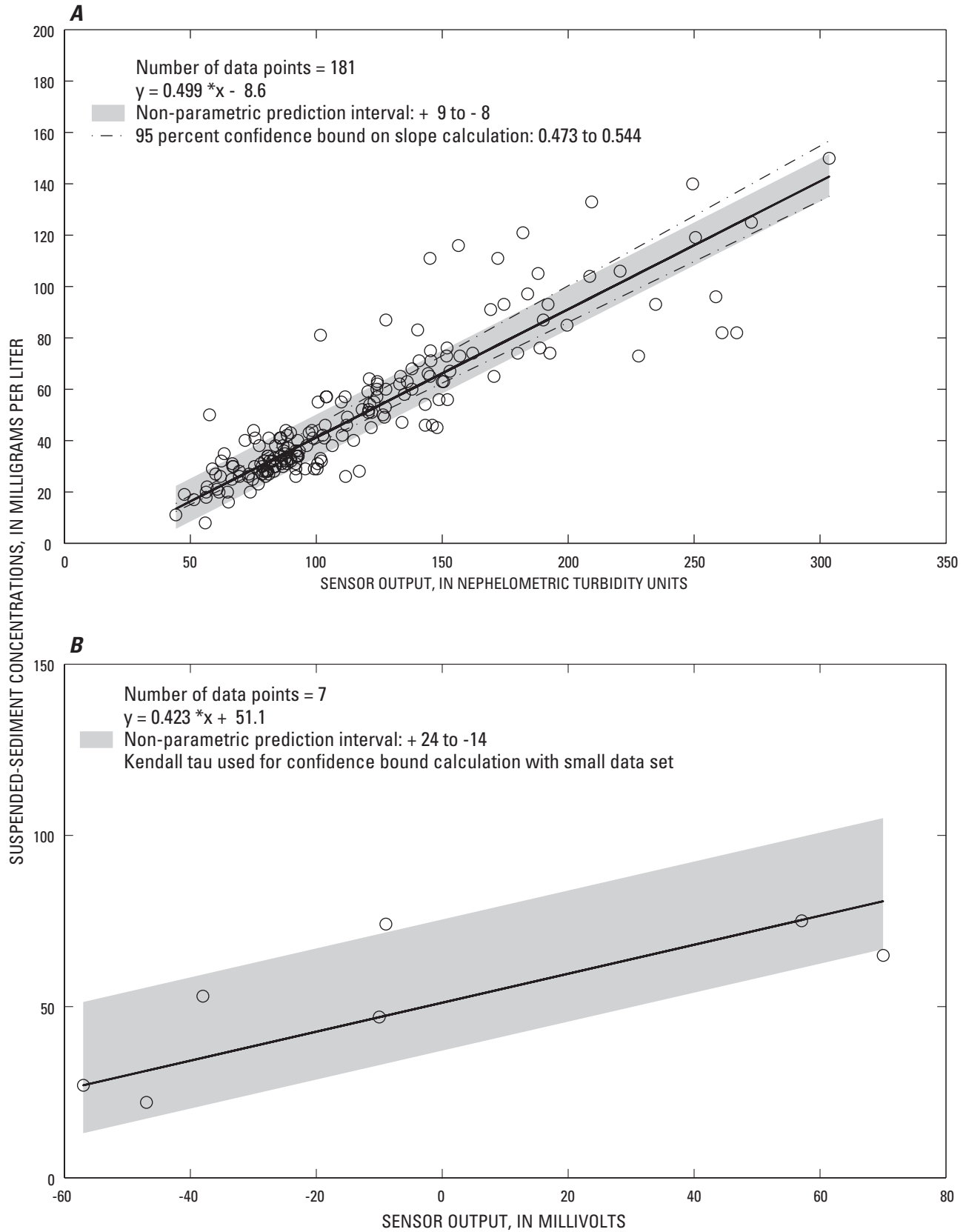
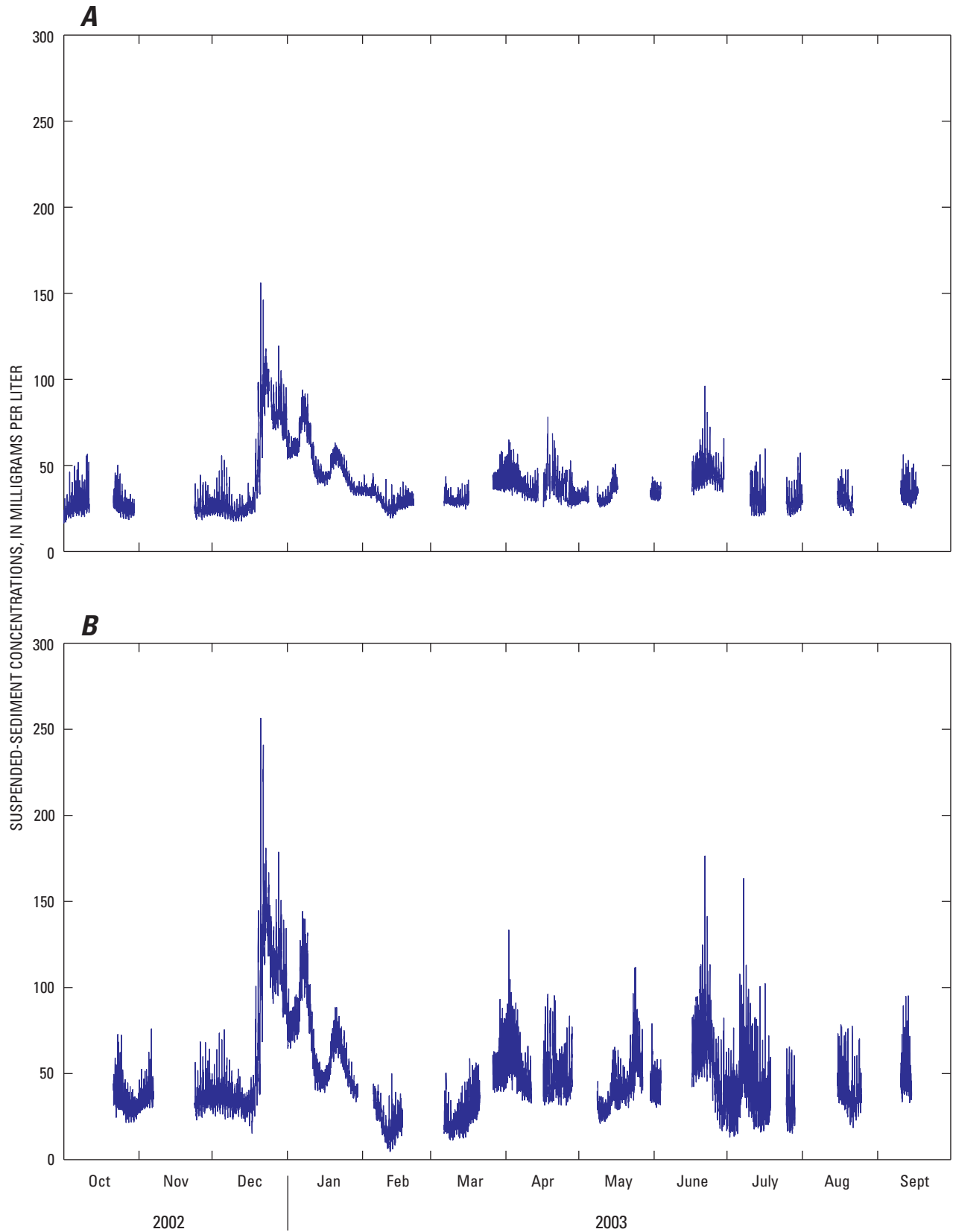


Figure 5. Calibration of near-bottom optical sensors, (A) October 1–February 5 and (B) February 5–September 30 at Mallard Island, Suisun Bay, California, water year 2003.



**Figure 6.** Time series of (A) near-surface and (B) near-bottom suspended-sediment concentrations calculated from sensor readings at Mallard Island, Suisun Bay, California, water year 2003.

## Benicia Bridge

## PERIOD OF CALIBRATION.—

NEAR-SURFACE SENSOR (A): October 1, 2002, to May 20, 2003, and July 23, 2003, to August 28, 2003 (*fig. 7A*).

NEAR-SURFACE SENSOR (B): May 20, 2003, to July 2, 2003 (*fig. 7B*).

NEAR-BOTTOM SENSOR: WY 2003 (*fig. 8*).

## NUMBER OF DATA POINTS.—

NEAR-SURFACE SENSOR (A): 31 (9 from WY 2003).

NEAR-SURFACE SENSOR (B): 4 (4 from WY 2003).

NEAR-BOTTOM SENSOR: 45 (16 from WY 2003).

## CALCULATED LINEAR CORRELATION EQUATION.—

NEAR-SURFACE SENSOR (A):  $SSC = 0.939 \times NTU + 2.2$ .

NEAR-SURFACE SENSOR (B):  $SSC = 1.410 \times NTU + 6.0$ .

NEAR-BOTTOM SENSOR:  $SSC = 1.204 \times NTU + 1.9$ .

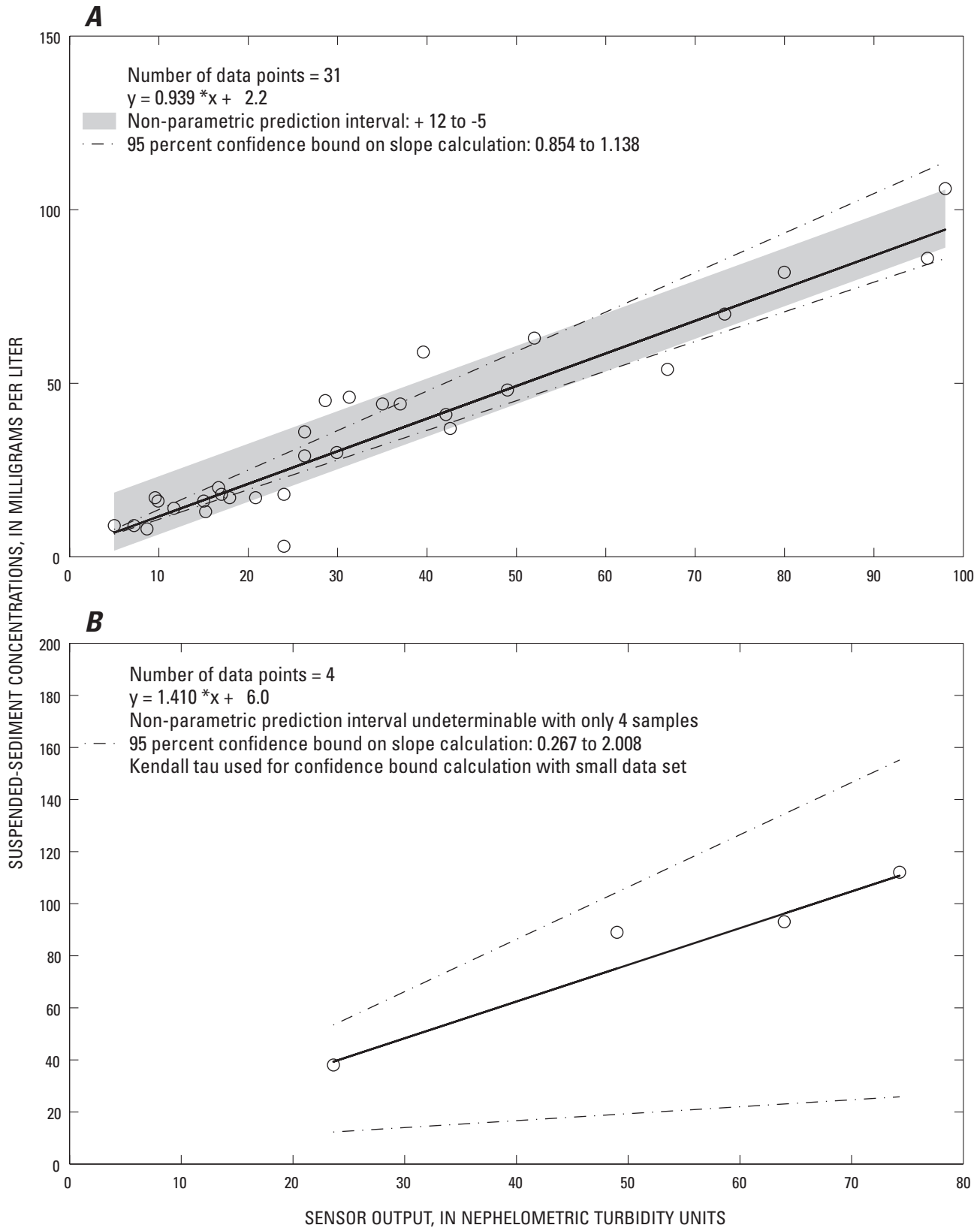
## NONPARAMETRIC PREDICTION INTERVAL.—

NEAR-SURFACE SENSOR: +12 to -5 mg/L.

NEAR-SURFACE SENSOR: undeterminable with 4 samples.

NEAR-BOTTOM SENSOR: +10 to -18 mg/L.

REMARKS.—Interruptions in record were caused by fouling or malfunction of the sensing and(or) recording instruments. MLLW was approximately 80 ft at the site but approximately 60 ft immediately adjacent, therefore, the near-bottom sonde was set approximately 25 ft above the bottom so that the data are representative of the surrounding area. The calibration used for data collected at the near-surface location from October 1, 2002, to May 20, 2003, and July 23, 2003, to August 28, 2003, was developed from samples collected during the deployment of two Hydrolab sensors. A +10.1-nephelometric turbidity unit shift to the near-surface sensor calibration, calculated from water samples collected during the deployment of a third Hydrolab sensor with a different response and not shown on figure 7A (not used to develop calibration), was applied from July 23, 2003, to August 28, 2003. The second calibration used for data collected at the near-surface location was developed from water samples collected during the deployment of a YSI sensor from May 20, 2003, to July 2, 2003. The four water samples collected for the YSI sensor were insufficient for determining a nonparametric prediction interval. Several different sensors were used in the near-bottom location. Because the different sensors (all Hydrolabs) responded similarly to the uniform sediment characteristics found in San Francisco Bay (Schoellhamer and others, 2003), the calibration was developed by combining water samples collected during each sensor deployment. The calculated SSC time-series data collected during WY 2003 are presented in *figure 9*.



**Figure 7.** Calibration of near-surface optical sensors, (A) October 1–May 20, July 23–August 28 and (B) May 20–July 2 at Benicia Bridge, Suisun Bay, California, water year 2003.

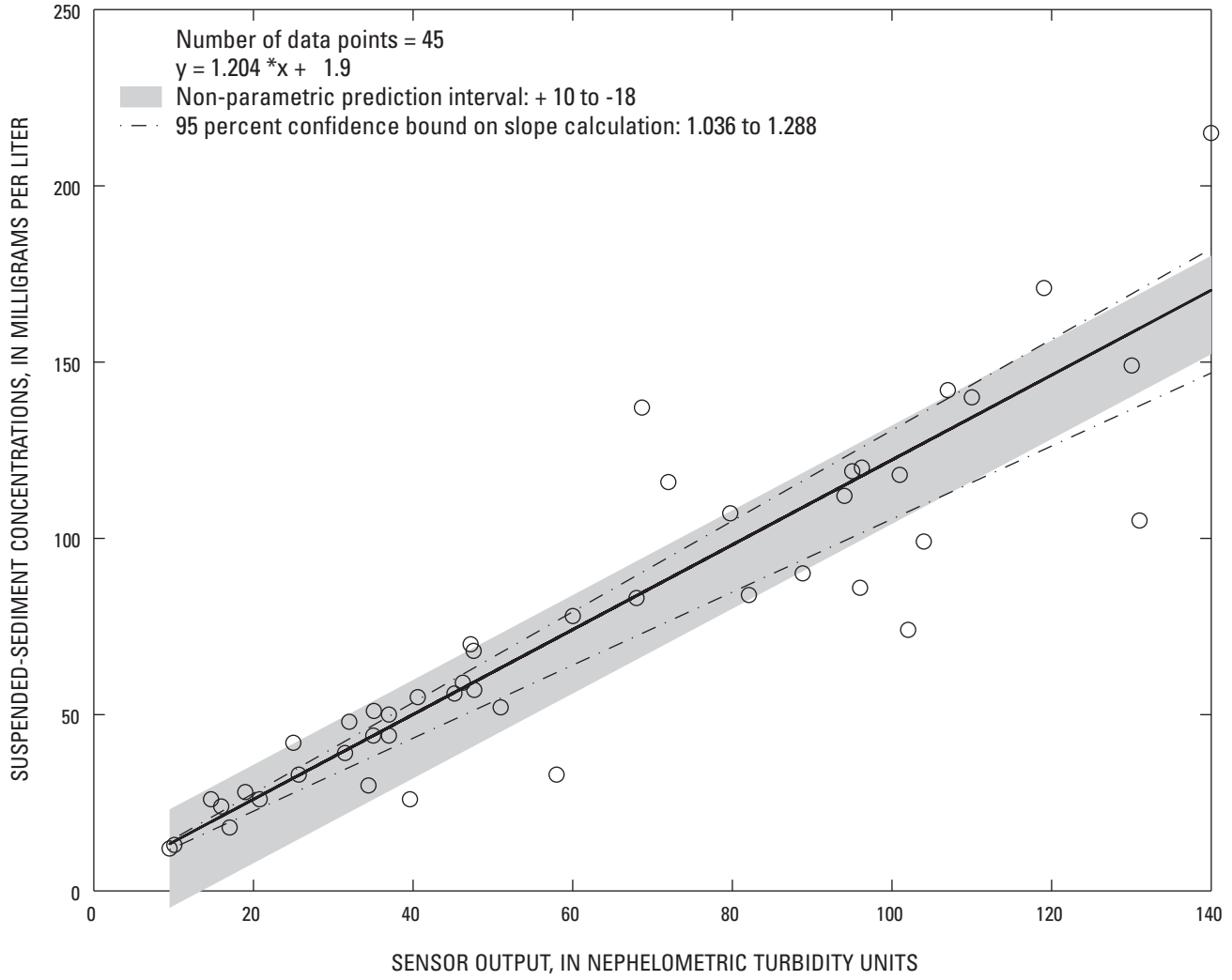
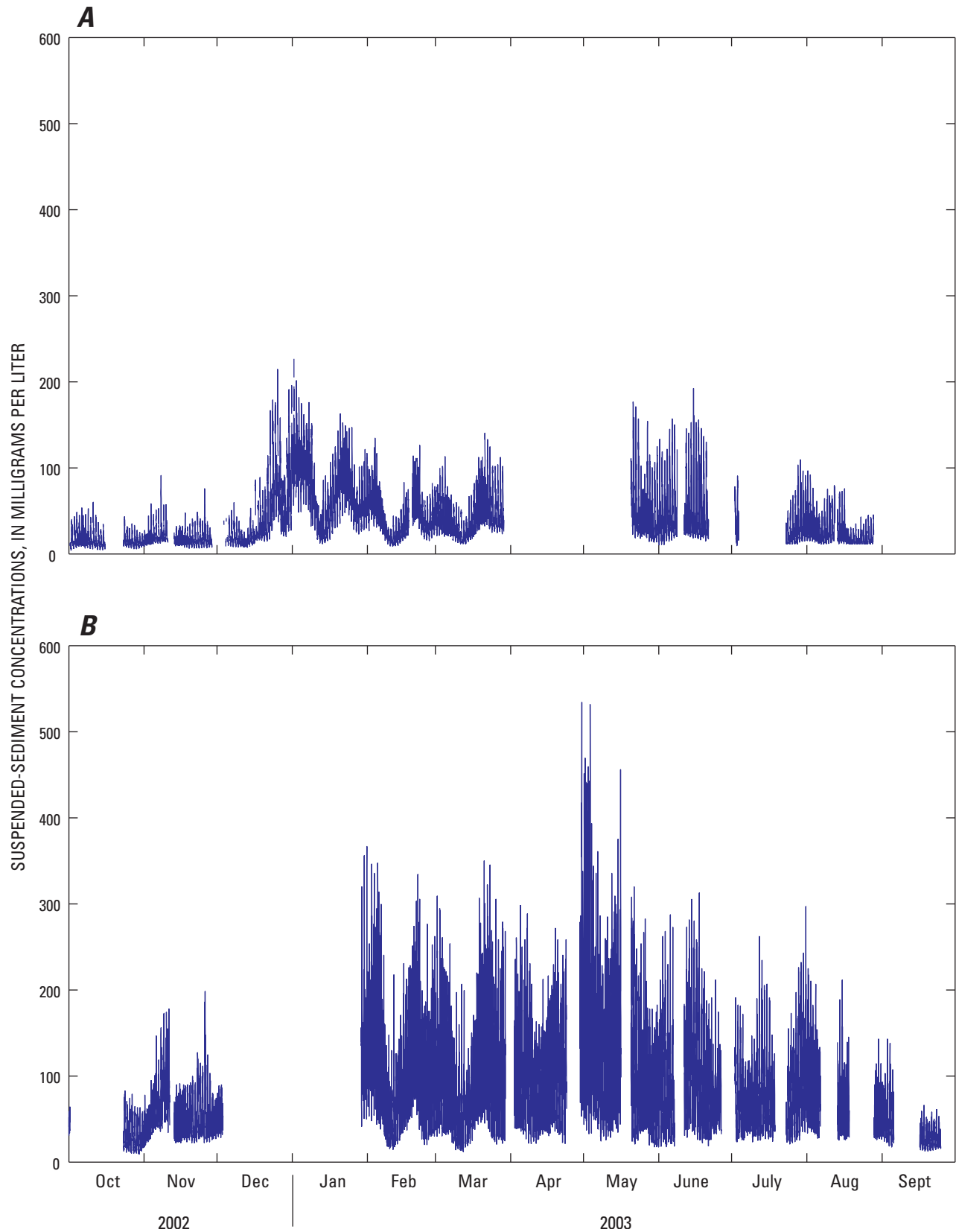


Figure 8. Calibration of near-bottom optical sensor at Benicia Bridge, Suisun Bay, California, water year 2003.





**Figure 9.** Time series of (A) near-surface and (B) near-bottom suspended-sediment concentrations calculated from sensor readings at Benicia Bridge, Suisun Bay, California, water year 2003.

## San Pablo Bay

### Carquinez Bridge

PERIOD OF CALIBRATION.—

MID-DEPTH SENSOR: WY 2003 (*fig. 10*).

NEAR-BOTTOM SENSOR (A): October 1, 2002, to November 12, 2002 (*fig. 11A*).

NEAR-BOTTOM SENSOR (B): January 29, 2003, through WY 2003 (*fig. 11B*).

NUMBER OF DATA POINTS.—

MID-DEPTH SENSOR: 54 (20 from WY 2003).

NEAR-BOTTOM SENSOR (A): 60 (2 from WY 2003).

NEAR-BOTTOM SENSOR (B): 10 (9 from WY 2003).

CALCULATED LINEAR CORRELATION EQUATION.—

MID-DEPTH SENSOR:  $SSC = 0.978 \times NTU + 4.5$ .

NEAR-BOTTOM SENSOR (A):  $SSC = 0.985 \times NTU + 5.3$ .

NEAR-BOTTOM SENSOR (B):  $SSC = 1.404 \times NTU + 9.6$ .

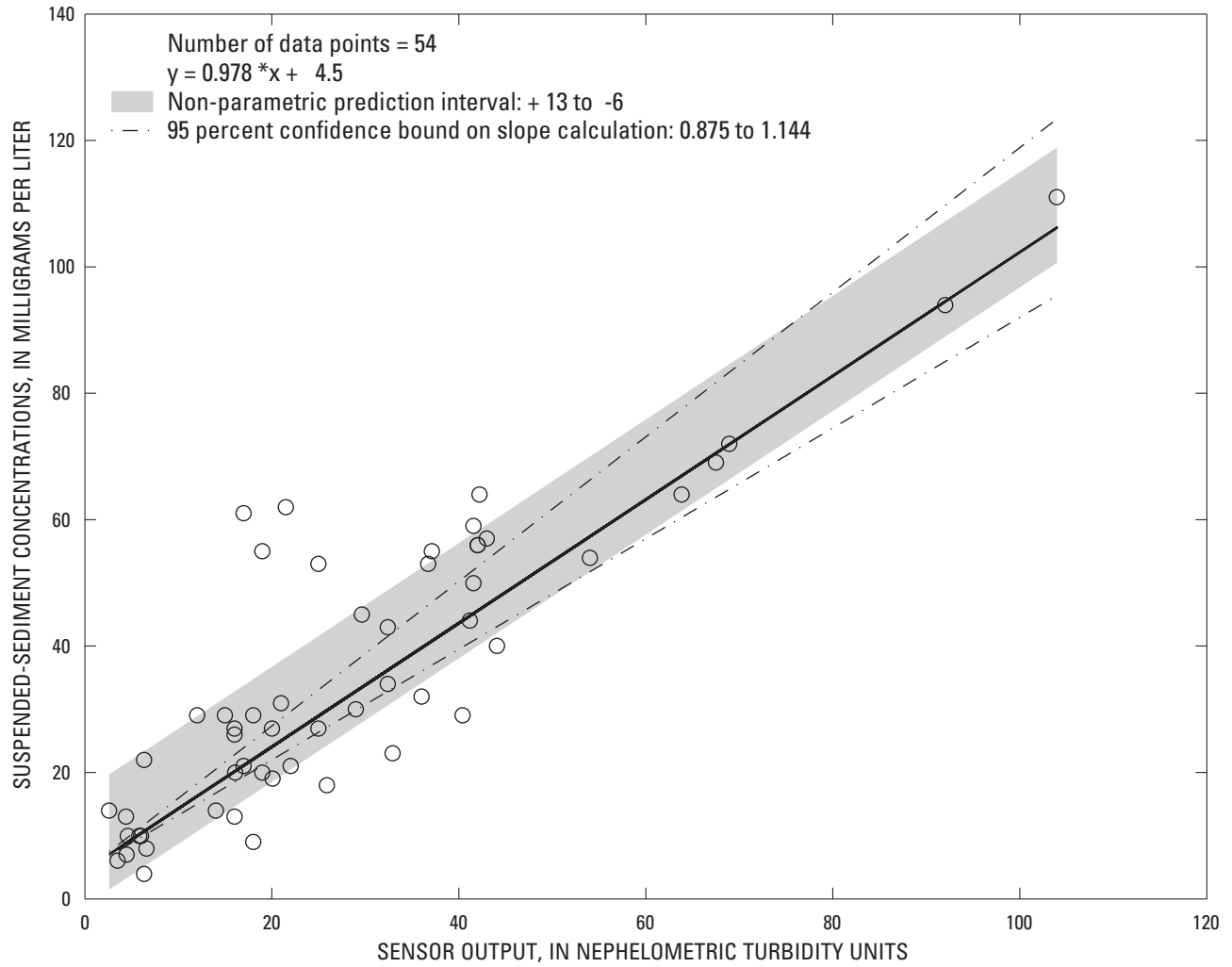
NONPARAMETRIC PREDICTION INTERVAL.—

MID-DEPTH SENSOR: +13 to -6 mg/L.

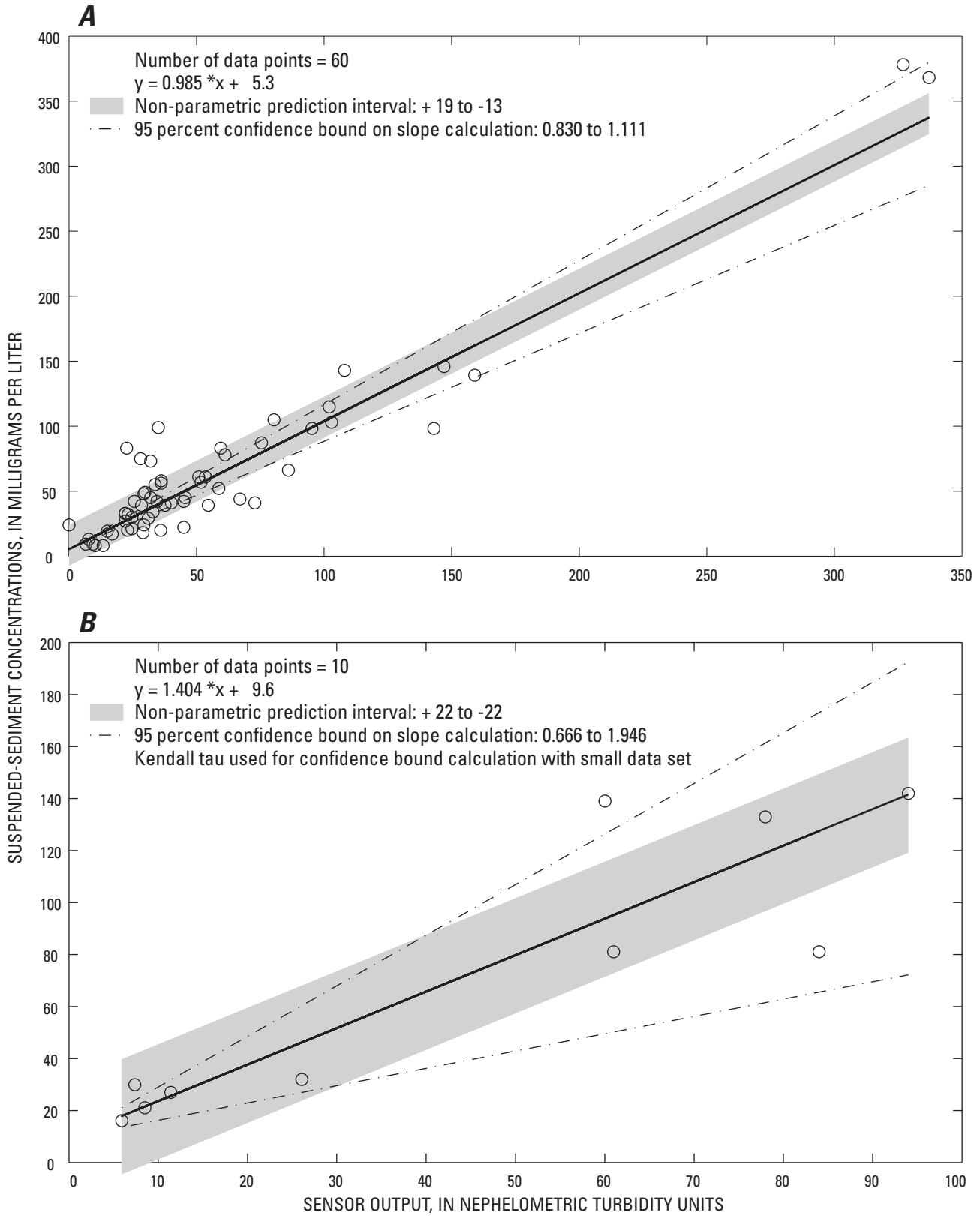
NEAR-BOTTOM SENSOR (A): +19 to -13 mg/L.

NEAR-BOTTOM SENSOR (B): +22 to -22 mg/L.

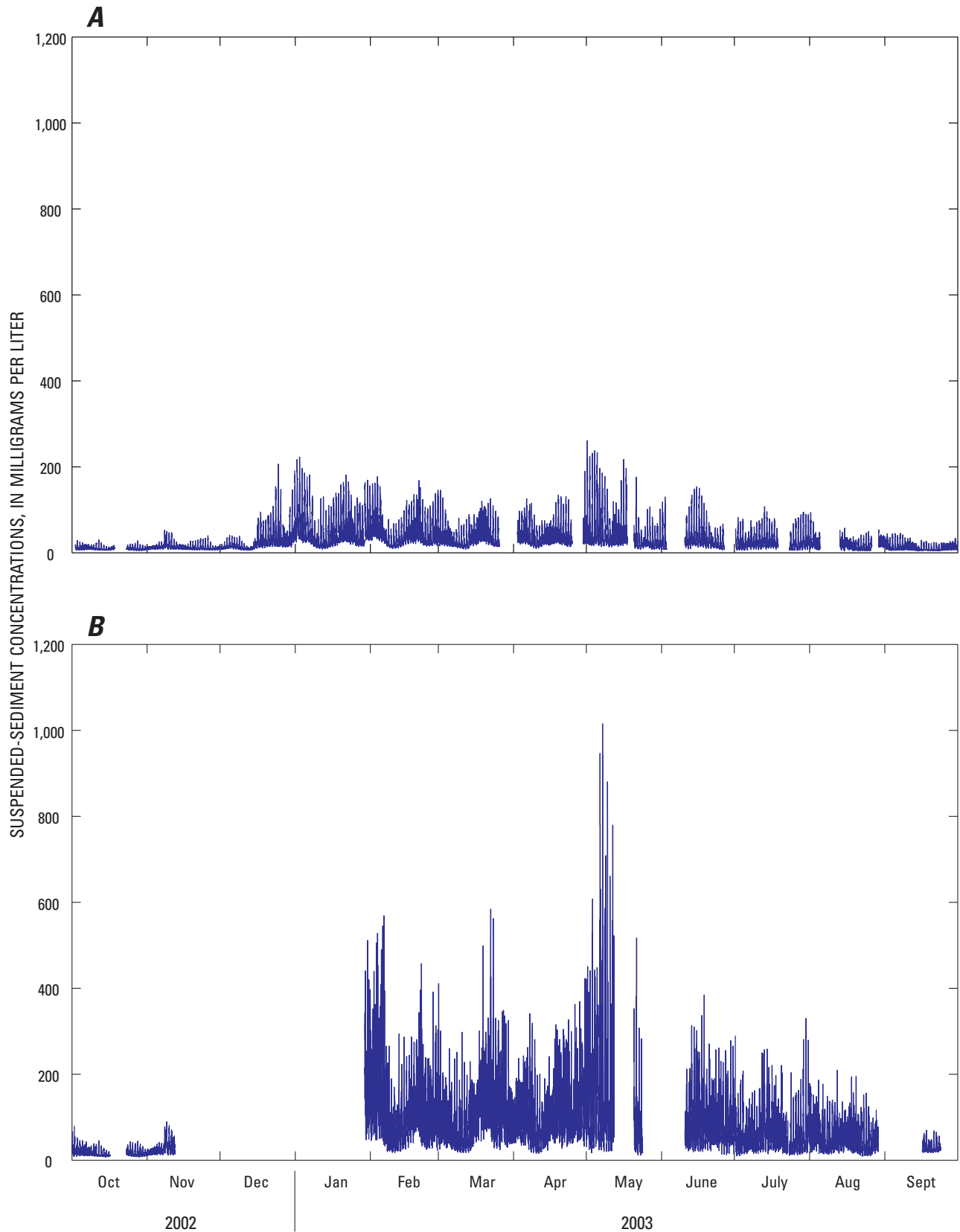
REMARKS.—Interruptions in record were caused by fouling or malfunction of the sensing and(or) recording instruments. The near-bottom sensor malfunctioned and was pulled on November 12, 2002, and a replacement sensor was deployed on January 29, 2003. The near-bottom replacement sensor was calibrated on March 11, 2003, and recalibrated on April 2, 2003, resulting in a +56.8-nephelometric turbidity unit shift being applied during this period. The calculated SSC time-series data collected during water year 2003 are presented in *figure 12*.



**Figure 10.** Calibration of mid-depth optical sensor at Carquinez Bridge, San Pablo Bay, California, water year 2003.



**Figure 11.** Calibration of near-bottom optical sensors, (A) October 1–November 12 and (B) January 29–September 30 at Carquinez Bridge, San Pablo Bay, California, water year 2003.



**Figure 12.** Time series of (A) mid-depth and (B) near-bottom suspended-sediment concentrations calculated from sensor readings at Carquinez Bridge, San Pablo Bay, California, water year 2003.

## Mare Island Causeway

## PERIOD OF CALIBRATION.—

MID-DEPTH SENSOR (A): October 1, 2002, to January 7, 2003 (*fig. 13A*).

MID-DEPTH SENSOR (B): February 4, 2003, through WY 2003 (*fig. 13B*).

NEAR-BOTTOM SENSOR (A): October 1, 2002, to April 14, 2003 (*fig. 14A*).

NEAR-BOTTOM SENSOR (B): April 14, 2003, through WY 2003 (*fig. 14B*).

## NUMBER OF DATA POINTS.—

MID-DEPTH SENSOR (A): 47 (4 from WY 2003).

MID-DEPTH SENSOR (B): 7 (7 from WY 2003).

NEAR-BOTTOM SENSOR (A): 101 (9 from WY 2003).

NEAR-BOTTOM SENSOR (B): 15 (8 from WY 2003).

## CALCULATED LINEAR CORRELATION EQUATION.—

MID-DEPTH SENSOR (A):  $SSC = 0.527 \times mV - 14.8$ .

MID-DEPTH SENSOR (B):  $SSC = 0.589 \times mV + 22.7$ .

NEAR-BOTTOM SENSOR (A):  $SSC = 0.686 \times mV - 10.5$ .

NEAR-BOTTOM SENSOR (B):  $SSC = 1.026 \times mV - 0.5$ .

## NONPARAMETRIC PREDICTION INTERVAL.—

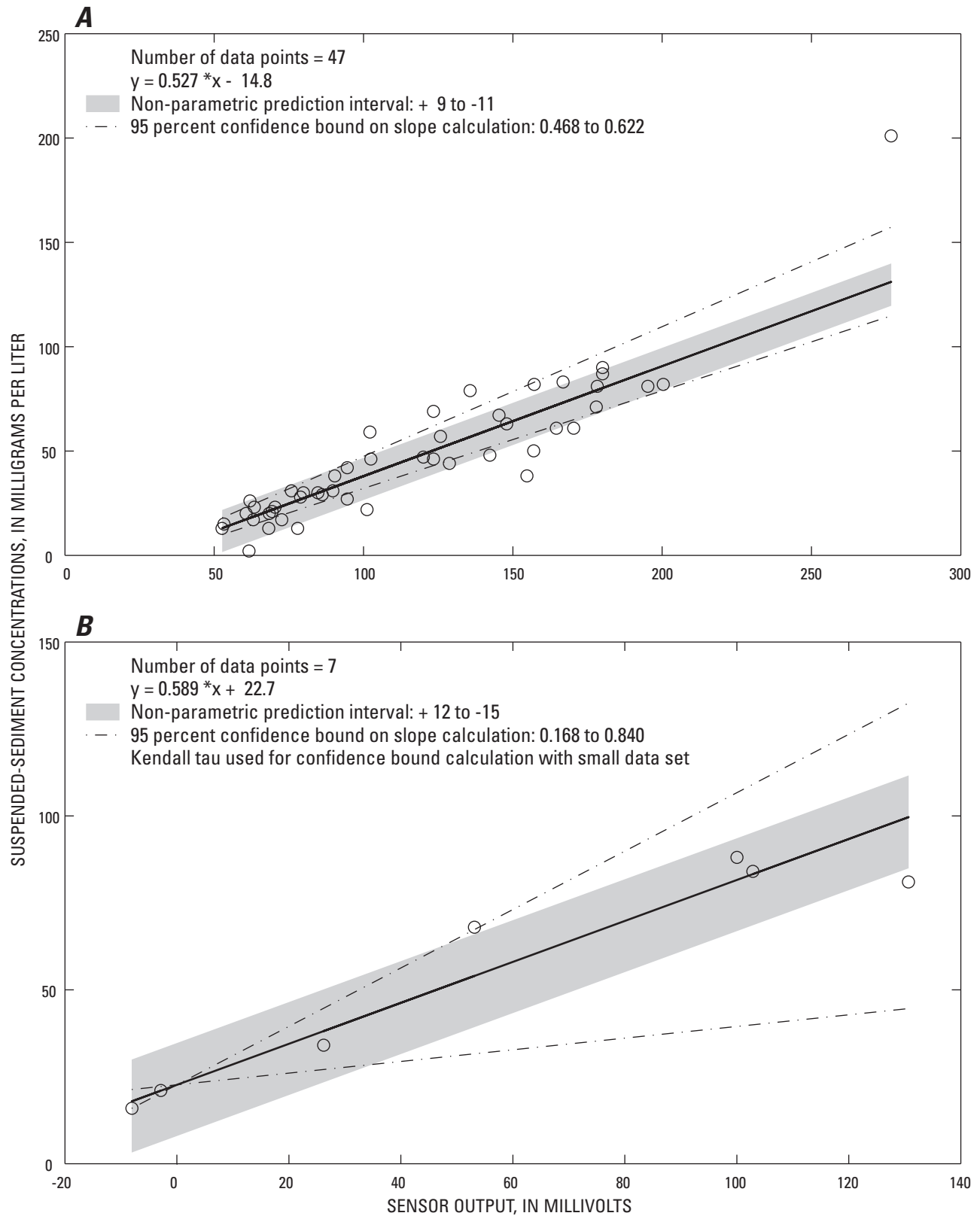
MID-DEPTH SENSOR (A): +9 to -11 mg/L.

MID-DEPTH SENSOR (B): +12 to -15 mg/L.

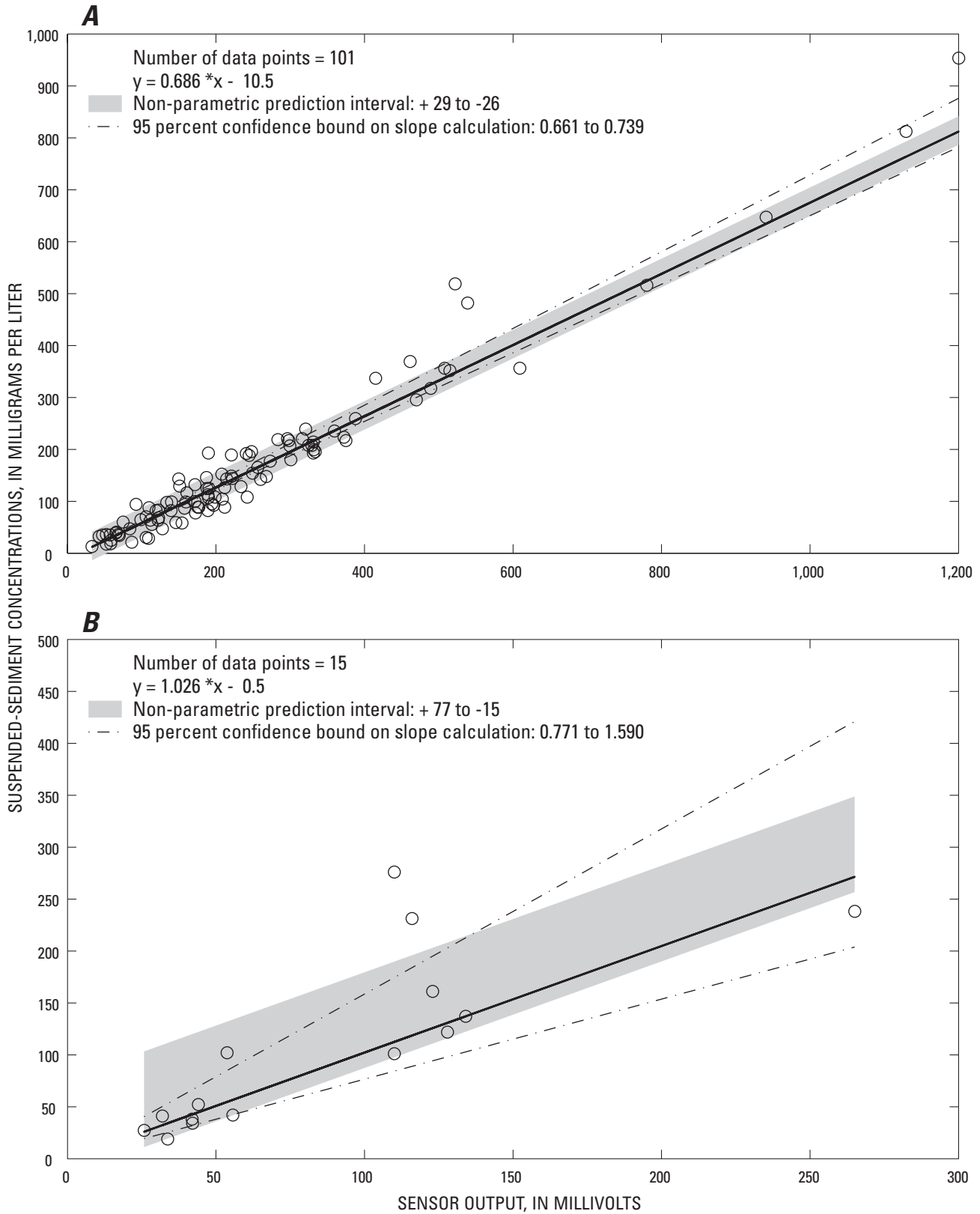
NEAR-BOTTOM SENSOR (A): +29 to -26 mg/L.

NEAR-BOTTOM SENSOR (B): +77 to -15 mg/L.

REMARKS.—Interruptions in record were caused by fouling or malfunction of the sensing and(or) recording instruments. The mid-depth sensor was replaced on January 7, 2003, because the output had drifted. The mid-depth replacement sensor was removed on February 4, 2003, because the instrument gain was found to be set incorrectly resulting in lost data during this period. The calibration of the near-bottom sensor changed after the site visit on April 14, 2003, possibly due to the optical window being scratched during cleaning. The calibration developed after April 14, 2003, for the near-bottom sensor included seven water samples collected in WY 2004 to help define the calibration. The calculated SSC time-series data collected during WY 2003 are presented in *figure 15*.

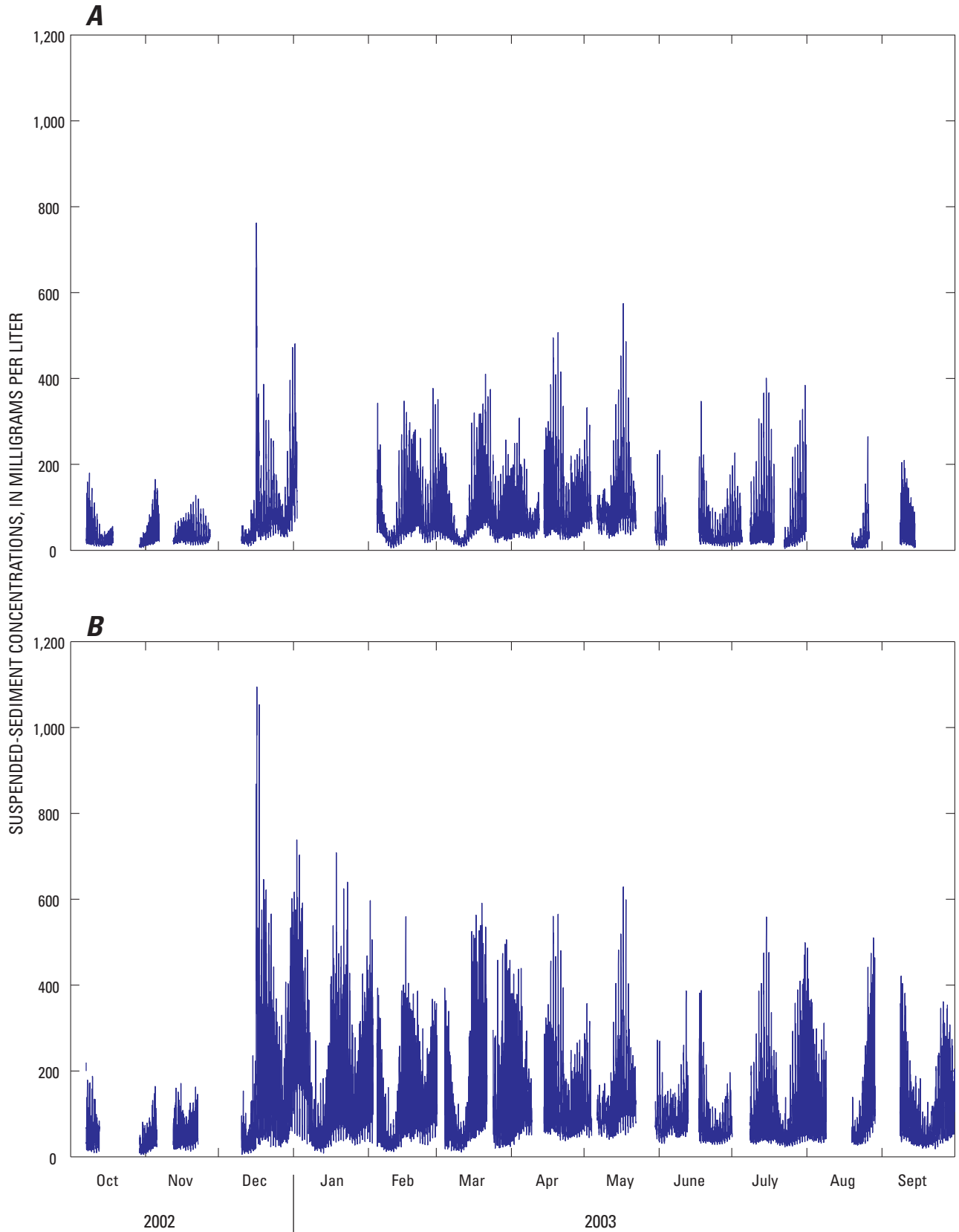


**Figure 13.** Calibration of mid-depth optical sensors, (A) October 1–January 7 and (B) February 4–September 30 at Mare Island Causeway, San Pablo Bay, California, water year 2003.



**Figure 14.** Calibration of near-bottom optical sensors, (A) October 1–April 14 and (B) April 14–September 30 at Mare Island Causeway, San Pablo Bay, California, water year 2003.





**Figure 15.** Time series of (A) mid-depth and (B) near-bottom suspended-sediment concentrations calculated from sensor readings at Mare Island Causeway, San Pablo Bay, California, water year 2003.

## Channel Marker 9

PERIOD OF CALIBRATION.—

NEAR-BOTTOM SENSOR: WY 2003 (*fig. 16*).

NUMBER OF DATA POINTS.—

NEAR-BOTTOM SENSOR: 30 (22 from WY 2003).

CALCULATED LINEAR CORRELATION EQUATION.—

NEAR-BOTTOM SENSOR:  $SSC = 1.699 \times NTU + 0.5$ .

NONPARAMETRIC PREDICTION INTERVAL.—

NEAR-BOTTOM SENSOR: +27 to -12 mg/L.

REMARKS.—Interruptions in record were caused by fouling or malfunction of the sensing and(or) recording instruments. The calculated SSC time-series data collected during WY 2003 are presented in *figure 17*.

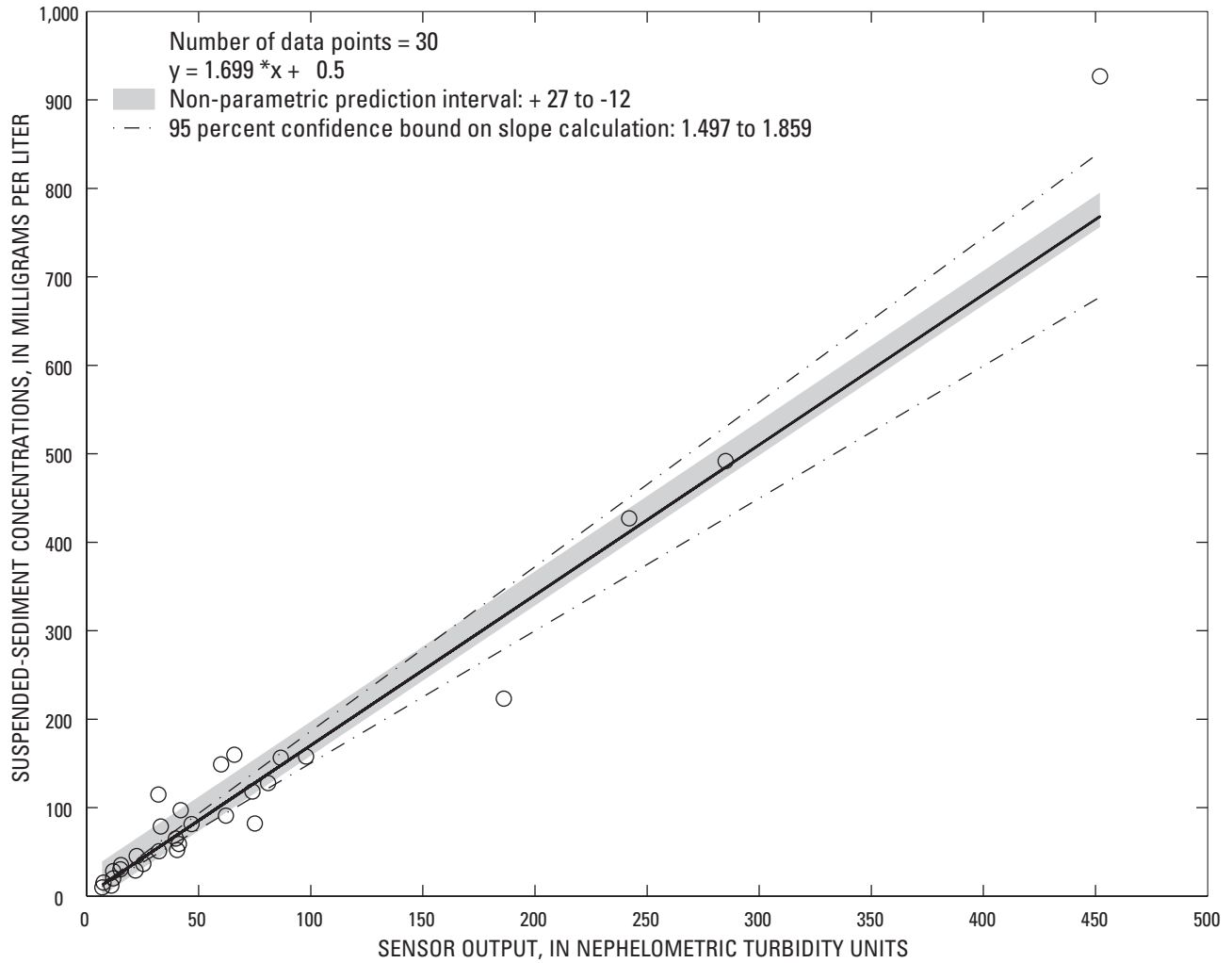
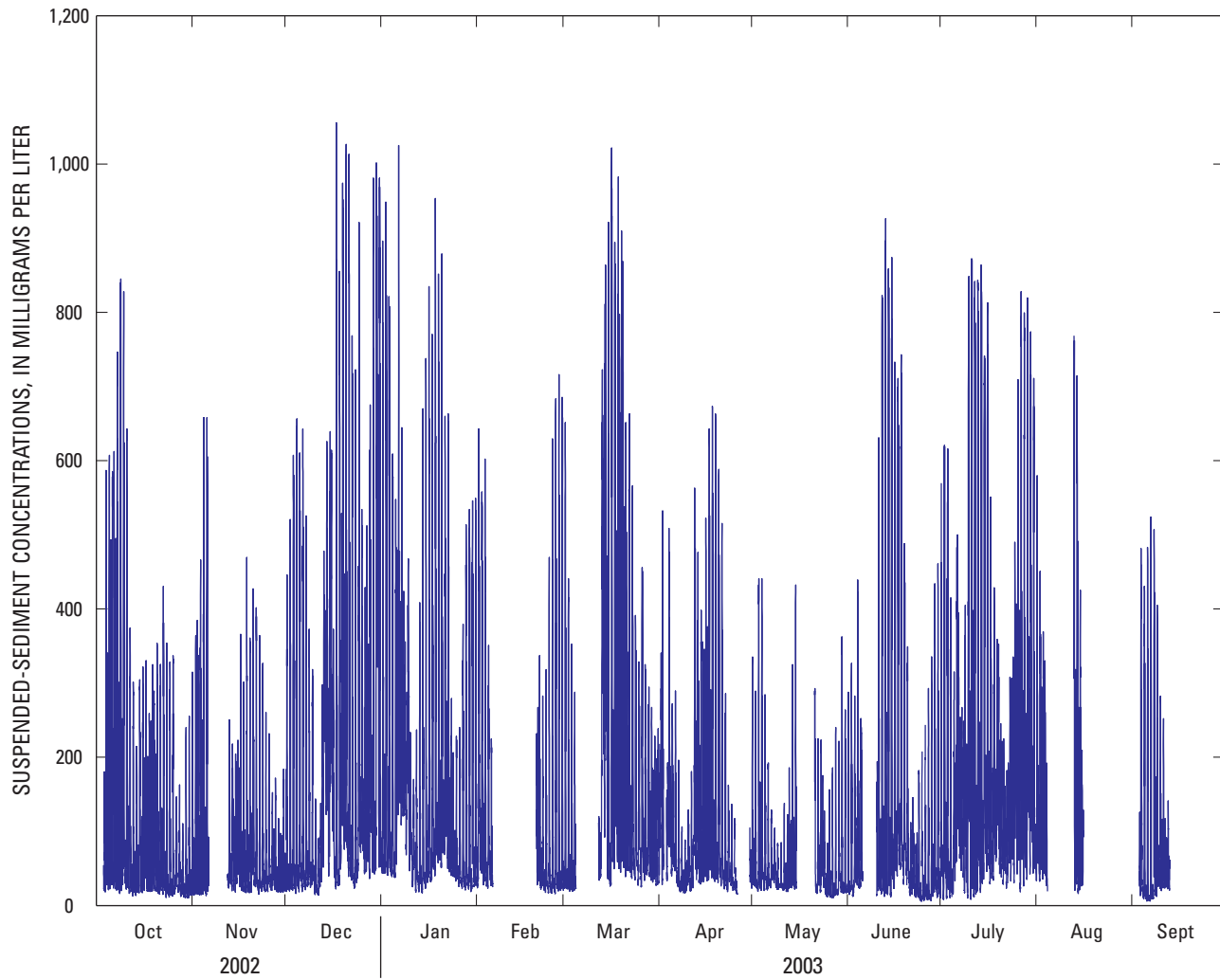


Figure 16. Calibration of near-bottom optical sensor at Channel Marker 9, San Pablo Bay, California, water year 2003.



**Figure 17.** Time series of near-bottom suspended-sediment concentrations calculated from sensor readings at Channel Marker 9, San Pablo Bay, California, water year 2003.

## Central San Francisco Bay

### Point San Pablo

PERIOD OF CALIBRATION.—

MID-DEPTH SENSOR (A): October 1, 2002, to February 5, 2003, and April 30, 2003, through WY 2003 (*fig. 18A*).

MID-DEPTH SENSOR (B): February 5, 2003, to April 3, 2003 (*fig. 18B*).

NEAR-BOTTOM SENSOR: WY 2003 (*fig. 19*).

NUMBER OF DATA POINTS.—

MID-DEPTH SENSOR (A): 16 (6 from WY 2003).

MID-DEPTH SENSOR (B): 8 (1 from WY 2003).

NEAR-BOTTOM SENSOR: 9 (all from WY 2003).

CALCULATED LINEAR CORRELATION EQUATION.—

MID-DEPTH SENSOR (A):  $SSC = 1.940 \times NTU - 0.8$ .

MID-DEPTH SENSOR (B):  $SSC = 1.008 \times NTU + 6.7$ .

NEAR-BOTTOM SENSOR:  $SSC = 2.170 \times NTU + 7.2$ .

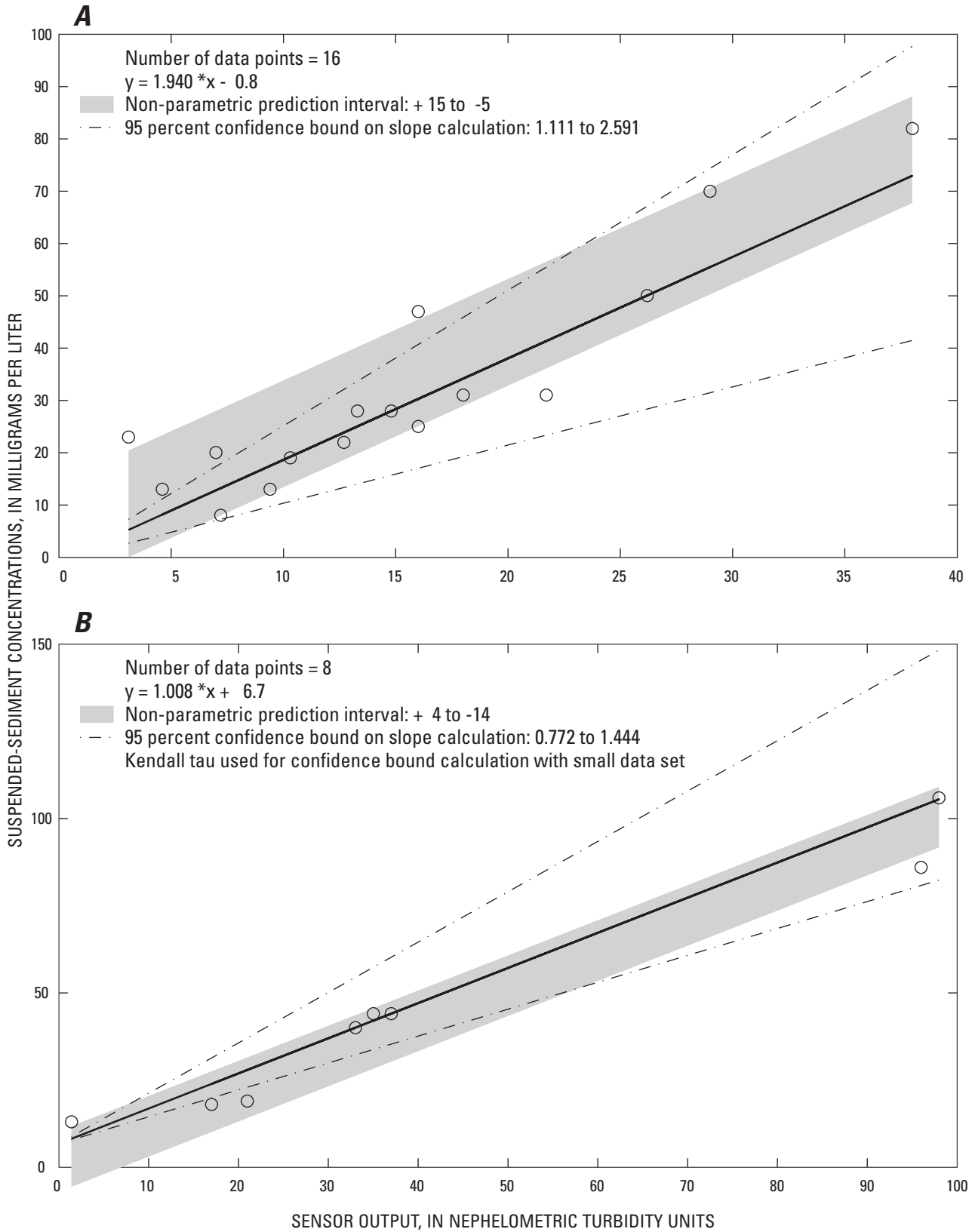
NONPARAMETRIC PREDICTION INTERVAL.—

MID-DEPTH SENSOR (A): +15 to -5 mg/L.

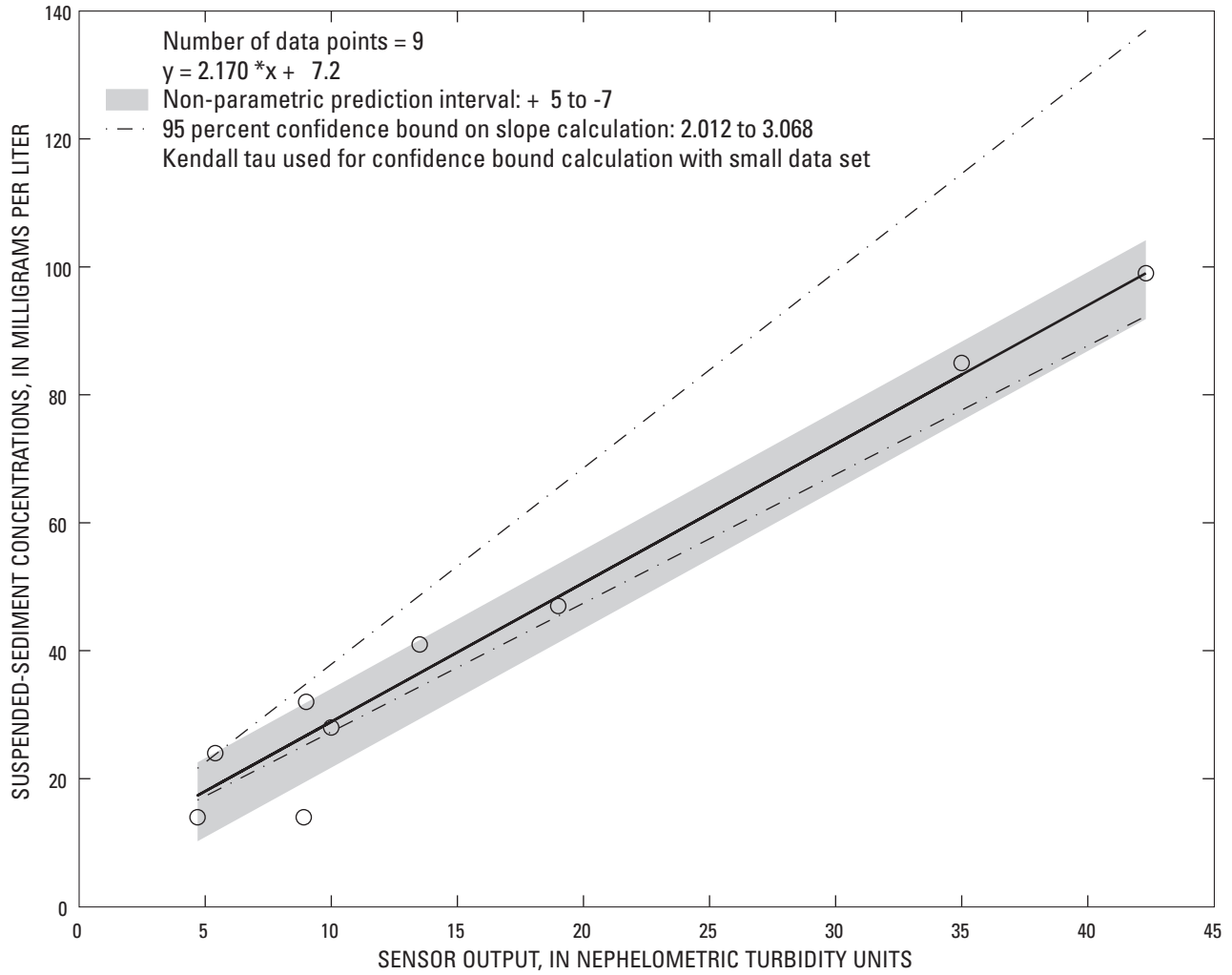
MID-DEPTH SENSOR (B): +4 to -14 mg/L.

NEAR-BOTTOM SENSOR: +5 to -7 mg/L.

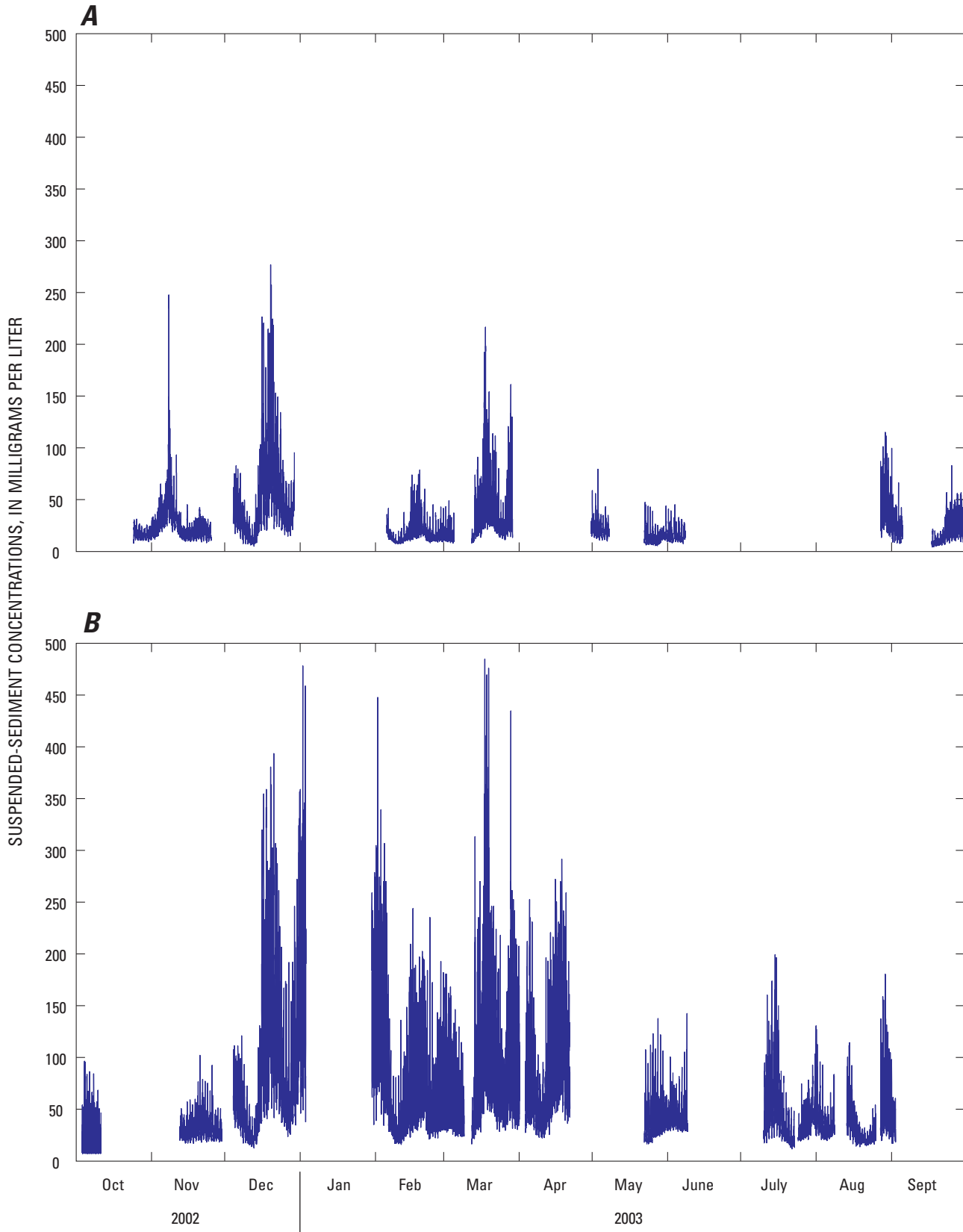
REMARKS.—Interruptions in record were caused by fouling or malfunction of the sensing and(or) recording instruments. The mid-depth calibration (*fig. 18A*) was developed from water samples collected during the deployment of two Hydrolab sensors. The third Hydrolab sensor used at the mid-depth location from February 5, 2003, to April 3, 2003, had a much different signal response and a separate calibration was developed (*fig. 18B*). Three Hydrolab sensors were used at the near-bottom position which responded similarly to the uniform sediment characteristics found in San Francisco Bay (Schoellhamer and others, 2003), and the calibration was developed by combining water samples collected during each sensor deployment. The calculated SSC time-series data collected during WY 2003 are presented in *figure 20*.



**Figure 18.** Calibration of mid-depth optical sensors, (A) October 1–February 5, April 30–September 30, and (B) February 5–April 3 at Point San Pablo, Central San Francisco Bay, California, water year 2003.



**Figure 19.** Calibration of near-bottom optical sensor at Point San Pablo, Central San Francisco Bay, California, water year 2003.



**Figure 20.** Time series of (A) mid-depth and (B) near-bottom suspended-sediment concentrations calculated from sensor readings at Point San Pablo, Central San Francisco Bay, California, water year 2003.



## South San Francisco Bay

### San Mateo Bridge

PERIOD OF CALIBRATION.—

MID-DEPTH SENSOR: WY 2003 (*fig. 21A*).

NEAR-BOTTOM SENSOR: WY 2003 (*fig. 21B*).

NUMBER OF DATA POINTS.—

MID-DEPTH SENSOR: 39 (16 from WY 2003).

NEAR-BOTTOM SENSOR: 32 (16 from WY 2003).

CALCULATED LINEAR CORRELATION EQUATION.—

MID-DEPTH SENSOR:  $SSC = 0.592 \times mV + 2.2$ .

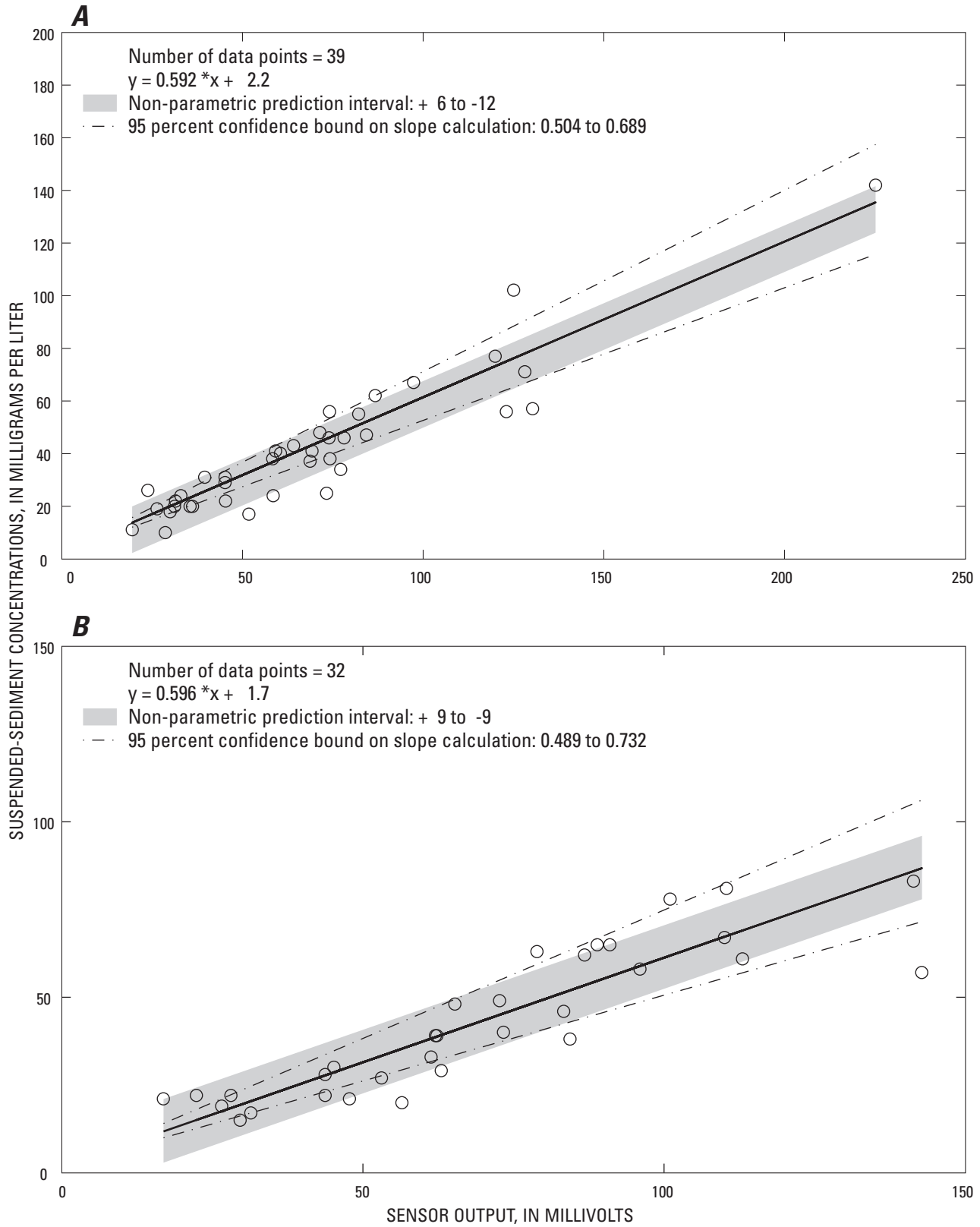
NEAR-BOTTOM SENSOR:  $SSC = 0.596 \times mV + 1.7$ .

NONPARAMETRIC PREDICTION INTERVAL.—

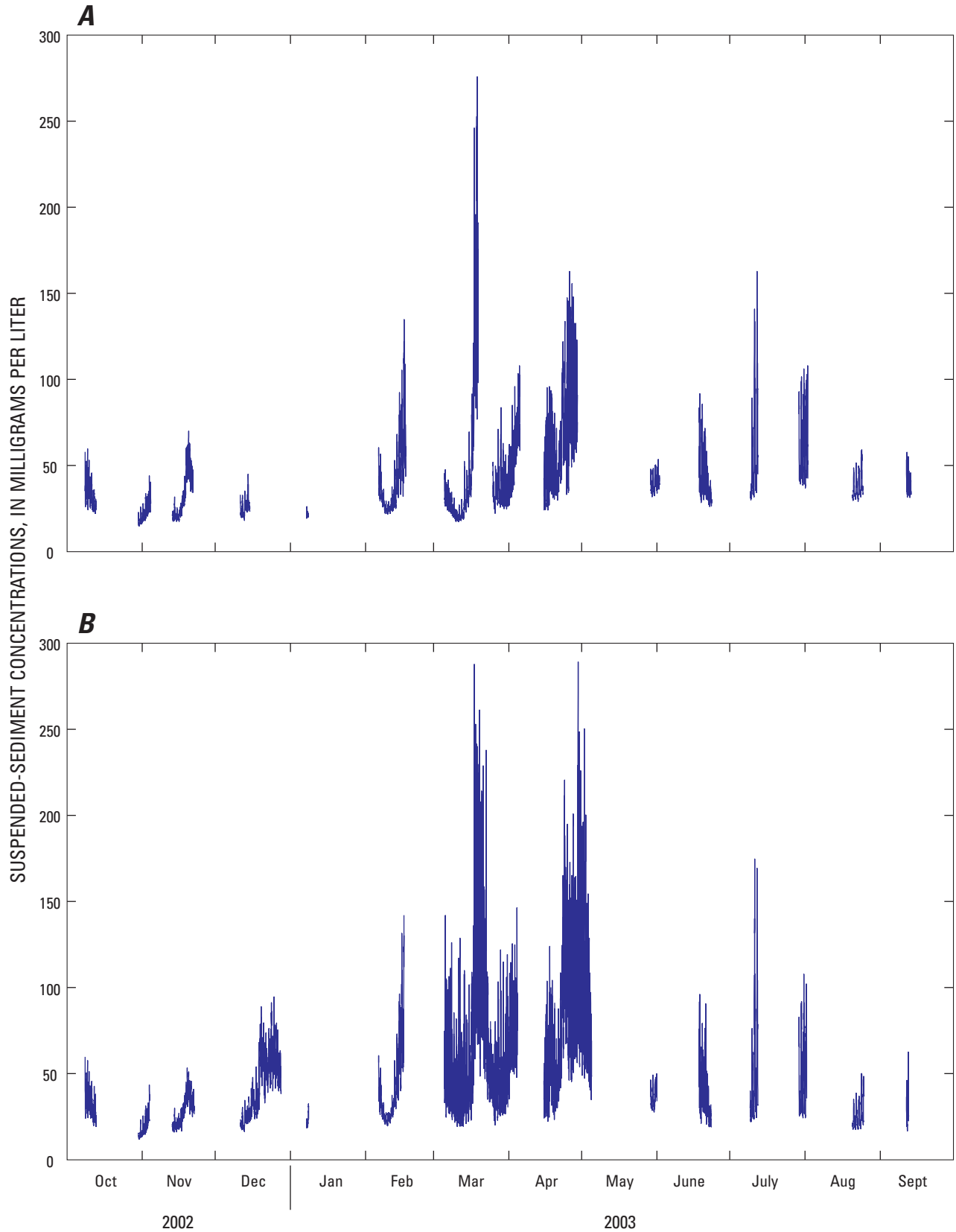
MID-DEPTH SENSOR: +6 to -12 mg/L.

NEAR-BOTTOM SENSOR: +9 to -9 mg/L.

REMARKS.—Interruptions in record were caused by fouling or malfunction of the sensing and(or) recording instruments. A +8.2-millivolt shift to the near-bottom sensor calibration, calculated from a water sample not shown on *figure 21B* (not used to develop calibration), was applied from August 20, 2003, to September 9, 2003. The calculated SSC time-series data collected during WY 2003 are presented in *figure 22*.



**Figure 21.** Calibration of (A) mid-depth and (B) near-bottom optical sensors at San Mateo Bridge, South San Francisco Bay, California, water year 2003.



**Figure 22.** Time series of (A) mid-depth and (B) near-bottom suspended-sediment concentrations calculated from sensor readings at San Mateo Bridge, South San Francisco Bay, California, water year 2003.

## Dumbarton Bridge

PERIOD OF CALIBRATION.—

MID-DEPTH SENSOR: WY 2003 (*fig. 23A*).

NEAR-BOTTOM SENSOR: WY 2003 (*fig. 23B*).

NUMBER OF DATA POINTS.—

MID-DEPTH SENSOR: 24 (14 from WY 2003).

NEAR-BOTTOM SENSOR: 79 (16 from WY 2003).

CALCULATED LINEAR CORRELATION EQUATION.—

MID-DEPTH SENSOR:  $SSC = 0.725 \times mV - 4.8$ .

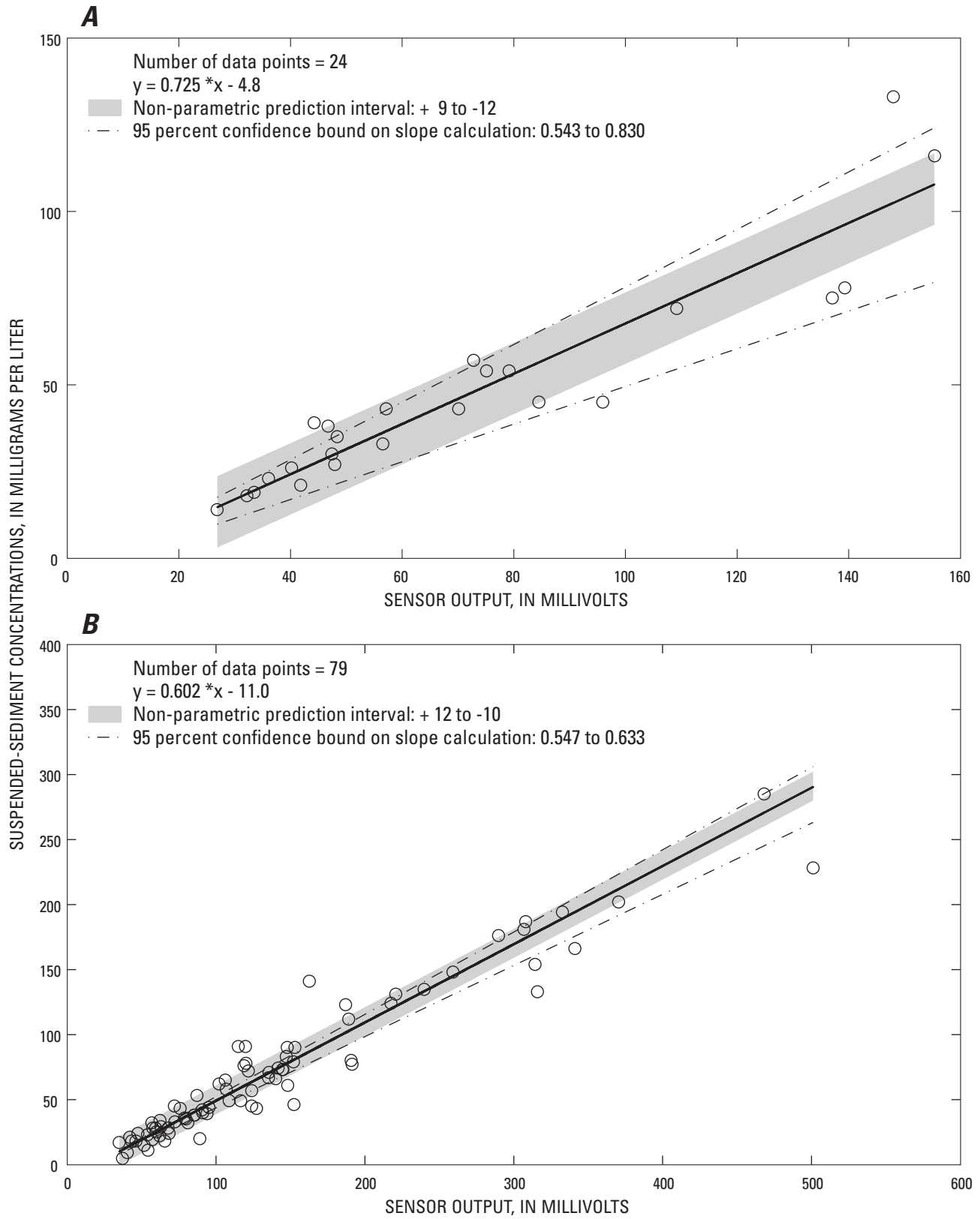
NEAR-BOTTOM SENSOR:  $SSC = 0.602 \times mV - 11.0$ .

NONPARAMETRIC PREDICTION INTERVAL.—

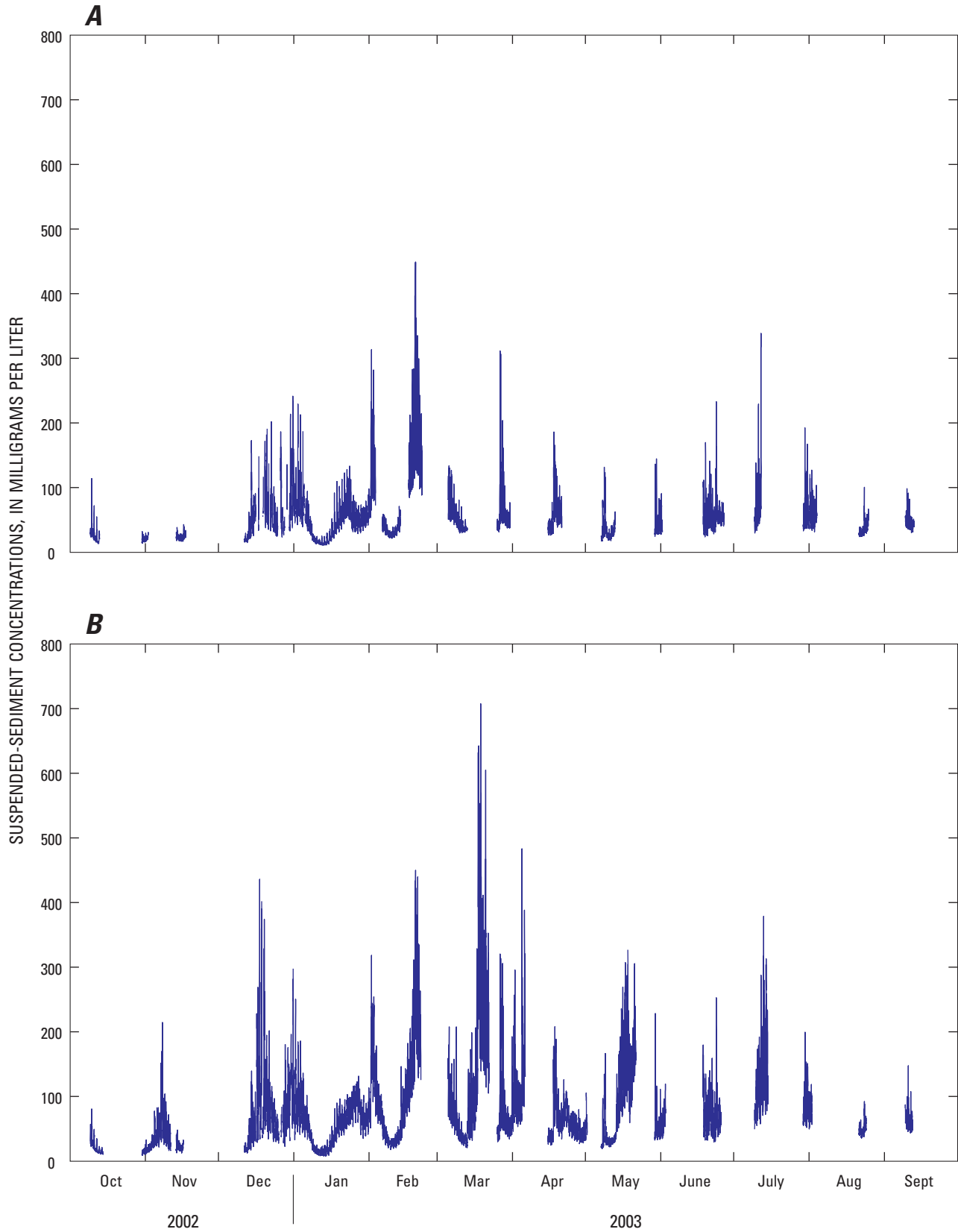
MID-DEPTH SENSOR: +9 to -12 mg/L.

NEAR-BOTTOM SENSOR: +12 to -10 mg/L.

REMARKS.—Interruptions in record were caused by fouling or malfunction of the sensing and(or) recording instruments. The calculated SSC time-series data collected during WY 2003 are presented in *figure 24*.



**Figure 23.** Calibration of (A) mid-depth and (B) near-bottom optical sensors at Dumbarton Bridge, South San Francisco Bay, California, water year 2003.



**Figure 24.** Time series of (A) mid-depth and (B) near-bottom suspended-sediment concentrations calculated from sensor readings at Dumbarton Bridge, South San Francisco Bay, California, water year 2003.

## Channel Marker 17

## PERIOD OF CALIBRATION.—

MID-DEPTH SENSOR: WY 2003 (*fig. 25A*).NEAR-BOTTOM SENSOR: WY 2003 (*fig. 25B*).

## NUMBER OF DATA POINTS.—

MID-DEPTH SENSOR: 115 (15 from WY 2003).

NEAR-BOTTOM SENSOR: 90 (16 from WY 2003).

## CALCULATED LINEAR CORRELATION EQUATION.—

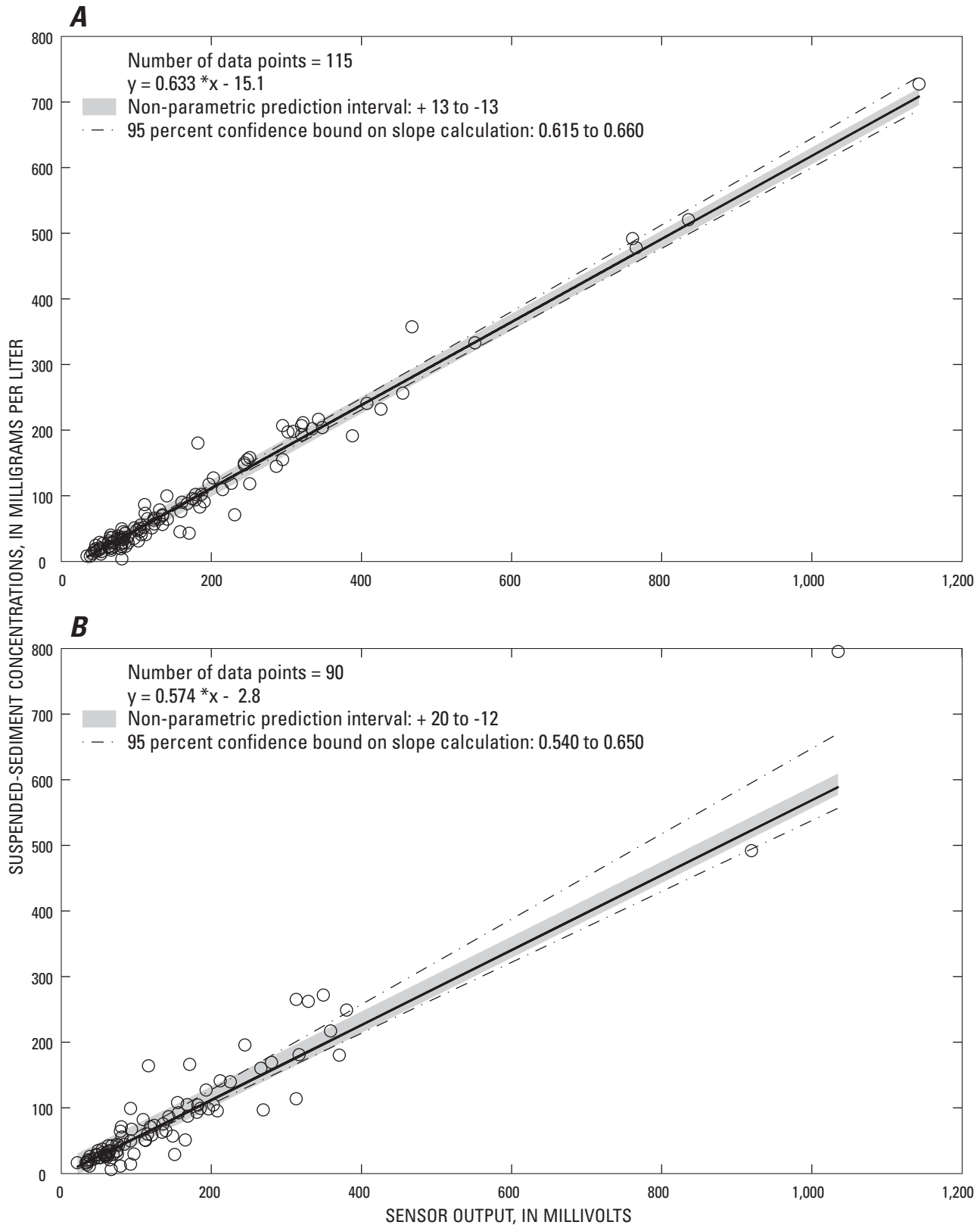
MID-DEPTH SENSOR:  $SSC = 0.633 \times mV - 15.1$ .NEAR-BOTTOM SENSOR:  $SSC = 0.574 \times mV - 2.8$ .

## NONPARAMETRIC PREDICTION INTERVAL.—

MID-DEPTH SENSOR: +13 to -13 mg/L.

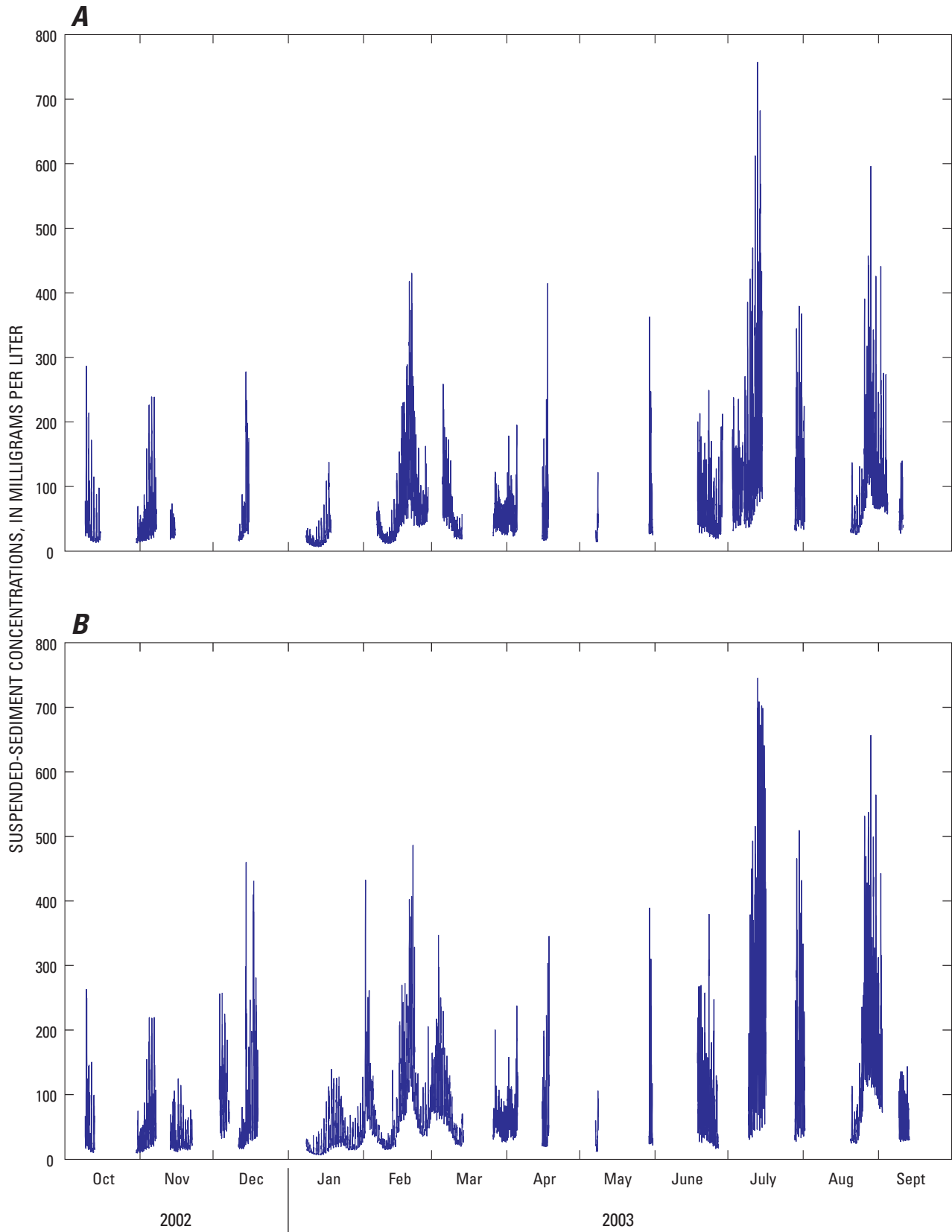
NEAR-BOTTOM SENSOR: +20 to -12 mg/L.

REMARKS.—Interruptions in record were caused by fouling or malfunction of the sensing and(or) recording instruments. The calculated SSC time-series data collected during WY 2003 are presented in *figure 26*.



**Figure 25.** Calibration of (A) mid-depth and (B) near-bottom optical sensors at Channel Marker 17, South San Francisco Bay, California, water year 2003.





**Figure 26.** Time series of (A) mid-depth and (B) near-bottom suspended-sediment concentrations calculated from sensor readings at Channel Marker 17, South San Francisco Bay, California, water year 2003.

## Summary

Suspended-sediment concentration (SSC) data were collected by the U.S. Geological Survey (USGS) at two sites in Suisun Bay, three sites in San Pablo Bay, one site in Central San Francisco Bay, and three sites in South San Francisco Bay during water year 2003. Three types of optical sensors, each controlled by electronic data loggers, were used to monitor suspended sediment. Water samples were collected to calibrate the output of the optical sensors to SSC, and the recorded data were recovered and edited. Water-sample sediment concentration data are available in the USGS sediment database. Time-series data are available in the USGS automated data-processing system database. The calculated SSC data are available from the USGS (accessed July 15, 2004).

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