Prepared in cooperation with the Houston-Galveston Area Council and
the Texas Commission on Environmental Quality under the authorization
of the Texas Clean Rivers Act and applicable Federal law

Streamflow and Water-Quality Properties in the West Fork San Jacinto River Basin and Regression Models to Estimate Real-Time Suspended-Sediment and Total Suspended-Solids Concentrations and Loads in the West Fork San Jacinto River in the Vicinity of Conroe, Texas, July 2008–August 2009

Scientific Investigations Report 2010–5171

U.S. Department of the Interior
U.S. Geological Survey

Front cover:

Top, Monitor well at station 08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Texas, Sept. 5, 2008.

Middle, Downstream view of West Fork San Jacinto River at station 08068000 West Fork San Jacinto River near Conroe, Texas, Oct. 24, 2008.

Bottom, Downstream view of West Fork San Jacinto River at station 08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Texas, Sept. 5, 2008.

Back cover:

Top, Upstream view of West Fork San Jacinto River at station 08068000, Sept. 5, 2008.

Middle, Downstream view of West Fork San Jacinto River at station 08068000, Aug. 27, 2009.

Bottom, Gage and monitor well at station 08068000, Sept. 5, 2008.

All photographs by Lee J. Bodkin, U.S. Geological Survey.

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U.S. Department of the Interior
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Conversion Factors, Datums, and Water-Quality Units

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ton per day (ton/d)	0.9072	metric ton per day

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32$$

Datums

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Vertical coordinate information is referenced to National Geodetic Vertical Datum of 1929 (NGVD 29).

Water-Quality Units

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Turbidity is given in Formazin nephelometric units (FNU).

Streamflow and Water-Quality Properties in the West Fork San Jacinto River Basin and Regression Models to Estimate Real-Time Suspended-Sediment and Total Suspended-Solids Concentrations and Loads in the West Fork San Jacinto River in the Vicinity of Conroe, Texas, July 2008–August 2009

By Lee J. Bodkin and Jeannette H. Oden

Abstract

To better understand the hydrology (streamflow and water quality) of the West Fork San Jacinto River Basin downstream from Lake Conroe near Conroe, Texas, including spatial and temporal variation in suspended-sediment (SS) and total suspended-solids (TSS) concentrations and loads, the U.S. Geological Survey, in cooperation with the Houston-Galveston Area Council and the Texas Commission on Environmental Quality, measured streamflow and collected continuous and discrete water-quality data during July 2008–August 2009 in the West Fork San Jacinto River Basin downstream from Lake Conroe.

During July 2008–August 2009, discrete samples were collected and streamflow measurements were made over the range of flow conditions at two streamflow-gaging stations on the West Fork San Jacinto River: West Fork San Jacinto River below Lake Conroe near Conroe, Texas (station 08067650) and West Fork San Jacinto River near Conroe, Texas (station 08068000). In addition to samples collected at these two main monitoring sites, discrete sediment samples were also collected at five additional monitoring sites to help characterize water quality in the West Fork San Jacinto River Basin. Discrete samples were collected semimonthly, regardless of flow conditions, and during periods of high flow resulting from storms or releases from Lake Conroe. Because the period of data collection was relatively short (14 months) and low flow was prevalent during much of the study, relatively few samples collected were representative of the middle and upper ranges of historical daily mean streamflows.

The largest streamflows tended to occur in response to large rainfall events and generally were associated with the largest SS and TSS concentrations. The maximum SS and TSS concentrations at station 08067650 (180 and 133 milligrams per liter [mg/L], respectively) were on April 19, 2009, when the instantaneous streamflow was the third largest associated with a discrete sample at the station. SS concentrations were 25 mg/L or less in 26 of 29 environmental samples and TSS concentrations were 25 mg/L or less in 25 of 28 environmental samples. Median SS and TSS concentrations were 7.0 and 7.6 mg/L, respectively. At station 08068000, the maximum SS concentration (1,270 mg/L) was on April 19, 2009, and the maximum TSS concentration (268 mg/L) was on September 18, 2008. SS concentrations were 25 mg/L or less in 16 of 27 of environmental samples and TSS concentrations were 25 mg/L or less in 18 of 26 environmental samples at the station. Median SS and TSS concentrations were 18.0 and 14.0 mg/L, respectively.

The maximum SS and TSS concentrations for all five additional monitoring sites were 3,110 and 390 mg/L, respectively, and the minimum SS and TSS concentrations were 5.0 and 1.0 mg/L, respectively. Median concentrations ranged from 14.0 to 54.0 mg/L for SS and from 11.0 to 14.0 mg/L for TSS.

Continuous measurements of streamflow and selected water-quality properties at stations 08067650 and 08068000 were evaluated as possible variables in regression equations developed to estimate SS and TSS concentrations and loads. Surrogate regression equations were developed to estimate SS and TSS loads by using real-time turbidity and streamflow data; turbidity and streamflow resulted in the best regression models for estimating near real-time SS and TSS concentrations for stations 08097650 and 08068000.

Relatively large errors are associated with the regression-computed SS and TSS concentrations; the 90-percent prediction intervals for SS and TSS concentrations were ±48.9 and ±43.2 percent, respectively, for station 08067650 and ±47.7 and ±43.2 percent, respectively, for station 08068000. Regression-computed SS and TSS concentrations were

corrected for bias before being used to compute SS and TSS loads. The total estimated SS and TSS loads during July 2008–August 2009 were about 3,540 and 1,900 tons, respectively, at station 08067650 and about 156,000 and 72,000 tons, respectively, at station 08068000. Because the estimated SS and TSS concentrations derived from the regression equations contained large error components, the computed load estimates are inferred to also include large errors. Loads were about 40 times larger at station 08068000 compared with loads at station 08067650, likely because flow at station 08067650 (2.5 miles downstream from Lake Conroe) is more representative of water-quality properties of releases from Lake Conroe, whereas flow at station 08068000 (11 miles downstream from station 08067650) is more representative of water-quality properties in the West Fork San Jacinto River.

Introduction

Water-supply and water-quality concerns have increased the need to better understand the hydrology of the West Fork San Jacinto River Basin, Tex. (fig. 1), particularly the spatial and temporal variability of suspended-sediment (SS) and total suspended-solids (TSS) concentrations and loads in relation to streamflow, and other water-quality properties. Surficial mining of sand and gravel and the rapidly growing population of Montgomery County, Tex., where much of the West Fork San Jacinto River and its tributaries are located, have increased concerns among water managers about the effects of mining and urbanization on water supply and water quality in the West Fork San Jacinto River Basin.

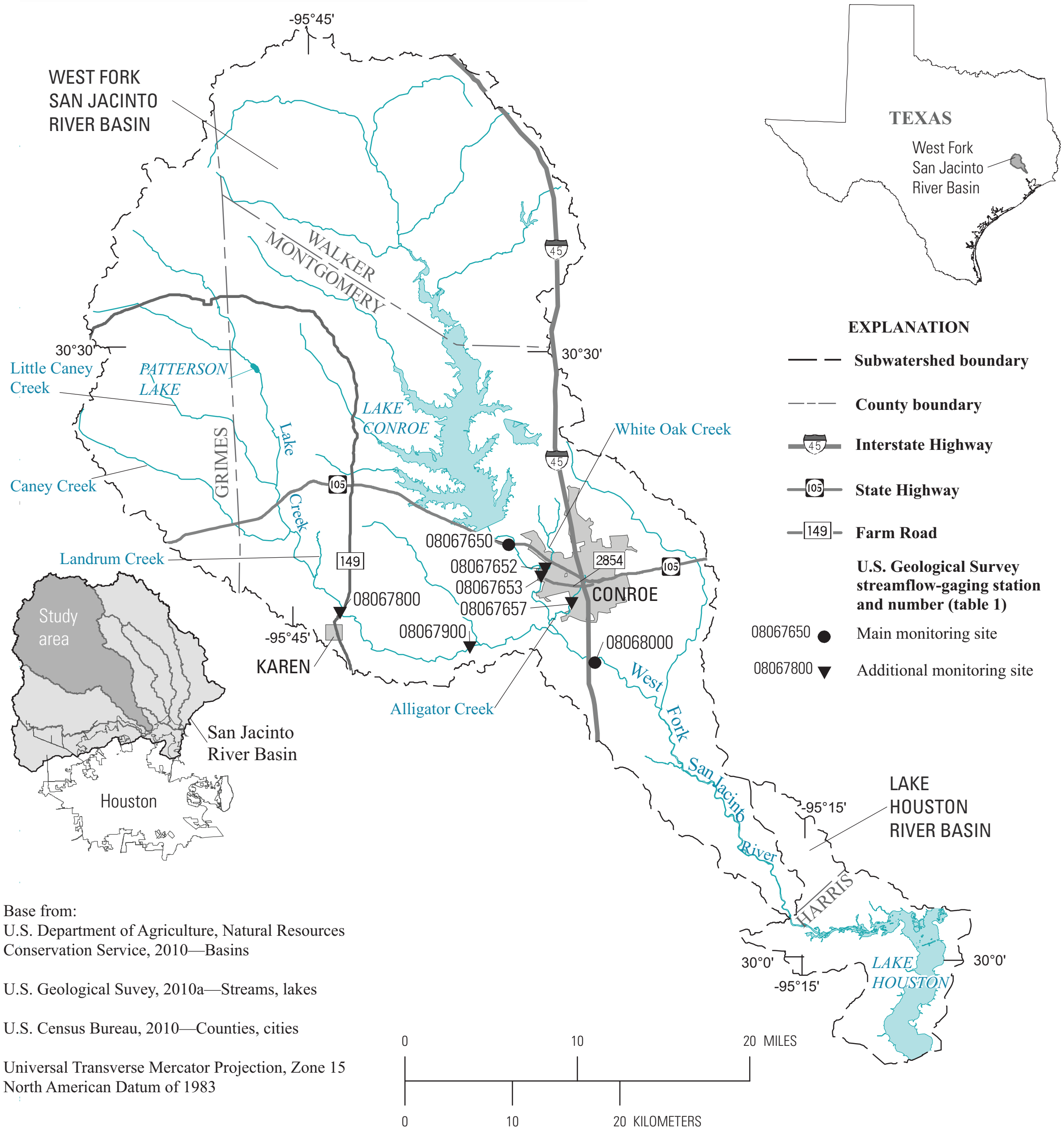
The Texas Commission on Environmental Quality (TCEQ) administers water-quality management programs with the goal of protecting, maintaining, and restoring water resources in Texas (Texas Commission on Environmental Quality, 2010). One such program is the Texas Clean Rivers Program (CRP), which was established by the 1991 Texas Legislature (Texas Administrative Code, 2007). Under the CRP, water-quality monitoring and assessments in 23 river and coastal basins statewide are done by partner agencies. The Houston-Galveston Area Council (H–GAC) is TCEQ's partner agency for a 13-county service area in southeastern Texas that includes the Houston metropolitan area (fig. 1). Every 2 years, CRP partners collect water-quality data from water bodies that are not monitored routinely. Data from these special studies help determine whether additional assessment is needed to evaluate human health concerns, status of ecological conditions, or designated stream uses.

Measurements of SS and TSS concentrations, as well as certain water-quality properties such as turbidity, can be used to evaluate SS and TSS loads if sufficient measurements are made characterizing the range of hydrologic conditions for sufficient time. As explained by Oden and others (2009, p. 21), "Turbidity is inversely proportional to transparency depth and is a measure of the scattering of light (American Society for Testing and Materials, 2003). Thus, a decrease in the amount of transparency in water seems appropriate as a possible indicator for an increase in the amount of SS in the water." To better understand the hydrology (streamflow and water quality) in the West Fork San Jacinto River Basin, the U.S. Geological Survey (USGS), in cooperation with H–GAC and TCEQ, measured streamflow (discharge) and collected continuous and discrete water-quality data during the period July 2008–August 2009 at monitoring sites in the West Fork San Jacinto River Basin downstream from Lake Conroe (fig. 1). Samples for SS and TSS analysis were collected during the study to characterize SS and TSS concentrations and loads in the West Fork San Jacinto River Basin, as well as to document differences in loads obtained by using either SS or TSS data in the West Fork San Jacinto River at two USGS streamflow-gaging stations (table 1) downstream from Lake Conroe.

Previous USGS studies have shown that when TSS concentrations are used to estimate SS loads, the results are often biased low compared with loads estimated by using SS concentrations, particularly if sand constitutes more than about 20 percent of the mass of the water-sediment mixture. The TSS analytical method tends to produce data that are negatively biased by 25 to 34 percent with respect to SS concentrations in samples collected at the same time (U.S. Geological Survey, 2000b). Differences between load estimates derived from SS and TSS data can also vary greatly at a given site depending on streamflow (Gray and others, 2000; Glysson, Gray, and Conge, 2000; Glysson, Gray, and Schwarz, 2001; U.S. Geological Survey, 2000a). However, in some basins where sediment loads include only small amounts of sand, TSS concentrations can sometimes be used effectively to characterize sediment loads. In such basins, the similarity of SS and TSS concentrations over the range of expected flows at a given site needs to be well documented (U.S. Geological Survey, 2000a). Surrogate relations and load estimates were derived for both SS and TSS data; differences between loads obtained by using either SS or TSS data are depicted, but an evaluation of the effectiveness of using TSS data to characterize sediment loads in the study basin was beyond the scope of this study.

Purpose and Scope

This report describes streamflow and water-quality properties for July 2008–August 2009 in the West Fork San Jacinto River Basin downstream from Lake Conroe and documents the regression models developed to estimate SS and TSS concentrations and loads at two USGS streamflow-gaging stations on the main stem of the West Fork San Jacinto River. Continuous monitors measured selected water-quality properties (water temperature, specific conductance, pH, dissolved oxygen, and turbidity) at stations 08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Tex., located at the State Highway 105 bridge (hereinafter station



Base from:
U.S. Department of Agriculture, Natural Resources Conservation Service, 2010—Basins

U.S. Geological Suvey, 2010a—Streams, lakes

U.S. Census Bureau, 2010—Counties, cities

Universal Transverse Mercator Projection, Zone 15
North American Datum of 1983

Figure 1. Location of monitoring sites in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009.

08067650) and 08068000 West Fork San Jacinto River near Conroe, Tex., located at the Interstate Highway 45 bridge (hereinafter station 08068000). Water-quality properties were characterized in a preliminary manner by using summary statistics of water-quality data from stations 08067650 and 08068000 and from five additional monitoring sites on tributaries to the West Fork San Jacinto River downstream from Lake Conroe. Periodic streamflow measurements were made and discrete water-quality samples were collected semimonthly during July 2008–August 2009 for selected water-quality properties and constituents (SS, TSS, water temperature, specific conductance, pH, dissolved oxygen, and turbidity) at stations 08067650 and 08068000 and the five additional monitoring sites. Techniques used to collect and analyze these samples are documented.

Description of Study Area

The headwaters of the West Fork San Jacinto River originate in Walker County, Tex. (fig. 1). The drainage area of the West Fork San Jacinto River is 990 square miles (mi^2). Lake

Table 1. Description of monitoring sites in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009.

[M, main site; n/a, not applicable, --, data not available; A, additional site; FM, Farm Road]

U.S. Geological Survey station name	U.S. Geological station number (fig. 1)	Texas Commission on Environmental Quality station number	Latitude (degrees minutes seconds)	Longitude (degrees minutes seconds)	Date monitoring established		Drainage area (square miles)	Sampling site designation
					Discharge	Water quality		
West Fork San Jacinto River below Lake Conroe near Conroe, Tex.	08067650	11251	30°20'31.09"	95°32'33.50"	August 1972	July 2008	451	M
West Fork San Jacinto River near Conroe, Tex.	08068000	11245	30°14'43.11"	95°27'27.83"	July 1939	July 2008	828	M
White Oak Creek at Memorial Drive, Conroe, Tex.	08067652	20731	30°19'17.48"	95°30'28.09"	n/a		--	A
West Fork San Jacinto River at FM 2854 near Conroe, Tex.	08067653	11250	30°18'52.67"	95°30'41.18"	n/a		--	A
Alligator Creek at Sergeant Ed Holcomb Road, Conroe, Tex.	08067657	20732	30°17'35.11"	95°28'52.59"	n/a		--	A
Lake Creek at FM 149 near Karen, Tex.	08067800	18191	30°16'49.26"	95°42'20.17"	n/a		--	A
Lake Creek near Conroe, Tex.	08067900	11367	30°15'13.59"	95°34'44.38"	n/a		--	A

Creek is a major tributary to the West Fork San Jacinto River and Lake Creek tributaries include Landrum Creek, Caney Creek, and Little Caney Creek. White Oak and Alligator Creeks also are tributaries to the West Fork San Jacinto River. The drainage area of the West Fork San Jacinto River is 451 mi^2 at station 08067650 and 828 mi^2 at station 08068000.

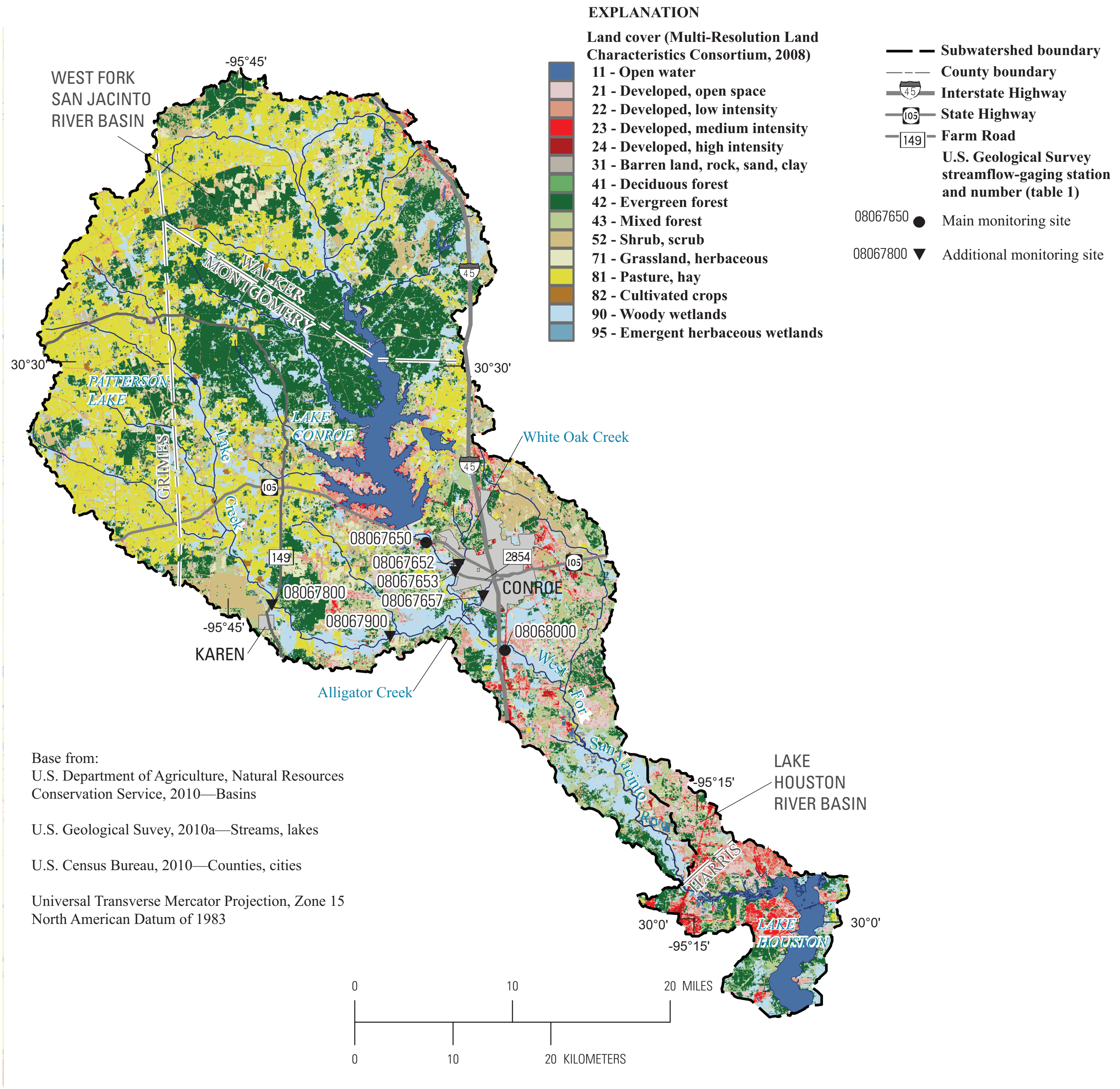
The West Fork San Jacinto River provides much of the inflow to Lake Conroe, a reservoir impounded in 1973 to help meet municipal water-supply needs of Houston (Villalon and others, 1998). The normal operating level of Lake Conroe is 201 feet (ft) above the National Geodetic Vertical Datum of 1929, corresponding to a storage volume of 430,300 acre-feet (acre-ft) (U.S. Geological Survey, 2010b). Downstream from Lake Conroe, the West Fork San Jacinto River flows through Montgomery County and a small part of Harris County before becoming one of several streams impounded by Lake Houston, a reservoir impounded in 1954 and another municipal water-supply reservoir for Houston (Villalon and others, 1998). The maximum design elevation of 44.5 ft for Lake Houston corresponds to a capacity of 133,990 acre-ft (U.S. Geological Survey, 2010b).

The northern part of the West Fork San Jacinto River Basin is a gently rolling area, most of which is heavily timbered. The southern part of the basin is mostly prairie (Hughes and Rawson, 1966). Broad, shallow stream valleys (along with remnants of older, abandoned stream valleys) cut through the study area. Pine, oak, and other trees grow along the banks of streams throughout the study area. Land cover in the West Fork San Jacinto River Basin includes municipal, commercial, agricultural, forested, and residential areas. Land cover downstream from Lake Conroe is predominately a woody wetland with some hay pastures and mixed forest (fig. 2). Conroe and other towns and cities in the basin consist of a mix of land covers from open space to high-intensity developments, such as apartments. Population density ranges from 44 to 549 people per square mile (U.S. Census Bureau, 2000). Land-surface elevation in the basin ranges from about 381 ft at the headwaters to 43 ft at Lake Houston.

The climate of the study area is humid subtropical (Larkin and Bomar, 1983) and is characterized by high relative humidity, long hot summers, and short temperate winters. Monthly rainfall in 7 of the 14 months of the study (July 2008–August 2009) was less than the mean monthly rainfall recorded at National Weather Service station 411956 in Conroe (fig. 3). Although total rainfall at Conroe during the 14-month study period was 60.23 inches (in.) compared with the long-term (1983–2009) average of 56.27 in., 19.27 of the 60.23 in. of rainfall fell in 2 months—September 2008 and April 2009 (fig. 3). The maximum monthly total was 10.13 in. for September 2008, and the minimum monthly total was 0.33 in. for June 2009 (National Climatic Data Center, 2008 and 2009).

Data-Collection and Regression Methods

Except as otherwise noted, all data collection followed surface-water quality monitoring (SWQM) procedures for



Base from:
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U.S. Geological Suvey, 2010a—Streams, lakes

U.S. Census Bureau, 2010—Counties, cities

Universal Transverse Mercator Projection, Zone 15
North American Datum of 1983

Figure 2. Land use in the San Jacinto River Basin, Texas, July 2008–August 2009.

water and sediment (Texas Commission on Environmental Quality, 2008; chapters 2, 3, 5, 8, and 10). These procedures are further described in the quality-assurance project plan (QAPP) developed for the study (Jean Wright, Houston-Galveston Area Council, written commun., 2008).

Streamflow Measurements

Streamflow measurements were made periodically in conjunction with the collection of discrete water-quality samples following standard USGS methods (Rantz and others, 1982). During July 2008–August 2009, six streamflow measurements were made at each of the two main monitoring sites (stations 08067650 and 08068000). Water-surface elevation (stage) referenced to the gage datum was also measured continuously at the stations by using a noncontact radar stage sensor (Blanchard, 2007) mounted at station 08068000 and a submersible pressure transducer (Freeman and others, 2004) at station 08067650. Stage was recorded to the nearest 0.01 ft every 15 minutes, and data were transmitted every

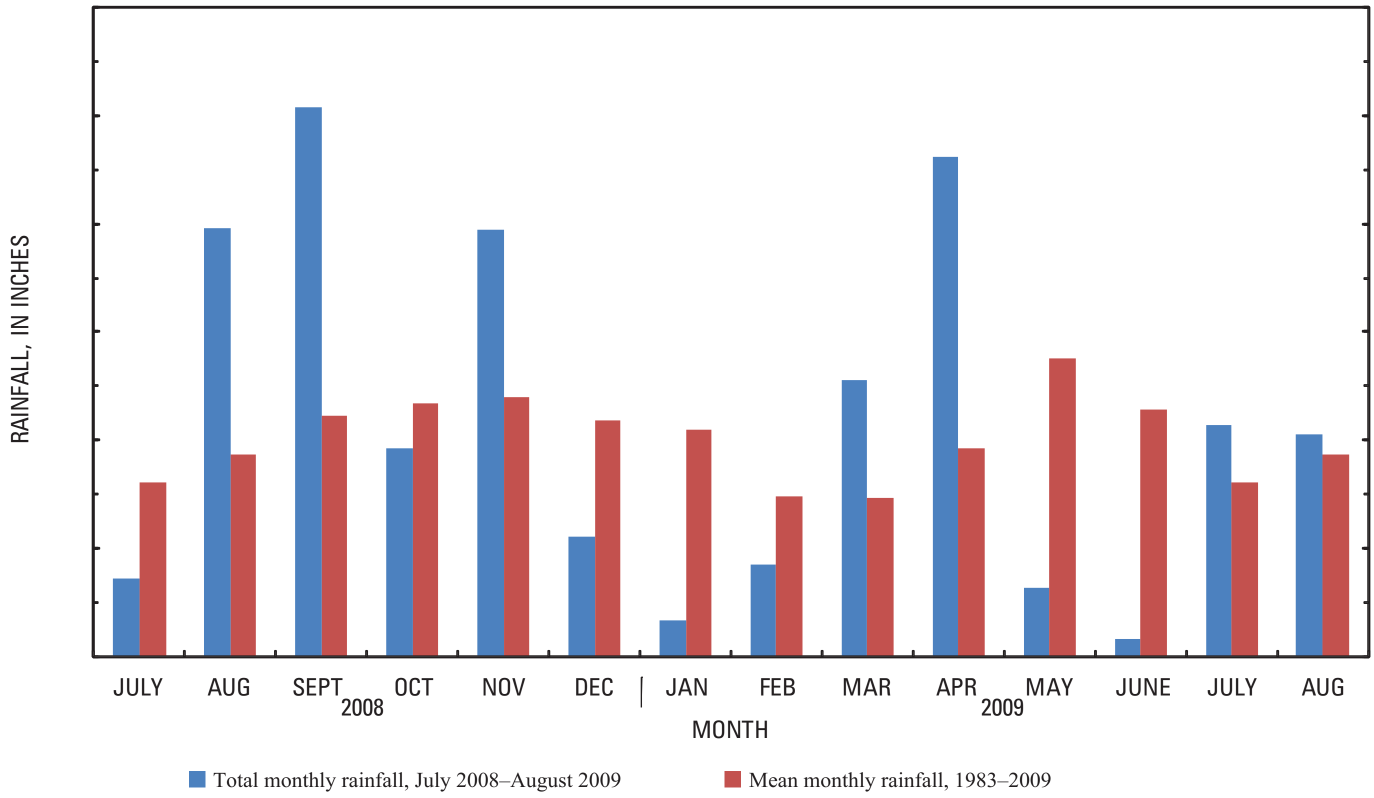


Figure 3. Total monthly rainfall (July 2008–August 2009) and mean monthly rainfall (1983–2009) at National Weather Service station 411956 in Conroe, Texas.

4 hours by the Geostationary Operational-Environmental Satellite (GOES) to the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2010b).

Stage-discharge relations developed on the basis of periodic streamflow measurements were used to compute a continuous record of streamflow at stations 0806750 and 08068000 (Kennedy, 1983, 1984). The stage also was measured to determine instantaneous streamflow at the time each discrete water-quality sample was collected. All real-time streamflow (discharge) values met USGS accuracy standards (Rantz and others, 1982). The stage-discharge relation at station 08067650 typically is maintained for streamflow of more than 10 cubic feet per second (ft^3/s). For the study period, additional low-flow measurements (less than10 ft^3/s) were made to extend the stage-discharge relation to include streamflow between 0 and 10 ft^3/s.

In addition to six streamflow measurements at stations 08067650 and 08068000, three to eight streamflow measurements were made at each of the five additional monitoring sites in conjunction with the collection of water-quality samples. When the stream was relatively shallow (water depths less than 3 ft), streamflow measurements were made while wading by using a Sontek/YSI rod-mounted acoustic-velocity meter. Tethered acoustic Doppler current profilers were used to measure streamflow that was too deep to wade by using methods described in Oberg and others (2005).

Continuous Measurements of Water-Quality Properties

Continuous measurements of selected water-quality properties (water temperature, specific conductance, pH, dissolved oxygen, and turbidity) were made at stations 08067650 and 08068000 for evaluation as possible variables in development of regression equations to estimate SS and TSS concentrations and loads. Continuous water-quality properties were measured every 15 minutes by using a Sontek/YSI 6920 V2–2 multiprobe water-quality sonde, and data were transmitted every 4 hours by GOES to the NWIS database (U.S. Geological Survey, 2010b) The water-quality monitors were calibrated and the data were processed following methods in the SWQM procedures (Texas Commission on Environmental Quality, 2008; chapter 8). Field procedures, calibration of the continuous water-quality monitors, and record computation and review methods also followed Wagner and others (2006) and are further outlined in the QAPP (Jean Wright, Houston-Galveston Area Council, written commun., 2008). The turbidity sensor was calibrated following USGS guidelines (Wagner and others, 2006; U.S. Geological Survey, variously dated) and further outlined in the QAPP because the SWQM procedures do not include a discussion on turbidity sensors. Before being deployed, each monitor was calibrated at the USGS Texas Water Science Center, Gulf Coast Program Office laboratory in The Woodlands, Tex. Four water-quality monitors were used during the study, with two deployed at any given time—one at station 08067650 and one at station 08068000. Each water-quality monitor was deployed for about 14 days and then replaced with one that had been recalibrated; this rapid replacement cycle helped maintain a continuous record of calibrated water-quality data and eliminated potential problems associated with biofouling (Wagner and others, 2006). Post calibration was done after the water-quality monitor was retrieved from the field to determine if the instrument readings had changed compared with the initial calibration. If any selected water-quality property exceeded a set guideline in the SWQM procedures (Texas Commission on Environmental Quality, 2008; chapter 8), the data for that property were invalidated for the deployment period. All real-time water-quality properties used to compute the load estimates met the accuracy requirements specified in the QAPP.

The water-quality monitors were installed differently at stations 08067650 and 08068000. The water-quality monitor at station 08067650 was installed using a swinging flow-through well constructed of schedule 80 polyvinyl chloride (PVC) pipe with holes in the bottom 3 ft, allowing water to pass through the well. The well was hung from the State Highway 105 bridge at station 08067650 by a heavy-duty chain to facilitate movement during larger streamflows, minimizing the likelihood of damage caused by channel debris and maximizing the likelihood of the monitor remaining near the centroid of flow. Similar to the installation at station 08067650, the water-quality monitor at station 08068000 also was installed in a flow-through well of PVC pipe with holes in the bottom 3 ft. Unlike the swinging-well design at station 08067650, a fix-mounted design was used at station 08068000. Because of the height of the bridge at station 08068000, a swinging-well design could not safely be implemented; the well containing the monitor was mounted on a bridge pier in the deepest part of the channel where streamflow velocity was likely largest. Periodically throughout the study period, water-quality properties (water temperature, specific conductance, pH, dissolved oxygen, and turbidity) were measured across the entire channel, by using one of the spare monitors, to verify that the streamflow was well mixed and that the installed monitors were providing water-quality data representative of the flow at each gage. On average, water-quality properties measured across the channel by using the spare monitor varied by 5 percent or less compared with water-quality properties measured continuously by the monitors installed at stations 08067650 and 08068000.

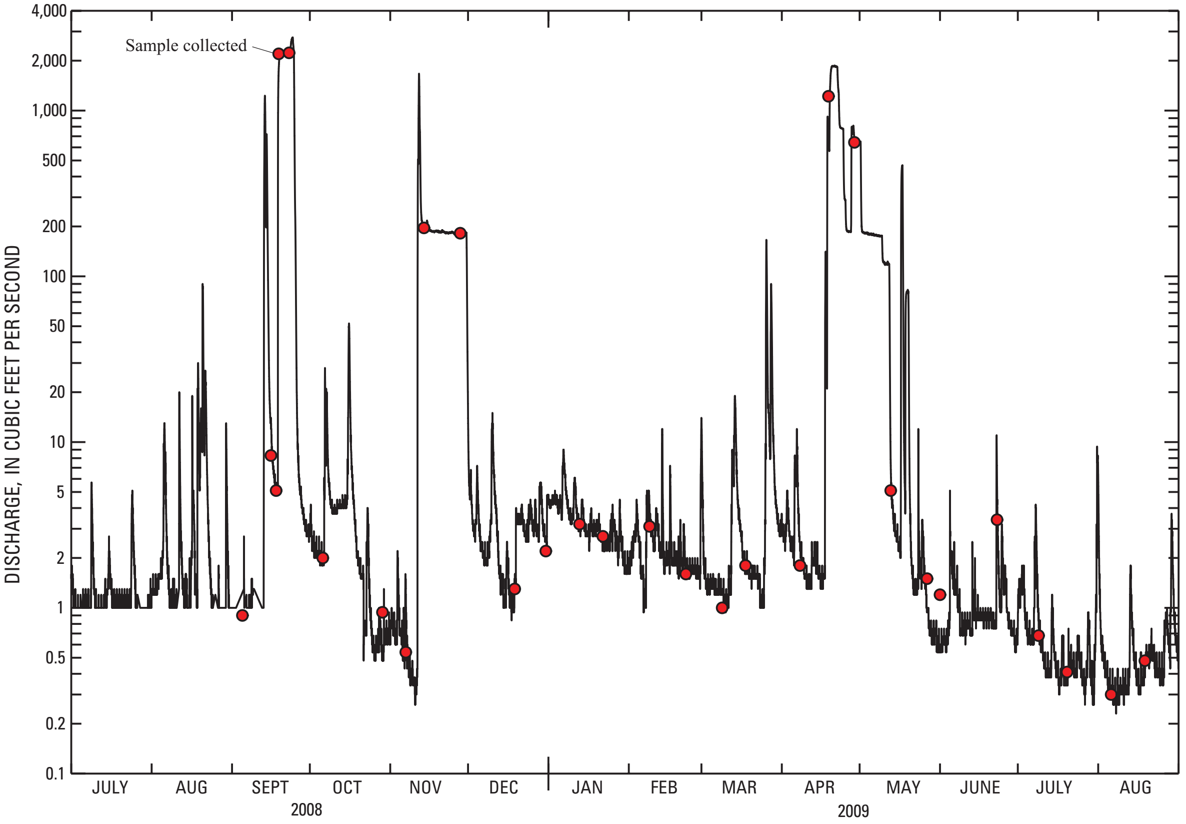
Discrete Water-Quality Sampling

Water-quality samples were periodically collected at each station following guidelines in the USGS "National Field Manual for the Collection of Water-Quality Data" (U.S. Geological Survey, variously dated). During July 2008–August 2009, 29 and 27 discrete samples were collected at stations 08067650 and 08068000, respectively, and analyzed for SS, TSS, and selected water-quality properties (water temperature, specific conductance, pH, dissolved oxygen, and turbidity). At each station, some discrete samples were collected semimonthly without regard to hydrologic conditions, whereas other samples were collected during periods of high flow resulting from storms or releases from Lake Conroe (fig. 4). At each of the five additional monitoring sites, routine samples were collected five times throughout the study period as well as one to three samples during periods of high flow resulting from storms.

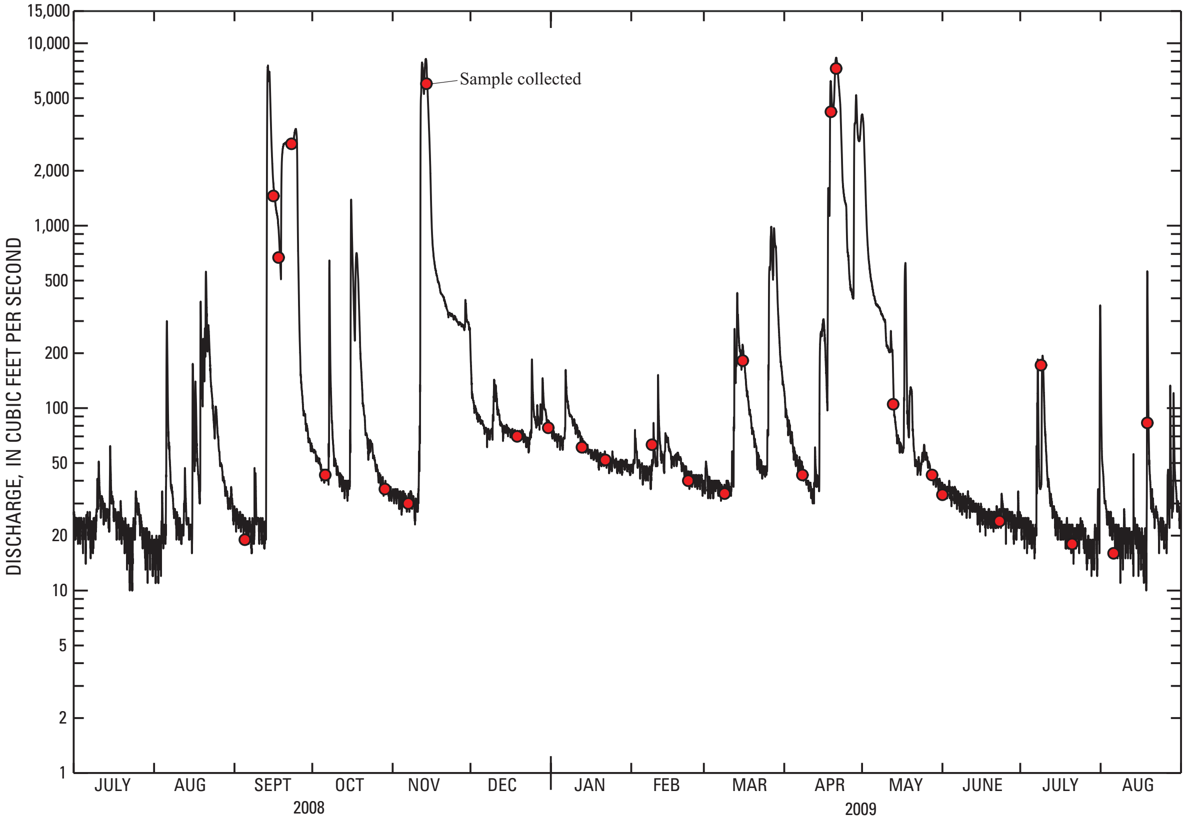
Discrete water-quality samples were collected by either the equal-width increment (EWI) or the grab sampling method. When streamflow was sufficient, EWI samples were collected by dividing the river into five or more equal-width sampling increments. By ensuring the volume of the overall sample is proportional to the amount of discharge in each equal-width sampling increment, an isokinetic depth-integrated sample is collected (U.S. Geological Survey, variously dated). EWI samples were collected when conditions permitted, either while wading the stream or from a bridge. When streamflow was not sufficient to use the EWI method, grab samples were collected from the centroid of flow by using methods described in the SWQM procedures (Texas Commission on Environmental Quality, 2008; chapter 5). When EWI samples were collected, the selected water-quality properties were measured in each EWI to determine uniformity of water-quality properties across the stream channel. The same water-quality properties measured in each increment of flow for the EWI samples were measured at the centroid of flow for grab samples.

Samples representing each vertical for the EWI method (or the sample representing the single vertical for the grab method) were poured into a plastic churn, mixed, and dispensed into sample bottles. Environmental and replicate samples were dispensed from the churn. The resulting composite water-sediment samples were horizontally and vertically averaged throughout the stream cross section and are assumed to represent the average streamflow-weighted SS concentration (Edwards and Glysson, 1999; U.S. Geological Survey, 2006a). Samples for SS analysis were shipped to the USGS Kentucky Water Science Center Sediment Laboratory in Louisville, Ky., for the analysis of SS concentration and sand/fine separation; samples for TSS analysis were shipped to the Eastex Environmental Laboratory in Coldspring, Tex.

During the study, three different wading cross sections were used for collecting samples at station 08068000. Before November 2008, the original cross section where samples were collected was 10 ft downstream from the water-quality monitor. After the channel was scoured during a period of high flow in November 2008, the wading cross section was relocated 800 ft downstream from the water-quality monitor



A. 08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Texas



B. 08068000 West Fork San Jacinto River near Conroe, Texas

Figure 4. Hydrographs showing streamflow and sample collection at station (A) 08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Texas, and (B) 08068000 West Fork San Jacinto River near Conroe, Texas, July 2008–August 2009.

because flow in the cross section near the monitor was too deep to wade. The original cross section was still sampled during high-flow conditions from the bridge by using a crane, four-wheel base, and appropriate sampler (U.S. Geological Survey, variously dated). During August–November 2008, eight samples were collected by wading or from the bridge at the original station 08068000 cross section near the water-quality monitor. During December 2008–February 2009, five samples were collected by wading at the cross section 800 ft downstream from the water-quality monitor. In January 2009, H–GAC employees accompanied USGS employees on a field trip to the sites to observe the collection of discrete water-quality samples, measurement of streamflow, and maintenance of the monitors. The H–GAC employees noted that debris deposited on the piers of a railroad bridge between the original sampling cross section and the new sampling cross section had created a pool of backwater in the stream and were concerned that the backwater was potentially creating a settling pool for SS. Because the water-quality monitor was upstream from this possible settling pool, there was concern that the continuous water-quality readings measured by the monitor might not be representative of water quality downstream from the pool; between December 2008 and February 2009, all wading samples were collected downstream from the pool at the new sampling cross section. To eliminate any possible effects of the pool on SS concentration, a third sampling cross section was selected about 2,000 ft upstream from the water-quality monitor in a reach where there were no channel controls, debris piles, or inflows. During February–August 2009, 14 samples were collected at station 08068000 while wading the cross section 2,000 ft upstream from the water-quality monitor. Because a comparison of turbidity readings measured upstream and downstream from the potential settling pool did not indicate any appreciable differences, all sample results were included in the development of regression equations to estimate SS and TSS concentrations and loads.

Because only 14 months of data were collected, all results of this study are considered preliminary. It is preferred that monthly samples be collected for at least 24 to 36 months to obtain a dataset more representative of the typical range of hydrologic conditions; data typical of the range of hydrologic conditions facilitate accurate calibration of regression models used to predict water-quality properties. Although the sample total is relevant, the distribution of the data over the range of observed SS, turbidity, and streamflow values for a site is of paramount importance (Rasmussen and others, 2009). The turbidity data (table 2) were well distributed over the range of streamflow during the study period (figs. 4A and 4B), but relatively dry conditions during much of the study resulted in a smaller range of flow compared with that typically observed in the West Fork San Jacinto River, particularly during periods of 2 or more years.

Although 14 months is not sufficient to establish an accurate surrogate relation to estimate SS and TSS loads by using continuously monitored water-quality properties and streamflow (Rasmussen and others, 2009), all relatively large streamflow events that did occur during the study period were sampled. The range of streamflow during the study was well characterized by the samples collected (figs. 4A and 4B).

Analytical Methods

Sediment samples were analyzed for SS concentration and sand/fine separation. The samples were analyzed in accordance with standard protocols established by the USGS (Guy, 1969) and American Society for Testing and Materials (2007).

Lietz and Debiak (2006) describes in detail the methods used for the analysis of fluvial sediment concentrations and sand/fine separation and states that (p. 9), “Sand/fine separations were used to determine the amount of material that was larger or smaller than sand size. The term ‘fine’ refers to material that passes through a 0.0625-millimeter (0.0024-in.) mesh sieve, and ‘sand’ refers to particles that are retained on the sieve.” Sample holding time and analytical procedures followed protocols established by Shreve and Downs (2005).

Eastex Environmental Laboratories analyzed samples for TSS concentrations; Eastex Environmental Laboratory was accredited by the National Environmental Laboratory Accreditation Conference to analyze samples for TSS by method 2540D during July 2008–August 2009 (Daniel Bowen, Eastex Environmental Laboratory, Coldspring, Tex., written commun., 2009). Method 2540D is described by the American Public Health Association (2005).

Quality Assurance

Quality-assurance (QA) requirements for sample collection, data management, and documentation described by the SWQM procedures (Texas Commission on Environmental Quality, 2008; chapter 10) were followed; QA requirements also were included in the study QAPP (Jean Wright, Houston-Galveston Area Council, written commun., 2008). Quality-control samples included 14 replicate samples; about 25 percent of all samples were replicates (table 2).

Replicate SS and TSS samples were collected and analyzed to determine the precision of the results. The replicate samples were collected by splitting a water sample mixed in a single container (plastic churn splitter) into two bottles, one representing the environmental sample and one the replicate sample. The replicate sample is also referred to as a field split by TCEQ (Texas Commission on Environmental Quality, 2008). The samples were split immediately after collection from the stream using the churn splitter and then shipped to the laboratory as separate samples. The identities of the environmental and replicate samples were not revealed to the laboratory. The relative percent difference (RPD) was determined for each set of split samples as a measure of variability. Replicate samples were compared with associated

Table 2. Water-quality data in samples from two main monitoring sites (stations 08067650 and 08068000) in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009.

[ft^3/s, cubic feet per second; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; FNU, Formazin nephelometric units; >, greater than; mm, millimeter; ER, environmental routine; --, sample not collected; EE, environmental event; *SR*, split replicate]

Station name	Date	Time	Sample type	Discharge (ft^3/s)	Water temperature (°C)	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen concentration (mg/L)	Turbidity (FNU)[1]	Suspended-sediment concentration (mg/L)	Total suspended-solids concentration (mg/L)	Sand/fine separation (percent >0.0625 mm)
08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Tex.	9/5/2008	1335	ER	0.90	26.7	469	7.9	7.7	5.1	13	9.4	79
	9/16/2008	1150	ER	8.3	23.5	253	7.2	4.6	18.2	23	--	98
	9/18/2008	1305	ER	5.1	22.4	310	7.2	3.1	8.6	14	10.4	76
	9/19/2008	1525	EE	2,200	26.1	247	8.3	8.4	11.5	45	26.8	47
	9/23/2008	1338	EE	2,230	26.1	247	7.6	7.6	8.3	73	45.0	50
	10/6/2008	1223	ER	2.0	23.2	464	7.3	5.3	2.9	3.0	4.8	93
	10/29/2008	1258	ER	.94	14.4	464	7.4	7.5	4.9	6.0	3.6	93
	11/7/2008	1118	ER	.54	17.7	494	7.4	4.9	2.8	6.0	4.2	94
	11/14/2008	1430	EE	196	20.0	247	8.0	9.1	10.9	21	21.5	92
	11/28/2008	1225	EE	182	17.6	250	7.9	9.3	4.0	11	8.8	52
	12/19/2008	1028	ER	1.3	15.1	414	7.5	7.7	3.8	6.0	7.6	92
	12/19/2008	*1033*	*SR*	*1.3*	*15.1*	*414*	*7.5*	*7.7*	*3.8*	*6.0*	*6.5*	*85*
	12/31/2008	0956	ER	2.2	11.4	394	7.6	8.2	8.6	10	6.6	97
	1/13/2009	1103	ER	3.2	9.7	436	7.6	10.6	4.4	5.0	3.5	98
	1/13/2009	*1108*	*SR*	*3.2*	*9.7*	*436*	*7.6*	*10.6*	*4.4*	*5.0*	*2.5*	*96*
	1/22/2009	1223	ER	2.7	10.7	470	7.9	13.0	2.6	4.0	3.0	97
	2/9/2009	1123	ER	3.1	16.2	358	7.5	8.3	7.8	9.0	9.0	99
	2/9/2009	*1128*	*SR*	*3.1*	*16.2*	*358*	*7.5*	*8.3*	*7.8*	*10*	*7.5*	*99*
	2/23/2009	1035	ER	1.6	12.0	480	8.0	11.8	1.3	3.0	4.0	96
	3/9/2009	1428	ER	1.0	23.0	446	8.0	10.3	3.2	6.0	6.0	98
	3/18/2009	1253	ER	1.8	18.0	413	7.5	8.8	6.6	10	12.5	91
	4/8/2009	1148	ER	1.8	16.2	353	7.6	7.7	8.6	10	7.0	98
	4/19/2009	1318	EE	1,220	19.2	254	7.8	9.6	36.2	180	133	69
	4/29/2009	1315	EE	643	21.0	253	7.7	8.8	7.5	20	12.0	75
	5/13/2009	1400	ER	5.1	27.0	321	7.3	5.9	3.6	7.0	6.8	90
	5/13/2009	*1405*	*SR*	*5.1*	*27.0*	*321*	*7.3*	*5.9*	*3.6*	*31*	*7.2*	*98*
	5/27/2009	1130	ER	1.5	25.0	414	7.3	4.6	6.3	8.0	10.0	94
	6/1/2009	1320	ER	1.2	25.1	474	7.6	7.0	3.7	7.0	9.0	87
	6/1/2009	*1325*	*SR*	*1.2*	*25.1*	*474*	*7.6*	*7.0*	*3.7*	*9.0*	*6.5*	*73*
	6/23/2009	0835	ER	3.4	27.9	528	7.6	4.3	2.4	4.0	7.5	94
	7/9/2009	1310	ER	.68	30.5	450	7.9	8.3	2.4	5.0	5.0	92
	7/9/2009	*1315*	*SR*	*.68*	*30.5*	*450*	*7.9*	*8.3*	*2.4*	*5.0*	*2.0*	*91*
	7/20/2009	1240	ER	.41	27.7	508	7.9	7.4	1.6	4.0	10.0	86
	8/6/2009	1045	ER	.30	28.8	459	7.7	4.8	3.6	5.0	6.4	96
	8/6/2009	*1050*	*SR*	*.30*	*28.8*	*459*	*7.7*	*4.8*	*3.6*	*5.0*	*5.0*	*88*
	8/19/2009	1100	ER	.48	27.1	473	7.7	4.8	2.4	2.0	4.3	94

Table 2. Water-quality data in samples from two main monitoring sites (stations 08067650 and 08068000) in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009—Continued.

Station name	Date	Time	Sample type	Discharge (ft^3/s)	Water temperature (°C)	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen concentration (mg/L)	Turbidity (FNU)[1]	Suspended-sediment concentration (mg/L)	Total suspended-solids concentration (mg/L)	Sand/fine separation (percent >0.0625 mm)
08068000 West Fork San Jacinto River near Conroe, Tex.	9/5/2008	1045	ER	19.0	26.7	1,000	7.8	9.3	5.2	6.0	4.2	83
	9/16/2008	1040	EE	1,460	24.0	142	7.0	5.0	72.0	33	--	66
	9/18/2008	1130	EE	669	22.8	155	7.1	5.8	39.0	81	268	81
	9/23/2008	1057	EE	2,800	25.9	252	7.7	7.5	22.7	147	68.7	39
	10/6/2008	1048	ER	43.0	24.1	746	7.4	7.4	12.9	18	19.2	97
	10/29/2008	1435	ER	36.0	17.9	521	7.4	10.1	11.5	9.0	4.6	98
	11/7/2008	1335	ER	30.0	20.7	702	7.8	10.8	11.0	19	17.4	97
	11/14/2008	930	EE	6,000	18.4	109	7.0	6.3	108	1,160	195	19
	12/19/2008	1323	ER	70.0	18.2	447	7.7	11.5	7.3	11	14.5	92
	12/19/2008	*1328*	*SR*	*70.0*	*18.2*	*447*	*7.7*	*11.5*	*7.3*	*10*	*23.0*	*96*
	12/31/2008	1108	ER	78.0	12.9	453	7.5	10.3	12.3	14	8.8	95
	1/13/2009	1246	ER	61.0	11.5	548	7.6	11.8	7.3	10	4.0	91
	1/13/2009	*1251*	*SR*	*61.0*	*11.5*	*548*	*7.6*	*11.8*	*7.3*	*10*	*5.5*	*99*
	1/22/2009	1458	ER	52.0	13.8	673	8.3	15.3	5.3	7.0	1.5	91
	2/9/2009	1353	ER	63.0	18.1	639	7.5	10.2	7.1	11	10.5	85
	2/9/2009	*1358*	*SR*	*63.0*	*18.1*	*639*	*7.5*	*10.2*	*7.1*	*12*	*9.5*	*92*
	2/23/2009	1355	ER	40.0	15.9	606	7.6	11.5	4.3	8.0	6.0	96
	3/9/2009	1123	ER	34.0	22.2	672	7.5	8.7	1.8	10	9.5	88
	3/16/2009	1105	ER	182	13.4	322	7.4	9.5	39.9	56	42.0	90
	4/8/2009	1548	ER	43.0	21.0	572	7.7	10.6	9.2	12	6.5	94
	4/19/2009	1735	EE	4,200	19.8	175	7.2	7.1	110	1,270	254	19
	4/21/2009	1230	EE	7,300	20.0	154	7.1	6.7	64.0	347	97.0	17
	5/13/2009	1038	ER	105	25.8	396	7.4	7.6	14.2	66	18.0	99
	5/13/2009	*1043*	*SR*	*105*	*25.8*	*396*	*7.4*	*7.6*	*14.2*	*57*	*16.0*	*98*
	5/28/2009	0803	ER	43.0	23.6	603	7.3	6.8	7.2	50	7.5	99
	6/1/2009	1040	ER	33.5	24.5	612	7.5	9.0	5.9	10	10.0	87
	6/1/2009	*1045*	*SR*	*33.5*	*24.5*	*612*	*7.5*	*9.0*	*5.9*	*84*	*10.5*	*99*
	6/23/2009	1455	ER	24.0	32.4	903	8.0	10.2	10.0	17	13.5	91
	7/9/2009	1013	ER	172	30.0	287	7.4	6.1	68.8	134	102	96
	7/9/2009	*1018*	*SR*	*172*	*30.0*	*287*	*7.4*	*6.1*	*68.8*	*132*	*110*	*96*
	7/21/2009	1208	ER	18.0	29.4	1,119	8.0	10.0	7.5	14	11.0	91
	8/6/2009	1150	ER	16.0	31.0	888	7.7	7.8	14.6	25	16.6	84
	8/6/2009	*1155*	*SR*	*16.0*	*31.0*	*888*	*7.7*	*7.8*	*14.6*	*23*	*18.2*	*95*
	8/19/2009	1200	ER	83.0	27.0	310	7.3	5.8	226	233	160	98

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[1] Determined by shining an incident beam of light into a parcel of water and measuring the reflected light at an angle of 90 degrees to the incident light.

environmental samples by computing the RPD for each constituent with the equation,

$$RPD = |C_1 - C_2|/((C_1 + C_2)/2) \times 100, \qquad (1)$$

where

C_1 is the SS or TSS concentration, in milligrams per liter, from the environmental sample; and

C_2 is the SS or TSS concentration, in milligrams per liter, from the replicate (field-split) sample.

In accordance with the QAPP (Jean Wright, Houston-Galveston Area Council, written commun., 2008), RPDs of 20 percent or less were judged to indicate acceptable agreement between analytical results if the concentrations were sufficiently large compared with the laboratory reporting level (LRL). The RPDs for 11 of 14 replicate sample pairs (79 percent) analyzed for SS or TSS were 20 percent or smaller. If the RPD computed for an environmental sample and its replicate exceeded 20 percent, the results were further evaluated to determine if the environmental sample result should be included among data used to develop regression equations to estimate SS and TSS concentrations. Streamflow and all water-quality properties measured when the sample was collected were used to determine if the environmental and replicate sample results were valid. If the replicate sample result was determined to be invalid but the associated environmental sample result was determined to be valid, the environmental sample result was still included in the analysis. The RPD criteria was larger for samples collected during low-flow conditions, which typically yielded much lower SS and TSS concentrations compared with concentrations during larger flows. The RPD in eight replicate samples collected during low flow exceeded 20 percent when the SS or TSS concentrations were at or near the LRL. The RPD in split pairs of samples collected at station 08067650 ranged from 0 to 126 percent for SS and TSS, with a mean RPD of 27 percent. The maximum RPD was for the SS concentration in a split pair collected May 13, 2009; the SS concentration was 7.0 mg/L in the environmental sample and 31 mg/L in the replicate sample. The environmental SS concentration was determined acceptable because it was similar to the TSS concentrations; TSS was 6.8 mg/L in the environmental sample and 7.2 mg/L in the replicate sample. The replicate sample SS concentration for the May 13, 2009, sample was determined erroneous, likely because of variance between the SS sample pairs introduced during sample processing. The water sample was split into two sets of containers using a churn splitter, and nonrepresentative suspended-material samples can result from inadequate churning during sample processing (U.S. Geological Survey, variously dated; Wilde and others, 2004 with updates through 2009). The May 13, 2009, SS replicate sample was likely the last sample collected, and sample volume was likely insufficient to adequately churn the volume that was removed from the churn for this sample. For split samples collected at station 08068000, the RPDs for SS and TSS concentrations ranged from 0 to 157 percent, with a mean RPD of 23 percent. The maximum RPD was for the SS concentration in a split pair collected June 1, 2009. The SS concentration was 10 mg/L in the environmental sample and 84 mg/L in the replicate sample. As in the case of the May 13, 2009 sample, the environmental SS concentration was determined acceptable, and the split sample concentration was determined erroneous, likely because of the same problems that affected the May 13, 2009, replicate sample SS concentration at station 08067650. The May 13, 2009, and June 1, 2009, environmental concentrations were included in the dataset used to develop the SS concentration regression equations.

Field blanks were used to assess whether any contamination was introduced into the environmental samples during sampling and analysis. Field blanks were collected by passing deionized water through sampling equipment in the field. Field blanks were collected and processed at sampling sites prior to the collection of environmental samples. Equipment blanks were processed or collected at the Gulf Coast Program Office laboratory to determine if all applicable cleaning procedures for sample splitters and the equipment used for sample collection were adequate to produce samples free of equipment-related contamination. Field and equipment blanks were each collected twice during the study period and analyzed for SS and TSS concentrations. The field and equipment blanks collected in March 2009 had SS and TSS concentrations less than their respective LRL. The second set of field and equipment blanks collected in August 2009 had SS concentrations equal to the LRL of 1.0 and TSS concentrations less than the LRL (table 3).

Regression Methods

S–PLUS statistical software (TIBCO Software Inc., 2008) was used to develop multiple linear regression equation models for estimating real-time SS and TSS concentrations. The regression equation methods used in this report are described by Helsel and Hirsch (2002) and Rasmussen and others (2009).

Streamflow and Water-Quality Properties in the West Fork San Jacinto River Basin

Streamflow at station 08067650 historically has ranged from no flow on numerous days to 56,000 ft^3/s recorded in October 1994 (U.S. Geological Survey, 2010b). Instantaneous streamflow for samples collected at station 08067650 ranged from 0.30 ft^3/s on August 6, 2009, to 2,230 ft^3/s on September 23, 2008 (table 2). About 75 percent of the samples were collected during either normal or below-normal base-flow conditions. For example, of the 29 discrete water-quality samples collected at station 08067650, 23 samples were collected when streamflow ranged from 0.30 to 8.3 ft^3/s, 2 samples when

Table 3. Suspended-sediment and total suspended-solids concentrations in field and equipment blank samples from sites in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009.

[mg/L, milligrams per liter; FB, field blank; <, less than; EB, equipment blank]

Site name	U.S. Geological Survey site number	Date	Sample type	Suspended-sediment concentration (mg/L)	Total suspended-solids concentration (mg/L)
West Fork San Jacinto River near Conroe, Tex.	08068000	3/9/2009	FB	<0.5	<1.0
Gulf Coast Program Office laboratory, The Woodlands, Tex.	301056095265000	3/9/2009	EB	<.5	<1.0
West Fork San Jacinto River near Conroe, Tex.	08068000	8/6/2009	FB	1.0	<1.0
Gulf Coast Program Office laboratory, The Woodlands, Tex.	301056095265000	8/6/2009	EB	1.0	<1.0

streamflow was 182 and 196 ft^3/s, and 4 samples when streamflow ranged from 643 to 2,230 ft^3/s (table 2).

Instantaneous streamflow for samples collected at station 08068000 ranged from 16.0 ft^3/s on August 6, 2009, to 7,300 ft^3/s on April 21, 2009 (table 2). Since installation of station 08068000 in 1939, streamflow has ranged from an annual 7-day minimum (lowest mean value for any 7-consecutive-day period in 1 year) of 11.0 ft^3/s on August 18, 1981, to a maximum peak flow of 115,000 ft^3/s on October 18, 1994 (U.S. Geological Survey, 2010b). Of the 27 discrete water-quality samples collected at station 08068000, 21 samples were collected when streamflow ranged from 16.0 to 182 ft^3/s, 2 samples when streamflow was 669 and 1,460 ft^3/s, and 4 samples when streamflow ranged from 2,800 to 7,300 ft^3/s (table 2).

At stations 08067650 and 08068000, streamflow amounts were relatively small most days of the study period compared with historical averages (daily mean streamflows) for the period of record (August 1972–August 2009 for station 08067650; July 1939–August 2009 for station 08068000). To illustrate the relatively low flows during much of the study, historical mean monthly streamflow for 1983–2009 is compared with the monthly mean streamflow for the study period (July 2008–August 2009) at station 08068000 (fig. 5).

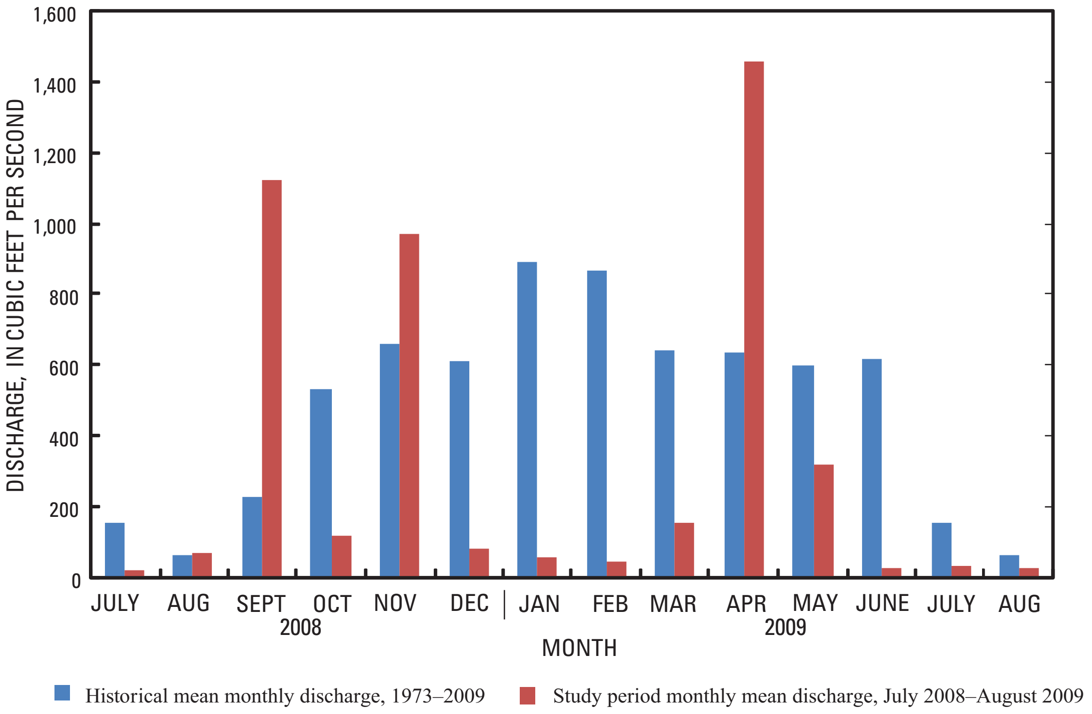

Figure 5. Comparison of historical mean monthly streamflow (1973–2009) and monthly mean streamflow (July 2008–August 2009) at station 08068000 West Fork San Jacinto River near Conroe, Texas.

Because of the persistent low flow during much of the study, relatively few samples were collected when instantaneous streamflow was representative of the middle and upper ranges of historical daily mean streamflows. Streamflow and sample collection during July 2008–August 2009 at stations 08067650 and 08068000 are shown in figs. 4A and 4B, respectively.

All streamflow measurements and discrete water-quality data for samples collected at the two main monitoring sites, stations 08067650 and 08068000, are listed in table 2; streamflow measurements and discrete water-quality data for samples collected at the five additional monitoring sites are listed in table 4. Streamflow, SS, TSS, and water-quality property data for all stations are stored in the NWIS database (U.S. Geological Survey, 2010b) in accordance with USGS protocols (U.S. Geological Survey, 2006b).

Summary statistics for selected water-quality data for samples collected at stations 08067650 and 08068000 are listed in table 5. The maximum SS and TSS concentrations at station 08067650 (180 and 133 mg/L, respectively) were in the April 19, 2009 sample (table 2). The instantaneous streamflow for the April 19, 2009, sample at station 08067650 (1,220 ft^3/s) was the third largest associated with a discrete sample. Except for the SS concentration of 180 mg/L, all other SS concentrations at station 08067650 were less than 75 mg/L. SS concentrations of 25 mg/L or less were measured in 26 of 29 (90 percent) environmental samples collected at this station, and TSS concentrations of 25 mg/L or less were measured in 25 of 28 environmental samples. Median SS and TSS concentrations were 7.0 and 7.6 mg/L, respectively (table 5).

At station 08068000, the maximum SS concentration of 1,270 mg/L was in the April 19, 2009, sample; instantaneous streamflow was 4,200 ft^3/s, the third largest for a discrete sample collected at this station (table 2). SS concentrations were 25 mg/L or less in 16 of 27 of environmental samples, and TSS concentrations were 25 mg/L or less in 18 of 26 environmental samples. The maximum TSS concentration at station 08068000 was 268 mg/L in the Sept. 18, 2008 sample; instantaneous streamflow was 669 ft^3/s, the sixth largest for a discrete sample at this station. Median SS and TSS concentrations were 18.0 and 14.0 mg/L, respectively (table 5).

The largest streamflows were generally associated with the largest SS and TSS concentrations, and these tended to occur in response to large rainfall events. The September 2008 samples were collected during a month when the total rainfall was 10.13 in., compared with the normal (mean monthly) rainfall (1983–2009) of 4.46 in. at National Weather Service station 411956 in Conroe (fig. 3), mostly because of a few large storm events associated with Hurricane Ike, which made landfall near Galveston, Tex., about 50 miles (mi) southeast of Houston, on September 13, 2008.

Of the five samples collected during September 2008 at station 08067650 (table 2), three were collected when streamflow was low (0.90 to 8.3 ft^3/s); SS concentrations for these samples ranged from 13 to 23 mg/L and TSS concentrations for two samples were 9.4 and 10.4 mg/L (TSS sample not collected on September 16, 2008). Two samples were collected during September 19–23, 2008, when streamflow, elevated because of Hurricane Ike, ranged from 2,200 ft^3/s (September 19, 2008) to 2,230 ft^3/s (September 23, 2008). SS concentrations were 45 and 73 mg/L and TSS concentrations were 26.8 and 45.0 mg/L on September 19 and 23, 2008, respectively.

Of the four samples collected during September 2008 at station 08068000 (table 4), one was collected when streamflow was low (19 ft^3/s); the SS and TSS concentrations for this sample were 6.0 and 4.2 mg/L, respectively. Three samples were collected during September 16–23, 2008, when streamflow ranged from 669 to 2,800 ft^3/s. SS concentrations ranged from 33 to 147 mg/L during September 16–23, 2008; TSS concentrations were 68.7 and 268 mg/L on September 23 and 18, 2008, respectively.

Similar to the September 2008 samples, the April 2009 samples were collected when rainfall greatly exceeded the mean monthly rainfall (1983–2009) at National Weather Service station 411956 in Conroe; the total rainfall in April 2009 was 9.24 in. compared with the normal (mean monthly 1983–2009) of 3.85 in. (fig. 3). Similar to the patterns observed during September 2008, the largest SS and TSS concentrations were measured when streamflow was relatively large.

To help preliminary characterization of streamflow and water quality in the West Fork San Jacinto River Basin, water-quality data were also collected at five additional monitoring sites established for the study: stations 08067652 White Oak Creek at Memorial Drive, Conroe, Tex. (White Oak Creek); 08067653 West Fork San Jacinto River at Farm Road (FM) 2854 near Conroe, Tex. (West Fork FM 2854); 08067657 Alligator Creek at Sergeant Ed Holcomb Road, Conroe, Tex. (Alligator Creek); 08067800 Lake Creek at FM 149 near Karen, Tex. (Lake Creek at FM 149); and 08067900 Lake Creek near Conroe, Tex. (Lake Creek Conroe). Water-quality data for the five additional monitoring sites are listed in table 4. The median SS and TSS concentrations were 54.0 and 14.0 mg/L at White Oak Creek; 14.0 and 13.0 mg/L at West Fork FM 2854; 17.0 and 13.0 mg/L at Alligator Creek; 26.0 and 12.0 mg/L at Lake Creek FM 149; and 39.0 and 11.0 mg/L at Lake Creek Conroe, respectively (table 5). The maximum SS and TSS concentrations for the five additional monitoring sites were 3,110 and 390 mg/L, respectively (table 5) at White Oak Creek on April 28, 2009 (table 4). The minimum SS concentration was 5.0 mg/L at Alligator Creek on April 8, 2009, and the minimum TSS concentration was 1.0 mg/L at West Fork FM 2854 on July 20, 2009.

Table 4. Water-quality data in samples from five additional monitoring sites (stations 08067652, 08067653, 08067657, 08067800, and 08067900) in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009.

[ft^3/s, cubic feet per second; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; FNU, Formazin nephelometric units; >, greater than; mm, millimeter; ER, environmental routine; EE, environmental event; --, sample not collected]

U.S. Geological Survey station name	U.S. Geological Survey station number (fig. 1)	Texas Commission on Environmental Quality station number	Date	Time	Sample type	Discharge (ft^3/s)	Water temperature (°C)	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen concentration (mg/L)	Turbidity (FNU)[1]	Suspended-sediment concentration (mg/L)	Total suspended-solids concentration (mg/L)	Sand/fine separation (percent >0.0625 mm)
White Oak Creek at Memorial Drive, Conroe, Tex.	08067652	20731	3/16/2009	1408	ER	7.6	18.5	184	7.4	9.2	17.9	37	14.0	51
			4/8/2009	1308	ER	6.4	17.8	189	7.5	9.4	10.2	26	10.0	45
			4/19/2009	1443	EE	21.1	21.6	135	7.0	8.1	120	385	114	39
			4/28/2009	1353	EE	40.0	21.6	63	6.5	8.3	1,232	3,110	390	32
			5/27/2009	1443	ER	6.5	23.5	195	7.5	8.1	19.1	54	17.0	82
			6/22/2009	1355	ER	3.7	28.4	163	7.8	7.7	15.8	139	12.5	9.0
			7/20/2009	1450	ER	3.8	27.6	191	7.7	7.7	8.2	14	10.0	72
West Fork San Jacinto River at FM 2854 near Conroe, Tex.	08067653	11250	12/19/2008	1205	ER	12.5	17.3	264	7.6	9.6	8.9	10	9.5	95
			3/18/2009	1348	ER	11.7	19.9	266	7.5	9.1	16.9	18	18.0	99
			4/28/2009	1425	EE	680	21.0	182	7.4	8.3	488	714	56.0	76
			5/27/2009	1243	ER	9.9	24.3	261	7.5	7.3	12.8	43	13.0	99
			6/22/2009	1455	ER	4.7	30.0	252	7.8	7.8	8.0	8.0	13.0	99
			7/20/2009	1340	ER	5.0	28.0	252	8.2	9.3	6.7	9.0	1.0	96
Alligator Creek at Sergeant Ed Holcomb Road. Conroe, Tex.	08067657	20732	3/16/2009	1238	ER	1.6	16.7	296	7.9	9.6	29.3	17	15.0	98
			4/8/2009	1438	ER	.15	22.3	448	8.2	11.3	6.0	5.0	3.0	90
			4/19/2009	1600	EE	4.4	25.0	262	7.7	7.7	58.7	68	27.0	100
			4/28/2009	1245	EE	693	22.0	84	7.7	8.3	216	450	66.0	16
			5/28/2009	0840	ER	.18	24.0	478	7.9	6.8	11.6	7.0	6.0	88
			6/22/2009	1315	ER	.014	31.1	634	8.7	8.6	14.3	15	11.5	97
			7/21/2009	1050	ER	.16	28.3	569	8.4	6.7	17.5	17	13.0	97
Lake Creek at FM 149 near Karen, Tex.	08067800	18191	11/28/2009	1020	EE	22.5	14.9	684	7.6	8.5	21.1	26	28.0	98
			3/18/2009	1020	ER	22.5	14.9	684	7.6	8.5	21.1	26	28.0	98
			4/8/2009	1010	ER	6.7	15.1	520	7.6	8.0	13.2	16	12.0	97
			4/19/2009	1048	EE	6,360	18.9	157	7.0	4.9	49.2	165	82.0	52
			4/30/2009	1303	EE	1,630	23.7	164	7.1	4.3	40.7	90	--	87
			5/27/2009	0950	ER	2.5	25.6	452	7.4	5.9	8.9	55	12.0	97
			6/23/2009	1008	ER	.01	28.1	562	7.5	4.1	3.0	6.0	8.5	93
			7/20/2009	1110	ER	.31	27.4	314	7.5	4.3	9.7	14	12.0	98
Lake Creek near Conroe, Tex.	08067900	11367	11/28/2008	1118	EE	18.2	16.8	253	7.4	8.6	8.6	218	7.6	5.0
			12/19/2008	0923	ER	14.8	14.8	276	7.5	9.1	6.1	7.0	11.0	91
			3/16/2009	1603	ER	77.9	14.5	557	7.8	9.9	30.0	39	42.5	96
			4/30/2009	1120	EE	1,320	23.0	134	7.2	4.9	34.3	203	--	30
			5/27/2009	1500	ER	9.1	25.8	289	7.5	7.5	10.9	46	9.5	98
			6/23/2009	1135	ER	2.7	29.0	228	7.4	6.2	9.2	13	11.0	96
			7/21/2009	0930	ER	3.5	27.9	221	7.5	5.7	17.7	21	13.0	94

[1] Determined by shining an incident beam of light into a parcel of water and measuring the reflected light at an angle of 90 degrees to the incident light.

Table 5. Summary statistics for selected water-quality data in samples from monitoring sites in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009.

[n, number of samples; FM, Farm Road; ft^3/s, cubic feet per second; FNU, Formazin nephelometric units; mg/L, milligrams per liter]

Property or constituent	Main monitoring sites								Additional monitoring sites							
	08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Tex. (n = 29)				08068000 West Fork San Jacinto River near Conroe, Tex. (n = 27)				08067652 White Oak Creek at Memorial Drive, Conroe, Tex. (n = 7)				08067653 West Fork San Jacinto River at FM 2854 near Conroe, Tex. (n = 6)			
	Maximum	Minimum	Mean	Median	Maximum	Minimum	Mean	Median	Maximum	Minimum	Mean	Median	Maximum	Minimum	Mean	Median
Discharge (ft^3/s)	2,230	0.30	232	2.0	7,300	16.0	877	61.0	40.0	3.7	12.7	6.5	680	4.7	121	10.8
Turbidity (FNU)	36.2	1.3	6.68	4.4	226	1.8	33.5	11.5	1,232	8.2	203	17.9	488	6.7	90.3	10.9
Suspended-sediment concentration (mg/L)	180	2.0	17.9	7.0	1,270	6.0	140	18.0	3,110	14.0	538	54.0	714	8.0	134	14.0
Total suspended-solids concentration (mg/L)	[1]133	[1]3.0	[1]14.2	[1]7.6	[2]268	[2]1.5	[2]52.7	[2]14.0	390	10.0	81.1	14.0	56.0	1.0	18.4	13.0

Property or constituent	Additional monitoring sites—Continued											
	08067657 Alligator Creek at Sergeant Ed Holcomb Road, Conroe, Tex. (n = 7)				08067800 Lake Creek at FM 149 near Karen, Tex. (n = 8)				08067900 Lake Creek near Conroe, Tex. (n = 7)			
	Maximum	Minimum	Mean	Median	Maximum	Minimum	Mean	Median	Maximum	Minimum	Mean	Median
Discharge (ft^3/s)	693	0.015	99.9	0.18	6,360	0.01	1,006	14.6	1,320	2.7	207	14.8
Turbidity (FNU)	216	6.0	50.4	17.5	49.2	3.0	20.8	17.2	34.3	6.1	16.7	10.9
Suspended-sediment concentration (mg/L)	450	5.0	82.7	17.0	165	6.0	49.8	26.0	218	7.0	78.1	39.0
Total suspended-solids concentration (mg/L)	66.0	3.0	20.2	13.0	82	8.5	26.1	12.0	42.5	7.6	15.8	11.0

[1] n = 28.

[2] n = 26.

Regression Models to Estimate Real-Time Suspended-Sediment and Total Suspended-Solids Concentrations and Loads

As explained by Anderson and Rounds (2010), the basic form of regression models to estimate real-time SS and TSS concentrations by using data from continuous monitors and periodic water-quality samples is described by equation 2:

$$y = f(X_1, X_2, \ldots, X_n), \qquad (2)$$

where

y is the dependent variable;

$X_1, X_2, \ldots, X_n$ are explanatory variables; and

$f(\;)$ is a notation that indicates y is a function of the indicated explanatory variables.

The primary explanatory variables (potential predictive variables) for regression models to estimate real-time SS and TSS concentrations and loads evaluated for this report included streamflow (discharge), water temperature, specific conductance, pH, dissolved oxygen, and turbidity. The purpose of the predictive variables was to provide a means to estimate the dependent variable (Oden and others, 2009), which for this report were either SS or TSS concentration, the primary variables evaluated. Each regression equation can be used to estimate concentrations in “real time” on the basis of the predictive variables measured continuously by the water-quality monitors. Instantaneous loads can also be estimated by multiplying the estimated concentration by the corresponding streamflow value and applying a conversion factor. An adequate model-calibration dataset consists of an appropriate number of instantaneous, discrete samples analyzed for SS and TSS, as well as concurrent turbidity and streamflow measurements collected throughout the observed range of hydrologic conditions for the period of record (Glysson, 1989b; Rasmussen and others, 2009).

In addition to concurrent measurements of turbidity and streamflow, other variables such as stream stage, rates of streamflow rise and fall, rainfall rates and intensity, seasonality, sediment sources, and land use are useful for estimating SS and TSS concentrations and loads in streams (Rasmussen and others, 2009). All these potential predictive variables, as they relate to response variables (SS and TSS concentrations), were evaluated, but not all are included in this report. The evaluation included the comparison of all measured real-time water-quality data constituents as they relate to SS and TSS data. Each potential predictive variable was plotted in relation to a response variable in a scatter plot to help identify variables that can be used as surrogates for estimating SS and TSS loads. For example, when two variables such as turbidity and SS correlate, the presence of one might be useful for predicting the presence of the other.

Data transformations were done prior to developing the regression equations to make the residuals more symmetric, linear, and homoscedastic. Measured and predictive variables will ideally plot on a straight regression line and display homoscedasticity (constant variance about the regression line) (Gray and others, 2000). Normally distributed predictive and response variables (bell-shaped continuous probability distribution centered on a mean) with linear relations and constant variance are required for statistically valid multiple linear regression applications (Oden and others, 2009). Initial scatter plots of all possible predictive and response variables indicated that a transformation of the data would be necessary to improve linearity and compensate for non-normality. For water-quality data, logarithmic transformations of the predictive and response variables are frequently used to improve linearity and to compensate for non-normality and heteroscedasticity in model residuals (Oden and others, 2009). Because of the limited duration of the study (14 months) and relatively small dataset, the relations between measured and predictive variables were less than optimal and the data allowed only a few possible transformations to improve the symmetry, linearity, and homoscedasticity of predicted and response variable relations. Comparisons of linear (untransformed) and log transformed data are presented for station 08068000 to demonstrate how the transformations improved the computation of SS and TSS concentrations (figs. 6 and 7). The improved linearity of the relation between turbidity and streamflow for station 08068000 gained by log transformation is shown in figure 8.

The transformation that provided the most linear fit was accomplished by transforming the predictive and response variables by using a base-10 logarithmic ($\log_{10}$) transformation; $\log_{10}$ transformations were used successfully to normalize the residuals of estimated SS and TSS concentrations. The constant variance throughout the range of estimated SS and TSS concentrations, the normality of the residuals, and the vertically centered linear pattern (near the zero residual line) supported the selection of a $\log_{10}$ transformation.

Once the optimal transformations are selected for the predictive and response variables, different combinations of predictive variables were evaluated to develop a best-fit multiple linear regression model of the form:

$$y = aX_1 + bX_2 + \ldots mX_n + \epsilon, \qquad (3)$$

where

$a, b, \ldots m$ are regression coefficients;

ϵ is an error term, or intercept; and

$X_1, X_2, \ldots, X_n$ are explanatory variable as described in equation 2 (Anderson and Rounds, 2010).

Of the potential predictive variables (streamflow, water temperature, specific conductance, pH, dissolved oxygen concentration, and turbidity), only streamflow, water temperature, specific conductance, and turbidity were rigorously evaluated

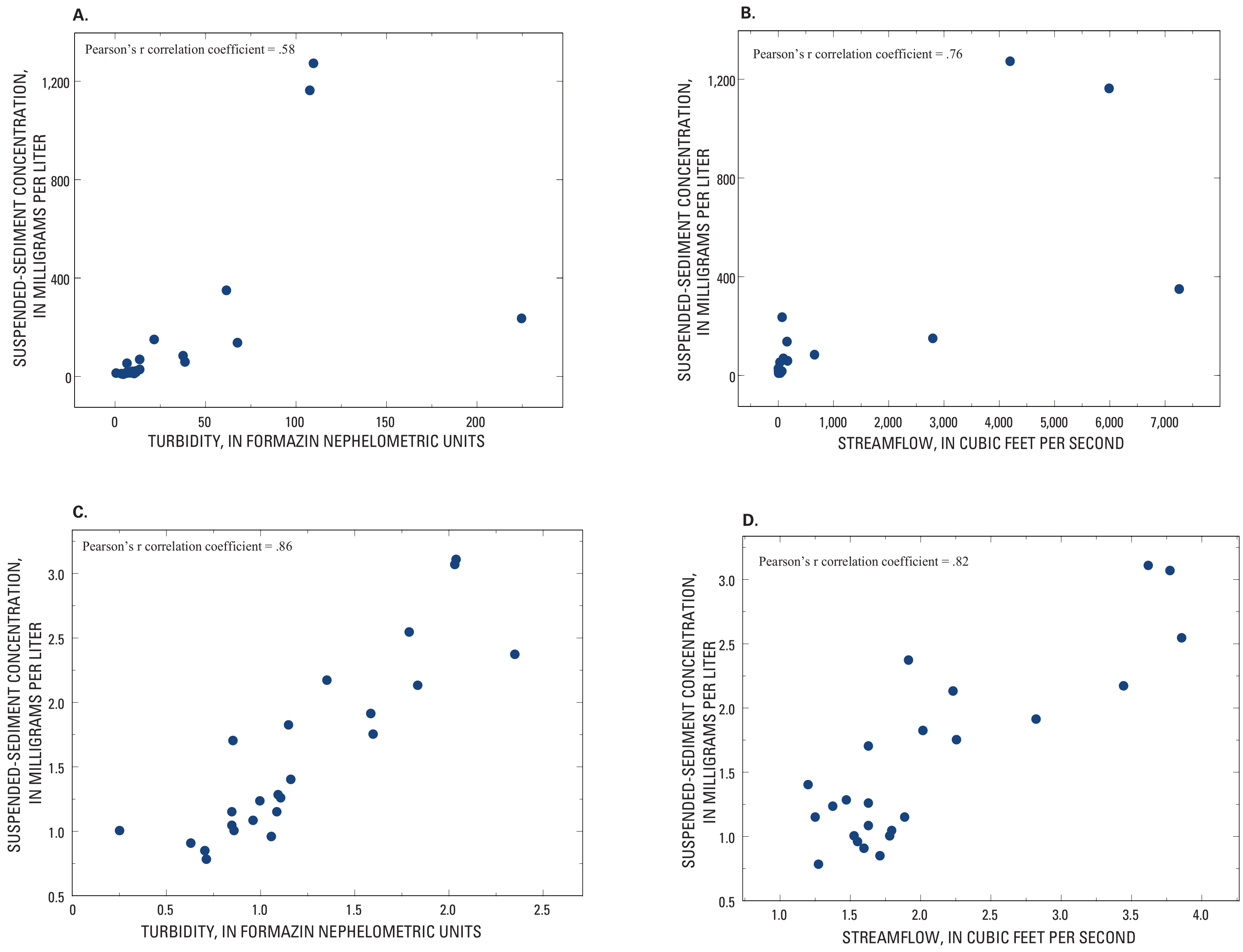

Figure 6. Relation between suspended-sediment concentration (in linear space) and (A) turbidity and (B) streamflow and between suspended-sediment concentration (in $\log_{10}$ space) and (C) turbidity and (D) streamflow for station 08068000 West Fork San Jacinto River near Conroe, Texas, July 2008–August 2009.

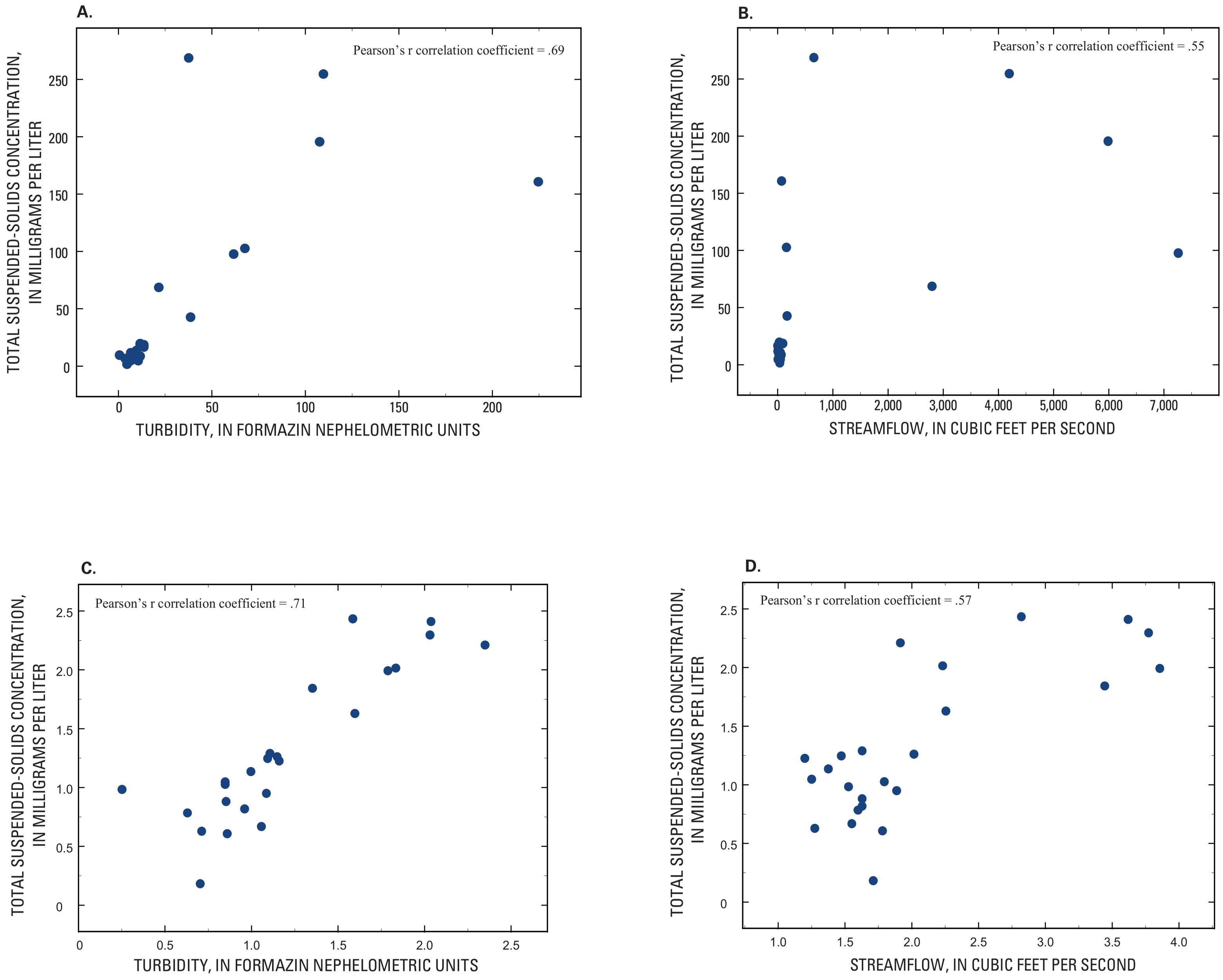

Figure 7. Relation between total suspended-solids concentration (in linear space) and (A) turbidity and (B) streamflow and between total suspended-solids concentration (in $\log_{10}$ space) and (C) turbidity and (D) streamflow for station 08068000 West Fork San Jacinto River near Conroe, Texas, July 2008–August 2009.

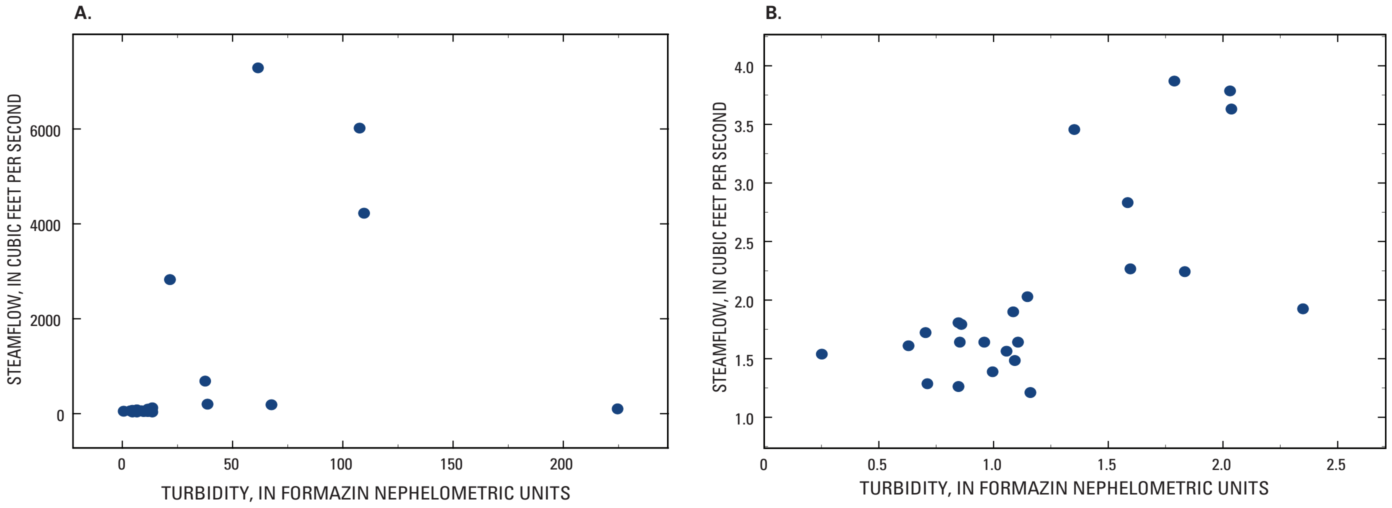

Figure 8. Relation between (A) streamflow and turbidity (in linear space) and (B) streamflow and turbidity (in $\log_{10}$ space) for station 08068000 West Fork San Jacinto River near Conroe, Texas, July 2008–August 2009.

as potential predictive variables; previous studies have established the relation of these variables to SS concentrations and loads (Oden and others, 2009; Rasmussen and others, 2009; Anderson and Rounds, 2010).

The coefficient of determination (R^2) describes the proportion of the total sample variability in the response explained by the regression model. The coefficient will only increase as additional explanatory variables are added to the model; thus, it might not be an appropriate criterion for determining the usefulness of a model that has numerous explanatory variables (Helsel and Hirsch, 2002). The adjusted R^2 (R^2_a) statistic compensates for this by assessing a “penalty” for the number of explanatory variables in the model; adding additional explanatory variables increases the value of R^2_a only when the predictive capability of the model increases. Choosing a model with the largest R^2_a is equivalent to choosing a model with the lowest mean standard error (Helsel and Hirsch, 2002). Review of the transformed data scatter plots and R^2_a values determined that water temperature and specific conductance, as predictive variables, had little relation to either SS or TSS concentrations and subsequently were not used in the regression equations.

Multiple Linear Regression Model Results

In this study, the predictive variables that provided the most accurate surrogate relation for estimating SS and TSS concentrations were turbidity and streamflow (discharge). The data for these two predictive variables yielded the largest R^2_a values and provided the best-fit linear regression model. R^2_a values at station 08067650 were .8815 and .695 for SS and TSS concentrations, respectively, and R^2_a values at station 08068000 were .819 and .7906 for SS and TSS concentrations, respectively (table 6). A multiple linear regression (MLR) model was developed by using turbidity and streamflow as these properties relate to SS and TSS concentrations. The following regression analysis is site specific and applies to an MLR model.

Equations for the MLR models relating turbidity and streamflow data to estimate SS and TSS concentrations for stations 08067650 (equations 4 and 5) and 08068000 (equations 6 and 7) for data collected during July 2008–August 2009 are shown below. Basic model information, regression coefficients, model diagnostics, and Duan’s bias correction factor (Duan, 1983) are listed in table 6; a summary of the regression analysis for each MLR model is provided in appendix 1.

Equations 4 and 5 were the best-fit regression equations for estimating SS concentration (SSC) and TSS concentration, respectively, at station 08067650:

$$\log_{10}(\mathrm{SSC}) = 0.7711 * \log_{10}(\mathrm{Turbidity}) + 0.1760 * \log_{10}(\mathrm{Streamflow}) + 0.2968, \text{ and} \qquad (4)$$

$$\log_{10}(\mathrm{TSS}) = 0.5525 * \log_{10}(\mathrm{Turbidity}) + 0.1394 * \log_{10}(\mathrm{Streamflow}) + 0.4621. \qquad (5)$$

Equations 6 and 7 were the best-fit regression equations for estimating SS and TSS concentrations, respectively, at station 08068000:

$$\log_{10}(\mathrm{SSC}) = 0.7350 * \log_{10}(\mathrm{Turbidity}) + 0.3436 * \log_{10}(\mathrm{Streamflow}) - 0.0677, \text{ and} \qquad (6)$$

$$\log_{10}(\mathrm{TSS}) = 0.8140 * \log_{10}(\mathrm{Turbidity}) + 0.2262 * \log_{10}(\mathrm{Streamflow}) - 0.1252. \qquad (7)$$

Table 6. Summary of linear regression evaluation statistics for equations using turbidity and streamflow as predictive variables to estimate suspended-sediment and total suspended-solids concentrations at two main monitoring sites (stations 08067650 and 08068000) in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009.

Evaluation statistic	08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Tex.		08068000 West Fork San Jacinto River near Conroe, Tex.	
	Suspended sediment	Total suspended solids	Suspended sediment	Total suspended solids
Number of measurements	29	28	27	26
Adjusted coefficient of determination (R^2a)	.8815	.695	.819	.7906
Variance inflation factor (VIF)	2.02	1.68	2.02	1.93
Root mean-square error (RMSE)	.147	.196	.282	.282
Prediction error sum of squares (PRESS)	.562	.960	1.91	1.83
90-percent prediction interval	±48.9 percent	±43.2 percent	±47.7 percent	±43.2 percent
Duan’s bias correction factor (BCF) (Duan, 1983)	1.05	1.05	1.23	1.17

Evaluation of Regression Models

A series of evaluations were done to evaluate accuracy and validity of the regression models. First, correlation coefficients were determined. Correlation coefficients measure the strength of association between two variables (Helsel and Hirsch, 2002). The most commonly used correlation is Pearson’s r. This correlation is also called the linear correlation coefficient because r measures the linear association between two variables (Helsel and Hirsch, 2002). When there is no correlation between two variables, r = 0. Generally, the closer the correlation coefficient is to 1 (perfect positive correlation), the stronger the association between variables (Rasmussen and others, 2009). For example, at station 08068000 the correlation coefficients for each equation ranged from .55 to .86 (figs. 6 and 7). The relation between measured or estimated SS concentrations and turbidity by using the best-fit regression model for station 08068000 is shown in figure 9A; the relation between measured or estimated TSS concentrations and turbidity is shown in figure 9B.

Because the regression equation models developed during this study contained two predictive variables, an evaluation of multicollinearity was done to ensure that the predictive variables were not highly correlated with each other, which can result in unreliable models (Rasmussen and others, 2009). Helsel and Hirsch recommend computing a variance inflation factor (VIF) as a means of measuring multicollinearity. A VIF larger than 10 indicates multicollinearity between variables and that either variable would explain about the same amount of variability and that the two variables combined should not be used as predictive variables in a MLR model (Helsel and Hirsch, 2002). The scatter plots (fig. 8) and VIF values (table 6) for turbidity and streamflow data indicate that the multicollinearity of these variables is small and that both variables can be used as predictive variables in a MLR model to estimate SS and TSS concentrations. The VIF values for the MLR models developed ranged from 1.68 to 2.02.

The root-mean-square error (RMSE) also was used to evaluate the regression models. The RMSE is the measure of the variance between observed and regression-computed values (Rasmussen and others, 2009). Minimizing the RMSE is one of the criteria for selecting predictive variables: “Methods whose estimates are closer to the true value have lower RMSEs, and are considered better” (Helsel and Hirsch, 2002, p. 358). Another tool for evaluating regression equation models is an evaluation tool derived from the RMSE, the prediction error sum of squares (PRESS). The PRESS statistic is one of the best measures of the quality of a regression model (Helsel and Hirsch, 2002). An equation that produces the least error when making new predictions is obtained by minimizing the PRESS statistic (Helsel and Hirsch, 2002). A summary of linear regression evaluation statistics (RMSE and PRESS statistic) for the regression equations to estimate SS and TSS concentrations for stations 08067650 and 08068000 is provided (table 6). The RMSE computed for each regression equation ranged from 0.147 to 0.282, which were higher than desired and indicated appreciable variance between the measured and regression-computed values. The PRESS statistic for each equation developed ranged from 0.562 to 1.91, indicating that a large amount of error was generated in the results derived from the equations.

The measure of variance (model residuals) between observed values and values predicted (estimated) by the regression model provides another diagnostic tool to evaluate the accuracy of regression models. Model residuals are defined as the difference between the observed values and the model estimated values. The residual error (e_i) for the estimated SS and TSS concentrations should follow a normal distribution with a mean of zero and a constant variance (Helsel and Hirsch, 2002). A residual value of zero indicates that the

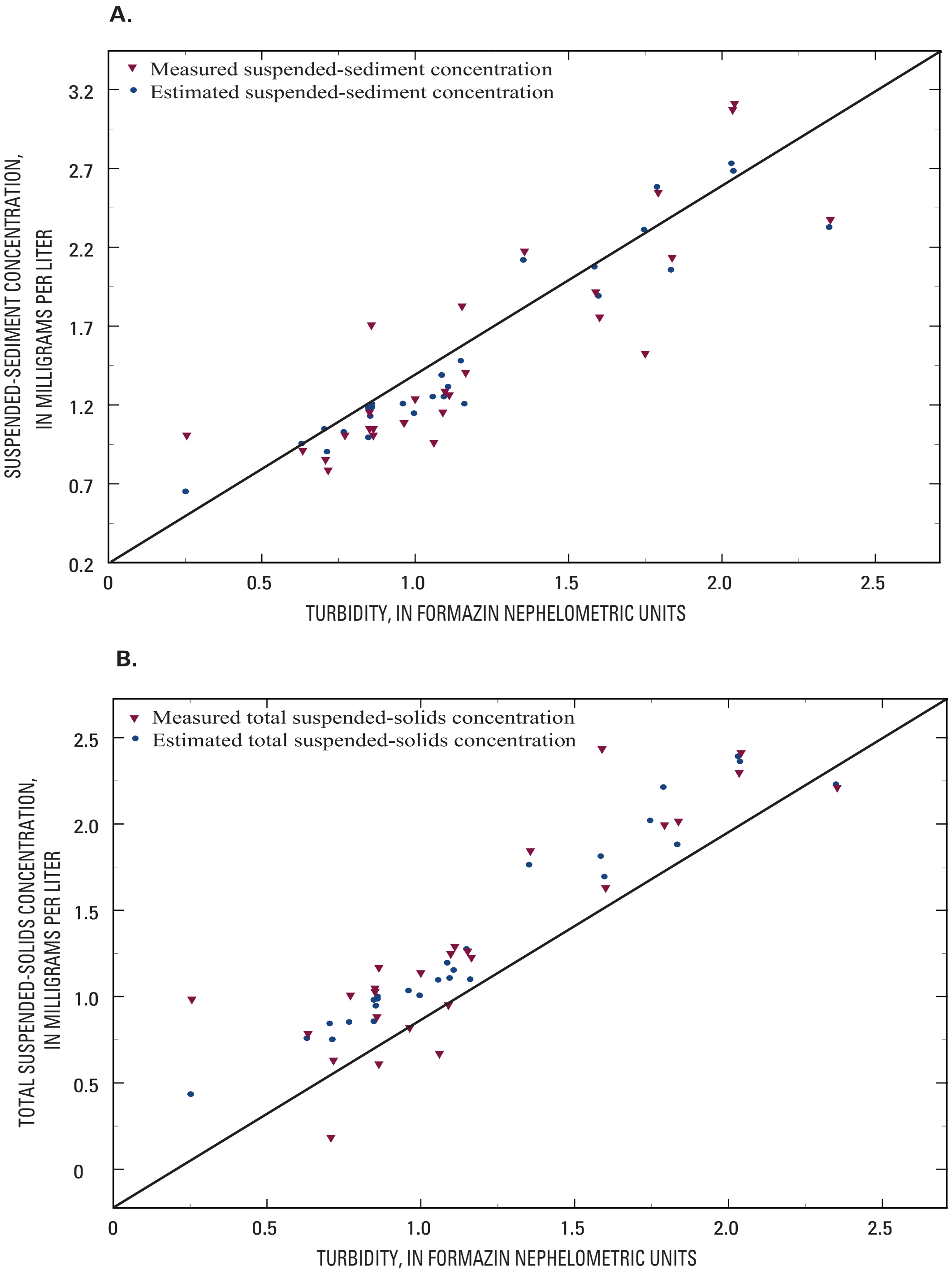

Figure 9. Relation between (A) measured or estimated suspended-sediment concentration and turbidity and (B) measured or estimated total suspended-solids concentration and turbidity at station 08068000 West Fork San Jacinto River near Conroe, Texas, July 2008–August 2009.

model estimated SS or TSS concentrations is equal to the observed value. A positive value indicates that the observed value was larger than the estimated value, and a negative value indicates that the observed value was less than the estimated value (Rasmussen and others, 2009). The normality of the residuals was evaluated by plotting the residuals on a normal-probability plot and computing the probability plot correlation coefficient (PPCC) (figs. 10 and 11). Normally distributed residuals are linear and equally distributed over a normal-probability plot and have a larger PPCC compared with non-normally distributed residuals. The probability plots and PPCC values for the regression equations indicate that the $\log_{10}$ transformations (equations 4–7) resulted in residuals that meet all these criteria. The PPCC values for the regression equations that were developed to estimate SS and TSS concentrations and loads ranged from 0.9892 to 0.9928, close to the maximum possible PPCC value (1.0).

To assess the uncertainty of the regression-computed SS and TSS concentrations, prediction intervals were computed for all data generated in this study. Prediction intervals can be used to evaluate the uncertainty of regression-computed SS and TSS concentrations (Helsel and Hirsch, 2002). For a given predictive variable, the 90-percent prediction interval represents a range of values within which there is a 90-percent certainty that the true SS or TSS concentration occurs. The prediction interval for a single response (y_i) is approximately:

$$E(y_i) \text{ +/- } t \text{ x } s, \tag{8}$$

where

$E(y_i)$ is the regression-computed value, at xi;

t is the value of the student's t distribution having n-2 degrees of freedom (n is the number of observations) with the exceedance probability of $\alpha/2$ (alpha value obtained from student's t distribution tables in the appendix of most statistics textbooks (for example, Iman and Conover, 1983, appendix A, p. 438–439) for 90-percent prediction interval $\alpha = 0.10$; and

s is the standard error of regression or the RMSE (Rasmussen and others, 2009).

The larger the 90-percent prediction interval, the more uncertainty there is associated with the regression computed SS and TSS concentrations (Rasmussen and others, 2009). The 90-percent prediction intervals for station 08067650 were ±48.9 percent for SS concentrations and ±43.2 percent for TSS concentrations and for station 08068000 were ±47.7 percent for SS concentrations and ±43.2 percent for TSS concentrations (table 6). The 90-percent prediction intervals could be smaller if data were collected over a longer period of time compared with the 14 months of data collected for these analyses.

Each of the linear regression models developed to estimate SS and TSS concentrations at stations 08067650 and 08068000 has uncertainty in the estimated values. The correlation coefficients and R^2_a values for each equation were less than .90; some were much less than 1.0, the value of a perfect correlation and perfect R^2_a value. The VIF values obtained for each equation indicated no appreciable multicollinearity among the predictive variables selected for each equation and that the selected variables would provide the most accurate equations possible for estimating SS and TSS concentrations and loads. The RMSE values obtained for each equation were higher than desired and indicated appreciable variance between the observed and regression-computed values. The main indicators of the measure of error for the values generated from these equations were the RMSE and PRESS values.

These evaluations indicate that a large amount of error was generated in the results derived from the equations. It is important to collect data over sufficient periods of time to cover a wide range of streamflow to accurately model SS and TSS concentrations and loads; data collected over shorter periods do not replicate the range of flow during longer periods, and the range of flow is related to concentrations and loads (Uhrich and Bragg, 2003).

Suspended-Sediment and Total Suspended-Solids Concentration and Load Computation

Using a $\log_{10}$ transformation of the response variables (SS and TSS concentrations) has an undesirable effect that needs to be considered when computing SS and TSS concentrations and loads; the regression estimates needs to be retransformed to the original units, a step that introduces a bias in computed SS and TSS concentrations (Miller, 1951; Koch and Smillie, 1986) unless the data are perfectly and positively correlated (as the R^2_a approaches 1.0, the bias correction factor [BCF] also approaches 1.0). The bias arises because regression estimates are the mean of the y given x, in log units, and retransformation of these estimates is not equal to the mean of the y given x, in linear space. To correct this retransformation bias, Duan (1983) introduced a nonparametric BCF called the "smearing" estimator (Helsel and Hirsch, 2002). The equation to compute the smearing BCF for $\log_{10}$ transformations is as follows:

$$\text{BCF} = \frac{\sum_{i}^{n} = 1^{10^{e_i}}}{n} \tag{9}$$

where

n is the number of samples; and

e_i is the residual in log units (Rasmussen and others, 2009).

Regression-computed SS and TSS concentrations for stations 08067650 and 08068000 were corrected for bias by multiplying the retransformed SS and TSS concentrations by the BCF (Rasmussen and others, 2009). The BCFs computed for each regression equation in this study were larger than 1.0 (table 6). An example of the effect of the BCF on the model-estimated SS and TSS concentrations is evident in the relation between measured or estimated SS concentrations and turbidity at station 08068000 (fig. 9A). The closer the data points plot to the 1:1 relation line, the more accurate the regression equations.

A time series of SS or TSS discharge (SSQ or TSSQ) is computed from the estimated SS or TSS concentrations and the corresponding streamflow for each site. Instantaneous SSQ (SSQ_i) is computed by using SS concentrations in the following equation:

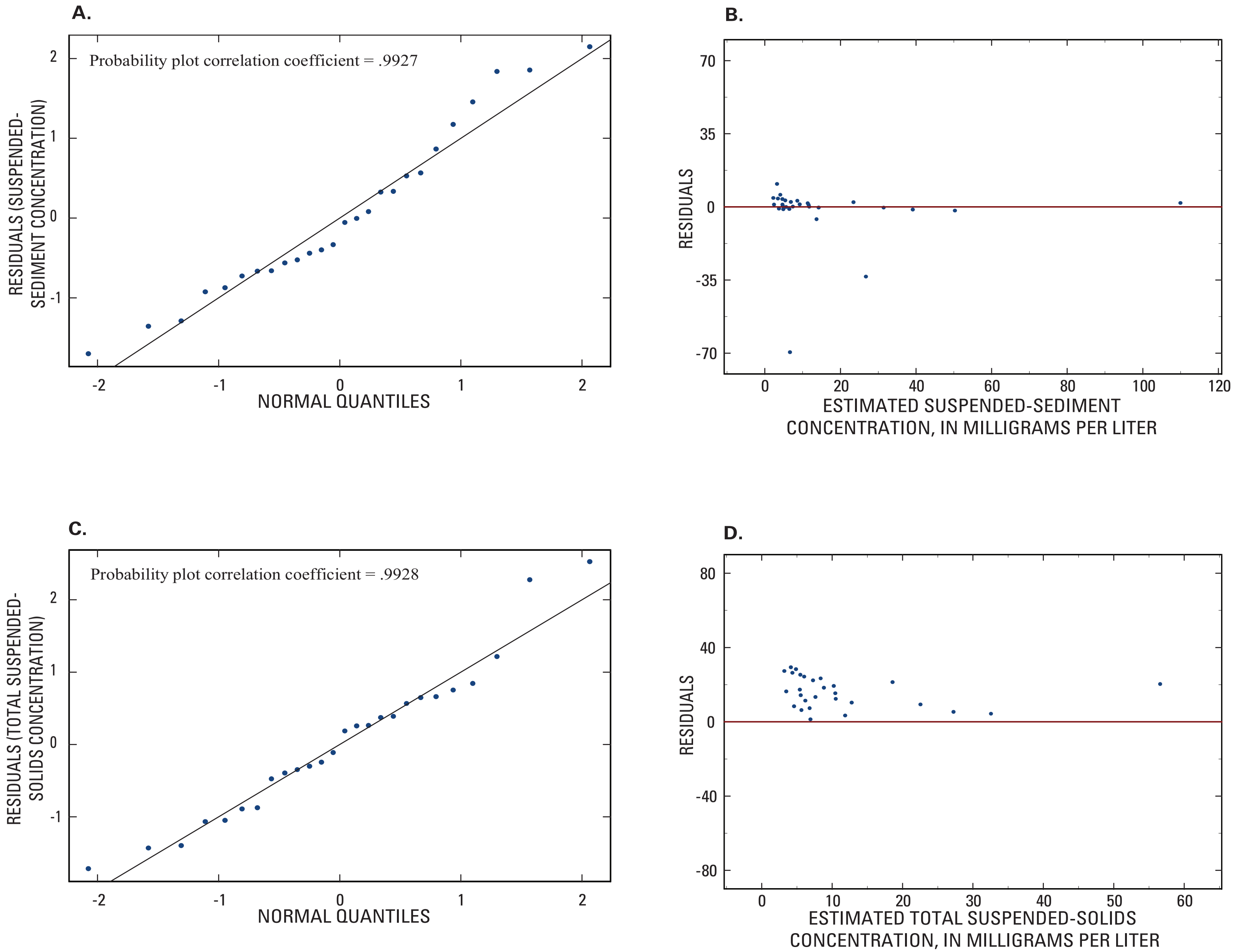

Figure 10. Estimated suspended-sediment concentrations (A) probability plot correlation coefficient and (B) residual plot; and estimated total suspended-solids concentrations (C) probability plot correlation coefficient and (D) residual plot for multiple linear regression models developed for station 08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Texas, July 2008–August 2009.

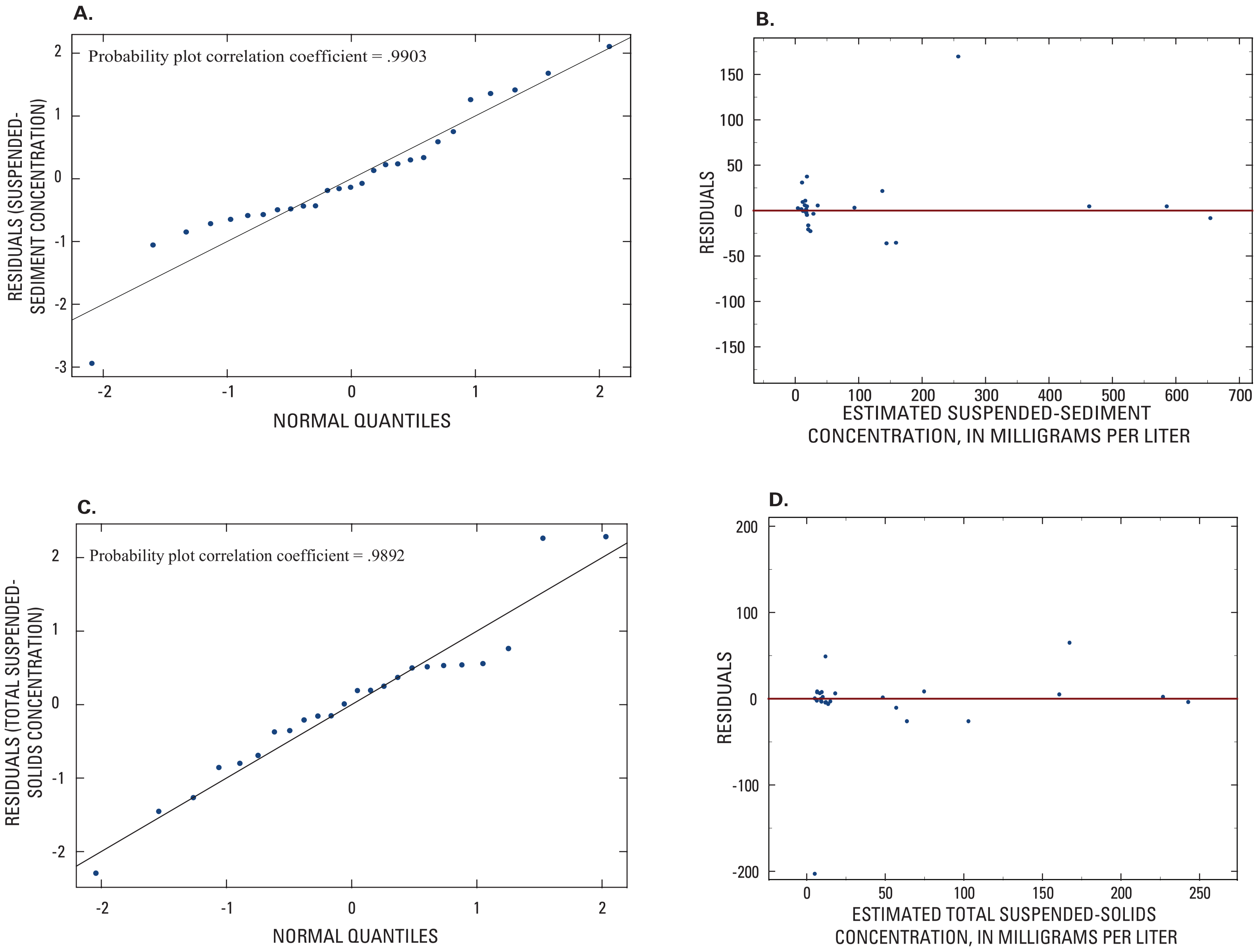

Figure 11. Estimated suspended-sediment concentrations (A) probability plot correlation coefficient and (B) residual plot; and estimated total suspended-solids concentrations (C) probability plot correlation coefficient and (D) residual plot for multiple linear regression models developed for station 08068000 West Fork San Jacinto River near Conroe, Texas, July 2008–August 2009.

$$SSQ_i = SSC_i \times Q_i \times c, \qquad (10)$$

where

SSQ_i is the computed instantaneous SSQ (computed instantaneous TSSQ [$TSSQ_i$]) for the *i*th value, in tons per 15 minutes;

SSC_i is the computed SS concentration (computed TSS concentration [$TSSC_i$]), for the *i*th value, in milligrams per liter;

Q_i is the streamflow for the *i*th value, in cubic feet per second; and

c is a constant, 0.000028, to convert the units to tons per 15 minutes.

Turbidity and streamflow were used as predictive variables to establish a surrogate relation to estimate SS and TSS loads. Using best-fit linear regressions on $\log_{10}$ transformed data, adjusted by applying the appropriate BCFs for each corresponding equation (table 6), the SS and TSS loads at stations 08067650 and 08068000 were estimated from the turbidity and streamflow values. SSQs or TSSQs were computed in 15-minute intervals by multiplying estimated SS or TSS concentrations (in milligrams per liter), respectively, by the corresponding streamflow (Q), in cubic feet per second and a correction factor (c) to convert the units to tons per 15 minutes (equation 10). The resulting 15-minute estimates were summed to determine the total daily SSQ (TSSQ). The monthly SSQ (TSSQ) is computed by summing each daily SSQ (TSSQ) for that month. The study period total SSQ (TSSQ) is computed by summing the monthly totals for the study period for stations 08067650 and 08068000 (tables 7 and 8). A few missing streamflow or turbidity values occurred sporadically throughout the study period and were ignored in the estimated SS and TSS loads. Turbidity values for September 17–October 6, 2008, deemed invalid because they did not meet the criteria specified for the post-calibration validation process, were not included in the regression equations to estimate SS and TSS concentrations or the ensuing SSQ and TSSQ computations.

SS or TSS loads for July 2008–August 2009 were estimated by summing the total daily SSQ or TSSQ for the study period to obtain loads in tons. The SS and TSS loads were about 40 times larger at station 08068000 compared with loads at station 08067650. Total estimated loads at station 08067650 during July 2008–August 2009 were 3,540 tons for SS and 1,900 tons for TSS (table 7). Minimum monthly total loads at station 08067650 were 0.10 ton for SS and 0.11 ton for TSS in January 2009; maximum monthly total loads were 1,790 tons for SS and 1,050 tons for TSS in April 2009. Total estimated loads at station 08068000 during July

Table 7. Estimated monthly and total study period (14 months) suspended-sediment and total suspended-solids loads computed from multiple linear regression models developed for station 08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Texas, July 2008–August 2009.

Month	Suspended-sediment load (tons)	Total suspended-solids load (tons)
July 2008	0.36	0.44
August 2008	33.5	15.4
[1]September 2008	579	236
[1]October 2008	13.7	7.72
November 2008	894	436
December 2008	.61	.55
January 2009	.10	.11
February 2009	1.94	1.71
March 2009	69.3	29.8
April 2009	1,793	1,047
May 2009	151	119
June 2009	.46	.50
July 2009	.69	.57
August 2009	.53	.45
Total for study period (July 2008–August 2009)	3,538	1,895

[1] Turbidity data for September 17–October 6, 2008, not used to compute estimated loads; thus, estimates could be biased low.

Table 8. Estimated monthly and total study period (14 months) suspended-sediment and total suspended-solids loads computed from multiple linear regression models developed for station 08068000 West Fork San Jacinto River near Conroe, Texas, July 2008–August 2009.

Month	Suspended-sediment load (tons)	Total suspended-solids load (tons)
July 2008	56.9	41.1
August 2008	1,475	992
[1]September 2008	27,091	12,461
[1]October 2008	2,860	1,680
November 2008	53,850	24,188
December 2008	288	178
January 2009	132	80.4
February 2009	95.3	61
March 2009	3,106	1,809
April 2009	60,390	27,218
May 2009	6,055	2,866
June 2009	39.3	26.5
July 2009	180	125
August 2009	446	308
Total for study period (July 2008–August 2009)	156,064	72,036

[1] Turbidity data for September 17–October 6, 2008, not used to compute estimated loads; thus, estimates could be biased low.

2008–August 2009 were 156,000 tons for SS and 72,000 tons for TSS (table 8). Minimum monthly total loads at station 08068000 were 39.3 tons for SS and 26.5 tons for TSS in June 2009; maximum monthly total loads were 60,400 tons for SS and 27,200 tons for TSS in April 2009. The location of the stations likely explains some of the differences in SS and TSS concentrations and loads at the two stations. Station 08067650 is 2.5 mi downstream from Lake Conroe, a reservoir with controlled outflow. Station 08068000 is 11 mi downstream from station 08067650, and several tributaries confluence with the West Fork San Jacinto River upstream from station 08068000 and downstream from station 08067650. The size and depth of Lake Conroe should allow most SS to settle before water is released from the reservoir. SS and TSS loads likely were larger at station 08068000 than at station 08067650 because flow at station 08068000 is more representative of water-quality properties in the West Fork San Jacinto River Basin compared with flow at station 08067650, which is more representative of the water-quality properties of releases from Lake Conroe.

The estimated SS and TSS concentrations derived from the regression equations contained large error components, thus inferring that the regression-computed load estimates also included large errors. The SS and TSS load estimates were derived by using models that were less than optimal in terms of their accuracy; the limited accuracy likely results from the relatively short period of data collection (14 months) and relatively small range in streamflow observed during the study period compared with the range of streamflow typically observed at stations 08067650 and 08068000 during longer periods.

Summary

To better understand the hydrology (streamflow and water quality) of the West Fork San Jacinto River Basin downstream from Lake Conroe near Conroe, Texas, including spatial and temporal variation of suspended-sediment (SS) and total suspended-solids (TSS) concentrations and loads, the U.S. Geological Survey (USGS), in cooperation with the Houston-Galveston Area Council and the Texas Commission on Environmental Quality, measured streamflow (discharge) and collected continuous and discrete water-quality data during July 2008–August 2009 in the West Fork San Jacinto River Basin downstream from Lake Conroe.

Discrete samples for SS and TSS analysis were collected at two USGS streamflow-gaging stations on the West Fork San Jacinto River: West Fork San Jacinto River below Lake Conroe near Conroe, Texas (station 08067650) and West Fork San Jacinto River near Conroe, Texas (station 08068000). Samples were collected and streamflow measurements were made over the range of flow conditions during the 14-month study. In addition to these two main monitoring sites, discrete samples were also collected at five additional monitoring sites. Water-quality properties were characterized in a preliminary manner by using summary statistics of water-quality data from the monitoring sites. Discrete samples were collected semimonthly, regardless of flow conditions, and during periods of high flow resulting from storms or releases from Lake Conroe.

The largest streamflows were generally associated with the largest SS and TSS concentrations, and these tended to occur in response to large rainfall events. The September 2008 samples were collected during a month when the total rainfall was 10.13 in., compared with the normal September rainfall of 4.46 in., mostly because of a few large storm events associated with Hurricane Ike, which made landfall near Galveston, Texas, on September 13, 2008. The maximum SS and TSS concentrations at station 08067650 (180 and 133 mg/L, respectively) were in the April 19, 2009 sample; instantaneous streamflow (1,220 ft^3/s) was the third largest associated with a discrete sample at this station. SS concentrations were 25 mg/L or less in 26 of 29 environmental samples collected at station 08067650, and TSS concentrations were 25 mg/L or less in 25 of 28 environmental samples. Median SS and TSS concentrations at station 08067650 were 7.0 and 7.6 mg/L, respectively.

At station 08068000, the maximum SS concentration (1,270 mg/L) was in the April 19, 2009 sample; instantaneous streamflow (4,200 ft^3/s) was the third largest associated with a discrete sample at this station. The maximum TSS concentration (268 mg/L) was in the September 18, 2008 sample; instantaneous streamflow (669 ft^3/s) was the sixth largest associated with a discrete sample at this station. SS concentrations were 25 mg/L or less in 16 of 27 of environmental samples, and TSS concentrations were 25 mg/L or less in 18 of 26 environmental samples at this station. Median SS and TSS concentrations at station 08068000 were 18.0 and 14.0 mg/L, respectively.

Water-quality data were also collected at five additional monitoring sites established for the study: stations 08067652 White Oak Creek at Memorial Drive, Conroe, Texas (White Oak Creek); 08067653 West Fork San Jacinto River at Farm Road (FM) 2854 near Conroe, Texas (West Fork FM 2854); 08067657 Alligator Creek at Sergeant Ed Holcomb Road, Conroe, Texas (Alligator Creek); 08067800 Lake Creek at FM 149 near Karen, Texas (Lake Creek at FM 149); and 08067900 Lake Creek near Conroe, Texas (Lake Creek Conroe). The median SS and TSS concentrations were 54.0 and 14.0 mg/L at White Oak Creek; 14.0 and 13.0 mg/L at West Fork FM 2854; 17.0 and 13.0 mg/L at Alligator Creek; 26.0 and 12.0 mg/L at Lake Creek FM 149; and 39.0 and 11.0 mg/L at Lake Creek Conroe, respectively. The maximum SS and TSS concentrations for the five additional monitoring sites were 3,110 and 390 mg/L, respectively, at White Oak Creek on April 28, 2009. The minimum SS concentration was 5.0 mg/L at Alligator Creek on April 8, 2009, and the minimum TSS concentration was 1.0 mg/L at West Fork FM 2854 on July 20, 2009.

Continuous measurements of streamflow and selected water-quality properties (water temperature, specific conductance, pH, dissolved oxygen, and turbidity) at stations

08067650 and 08068000 were evaluated as potential variables in regression equations developed to estimate SS and TSS concentrations and loads. Surrogate regression equations were developed to estimate SS and TSS loads by using real-time turbidity and streamflow data; of all possible predictive variables, turbidity and streamflow resulted in the best regression models for estimating near "real-time" SS and TSS concentrations in the West Fork San Jacinto River at stations 08097650 and 08068000.

A series of evaluations were done to determine the best variables for inclusion in the regression models and for evaluating accuracy and validity of the regression models. To improve the normal distribution of the predictive and response variables, base-10 logarithmic transformations were done on all data associated with the regression development. The data for the two best predictive variables, turbidity and streamflow, yielded the largest adjusted R-squared values and provided the best-fit linear regression model. The adjusted R-squared values were .8815 and .695 for SS and TSS, respectively, at station 08067650 and .819 and .7906 for SS and TSS, respectively, at station 08068000. The variance inflation factors for the regression models developed ranged from 1.68 to 2.02, indicating that the predictive variables selected for each equation were not affected by multicollinearity.

Each of the linear regression models developed for stations 08067650 and 08068000 to estimate SS and TSS on the basis of water-quality properties resulted in uncertainty in the estimated values. The main indicators of the measure of error for the values computed from the regression equations were the root-mean-square error and the prediction error sum of squares. The root-mean-square errors computed for the equations ranged from 0.147 to 0.282, which were higher than desired and indicated appreciable variance between the measured and regression-computed values. The prediction error sum of squares statistics for the equations ranged from 0.562 to 1.91. These evaluations indicate that a large amount of error was generated in the results derived from the equations. The measure of variance (model residuals) between observed and regression-computed values provides another diagnostic tool to evaluate the accuracy of the regression models. The probability plot correlation coefficient values for the equations ranged from 0.9892 to 0.9928. The probability plots and probability plot correlation coefficient values for the regression equations indicate that the base-10 logarithmic transformed data provide normally distributed residuals.

Relatively large errors are associated with the regression-computed SS and TSS concentrations; the 90-percent prediction intervals were ±48.9 percent for SS concentrations and ±43.2 percent for TSS concentrations for station 08067650 and ±47.7 percent for SS concentrations and ±43.2 percent for TSS concentrations. Regression-computed SS and TSS concentrations were corrected for bias before being used to compute SS and TSS loads. The total estimated SS and TSS loads during July 2008–August 2009 were about 3,540 and 1,900 tons, respectively, at station 08067650 and about 156,000 and 72,000 tons, respectively, at station 08068000. Because the estimated SS and TSS concentrations derived from the regression equations contained large error components, the computed load estimates are inferred to also include large errors. The SS and TSS loads were about 40 times larger at station 08068000 compared with loads at station 08067650, likely because station 08067650 is 2.5 mi downstream from a reservoir (Lake Conroe) with controlled releases and station 08068000 is 11 mi downstream from station 08067650; flow at station 08068000 is more representative of water-quality properties in the West Fork San Jacinto River Basin compared with station 08067650, which is more representative of water-quality properties of releases from Lake Conroe.

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Appendix 1—S–PLUS Output of Regression Model Development of Turbidity, Streamflow, Suspended-Sediment Concentration, and Total Suspended-Solids Concentration for Two Main Monitoring Sites (Stations 08067650 and 08068000) in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009.

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Appendix 1. S-PLUS output of regression model development of turbidity, streamflow, suspended-sediment concentration, and total suspended-solids concentration for two main monitoring sites (stations 08067650 and 08068000) in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009.

08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Tex.

```
      *** Linear Model ***

Call: lm(formula = Log.SSC ~ Log.Turb + Log.Q, data = SJ105Final, na.action
=
       na.exclude)
Residuals:
     Min       1Q   Median      3Q    Max
 -0.2329 -0.08147 -0.04112 0.09103 0.2795

Coefficients:
             Value Std. Error t value Pr(>|t|)
(Intercept) 0.2968 0.0711     4.1747  0.0003
   Log.Turb 0.7711 0.1106     6.9724  0.0000
      Log.Q 0.1760 0.0299     5.8838  0.0000

Residual standard error: 0.147 on 26 degrees of freedom
Multiple R-Squared: 0.89      Adjusted R-squared: 0.8815
F-statistic: 105.1 on 2 and 26 degrees of freedom, the p-value is 3.472e-013

Analysis of Variance Table

Response: Log.SSC

Terms added sequentially (first to last)
          Df Sum of Sq  Mean Sq  F Value         Pr(F)
 Log.Turb  1  3.794578 3.794578 175.6425 0.000000e+000
    Log.Q  1  0.747906 0.747906  34.6189 3.324109e-006
```

```
      *** Linear Model ***

Call: lm(formula = Log.TSS ~ Log.Turb + Log.Q, data = SJ105Final, na.action =
       na.exclude)
Residuals:
     Min      1Q    Median     3Q    Max
 -0.3439 -0.1057 -0.008282 0.1138 0.4791

Coefficients:
             Value Std. Error t value Pr(>|t|)
(Intercept) 0.4621 0.0998     4.6284  0.0001
   Log.Turb 0.5525 0.1618     3.4142  0.0022
      Log.Q 0.1394 0.0411     3.3922  0.0023

Residual standard error: 0.196 on 25 degrees of freedom
Multiple R-Squared: 0.7176      Adjusted R-squared: 0.695
F-statistic: 31.76 on 2 and 25 degrees of freedom, the p-value is 1.367e-007
1 observations deleted due to missing values

Analysis of Variance Table

Response: Log.TSS

Terms added sequentially (first to last)
          Df Sum of Sq  Mean Sq  F Value       Pr(F)
 Log.Turb  1  1.997912 1.997912 52.01955 0.000000147
    Log.Q  1  0.441948 0.441948 11.50699 0.002311299
Residuals 25  0.960174 0.038407
```

Appendix 1. S-PLUS output of regression model development of turbidity, streamflow, suspended-sediment concentration, and total suspended-solids concentration for two main monitoring sites (stations 08067650 and 08068000) in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009—Continued.

08068000 West Fork San Jacinto River near Conroe, Tex.

```
      *** Linear Model ***

Call: lm(formula = Log.SSC ~ Log.Turb + Log.Q, data = SJ45Final, na.action =
      na.exclude)
Residuals:
     Min      1Q   Median     3Q    Max
 -0.7866 -0.1484 -0.03622 0.1229 0.5753

Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept) -0.0677  0.1570    -0.4314  0.6700
   Log.Turb  0.7350  0.1544     4.7602  0.0001
      Log.Q  0.3436  0.0968     3.5509  0.0016

Residual standard error: 0.2822 on 24 degrees of freedom
Multiple R-Squared: 0.833      Adjusted R-squared: 0.819
F-statistic: 59.84 on 2 and 24 degrees of freedom, the p-value is 4.72e-010

Analysis of Variance Table

Response: Log.SSC

Terms added sequentially (first to last)
          Df Sum of Sq  Mean Sq  F Value       Pr(F)
 Log.Turb  1  8.526097 8.526097 107.0661 0.000000000
    Log.Q  1  1.004081 1.004081  12.6087 0.001624203
Residuals 24  1.911214 0.079634
```

```
      *** Linear Model ***

Call: lm(formula = Log.TSS ~ Log.Turb + Log.Q, data = SJ45Final, na.action =
      na.exclude)
Residuals:
     Min      1Q  Median     3Q   Max
 -0.6628 -0.1166 0.03594 0.1344 0.621

Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept) -0.1252  0.1597    -0.7844  0.4408
   Log.Turb  0.8140  0.1544     5.2735  0.0000
      Log.Q  0.2262  0.0981     2.3069  0.0304

Residual standard error: 0.2819 on 23 degrees of freedom
Multiple R-Squared: 0.8073      Adjusted R-squared: 0.7906
F-statistic: 48.18 on 2 and 23 degrees of freedom, the p-value is 5.969e-009
1 observations deleted due to missing values

Analysis of Variance Table

Response: Log.TSS

Terms added sequentially (first to last)
          Df Sum of Sq  Mean Sq  F Value      Pr(F)
 Log.Turb  1  7.234734 7.234734 91.03984 0.00000000
    Log.Q  1  0.422902 0.422902  5.32168 0.03041015
Residuals 23  1.827759 0.079468
```

Appendix 1. S–PLUS output of regression model development of turbidity, streamflow, suspended-sediment concentration, and total suspended-solids concentration for two main monitoring sites (stations 08067650 and 08068000) in the West Fork San Jacinto River Basin, Texas, July 2008–August 2009—Continued.

Explanation of Abbreviations and Terms

SSC	suspended-sediment concentration, in milligrams per liter
TSS	total suspended-solids concentration, in milligrams per liter
Turb	turbidity, in Formazin nephelometric units
Q	streamflow, in cubic feet per second
Log (x)	Base-10 logarithm of x
lm	linear model function in S-Plus
SJ105	San Jacinto River at State Highway 105; U.S. Geological Survey streamflow-gaging station 08067650 West Fork San Jacinto River below Lake Conroe near Conroe, Tex.
na.action	S-Plus function setting (argument) used to process missing values
na.exclude	S-Plus function setting (argument) to exclude missing values
min	minimum
1Q	first quartile
3Q	third quartile
max	maximum
std. error	standard error
t value	test statistic from the student's t distribution
Pr (F)	probability of the F value
Pr(>|t|)	probability of obtaining a t value at least as extreme as the one observed, if the null hypothesis is true
Residual standard error	standard error of the residuals
Df	degrees of freedom
Sum of Sq	sum of squares
Mean Sq	mean square
F Value	value of the F statistic, used to test statistical hypotheses about the mean
Call:	S-Plus invocation of the regression model
p-value	probability associated with the test statistic
Value Std. Error	standard error of the value

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