Historical Channel Adjustment and Estimates of Selected Hydraulic Values in the Lower Sabine River and Lower Brazos River Basins, Texas and Louisiana

By Franklin T. Heitmuller and Lauren E. Greene

In cooperation with the Texas Water Development Board

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Conversion Factors and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Pressure	
pound per square foot (lb/ft^2)	0.04788	kilopascal (kPa)

Datums

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

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

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Abstract

The U.S. Geological Survey, in cooperation with the Texas Water Development Board, evaluated historical channel adjustment and estimated selected hydraulic values at U.S. Geological Survey streamflow-gaging stations in the lower Sabine River Basin in Texas and Louisiana and lower Brazos River Basin in Texas to support geomorphic assessments of the Texas Instream Flow Program. Channel attributes including cross-section geometry, slope, and planform change were evaluated to learn how each river's morphology changed over the years in response to natural and anthropogenic disturbances. Historical and contemporary cross-sectional channel geometries at several gaging stations on each river were compared, planform changes were assessed, and hydraulic values were estimated including mean flow velocity, bed shear stress, Froude numbers, and hydraulic depth. The primary sources of historical channel morphology information were U.S. Geological Survey hard-copy discharge-measurement field notes. Additional analyses were done using computations of selected flow hydraulics, comparisons of historical and contemporary aerial photographs, comparisons of historical and contemporary ground photographs, evaluations of how frequently stage-discharge rating curves were updated, reviews of stage-discharge relations for field measurements, and considerations of bridge and reservoir construction activities. Based on historical cross sections at three gaging stations downstream from Toledo Bend Reservoir, the lower Sabine River is relatively stable, but is subject to substantial temporary scour-and-fill processes during floods. Exceptions to this characterization of relative stability include an episode of channel aggradation at the Sabine River near Bon Wier, Texas, during the 1930s, and about 2 to 3 feet of channel incision at the Sabine River near Burkeville, Texas, since the late 1950s. The Brazos River, at gaging stations downstream from Waco, Texas, has adjusted to a combination of hydrologic, sedimentary, and anthropogenic controls. Since the 1960s, numerous point bars have vertically accreted and vegetation has encroached along the channel margins, which probably promotes channel-bed incision to compensate for a reduction in cross-sectional area. Channel incision was detected at all gaging stations along the Brazos River, and the depth of incision is greatest in the lowermost gaging stations, exemplified by about 5 feet of channel-bed incision between 1993 and 2004 at Richmond, Texas. One notable exception to this pattern of incision was a period of aggradation at U.S. Geological Survey gaging station 08096500 Brazos River at Waco, Texas, during the late 1920s and 1930s, probably associated with upstream dam construction. Lateral channel migration rates along the Brazos River determined from aerial photographs are greatest between Waco and Hempstead, Texas, with numerous bends moving an average of more than 10 feet per year. Migration rates at selected bends downstream from Hempstead were measured as less than 10 feet per year, on average. Two tributaries of the Brazos River, the Little and Navasota Rivers, also were investigated for historical channel adjustment. The Little River near Cameron, Texas (08106500) has incised its channel bed about 12 feet since 1949, and the lower Navasota River shows complex adjustment to bridge construction activities and a channel avulsion.

Introduction

The Sabine River in Texas and Louisiana and the Brazos River in Texas are alluvial rivers; alluvial river channels are dynamic systems that adjust their geometry according to differential rates of streamflow (discharge) and sediment load (Knighton, 1998). Starting in the 1920s, several dams have been constructed on the Sabine and Brazos Rivers and their tributaries, and numerous bridges have been built and sometimes replaced multiple times, which has changed the natural flow regime and reduced or altered sediment loads downstream. Changes in channel geometry over time can reduce channel conveyance and thus streamflow, which can have adverse ecological effects.

A number of public agencies, institutions, and organizations in the United States and abroad currently (2009) are implementing instream flow programs for selected rivers and streams, which are intended to quantify various flows representing the natural flow regime and to maintain a set of environmental standards. One such program, the Texas Instream

Flow Program, is administered by three State agencies (Texas Commission on Environmental Quality, 2009; Texas Parks and Wildlife Department, 2009; and Texas Water Development Board, 2009). In accordance with recommendations by the National Academy of Sciences, the Texas Instream Flow Program includes four types of technical evaluations to define a "sound ecological environment" of a river system: (1) hydrology and hydraulics; (2) biology; (3) geomorphology and physical processes; and (4) water quality (National Research Council of the National Academies, 2005). The first rounds of evaluations are being done in priority basins, including the lower Sabine River (downstream from Toledo Bend Reservoir on the Texas-Louisiana border to the Gulf of Mexico), middle Trinity River, lower Brazos River (downstream from Waco, Tex., to the Gulf of Mexico), middle Brazos River, lower Guadalupe River, and lower San Antonio River.

The physical processes of erosion, sediment transport, and deposition govern the geometry of the channel and its association to overbank riparian environments. These processes are important to the Texas Instream Flow Program goal of defining a sound ecological environment because they help to maintain the physical template (habitats) on which aquatic and riparian ecosystems function. Accordingly, the U.S. Geological Survey (USGS), in cooperation with Texas Water Development Board, evaluated historical channel adjustment and estimated selected hydraulic values (mean velocity, bed shear stress, Froude numbers, and hydraulic depth) at three streamflow-gaging stations on the lower Sabine River and at 11 streamflow-gaging stations on the lower Brazos River using streamflow and channel data from the available historical records at each site. Historical channel adjustment and hydraulic values also were determined at one site on the middle Brazos River.

The historical records available at each gaging station were augmented using alternative techniques and additional sources of data for interpreting channel adjustment. The primary objective of the study was to investigate how the channel morphology of the rivers has changed in response to reservoirs and other anthropogenic disturbances. The results of this study are expected to aid ecological assessments in the lower Sabine River and lower Brazos River Basins for the Texas Instream Flow Program by documenting methods used to reconstruct historical channel geometry, establish trends in channel adjustment, and infer causes of that change.

Purpose and Scope

The purpose of this report is to document historical channel adjustment and estimates of selected hydraulic values in the lower Sabine and lower Brazos River Basins in response to reservoir and bridge construction, other anthropogenic disturbances, and naturally occurring fluvial processes. The report is structured as a series of analyses organized by streamflow-gaging station. Site-specific interpretations of channel adjustment and estimates of mean velocity, bed shear stress, Froude numbers, and hydraulic depth are provided for USGS gaging-station sites and extrapolated to longer channel reaches. Cross-sectional channel adjustment was quantified and hydraulic values were estimated at three streamflow-gaging stations in the lower Sabine River Basin, at 11 streamflow-gaging stations in the lower Brazos River Basin, and at one streamflow-gaging station in the middle Brazos River Basin. Historical USGS field-measurement data for entire periods of record were digitized and analyzed to quantify channel adjustments. Alternative techniques are used to quantitatively and qualitatively assess historical adjustments in channel geometry. These techniques, in addition to computation of mean velocity, bed shear stress, Froude numbers and hydraulic depth, comprise evaluation of updates to stage-discharge rating curves; evaluation of stage-discharge relations for field measurements; comparison of historical and contemporary aerial photographs (using georectification techniques); and comparison of historical and contemporary photographs taken on the ground (repeat ground photography).

In addition to documenting historical channel adjustments and estimates of hydraulic values, this report is intended to provide practitioners with (1) a procedural framework to use USGS streamflow data and other sources to quantify changes in channel morphology during the period of streamflow-gaging-station record, and (2) information on patterns of channel change in the aforementioned river basins. Currently (2009), Texas has more than 570 streamflow-gaging stations with field-measurement data that would be amenable to the analyses used in this report.

Previous Studies and Background Information

Changes in channel geometry tend to occur slowly in undisturbed systems but can be greatly accelerated in response to disturbances. In fluvial geomorphology, the term "channel adjustment" refers to river channel changes in three geometric dimensions: (1) channel slope (profile); (2) the planform, including meandering and braiding (pattern); and (3) cross-sectional form (shape). Historical adjustments to river channel geometry have been attributed to a number of influences, notably changes in hydrologic regime (Schumm, 1968; Blum and Valastro, 1989; Knox, 1995); indirect anthropogenic controls, including urbanization (Wolman, 1967) and land-cover change (Knox, 1977); and direct anthropogenic controls, including reservoir impoundment (Williams and Wolman, 1984; Graf, 2001) and channel modification (Brookes, 1988; Kondolf, 1997). Rapid and sustained adjustments to river channel geometry, on the order of years to decades, usually result in undesirable consequences, which can include increased (or decreased) flood frequency, damage to public and private infrastructure, hydrologic disconnection between channels and floodplains, and modification of unique habitat structures.

Assessing changes in river channel geometry requires historical sources of information. A variety of studies have addressed river channel adjustment as a result of hydrologic regime changes over thousands of years (Schumm, 1968; Blum and Valastro, 1989; Knox, 1995). The hydrologic

regime specifically refers to the type of seasonal precipitation patterns, storm characteristics (rainfall intensity, storm size, and so forth), and magnitude-frequency relations of floods and droughts (Charlton, 2008). Other studies have focused on shorter, contemporary timescales, usually as a result of direct or indirect anthropogenic controls (Williams and Wolman, 1984; Kondolf, 1997; Juracek, 2001).

Studies of channel adjustment can take advantage of advances in data collection over time, including aerial photographic surveys, satellite imagery, ground-elevation surveying improvements, and, most recently, **Li**ght **D**etection **A**nd **R**anging (LiDAR) technology. Much geospatial information can be attributed to improvements in computational resources, notably geographic information system (GIS) technology, which enables relatively rapid quantitative assessments of channel adjustment through time.

One of the basic requirements for assessing channel adjustment is establishing change or constancy in shape and bed elevation through time. To do so requires (1) elevation measurements of the channel bed and banks at a consistent location through time and (2) documentation of the reference elevation datum, whether geographic (North American Vertical Datum of 1929) or arbitrary (site specific). The USGS has operated thousands of streamflow-gaging stations in the United States since 1889, each with the specific purpose of quantifying the volume of flow in the river or stream through time, as well as other data-collection activities. Many of these gaging stations are no longer active, but almost 15,000 of them have publicly viewable discharge-measurement field data for various periods of record, summarized in the USGS National Water Information System (NWIS) (U.S. Geological Survey, 2008). These field measurements include water-surface width in feet, flow depth in feet, and flow velocity in feet per second; all are required for computation of discharge in cubic feet per second but also are useful to quantify cross-sectional channel geometry through time (Juracek and Fitzpatrick, 2008). Discharge measurements are made at gaging stations to account for (1) the entire range of flows at the site (highest to lowest flows and those in between) and (2) changes in cross section, channel, and overbank controls that affect cross-sectional area of flow and flow resistance (for example, channel-bed aggradation or degradation, channel expansion or contraction, or vegetation removal or growth on floodplains). Field measurements are used to generate and update on an ongoing basis a rating curve of stage (relative water-surface elevation) and discharge. Rating curves are a statistical tool used to (1) interpolate streamflow for all stages between the lowest and highest measurements and (2) extrapolate streamflow for all stages lower and higher than the most extreme measurements.

Although acoustic-Doppler technology is becoming increasingly common for making high-flow measurements (Costa and others, 2000), most discharge measurements have been made with current meters suspended from a bridge or cableway or by wading the stream with a hand-held current meter along a tagline across the channel perpendicular to the flow (Carter and Davidian, 1968). For one bridge, cable, or wading measurement, hydrologic technicians make multiple measurements of flow depth and mean velocity at specified intervals of water-surface width, so that the channel is subdivided into vertical sections, each with its own depth and mean velocity (Buchanan and Somers, 1969). Discharge is computed as the product of the mean velocity and area in each subdivision and summed for the total discharge. Depending on changes in section or channel controls, streamflow conditions, bridge locations, or simply transfer of site responsibilities from one technician to another, the exact cross section where measurements are made for one gaging station can shift upstream or downstream; however they often are made at a consistent location such as the upstream side of a bridge.

Individual field measurements of water-surface width, depth, and mean velocity are recorded in the field on hard-copy forms and stored at USGS water-science centers or Federal archives across the country. The majority of data analyzed in this report are derived from historical hard-copy field notes of USGS discharge measurements. For the stations investigated in this report, hard-copy field notes from the late 1970s to 2008 were available in USGS Texas Water Science Center files. For field notes prior to the late 1970s, an official recall of records from the Federal Archives in Fort Worth, Tex., was required. Currently (2009) no published or unpublished digital versions of these data exist.

Information on these hard-copy measurement forms can be used to graph cross-sectional geometry of the river channel at the discharge measurement site. If measurements are made at a consistently located cross section through time, changes in channel shape can be assessed for the period of record. Additionally, the USGS archives contain summaries of field-measurement data, including total water-surface width, cross-sectional area, mean velocity, gage height (stage), and discharge (streamflow), thereby providing another method to infer channel change through time by examining the relation between streamflow and values associated with channel shape (for example, water-surface width, cross-sectional area, gage height).

Changes in the relation of streamflow to gage height indicate that the cross section has changed (cross-sectional adjustment). A change in the cross section that increases gage height for a given discharge through time implies channel-bed aggradation (vertical accretion) or channel contraction, whereas a decrease in gage height for a given discharge through time implies channel-bed degradation or channel expansion. The simultaneous relations of discharge to water-surface width and cross-sectional area are useful for confirming cross-sectional adjustments.

An important limitation to assessments of channel adjustment using USGS streamflow data involves the extrapolation of site-specific interpretations to longer channel reaches. Gaging-station locations commonly are chosen because they differ from nearby reaches, simplifying the development of stable stage-discharge relations. For example, it is preferable to install fixed equipment at a cross section to measure flow through time where the cross section is not laterally active,

such as a straight reach with a stable channel, as opposed to a meander bend in an unconfined alluvial valley. Further, accurate stage-discharge relations are more easily developed if a fixed control along the channel bed is downstream, such as a localized bedrock exposure. How representative a gaging-station location is to the channel reach is important in studies that use gaging-station data to assess channel adjustment. The tendency to locate streamflow-gaging stations along relatively stable channel reaches likely provides a conservative understanding of morphologic stability for the larger river system.

Description of Study Area

The selected gaging stations (table 1) were in the lower Sabine River Basin or lower Brazos River Basin (fig. 1), except for 08096500 Brazos River at Waco, Tex., in the middle Brazos River Basin. The Sabine River Basin downstream from Toledo Bend Reservoir, unlike the Brazos River Basin downstream from Waco, has more surface exposures of Pleistocene terrace deposits, namely the sand and gravel deposits of the Deweyville terraces (Blum and others, 1995). Including the Deweyville terraces, the width of the valley downstream from Toledo Bend Reservoir ranges between approximately 3 and 6 miles. The lower Brazos River Basin is entirely in Texas and extends approximately from Waco to the Gulf of Mexico near Freeport, traversing the Gulf Coastal Plain physiographic province (Wermund, 1996), which is characterized by gently rolling to relatively flat topography. The Texas Gulf Coastal Plain consists of Cretaceous, Tertiary, and Pleistocene sedimentary strata, mostly characterized by alternating beds of sandstone and shale, gently dipping toward the southeast (The University of Texas at Austin, Bureau of Economic Geology, 1968a,b; 1970; 1975; 1982).

Set within the geologic framework are valleys consisting of Holocene alluvium and older Pleistocene terrace deposits with meandering rivers. The Brazos River downstream from Waco formed an alluvial valley that ranges between about 3 and 6 miles wide and locally contracts to less than 3 miles wide where relatively resistant valley margins occur. About 45 miles northwest of Freeport, the alluvial valley widens into an extensive alluvial-deltaic plain.

The climate of the lower Sabine River Basin and the Brazos River Basin is humid subtropical, common throughout East Texas and Louisiana. Near Waco, average annual precipitation is about 35 inches, and near Freeport, average annual precipitation is about 50 inches (Texas Parks and Wildlife Department, 2008). West of Waco, the climate transitions to semiarid; a large part of the Brazos River Basin is in this drier setting. The Sabine River valley downstream from Toledo Bend Reservoir is in the wettest part of the state, receiving on average about 55 inches of precipitation per year (Texas Parks and Wildlife Department, 2008).

Equally important as climate in controlling the hydrologic regime of the two river systems are numerous reservoirs that regulate downstream flow releases (fig. 1; table 2). The hydrologic regimes of the two rivers and their tributaries reflect the combined influences of climate, flow regulation, and drainage area (table 3). Whereas daily mean streamflow increases downstream for the Brazos and Sabine Rivers, average annual peak streamflow increases only slightly for the Sabine River and decreases for the Brazos River between Bryan and Rosharon as a result of flood attenuation and floodplain storage. Although some variability is evident, the discharge at flood stage (National Weather Service, 2008) decreases downstream for both rivers, greatly so for the Sabine River, possibly as a result of (1) greater channel incision rates and the associated increase in channel cross-sectional area immediately downstream from reservoir impoundments; (2) a gradual decrease in floodplain elevation and proximity to base level near the coast; or (3) a combination of channel-bed adjustment, base level, and floodplain elevations. Maximum recorded discharges for the selected gaging stations have occurred on different dates during the periods of record, indicating that diverse, location-dependent mechanisms are responsible for floods in the two basins.

The influence of flow regulation by upstream dams varies in each river system (table 4). Since flows have been regulated, median daily mean streamflow generally has increased in the Sabine River downstream from Toledo Bend Reservoir and has decreased slightly along the lower Brazos River. Little River and Navasota River, tributaries of the Brazos River, show a general increase in median daily mean streamflow (between 20 and 30 percent), although average daily mean streamflows are similar to pre-impoundment conditions. Average annual peak streamflow before and after impoundment of Toledo Bend Reservoir is similar for the Sabine River but has been substantially reduced along the lower Brazos River and Little River following the completion of upstream reservoirs. Further, it has been shown that cross-sectional channel geometry of the Brazos River has adjusted, likely as a result of decreased sediment loads associated with upstream reservoirs (Dunn and Raines, 2001). Navasota River average annual peak streamflow either was similar to pre-dam flows or increased following the construction of upstream reservoirs.

Acknowledgments

The authors thank Greg Malstaff and Mark Wentzel of the Texas Water Development Board for their guidance and support of this study. Also, the authors thank Jonathan Phillips (University of Kentucky) and John Elliott (USGS) for insightful reviews of the report.

Methods

The primary techniques used for evaluating channel adjustment were: (1) digitization of historical cross sections from USGS streamflow measurements; and (2) hydraulic analyses of historical cross sections. The following supplementary techniques for evaluating channel adjustments were used when

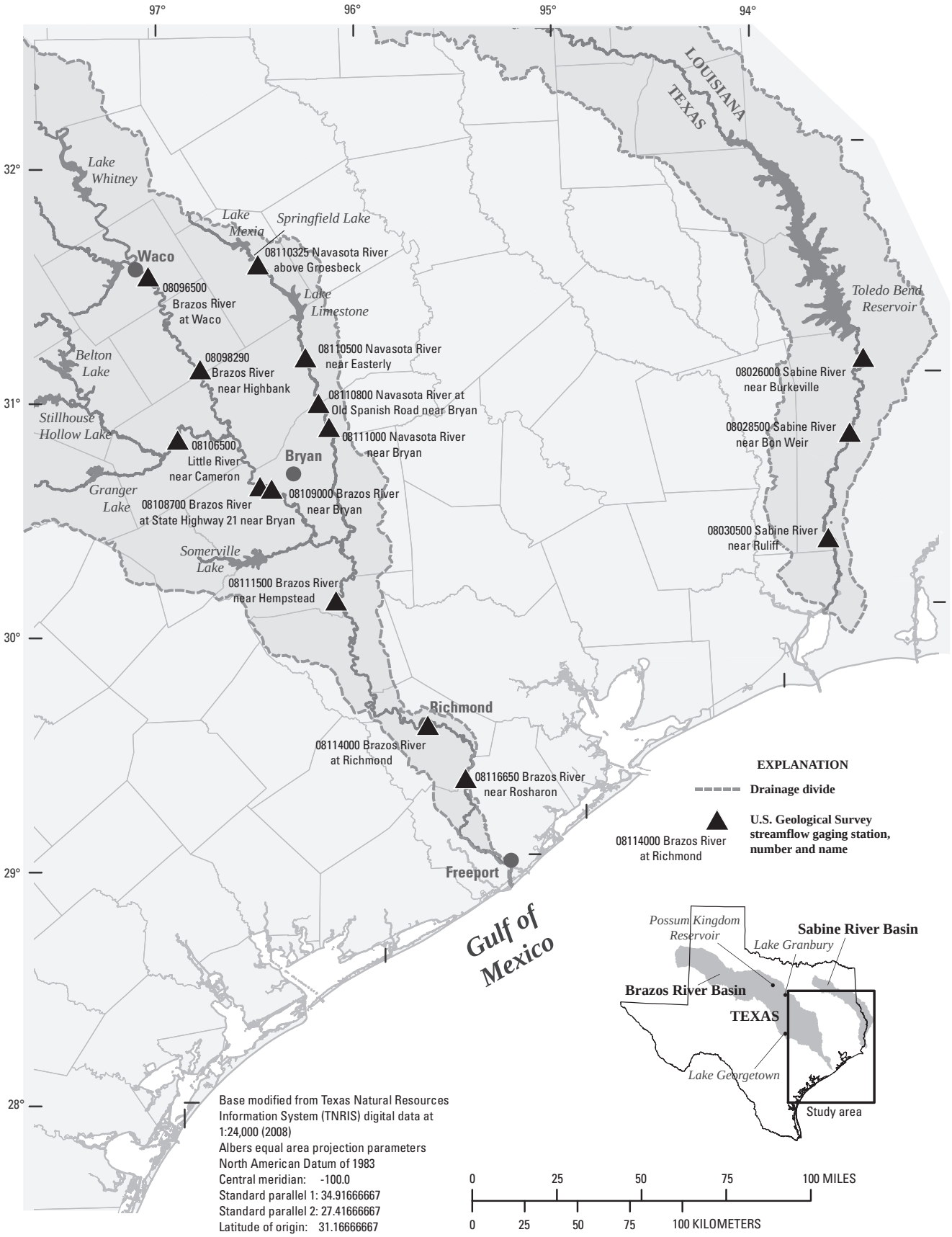

Figure 1. Location of U.S. Geological Survey streamflow-gaging stations examined for cross-sectional channel adjustment using historical field-measurement data, lower Sabine and lower Brazos River Basins, Texas, and Louisiana.

Table 1. U.S. Geological Survey streamflow-gaging stations examined for cross-sectional channel adjustment using historical field-measurement data, lower Sabine and lower Brazos River Basins, Texas and Louisiana.

[ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929; present, 2009; --, not available]

Station number (fig. 1)	Station name	Period of record	Bed-material composition	Stage-datum elevation (ft above NGVD 29)
08026000	Sabine River near Burkeville, Tex.	Sept. 1955–present	Sand	60.59
08028500	Sabine River near Bon Wier, Tex.	Oct. 1923–present	Sand	33.42
08030500	Sabine River near Ruliff, Tex.	Oct. 1924–present	Sand	-5.92
08096500	Brazos River at Waco, Tex.	Oct. 1898–present	Gravel and sand	349.3
08098290	Brazos River near Highbank, Tex.	Oct. 1965–present	Gravel, sand, and bedrock	279.3
08106500	Little River near Cameron, Tex.	Nov. 1916–present	Gravel and sand	281.9
08108700	Brazos River at State Highway 21 near Bryan, Tex.	July 1993–present	Sand	189.3
08109000	Brazos River near Bryan, Tex.	Aug. 1899–Dec. 1902; Mar. 1918–Dec. 1925; July 1926–Sept. 1993	Sand	192.3
08110325	Navasota River above Groesbeck, Tex.	June 1978–present	Fine sand and silt	396.6
08110500	Navasota River near Easterly, Tex.	Apr. 1924–present	Sand and silt	271.5
08110800	Navasota River at Old Spanish Road near Bryan, Tex.	Apr. 1997–present	Sand and silt	245.0
08111000	Navasota River near Bryan, Tex.	Jan. 1951–Mar. 1997	Sand and silt	224.6
08111500	Brazos River near Hempstead, Tex.	Oct. 1938–present	Sand	107.9
08114000	Brazos River at Richmond, Tex.	Jan. 1903–June 1906; Oct. 1922–present	Sand	27.94
08116650	Brazos River near Rosharon, Tex.	Apr. 1967–present	Sand	--

Table 2. Reservoirs regulating streamflow to U.S. Geological Survey streamflow-gaging stations, lower Sabine and lower Brazos River Basins, Texas and Louisiana.

Reservoir (fig. 1)	Purpose[1]	Stream impounded	Date of water impoundment
Toledo Bend Reservoir	Power generation, recreation, water supply	Sabine River	Oct. 3, 1966
Possum Kingdom Reservoir	Flood control, power generation, recreation, water supply	Brazos River	Mar. 21, 1941
Lake Granbury	Recreation, water supply	Brazos River	Sept. 15, 1969
Lake Whitney	Flood control, power generation, recreation, water supply	Brazos River	Dec. 10, 1951
Lake Waco	Flood control, recreation, water supply	North and South Bosque Rivers	[2]1929; Feb. 26, 1965
Belton Lake	Flood control, recreation, water supply	Leon River	Mar. 8, 1954
Stillhouse Hollow Lake	Flood control, recreation, water supply	Lampasas River	Feb. 19, 1968
Lake Georgetown	Flood control, recreation, water supply	North San Gabriel River	Mar. 3, 1980
Granger Lake	Flood control, recreation, water supply	San Gabriel River	Jan. 21, 1980
Somerville Lake	Flood control, recreation, water supply	Yegua Creek	Jan. 3, 1967
Lake Mexia	Recreation, water supply	Navasota River	June 5, 1961
Springfield Lake	Recreation, water supply	Navasota River	1939
Lake Limestone	Recreation, water supply	Navasota River	Oct. 16, 1978

[1] Reservoir information from Texas Water Development Board (1973, 1974) and Texas State Historical Association (2008).

[2] Original dam completed in 1929, but dam replaced in 1965.

Table 3. Hydrologic data summary for periods of record through February 27, 2008, of U.S. Geological Survey streamflow-gaging stations examined for cross-sectional channel adjustment using historical field-measurement data, lower Sabine and lower Brazos River Basins, Texas and Louisiana.

[mi², square miles; km², square kilometers; Q, discharge; ft³/s, cubic feet per second; m³/s, cubic meters per second; --, not available]

Station number and name (fig. 1)	Contributing drainage area [mi² (km²)]	Mean daily Q [ft³/s (m³/s)]	Median daily Q [ft³/s (m³/s)]	Flood stage Q[1] [ft³/s (m³/s)]	Average annual peak Q [ft³/s (m³/s)]	Maximum Q [ft³/s (m³/s)]	Hydrologic year of maximum Q
08026000 Sabine River near Burkeville, Tex.	7,482 (19,378)	5,530 (157)	2,590 (73)	63,000 (1,780)	32,500 (920)	124,000 (3,510)	1999
08028500 Sabine River near Bon Wier, Tex.	8,229 (21,313)	6,920 (196)	3,380 (96)	27,500 (779)	36,700 (1,040)	115,000 (3,260)	1953
08030500 Sabine River near Ruliff, Tex.	9,329 (24,162)	8,300 (235)	4,510 (128)	13,300 (377)	42,600 (1,210)	121,000 (3,430)	1953
08096500 Brazos River at Waco, Tex.	19,993 (51,782)	2,400 (68)	771 (22)	41,000 (1,160)	45,600 (1,290)	246,000 (6,970)	1936
08098290 Brazos River near Highbank, Tex.	20,870 (54,053)	2,840 (80)	1,000 (28)	[2]84,240 (2,390)	31,100 (881)	78,700 (2,230)	1986
08106500 Little River near Cameron, Tex.	7,065 (18,298)	1,780 (50)	468 (13)	23,000 (651)	40,600 (1,150)	647,000 (18,320)	1921
08108700 Brazos River at State Highway 21 near Bryan, Tex.	29,483 (76,361)	5,340 (151)	1,620 (46)	73,200 (2,070)	49,200 (1,390)	85,900 (2,430)	2007
08109000 Brazos River near Bryan, Tex.	29,949 (77,568)	5,290 (150)	1,780 (50)	-- (--)	62,300 (1,790)	[3]172,000 (4,870)	[3]1921; 1944
08110325 Navasota River above Groesbeck, Tex.	239 (619)	116 (3.3)	1 (.03)	3,730 (106)	9,790 (277)	27,200 (770)	1979
08110500 Navasota River near Easterly, Tex.	968 (2,507)	428 (12)	27 (.76)	2,810 (80)	[4]17,100 (484)	[5]90,000 (2,550)	[5]1899
08110800 Navasota River at Old Spanish Road near Bryan, Tex.	1,287 (3,333)	607 (17)	69 (2.0)	4,900 (139)	18,600 (527)	30,900 (875)	2007
08111000 Navasota River near Bryan, Tex.	1,454 (3,766)	[6]557 (16)	[6]53 (1.5)	-- (--)	14,200 (402)	66,600 (1,890)	1992
08111500 Brazos River near Hempstead, Tex.	34,314 (88,873)	7,050 (200)	2,560 (72)	103,000 (2,920)	55,400 (1,570)	143,000 (4,050)	1957
08114000 Brazos River at Richmond, Tex.	35,541 (92,051)	7,580 (215)	2,940 (83)	81,800 (2,320)	56,380 (1,600)	123,000 (3,480)	1929
08116650 Brazos River near Rosharon, Tex.	35,773 (92,652)	8,370 (237)	3,420 (97)	52,600 (1,490)	49,480 (1,400)	84,400 (2,390)	1995

[1] Flood stage from National Weather Service (2008); discharge associated with flood stage recorded from current (February 2008) U.S. Geological Survey stage-discharge rating tables.

[2] Determined by extension of current rating curve (February 2008), using a power function, for all stage-discharge pairings greater than or equal to 4,000 ft³/s.

[3] Peak discharge not available for hydrologic year 1921, although mean discharge for September 12, 1921, listed at 172,000 ft³/s (4,870 m³/s), suggesting peak discharge for entire period of record occurred on this date. Peak discharge for hydrologic year 1944 also 172,000 ft³/s (4,870 m³/s).

[4] Computed for period of record; does not include peak streamflow estimate from 1899.

[5] Peak estimate for documented flood stage in calendar year 1899; prior to period of record of gaging station.

[6] Computed for January 1951 to September 1994 because of intermittent data between October 1994 and March 1997.

possible: (a) evaluation of changes in stage-discharge rating curves; (b) evaluation of changes in stage-discharge relations of field measurements; (c) GIS analyses of river planform; (d) repeat ground photography at USGS streamflow-gaging stations; and (e) assessment of bridge construction activity at gaging stations and dam construction upstream from gaging stations. For this report, the term “hydraulic properties” is used to represent attributes of a given channel cross section, either measured in the field by hydrologic technicians making streamflow measurements or derived from measured channel

Table 4. Hydrologic data summary for pre- and post-regulation conditions through February 28, 2008, of U.S. Geological Survey streamflow-gaging stations examined for cross-sectional channel adjustment using historical field-measurement data, lower Sabine and lower Brazos River Basins, Texas and Louisiana.

[Q, discharge; ft^3/s, cubic feet per second; m^3/s, cubic meters per second]

Station number and name[1] (fig. 1)	Major regulating reservoir[2]; date of impoundment	Pre-regulation mean; median daily Q [ft^3/s (m^3/s)]	Post-regulation mean; median daily Q [ft^3/s (m^3/s)]	Percent difference between pre- and post-regulation mean; median daily Q	Pre-regulation average annual peak Q [ft^3/s (m^3/s)]	Post-regulation average annual peak Q [ft^3/s (m^3/s)]	Percent difference between pre- and post-regulation average annual peak Q	Pre-regulation maximum Q [ft^3/s (m^3/s)]	Post-regulation maximum Q [ft^3/s (m^3/s)]
08026000 Sabine River near Burkeville, Tex.	Toledo Bend Reservoir; Oct. 3, 1966	4,620 (131); 1,470 (42)	5,770 (163); 2,970 (84)	24.9; 102.0	[3]27,400 (776)	33,900 (960)	[3]23.7	[3]52,900 (1,500)	124,000 (3,510)
08028500 Sabine River near Bon Wier, Tex.	Toledo Bend Reservoir; Oct. 3, 1966	6,840 (194); 2,780 (79)	6,990 (198); 3,980 (113)	2.2; 43.2	37,100 (1,050)	36,400 (1,030)	-1.9	115,000 (3,260)	98,200 (2,780)
08030500 Sabine River near Ruliff, Tex.	Toledo Bend Reservoir; Oct. 3, 1966	8,420 (238); 3,830 (108)	8,190 (232); 5,040 (143)	-2.7; 31.6	43,300 (1,230)	41,700 (1,180)	-3.7	121,000 (3,430)	109,000 (3,090)
08096500 Brazos River at Waco, Tex.	Lake Whitney; Dec. 5, 1951	2,590 (73); 740 (21)	2,230 (63); 789 (22)	-13.9; 6.6	63,800 (1,810)	28,700 (813)	-55.0	246,000 (6,970)	101,000 (2,860)
08106500 Little River near Cameron, Tex.	Belton Lake; Mar. 8, 1954	1,760 (50); 422 (12)	1,800 (51); 510 (14)	2.3; 20.9	56,300 (1,590)	29,600 (838)	-47.4	647,000 (18,300)	116,000 (3,280)
08109000 Brazos River near Bryan, Tex.[4]	Lake Whitney; Dec. 5, 1951	5,630 (159); 1,960 (56)	5,090 (144); 1,660 (47)	-9.6; -15.3	76,400 (2,160)	50,900 (1,440)	-33.4	172,000 (4,870)	163,000 (4,620)
08110500 Navasota River near Easterly, Tex.	Lake Limestone; Oct. 16, 1978	428 (12); 25 (0.71)	428 (12); 30 (0.85)	0; 20.0	[5]16,700 (473)	17,700 (501)	6.0	[6]90,000 (2,550)	61,800 (1,750)
08111000 Navasota River near Bryan, Tex.[7]	Lake Limestone; Oct. 16, 1978	[8]542 (15); 50 (1.4)	[8]592 (17); 64 (1.8)	9.2; 28.0	13,400 (379)	38,200 (1,080)	185.1	17,000 (481)	66,600 (1,890)
08111500 Brazos Rivernear Hempstead, Tex.	Lake Whitney; Dec. 5, 1951	7,410 (210); 2,660 (75)	6,960 (197); 2,540 (72)	-6.1; -4.5	68,500 (1,940)	52,300 (1,480)	-23.6	116,000 (3,280)	143,000 (4,050)
08114000 Brazos River at Richmond, Tex.	Lake Whitney; Dec. 5, 1951	7,690 (218); 3,030 (86)	7,520 (213); 2,890 (82)	-2.2; -4.6	63,300 (1,790)	52,200 (1,480)	-17.5	123,000 (3,480)	119,000 (3,370)

[1] Stations 08098290, 08110325, and 08116650 not included because periods of record follow date of impoundment of major regulating reservoir.

[2] Major regulating reservoir qualitatively determined by upstream proximity of reservoir, purpose of reservoir, date of impoundment, and major tributary contributions.

[3] Based on 11 peak streamflow values available prior to impoundment of Toledo Bend Reservoir; might not reflect long-term peak-streamflow conditions.

[4] Period of record combined with 08108700 Brazos River at State Highway 21 near Bryan, Tex., and applied to post-impoundment statistics.

[5] Computed for period of record prior to Oct. 16, 1978; does not include peak-streamflow estimate of 90,000 ft^3/s (2,550 m^3/s) from 1899.

[6] Peak estimate for documented flood stage in calendar year 1899; prior to period of record of gaging station.

[7] Period of record combined with 08110800 Navasota River at Old Spanish Road near Bryan, Tex., and applied to post-impoundment statistics.

[8] Computed without period of record between October 1994 and March 1997 because of intermittent data.

properties. Hydraulic properties are channel cross-section area, channel slope, hydraulic radius, Manning's *n* roughness coefficient, and water-surface width. Hydraulic values were derived through various computational methods using the hydraulic properties. Hydraulic values are mean flow velocity, bed shear stress, Froude number, and hydraulic depth.

Use of Historical Cross Sections from USGS Streamflow Measurement Data to Evaluate Channel Adjustments

USGS hard-copy field-measurement notes (fig. 2) provide the primary source of data for constructing historical channel cross sections in the lower Sabine River and lower Brazos River Basins. For the gaging stations investigated in this study, discharge measurement notes for approximately the last 30 years were available at the USGS Texas Water Science Center offices in Austin and Houston, and older records were obtained from the Federal Archives in Fort Worth. Not all discharge measurement notes were obtainable for this study from the Federal Archives. USGS hydrologic technicians record hydraulic properties including water-surface elevation and channel-geometry information (cross-section area, hydraulic radius, and water-surface width) when measuring discharge. Estimates of additional hydraulic properties including channel slope and Manning's *n* roughness coefficient (Roberson and Crowe, 1980) were derived by the authors. An approximate value of channel slope at each gaging station was determined by extracting upstream and downstream channel elevations from 10-meter digital elevation models (DEMs) using historical information obtained from streamflow measurements. Manning's n roughness coefficients were computed using hydraulic radius and channel slope adjusted for each hydraulic computation to provide the closest match to the known streamflow.

The information required to reconstruct cross-sectional channel geometry from field notes includes weighted mean gage height (water-surface elevation), distance from initial point (cross-section distance), and depth below the water surface. In most cross-sectional measurements, depth is simply subtracted from weighted mean gage height at each section distance to reconstruct channel-bed and bank elevations.

Information digitized to reconstruct the cross section included "Weighted MGH" (mean gage height) on the form front (fig. 2A), as well as "Dist. (distance) from initial point" and "Depth" on the form back (fig. 2B). The weighted mean gage height represents the elevation of the water surface (stage) during the time of the streamflow measurement. At most USGS gaging stations, an arbitrary elevation datum is established; benchmarks and stage-recording equipment are surveyed with respect to that datum. Stage can be either manually measured using a previously installed staff gage or wire weight lowered to the water surface or read from recording instruments at the gage shelter. Discharge measurements typically take an hour or longer, especially if multiple overflow channels are measured, and the water stage can rise, fall, or remain stable during the course of the measurement. Because stage is known to vary over short periods of time during high flows or flow releases from upstream reservoirs, hydrologic technicians incrementally record the stage during the discharge measurement. The weighted mean gage height is computed by summing incremental gage heights by incremental streamflow and dividing the sum by total streamflow (Rantz and others, 1982). Although incremental stage measurements would more accurately define the water-surface elevation and, therefore, depths to the channel bed, this investigation used the weighted mean gage height to represent water-surface elevation. Because no substantial changes in gage height were noted during discharge measurements used in this study, cross-sectional geometry should accurately define historical channel-bed and bank elevations.

The distance from initial point (cross-section distance) represents the horizontal location where one of multiple depth and velocity measurements is made across the channel. For a series of low-flow wading measurements, the cross-section distance is usually not consistent through space and time because the zero distance of a tag line is established at a new, undesignated position on the bank each time a discharge measurement is made. A series of measurements made from a cableway or bridge, however, often have consistent cross-section distances through time because the cable or bridge rail is painted or otherwise marked. It is this consistency in streamwise position and section distance that enables comparison of cross-sectional channel geometry through time. The ability to compare cross sections through time can be severely compromised when section distance markers are changed, such as would occur when a new bridge is constructed, the measurement section is relocated up or downstream, or new marks are painted.

Water depth is measured by hydrologic technicians at each incremental position across the channel. At cableways and bridges, a torpedo-shaped weight and current meter are attached to a pre-measured and marked cable that is lowered by a manual or powered reel. During high-flow measurements, velocities sufficient to drag the cable and weight downstream are common, resulting in inaccurately large depth measurements. To determine the correct depth, a correction is applied to the wet-line depth using the angle between the descending cable and vertical (90 degrees) (Rantz and others, 1982). The corrected high-flow depths were used to reconstruct historical cross-sectional geometries.

Water depth varies considerably at one cross section through time as the result of scour-and-fill processes, especially for sand-bed rivers like the lower Brazos and Sabine Rivers. Scour-and-fill describes the condition by which bed sediment is entrained and eroded (scoured) as flow and associated stream power increase on the rising limb of the hydrograph, only to have sediment be redeposited (filled) as flow and stream power decrease on the falling limb of the hydrograph (fig. 3). For investigations of historical channel adjustment, it is important to account for and, if possible, minimize

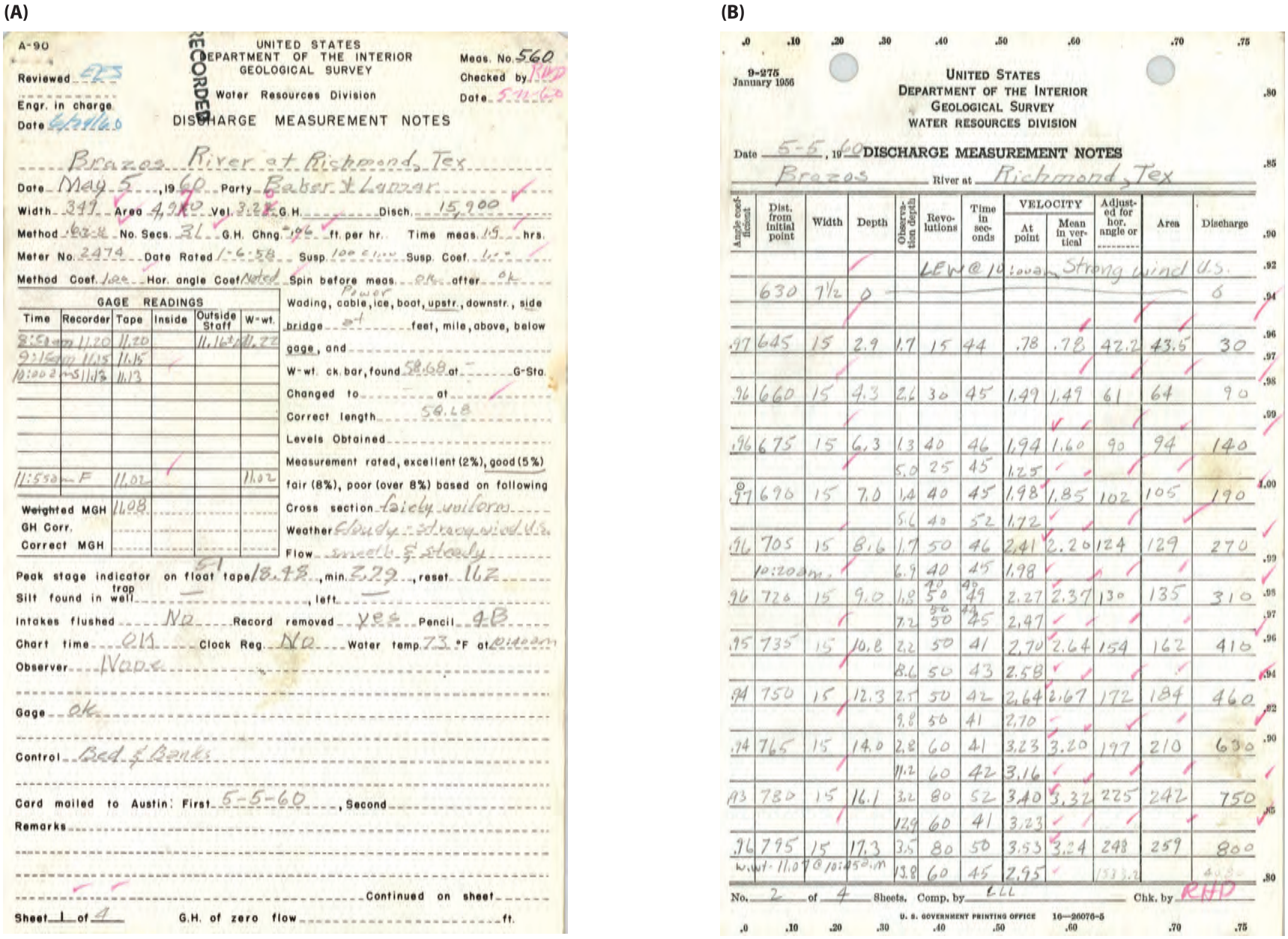

Figure 2. Example of front (A) and back (B) of field-measurement sheet for U.S. Geological Survey streamflow-gaging station 08114000 Brazos River at Richmond, Texas, May 5, 1960.

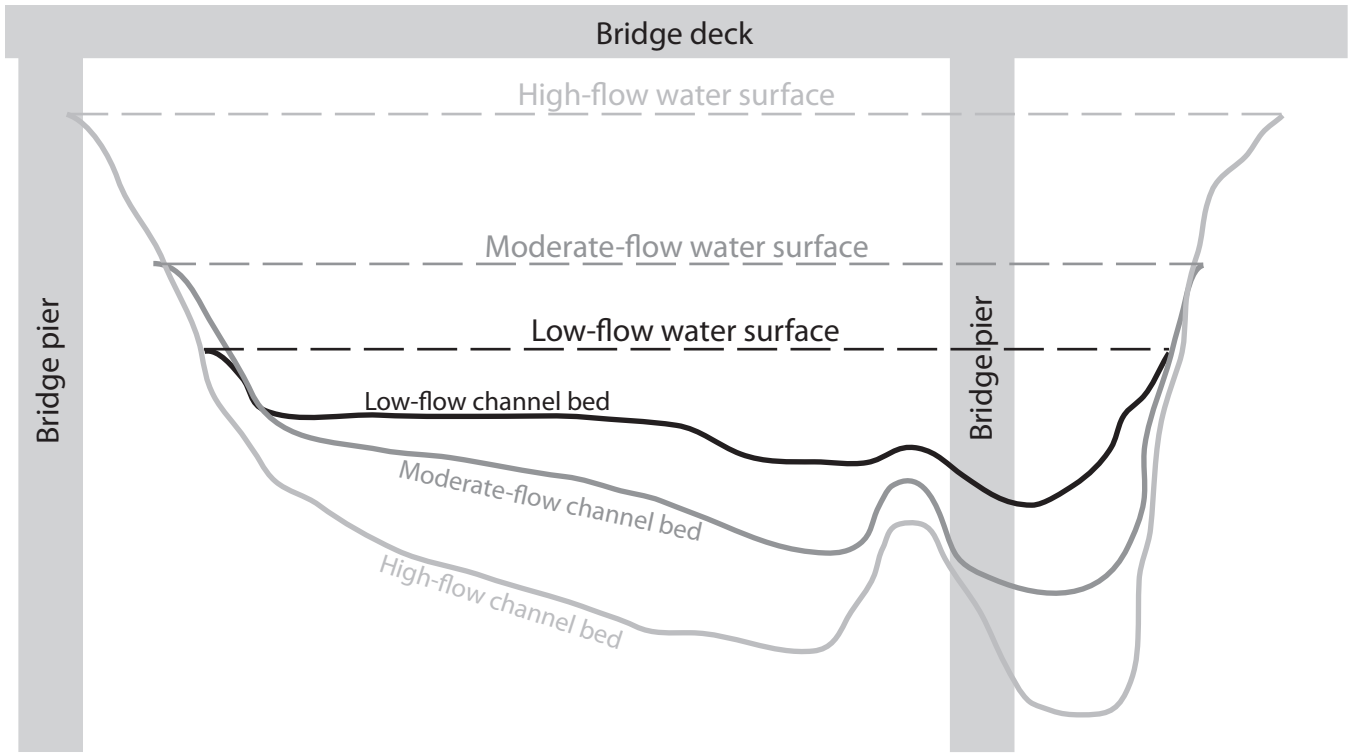

Figure 3. Conceptual diagram of scour-and-fill of a river channel bed for various flows at a bridge crossing.

variability associated with scour-and-fill processes. Therefore, more weight should be given to low flows incapable of much scour rather than high flows that mobilize bed material. Unfortunately for the purposes of this investigation, low-flow measurements were not consistently done at the same location and moderate or high flows from bridge crossings had to be relied upon to ensure a constant location. For example, 42 locations were used to make streamflow measurements at 08098290 Brazos River near Highbank, Tex., since 1977; most of these locations were used to make low-flow wading measurements. Other than dams, the installation of bridge structures, including channel-width contraction and bridge piers, also contributes to localized scour-and-fill (fig. 3). Interpretations of cross-sectional change through time must not overlook the hydraulic factors associated with bridges where none existed before, or where a new bridge design was used for replacement. Modifications to the conveyance capacity of bridge openings are likely to cause section-wide adjustments to channel geometry, and changes to bridge-pier shape or orientation are likely to cause localized adjustments to channel geometry. Finally, when interpreting historical cross sections of alluvial rivers, it is important to recognize the high likelihood of scour-and-fill processes during moderate and high flows.

Hydraulic Analyses of Historical Cross Sections

Simple hydraulic computations, including water-surface width, hydraulic depth, cross-sectional area, mean flow velocity, bed shear stress, and Froude number, were made for 0.5-foot stage increments at historical cross sections using WinXSPRO, version 3.0, a free U.S. Department of Agriculture, Forest Service (2005) software package. WinXSPRO takes the X and Y coordinates of the cross section and determines the channel width and cross-section area using other hydraulic values and properties. In contrast with field-measurement notes that represent a single water-surface width in the reconstructed cross section, WinXSPRO integrates the entire reconstructed cross section over a range of stage increments. Water-surface widths and cross sections determined using WinXSPRO software were used in all computations, not the water-surface widths and cross sections available from the field-measurement sheets. Hydraulic depth is the ratio of the cross-sectional area to the water-surface width. Bed shear stress is a fundamental variable in river studies used to relate flow conditions to sediment transport. It is difficult to accurately estimate this variable, particularly in complex flow fields (Biron and others, 2004). The Froude number also is a fundamental variable used in hydraulic studies to quantify the nature of the flow (subcritical or supercritical) depending on whether the Froude number is less than or greater than unity (Roberson and Crowe, 1980). As alluvial river channels approach stable conditions, the Froude number tends to attain a minimum value that reflects minimum bed-material motion and maximum channel stability under the constraints imposed by water discharge, sediment load, and particle size (Jia, 1990). Computations of mean flow velocity, bed shear

stress, and Froude number required cross-sectional geometry data, channel slope, and Manning's n roughness coefficient. An approximate value of channel slope at each gaging station was determined by extracting upstream and downstream channel elevations from 10-meter DEMs in GIS (table 5). Because channel elevations on the 10-meter DEMs remain erroneously constant for considerable lengths, a reach length ranging from 10 to 20 miles in the vicinity of the gaging station was used to compute channel slope. Streamflow is known from the historical discharge measurements, therefore Manning's *n* roughness coefficient value was adjusted for each hydraulic computation to provide the closest match to the known streamflow. Manning's *n* roughness is computed from the following equation:

$$U = (1.49/n)R^{2/3}S^{1/2}, \quad (1)$$

where

U is flow velocity, in feet per second;
n is Manning's roughness coefficient;
R is the hydraulic radius, in feet; and
S is channel slope, in feet per foot.

Discharge is computed from the following equation:

$$Q = UA, \quad (2)$$

where

Q is discharge, in cubic feet per second; and
A is cross-sectional area, in square feet.

An iterative process of adjusting the Manning's *n* roughness coefficient for a given DEM-estimated channel slope and cross-sectional area provided a best-fit estimate of the measured discharge. Using the best-fit estimate, hydraulic computations should approximate actual mean velocity, albeit with the simplification of disregarding variability introduced by migrating bedforms. Bed shear stress, however, is computed using channel slope without accounting for flow resistance and will be inaccurate if channel slope is not representative of on-the-ground conditions.

For cross sections with multiple overflows, hydraulic computations were made only for the main channel and the largest overflow channels, and field-measurement notes were used to determine streamflow values specific to each channel. For cross sections with inundated floodplains, hydraulic computations were made only for the main channel and, if applicable, the largest overflow channels; field-measurement notes were used to determine streamflow in each channel. To accompany graphical depictions of cross-sectional channel change through time, applicable hydraulic data are provided for 5-foot stage increments of historical cross sections. For hydraulic computations at stages below the water-surface elevation, Manning's n value was gradually increased as stage decreased and approached the channel bed because flow resistance usually increases near the bed. Depth-dependent increases of Manning's n were based on authors' judgment, and therefore computations of mean velocity and the Froude number represent modeled hydraulic behavior, not empirical data. Further, reported shear stress values also are modeled because of the dependence on DEM-derived channel slope estimates.

For hydraulic computations, WinXSPRO, Version 3.0, automatically sets the thalweg elevation to 0.0 feet. Hydraulic computations were made every 0.5 feet. The result is that WinXSPRO cross-sectional elevations are offset from USGS stage-datum elevations, unless the thalweg of the USGS stage is a factor of 0.5. For example, if a thalweg stage (USGS datum) was 0.2 feet for an actual cross-sectional measurement, and a USGS-stage target is desired at 10.0 feet, then the closest stage possible would be 10.2 feet. However, if a thalweg stage (USGS datum) was 1.5 feet for an actual cross-sectional measurement, and a USGS-stage target is desired at 10.0 feet, then the closest stage possible would be 10.0 feet because 1.5 is a factor of 0.5 (the increments computed by WinXSPRO).

Table 5. Channel slope values determined from 10-meter digital elevation models for reaches adjacent to U.S. Geological Survey streamflow-gaging stations used in study, lower Sabine and lower Brazos River Basins, Texas and Louisiana.

Station number	Station name	Dimensionless channel slope
08026000	Sabine River near Burkeville, Tex.	0.00015
08028500	Sabine River near Bon Wier, Tex.	.00015
08030500	Sabine River near Ruliff, Tex.	.00010
08096500	Brazos River at Waco, Tex.	.00030
08098290	Brazos River near Highbank, Tex.	.00020
08106500	Little River near Cameron, Tex.	.00040
08108700	Brazos River at State Highway 21 near Bryan, Tex.	.00020
08109000	Brazos River near Bryan, Tex.	.00020
08110325	Navasota River above Groesbeck, Tex.	.00050
08110500	Navasota River near Easterly, Tex.	.00050
08110800	Navasota River at Old Spanish Road near Bryan, Tex.	.00050
08111000	Navasota River near Bryan, Tex.	.00050
08111500	Brazos River near Hempstead, Tex.	.00015
08114000	Brazos River at Richmond, Tex.	.00015
08116650	Brazos River near Rosharon, Tex.	.00015

Alternative Techniques and Additional Sources of Data for Interpreting Channel Adjustment

A variety of alternative techniques and other sources of data were used to aid interpretation of historical

cross-sectional geometry and channel hydraulics through time. These include assessments of USGS stage-discharge rating curves, stage-discharge relations of field measurements, historical and contemporary aerial and ground photography, and bridge construction information for the gaging stations investigated in this report. The contemporary aerial photography consisted of digital orthophoto quarter-quadrangles (DOQQs) from 2004.

Stage-Discharge Rating Curves

Stage-discharge rating curves are developed and updated over time for USGS streamflow-gaging stations. A stage-discharge rating curve is defined by the relation between measured stage and measured discharge and is used to compute discharge from continuously monitored stage values. Stage-discharge rating curves typically are not static through time, but are updated as new measurement data become available. Cross-sectional geomorphic change can result in the need for a revision to a stage-discharge rating curve either because the capacity of a channel to convey streamflow is directly related to cross-sectional area or because local bed scour or fill results in a different water-surface elevation for a given discharge. For example, progressive incision, or lowering, of a channel bed through time results in decreasing stage values for a given streamflow. Alternatively, progressive channel-bed aggradation results in increasing stage values for a given streamflow. The relation of stage to discharge can provide a useful indicator of channel contraction (aggradation) or enlargement (degradation), but it is not possible to determine the relative or numerical changes in width or depth. Further, stage-discharge relations might change as the result of changing upstream or downstream controls, including changes in vegetation density or instream structures, and are not always associated with channel adjustment. Changes to channel roughness (Manning's *n* roughness coefficient) or channel slope also can modify stage-discharge relations. The frequency of updates to stage-discharge rating curves might not always reflect channel adjustments or changing control conditions, but might reflect changes in the frequency of rating-curve maintenance associated with protocol, funding, or personnel, or all factors. At best, stage-discharge rating curve updates can help to confirm channel cross-section adjustments independently determined from other methods.

In the ideal case, the sensitivity of stage-discharge rating curves to cross-sectional adjustments of channel geometry makes them useful indicators of geomorphic change (Juracek, 2001; Juracek and Fitzpatrick, 2008). Multiple updates to a stage-discharge rating curve during a relatively brief time span can imply a period of cross-sectional channel adjustment. For this investigation, all readily available stage-discharge rating curves were inventoried by their activation dates (table 6). Rating curve identification numbers and activation dates were recorded from NWIS. Unfortunately, in the Brazos River Basin, data mostly are limited to the last 25 years, but extend to earlier dates in the Sabine River Basin.

Stage-Discharge Relations of Field Measurements

As part of maintaining a USGS streamflow-gaging station, field measurements of discharge are summarized using USGS Form 9-207, which includes the discharge, gage height, width, cross-sectional area, mean velocity, and other data for all measurements made at one station, typically over the course of a water (hydrologic) year (October 1 through September 30 of the following year). Some, but not all, of these data are digitally available from NWIS (U.S. Geological Survey, 2008). For the streamflow-gaging stations investigated in this study, relations of measured gage height to measured discharge were analyzed for all digitally available measurements for the period of record. Measurements categorized as "poor" were not used (Rantz and others, 1982), and a few measurements were removed based on visual inspection of the information contained in the notes. Analyses of stage-discharge relations of field measurements were done to complement and reinforce interpretations of channel adjustment made from historical cross sections.

Aerial Photography

Some of the planform metrics associated with channel geometry that can be measured from aerial photography include meander wavelength, curvature, and channel width. The chronology of riparian landscape changes, including channel cutoffs and vegetation density, can also be inferred using aerial photographs. By comparing historical and more contemporary aerial photographs at a given site, time-averaged rates of various fluvial processes were inferred, including channel migration, bank erosion, point-bar accretion, and channel-bar development. For each site, the terms historical and contemporary are relative terms. Assessments of cross-sectional channel adjustment through time can benefit from an examination of historical aerial photography and comparison to contemporary imagery. For example, identification of channel cutoffs near the discharge-measurement location can help to explain localized changes to hydraulic variables, including mean flow velocity and associated adjustments to cross-sectional geometry. Likewise, channel migration rates near the discharge-measurement location can help explain lateral adjustments in cross-sectional geometry and the relative delivery of channel-bed sediment from sources immediately upstream. Channel migration rates should be interpreted with caution, however, because much erosion can occur in a very short time, and it is inappropriate to assume a uniform retreat of a cutbank (the outside, concave bank of a meander bend) through time. Further, migration rates normally are higher at meander bends than at straight reaches. Finally, changes in the density of riparian vegetation can help to explain channel width adjustments or changes in flow resistance and associated hydraulics.

Historical aerial photographs available from on-site USGS surface-water records were scanned, georeferenced

Table 6. Changes to stage-discharge rating curves at U.S. Geological Survey streamflow-gaging stations used in study, lower Sabine and lower Brazos River Basins, Texas and Louisiana.

[n/a, not applicable; USGS, U.S. Geological Survey; ADAPS, Automated Data Processing System; NWIS, National Water Information System]

Station number (fig. 1)	Station name	Rating curve number[1]	Month and year of implemented change[1]	Longevity of rating curve[1]
08026000	Sabine River near Burkeville, Tex.	1.0	September 1955	1 year
		2.0	October 1956	2 years
		3.0	October 1958	1 year
		2.0	October 1959	1 year
		4.0	October 1960	3 years
		5.0	October 1963	4 years
		6.0	October 1967	1 year, 9 months
		7.0	July 1969	3 years, 3 months
		8.0	October 1972	4 years
		9.0	October 1976	5 years
		10.0	October 1981	3 years, 7 months
		11.0	June 1985	3 years, 7 months
		12.0	January 1989	18 years, 9 months
		13.0	October 2007	n/a
08028500	Sabine River near Bon Wier, Tex.	1.0	October 1923	16 years
		1.1	October 1939	4 years
		1.2	October 1943	3 years
		1.3	October 1946	3 years
		2.0	October 1949	1 year
		2.1	October 1950	3 months
		2.2	January 1951	1 year, 4 months
		2.0	May 1952	4 months
		3.0	September 1952	1 year, 1 month
		4.0	October 1953	9 years
		5.0	October 1962	5 years
		6.0	October 1967	4 years
		7.0	October 1971	4 years
		8.0	October 1975	10 years
		9.0	October 1985	3 years, 3 months
		10.0	January 1989	11 years, 11 months
		11.0	December 2001	n/a
08030500	Sabine River near Ruliff, Tex.	1.0	October 1924	13 years
		1.2	October 1937	11 months
		1.3	September 1938	1 year, 8 months
		1.4	May 1940	3 years, 5 months
		1.5	October 1943	4 years
		1.6	October 1947	1 year
		1.7	October 1948	4 years, 10 months
		2.0	August 1953	2 years, 7 months
		3.0	March 1956	4 years, 10 months
		4.0	January 1961	13 years
		5.0	January 1974	9 months
		6.0	October 1974	11 years, 1 month
		7.0	November 1985	3 years, 2 months
		8.0	January 1989	17 years, 9 months
		9.0	October 2006	n/a

Table 6. Changes to stage-discharge rating curves at U.S. Geological Survey streamflow-gaging stations used in study, lower Sabine and lower Brazos River Basins, Texas and Louisiana—Continued.

Station number (fig. 1)	Station name	Rating curve number[1]	Month and year of implemented change[1]	Longevity of rating curve[1]
08096500	Brazos River at Waco, Tex.	7.0	October 1958	3 years, 2 months
		8.0	December 1961	1 year, 10 months
		9.0	October 1963	1 year, 1 month
		10.0	November 1964	11 months
		11.0	October 1965	3 years, 10 months
		12.0	August 1969	2 months
		14.0	October 1969	1 year
		15.0	October 1970	2 years, 6 months
		16.0	April 1973	3 years, 4 months
		17.0	August 1976	1 year, 2 months
		18.0	October 1977	5 years, 2 months
		19.0	December 1982	6 years, 10 months
		22.0	October 1989	5 years
		23.0	October 1994	9 years
		24.0	October 2003	2 years, 6 months
		25.0	April 2006	1 year
		25.1	April 2007	n/a
08098290	Brazos River near Highbank, Tex.	6.0	December 1982	3 years, 10 months
		7.0	October 1986	3 years, 3 months
		8.0	January 1990	1 year, 9 months
		9.0	October 1991	8 years
		10.0	October 1999	7 years, 6 months
		11.0	April 2007	6 months
		12.0	October 2007	n/a
08106500	Little River near Cameron, Tex.	15.0	December 1995	4 years, 10 months
		16.0	October 2000	2 years
		17.0	October 2002	5 years
		18.0	October 2007	n/a
08108700	Brazos River at State Highway 21 near Bryan, Tex.	1.0	June 1992	4 years, 4 months
		2.0	October 1996	2 years
		3.0	October 1998	2 years
		4.0	October 2000	2 years
		4.1	October 2002	4 years
		5.0	October 2006	8 months
		5.1	June 2007	n/a
08109000	Brazos River near Bryan, Tex.	8.0	October 1983	3 years
		9.0	October 1986	10 years, 6 months
08110325	Navasota River above Groesbeck, Tex.	1.0	June 1978	25 years, 4 months
		2.0	October 2003	n/a
08110500	Navasota River near Easterly, Tex.	11.0	February 1987	2 years, 8 months
		12.0	October 1989	n/a
08110800	Navasota River at Old Spanish Road near Bryan, Tex.	1.0	August 1996	1 year, 2 months
		2.0	October 1997	4 years
		3.0	October 2001	1 year, 4 months
		3.1	February 2003	3 years
		4.0	February 2006	1 year, 3 months
		4.1	May 2007	1 year, 2 months
		5.0	July 2008	n/a

Table 6. Changes to stage-discharge rating curves at U.S. Geological Survey streamflow-gaging stations used in study, lower Sabine and lower Brazos River Basins, Texas and Louisiana—Continued.

Station number (fig. 1)	Station name	Rating curve number[1]	Month and year of implemented change[1]	Longevity of rating curve[1]
08111000	Navasota River near Bryan, Tex.	11.0	November 1982	8 years, 11 months
		12.0	October 1991	1 year
		13.0	October 1992	4 years, 6 months
08111500	Brazos River near Hempstead, Tex.	9.0	October 1976	12 years, 3 months
		10.0	January 1989	12 years, 9 months
		11.0	October 2001	n/a
08114000	Brazos River at Richmond, Tex.	10.0	October 1984	3 years, 4 months
		11.0	February 1988	11 months
		12.0	January 1989	5 years, 9 months
		13.0	October 1994	1 year
		14.0	October 1995	6 years
		15.0	October 2001	n/a
08116650	Brazos River near Rosharon, Tex.	6.0	February 1988	6 years, 8 months
		7.0	October 1994	1 year
		8.0	October 1995	6 years
		10.0	October 2001	6 years, 6 months
		11.0	April 2008	n/a

[1] Rating curve data derived from a combination of the internal USGS surface-water database (ADAPS) and field measurements from the USGS NWIS. The ADAPS database typically has rating curve dates for only the last 20 to 30 years. Using the sequential rating-curve number system, a conservative value for total number of rating curves used per gaging station can be determined. Field measurements from NWIS commonly post the applicable rating curve and were used to extend the record farther back in time. However, field measurements are not made every day, thus it is not possible to determine an exact date for a rating curve change using these data.

to contemporary 2004 or 2005 DOQQs, and rectified in GIS. Historical photographs were not available for all gaging stations, mostly on the Sabine River. Ground coordinates (ground-control points) (for example, road intersections or building corners) were used to associate non-referenced historical photographs with georeferenced DOQQs. Root-mean-squared (RMS) errors of all ground-control points were small, minimizing the possibility of erroneous geographic associations. Using GIS, the historical and contemporary positions of meander-bend apexes near gaging stations were used to estimate channel migration rates, if applicable. Further, notes were made on other changes that could help explain cross-sectional channel adjustments, including nearby cutoffs and riparian vegetation density. Results from these analyses are individually presented in the section titled “Channel Adjustment and Estimation of Selected Hydraulic Properties.”

Repeat Ground Photography

Repeat ground photography is a technique whereby a contemporary photograph is taken at the same location from the same vantage point, using the same lens angle as a reference historical photograph. The technique has commonly been used to document landscape or vegetation change through time (Hastings and Turner, 1965; Malde, 1973; Bass, 2003; U.S. Geological Survey, 2009), but also has been used to document fluvial geomorphic change through time (Webb, 1996). Various historical ground photographs were located in USGS surface-water records of gaging stations investigated in this report, although none are included for the Sabine River. Historical photographs were scanned and printed, and two field trips were made to take repeat photographs at selected gaging stations in the Brazos River Basin. Unfortunately, efforts were not made to use the same lens angle as previous cameras, and photograph perspectives are different as a result. Contemporary photographs were taken with a Ricoh Caplio 500SE, Global Positioning System-enabled digital camera and qualitative comparisons of channel geometry and other physical conditions were made between historical and contemporary photographs. All descriptions referring to left and right bank are from the observers perspective looking downstream.

Bridge Construction Information

Streamflow-gaging stations on large rivers commonly are located at bridge crossings because flow depths are too large for wading measurements. Further, elevated highways commonly are constructed so that flows are conveyed under bridges or through culverts, thereby enabling efficient discharge measurements. As an artifact of engineering design, however, channel cross-sectional geometry at bridges usually is not representative of natural river conditions. Streamflow at

high stages is constricted to available openings through and under the roadway, and concentrated hydraulic forces result in localized geomorphic adjustments. Further, bridge support piers in the river can enhance or limit scour and fill patterns, often resulting in erosion on one side of a pier and deposition on the other side (fig. 3).

Despite the complications bridges introduce in cross-sectional channel-geometry assessments, patterns of geometric change through time can be evaluated if no substantial bridge-reconstruction efforts occur, which can abruptly alter the channel at or adjacent to the measurement section. For this reason, dates of bridge construction and reconstruction were reviewed for all appropriate gaging stations in this investigation (table 7) using a Website that serves as a portal for the 2007 National Bridge Inventory (Nationalbridges.com, 2008). The data are limited to the most recent bridge reconstruction; however, this limitation does not apply to the gaging stations in this study because periods of streamflow record do not overlap multiple bridge constructions.

Channel Adjustment and Estimates of Selected Hydraulic Properties

The techniques described in the “Methods” section of this report were applied at selected gaging stations in the lower Sabine and lower Brazos River Basins (fig. 1; table 1) to evaluate channel adjustment and to estimate selected hydraulic properties. Historical and contemporary cross-sectional channel geometries at several gaging stations on each river were compared; planform channel change was assessed; and hydraulic properties were estimated including mean velocity, bed shear stress, and Froude numbers. Some of the supplemental techniques used for interpretive guidance, including aerial and ground photography, were not applied at certain gaging stations, mostly in the lower Sabine River Basin, because data were not readily available. In other cases, field-measurement sheets were limited to incomplete periods of record, thus channel assessments are limited to the available period of record.

08026000 Sabine River near Burkeville, Texas

The Sabine River near Burkeville, Tex., streamflow-gaging station (08026000) is located at a bridge along State Highway (SH) 63 downstream from Toledo Bend Reservoir, and the sand-bed river (table 1) forms the boundary between Texas and Louisiana (fig. 1; fig. 4 at end of report). Streamflow measurements at the site began in September 1955 and continue to present (2009) (table 1); 13 stage-discharge rating curves have been used (table 6) for the period of record. Rating curves were frequently updated between 1955 and 1960. Stage-discharge relations determined from field measurements for the period of record do not indicate much channel adjustment in the late 1950s, but do indicate some channel degradation since the late 1970s or early 1980s (fig. 5 at end of report). The bridge at this site has been in place since 1937 and, therefore, no channel adjustments are attributed to construction activity (table 7).

The measurement site is at a meander bend and the asymmetrical cross-sectional geometry shows the gradual right point bar sloping toward the thalweg near the left cutbank side of the channel (fig. 6 at end of report). Historical cross sections for moderate flows (fig. 6A) show a well-developed mid-channel bar in 1956 that adjusts to an asymmetrical point-bar and cutbank pool sequence by 1963. Since the early 1960s, the asymmetry has maintained and gradual incision of the thalweg is coupled with less-prominent vertical accretion of sediment on the point bar. Thalweg incision of approximately 2 to 3 feet and point-bar accretion of approximately 2 feet has occurred since the 1960s. As a result of these processes, a definitive transverse streambed slope has developed that distinguishes the thalweg from the point-bar deposit. This change of cross-sectional geometry might be the result of increased median flows (table 4) following the completion of Toledo Bend Reservoir upstream, which is sufficient to maintain the thalweg depth by not allowing sandy bed sediment to accumulate in the left cutbank side of the channel. The abrupt bar near the thalweg in 1973 was the result of localized deposition adjacent to a bridge pier, which was not detected in other measurements. In addition to asymmetrical cross-sectional development, the channel cutbank has migrated approximately 20 feet to the left between 1956 and 2001, or an average of 0.44 foot per year. The point-bar deposit appears to simultaneously migrate with the cutbank, although variability in its position through time does not facilitate a quantification of its migration rate.

High-flow measurements at the site since 1957 show a more stable, mobile, bed cross-sectional channel geometry that conveys floods (fig. 6B). The asymmetry evident in the moderate-flow cross sections (fig. 6A) is preserved during high flows, but the relative uniform channel configuration through time indicates high flows are hydraulically sufficient to mobilize and transport material across the channel bed. Further, the thalweg in 1995 is approximately 2.5 feet lower than the general thalweg elevation of 1957, even though it is plausible to assume that channel-bed scour would be greater for the higher flow in 1957. This probably is because considerable quantities of sand-size sediment are trapped by Toledo Bend Reservoir, which reduces sediment supply to the site and thereby promotes channel incision.

The morphological results compare well to observations of channel shape and interpretations of adjustment at this site by Phillips (2003), who shows that the river channel is very active, with bank erosion, bar migration, and channel incision occurring since impoundment of Toledo Bend Reservoir. Historical cross sections (fig. 6) confirm the presence of a sandy toe slope at the base of the right bank. However, a series of erosional scarps depicted in Phillips (2003) are not evident on the left bank, probably because the vertical bank is maintained to minimize erosion near the bridge.

Computations of selected hydraulic properties for historical cross sections of the Sabine River near Burkeville are listed

Table 7. Bridge construction information at and near U.S. Geological Survey streamflow-gaging stations used in study, lower Sabine and lower Brazos River Basins, Texas and Louisiana.

[n/a, not applicable]

Station number (fig. 1)	Station name	Bridge construction activity[1]	Date of construction activity
08026000	Sabine River near Burkeville, Tex.	Bridge constructed	1937
08028500	Sabine River near Bon Wier, Tex.	Bridge constructed	1981
08030500	Sabine River near Ruliff, Tex.	Bridge constructed	1936
08096500	Brazos River at Waco, Tex.	Washington Street bridge constructed	1901
		LaSalle Street bridge constructed	1961
		State Highway 6/Loop 340 bridge constructed	1984
08098290	Brazos River near Highbank, Tex.	Bridge constructed	1955
08106500	Little River near Cameron, Tex.	Bridge constructed	2005
08108700	Brazos River at State Highway 21 near Bryan, Tex.	Bridge constructed	1986
08109000	Brazos River near Bryan, Tex.	n/a	n/a
08110325	Navasota River above Groesbeck, Tex.	State Highway 14 bridge constructed	1960
08110500	Navasota River near Easterly, Tex.	Bridge constructed	1959
		Bridge reconstructed	1981
08110800	Navasota River at Old Spanish Road near Bryan, Tex.	Bridge constructed	1956
08111000	Navasota River near Bryan, Tex.	Bridge constructed	1959
08111500	Brazos River near Hempstead, Tex.	Bridge constructed	1972
08114000	Brazos River at Richmond, Tex.	Westbound bridge constructed	1965
		Eastbound bridge constructed	1989
08116650	Brazos River near Rosharon, Tex.	Bridge constructed	1965

[1] Bridge construction information from *Nationalbridges.com* (2008), a private Website that queries information from the 2007 National Bridge Inventory, which contains data only for the present bridge but not for previous bridges at the site.

in table 8 at end of report. Variability through time is evident for width, depth, and area, but a general increase in cross-sectional area and mean velocity for moderate and high flows requires that more streamflow is conveyed by the channel for a given stage. This indicates that the channel is more efficiently conveying flow, probably as a result of thalweg incision.

08028500 Sabine River near Bon Weir, Texas

The Sabine River near Bon Weir, Tex., streamflow-gaging station (08028500) is located at a bridge along U.S. Highway 190 downstream from Toledo Bend Reservoir, and the sand-bed river (table 1) forms the boundary between Texas and Louisiana (figs. 1, 7 at end of report). Streamflow measurements at the site began in October 1923 and continue to present (2009) (table 1); 17 stage-discharge rating curves have been used (table 6) for the period of record. Rating curves were most frequently updated between 1950 and 1953. Stage-discharge relations determined from field measurements for the period of record indicate progressive channel degradation since the 1930s (fig. 8 at end of report). The bridge at this site was replaced in 1981 (table 7), thus two sequences of historical cross sections are provided because: (1) the bridge and discharge-measurement site were relocated about 200 feet downstream; (2) USGS measurement cross-section distances were changed; and (3) construction activity might have altered channel geometry.

The measurement site is at a meander bend and the asymmetrical cross-sectional geometry shows the gradual right point bar descending to the thalweg near the left cutbank side of the channel (fig. 9 at end of report). Between 1933 and 1940, an aggradational episode at the site filled the thalweg near the cutbank with nearly 13 feet of sediment and incised a new elevated thalweg across the point bar; and the channel cross section dramatically changed its geometry (fig. 9A,B). Between 1940 and 1980, the channel gradually reestablished asymmetry at the site with the thalweg on the left, or outside the meander bend. The elevation and uniform transverse slope of the early 1930s point-bar surface, however, was not fully restored by the late 1970s. Unlike 0802600 Sabine River near Burkeville, a progressive pattern of channel incision is not detected, either in moderate-flow or high-flow cross sections. Cutbank migration is not detected for moderate flows (fig. 9A) but is detected for high flows between 1932 and 1966 (fig. 9B) and amounts to approximately 30 feet, or an average of 0.88 foot per year. The 1976

cross section (fig. 9A) and the 1974 cross section (fig. 9B) might be associated with poor or rushed measurements, rather than actual migration of the cutbank to the right, because the measurement origin point on the left bank may not be correctly designated.

Since 1981, the cross-sectional geometry at the new bridge location is narrower and has a steeper right bank (fig. 9C,D) than the former bridge location. Since the mid-1980s, minor adjustment of the channel-bed elevation has occurred several times, which is common for sand-bed rivers. More distinctive, however, is the apparent migration of the channel thalweg to the right. Between 1984 and 2005, the thalweg has moved approximately 30 feet to the right, or an average of 1.43 feet per year, and the left channel bank has moved approximately 15 feet to the right, or an average of 0.71 foot per year. A number of large floods have occurred along the lower Sabine River during this time, including a peak of 98,200 cubic feet per second in July 1989 and 92,600 cubic feet per second in February 1999. These high-magnitude floods, combined with hydraulic changes associated with bridge construction in 1981, might explain migration of the thalweg to the right. Further evidence of the thalweg migration is shown by the chute cutoff of the point bar immediately downstream from the bridge (fig. 7A), which stranded a small point-bar ridge as an island. The apparent contraction of the left channel bank probably is related to anthropogenic bank-stabilization efforts to prevent erosion near the bridge structure and not because of natural deposition along the cutbank.

The morphological results generally support observations of channel shape and interpretations of adjustment at this site by Phillips (2003), who shows a steep left bank and a gradually sloping bar surface on the right side. Historical cross sections (fig. 9) confirm the steep left bank, but the gradually sloping bar is steeper on the right side of the channel at the USGS cross-section location. The cross section shown in Phillips (2003) is about 150 to 200 meters downstream, where the bar surface is better developed at the meander bend. Further, the downstream migration of the right point-bar deposit between 1994 and 2000 is confirmed by historical cross sections, indicating that the bar fully migrated downstream between 1994 and 1997.

Computations of selected hydraulic properties for historical cross sections of the Sabine River near Bon Wier are listed in tables 9 and 10 at end of report. Considerable variability through time is evident for width, depth, area, and velocity, mostly because of the 1930s episode of aggradation followed by the recovery of the channel to an asymmetrical shape. During the last 20 years, or since the bridge and measurement sections were moved downstream, channel hydraulics were generally stable compared to the previous 50 years.

08030500 Sabine River near Ruliff, Texas

The Sabine River near Ruliff, Tex., streamflow-gaging station (08030500) is located at a bridge along SH 12 downstream from Toledo Bend Reservoir, and the sand-bed river (table 1) within the alluvial-deltaic plain forms the boundary between Texas and Louisiana (figs. 1, 10 at end of report). Streamflow measurements at the site began in October 1924 and continue to present (2009) (table 1); 15 stage-discharge rating curves have been used (table 6) for the period of record. Rating curves were most frequently updated between 1937 and 1948. It is possible that the 1930s aggradation upstream at 08028500 Sabine River near Bon Wier might have migrated about 40 miles downstream by 1940, causing considerable cross-sectional adjustment. Further, the bridge at this site was replaced in 1936 (table 7) and its construction might have contributed to cross-sectional adjustment, reflected in frequent rating-curve updates. Stage-discharge relations determined from field measurements for the period of record show considerable variability during the 1930s and 1940s, and there is little evidence to indicate substantial aggradation or degradation for the period of record (fig. 11 at end of report). Beginning in the mid-1970s, most moderate-flow and high-flow measurements were made by boat approximately 6 miles downstream on Indian Bayou, Old River, and other overflow channels (fig. 12 at end of report). The Sabine River bifurcates into Indian Bayou and Old River upstream from the measurement sections.

The measurement site at the bridge is on a straight channel segment between two meander bends (fig. 10A). Moderate-flow and high-flow cross sections between 1960 and 1979 (fig. 13A,B at end of report) indicate relative channel stability during this time. About 1 to 2 feet of channel aggradation appears to have occurred during the 1970s, and a swale near the right bank filled in with sediment, although only one high-flow measurement in 1979 is used to support these observed changes. Historical cross sections of Indian Bayou and Old River, distributaries of the Sabine River approximately 6 miles downstream from the bridge crossing, were measured using inconsistent section distances, and therefore, the leftmost edge of water is assigned an arbitrary distance of zero (figs. 14A,B; 15A,B at end of report). As a result, no interpretations of lateral channel migration or bank erosion can be made, but channel-bed elevation adjustments and hydraulic computations are nonetheless valid. Cross-sectional geometry of Indian Bayou shows some fluctuation since the 1970s (fig. 14A,B). The highest channel-bed elevation occurred in 1977, and the lowest occurred in 1992 (fig. 14B), probably related to scour during a large flood in 1989 (total peak streamflow of 109,000 cubic feet per second). These scour-and-fill processes are expected for sand-bed channels. Additionally, the thalweg position migrated from the left to the right side of the channel between 1994 and 1999 (fig. 14A), possibly related to hydraulic processes during the February 1999 flood (total peak streamflow of 92,800 cubic feet per second). On the basis of available moderate- and high flow- cross section data, Old River, which conveys more streamflow than Indian Bayou, temporarily aggraded about 6 feet between 1976 and 1992 (fig. 15A,B), despite the 1989 flood, and shows that simultaneous sediment-transport processes can be different among

distributaries in deltaic environments. In summary, historical cross sections of Indian Bayou and Old River display temporary scour-and-fill processes, but overall morphology generally has been relatively stable since the 1970s.

The morphological results at the bridge crossing between 1960 and 1979 (fig. 13A,B) do not show the level of detail on the right bank as shown in Phillips (2003), which depicts a series of low-elevation scarps at this cross section. The irregularity of right bank topography in Phillips (2003) might indicate that lateral channel activity or incision has occurred since 1979, or that spacing between individual drops during the streamflow measurement was not sufficient to capture the subtle breaks in slope along the right bank. However, historical cross sections (fig. 13A,B) do show a relatively stable bar deposit adjacent to the right bank, supporting Phillips (2003) conclusion that sand is actively transported in this reach.

Computations of selected hydraulic properties for historical cross sections of the Sabine River, Indian Bayou, and Old River near Ruliff are listed in tables 11–13 at end of report. Generally, no substantial changes in hydraulics of the river channels are discernible since the 1960s, including width, depth, cross-sectional area, and mean velocity. Some fluctuation in these values likely is attributed to scour-and-fill processes common in sand-bed channels.

08096500 Brazos River at Waco, Texas

The Brazos River at Waco, Tex., streamflow-gaging station (08096500) is at a bridge along State Loop 340 east of downtown Waco (fig. 16 at end of report), and the gravel- and sand-bed river (table 1) at this location is downstream from a low-flow dam constructed in 1970 that maintains a narrow pool referred to as Lake Brazos. Two other bridges, at Washington Street and LaSalle Street, have been used to make flow measurements in Lake Brazos upstream from the present gage location, and data are presented for all three locations. Streamflow measurements at the site began in October 1898 and continue to present (2009) (table 1); at least 23 stage-discharge rating curves have been used (table 6) for the period of record. Since 1958, rating curves were most frequently updated during the 1960s. Stage-discharge relations determined from field measurements for the period of record show substantial aggradational and degradational episodes, with peak aggradation during the 1930s and progressive degradation since that time (fig. 17 at end of report). Two stage-discharge relations are given because the move from Washington Street to LaSalle Street in 1969 resulted in a change in gage datum and incomparable relations. All historical cross-section measurements for the three bridge locations were after the most recent bridge construction was complete at each of the locations (table 7); therefore cross-sectional adjustments are not attributed to construction activities. Measurements at the Washington Street bridge are from 1925 to 1966; measurements at the LaSalle Street bridge are from 1971 to 2002; and measurements from the State Loop 340 bridge are from 1986 to 1995.

One historical aerial photograph from 1981 was georeferenced and compared to a 2004 DOQQ in the vicinity of the present (2009) gaging station on State Loop 340 (fig. 18 at end of report). No discernible change in channel planform condition is evident along the straight reach near the present gaging station; however channel migration at downstream meander bends has occurred since 1981. The locations of two meander bends are noted in figure 18 by the letters A and B. One meander bend (A) 5,000 feet downstream from State Loop 340 has migrated to the right (south) approximately 115 feet, or an average of 5.0 feet per year between 1981 and 2004. Additionally, vegetation growth and associated benching, or sediment deposition along the banks, on the left point bar at this meander has slightly decreased channel width from about 790 to 750 feet at the meander apex. Another meander bend (B) 10,500 feet downstream from State Loop 340 has migrated to the left (north) approximately 330 feet, or an average of 14.3 feet per year between 1981 and 2004. Relatively rapid channel migration and flow direction here have facilitated the development of a chute across the right point-bar surface, and channel width at the meander apex has increased from about 790 to 950 feet. Additionally, a mid-channel bar formed just upstream from the meander bend between 1981 and 2004.

The Washington Street bridge measurement site is on a straight channel segment upstream from the low-water dam that forms Lake Brazos. High-flow cross sections between 1925 and 1966 (fig. 19A at end of report) indicate considerable variability through time, although overall change is very minimal, as the 1925 and 1966 cross sections appear to be the most similar among the six measurements. A period of channel aggradation is evident from 1925 to 1942, when the channel bed rose by approximately 7 feet and storage of sediment on the left side of the channel continued until at least 1949. The cause of the channel aggradation could be attributed to land-use intensification or mobilization of sediment associated with the 1929 completion of Lake Waco on the Bosque River, a tributary immediately upstream from downtown Waco. Hydraulic removal of the aggraded bed sediment began during the 1940s, and by 1966 the channel at Washington Street reacquired a shape similar to that of 1925. Cross-sectional geometry at the LaSalle Street bridge measurement site, located on a straight channel segment upstream from the low-water dam that forms Lake Brazos, also varies considerably between 1971 and 2002 (fig. 19B). Although a narrow thalweg in 1971 is deeper than that of any other measurement at this site, cumulative incision of the channel bed near the right bank and channel enlargement along the left side is apparent during this time (1971 to 2002), indicating that lacustrine processes in Lake Brazos do not overwhelm fluvial erosional processes. Approximately 4 feet of the channel bed near the right bank have been removed since 1971 and erosion has removed as much as about 100 feet of the upper part of the left channel slope. Cross sections at the State Loop 340 bridge downstream from the low-water dam show evidence of channel-bed incision between 1986 and 1995 (fig. 19C).

The channel bed has lowered approximately 2 feet during this time, with greater incision on the right side of the channel. The observed channel enlargement at LaSalle Street and channel incision at State Loop 340 can be attributed to decreased sediment loads resulting from upstream dams. Even though flood magnitudes have been dramatically reduced by controlling flows at the dams (table 4), the lack of an upstream sediment supply allows moderate floods to erode the channel boundary at the State Loop 340 bridge site without normal replacement of that material.

Computations of selected hydraulic properties for historical cross sections of the Brazos River at Waco are listed in tables 14–16 at end of report. Hydraulic properties, including hydraulic depth and cross-sectional area, at the Washington Street bridge are influenced by the aggradational phase of the 1930s and 1940s. Variation in mean velocity can be attributed to the diversity of flood magnitudes measured at this location, rather than changes in cross-sectional geometry. Hydraulic properties, including width and cross-sectional area, at the LaSalle Street bridge are influenced by gradual channel enlargement between 1971 and 2002. The small change in hydraulic depth indicates that channel width adjustments are responsible for the enlargement. Further, a relatively large disparity of mean velocity values between moderate and high flows indicates that cross-sectional area is less sensitive than velocity to increases in discharge, which is expected considering that constant water levels at the site result from the low-flow dam that forms Lake Brazos. Hydraulic properties, including hydraulic depth and cross-sectional area, at the State Loop 340 bridge have been influenced by channel-bed incision. For a given stage, mean depth and flow velocity increased through time and associated flow resistance decreased.

08098290 Brazos River near Highbank, Texas

The Brazos River near Highbank, Tex., streamflow-gaging station (08098290) is located at a bridge along Texas Farm-to-Market Road (FM) 413 (fig. 20 at end of report), and the gravel- and sand-bed river (table 1) thinly overlies shale bedrock. Streamflow measurements at the site began in October 1965 and continue to present (2009) (table 1); at least 12 stage-discharge rating curves have been used (table 6) for the period of record. Since 1982, rating curves were most frequently updated during the 1980s. Stage-discharge relations determined from field measurements indicate slight channel degradation during the period of record (fig. 21 at end of report). The bridge at this site has been in place since 1955, thus no channel adjustments are attributed to construction activity (table 7).

One historical aerial photograph from 1960 was georeferenced and compared to a 2005 DOQQ in the vicinity of the gaging station (fig. 22 at end of report). One of the more evident changes since 1960 is the considerable growth of vegetation along the channel banks, which is expected to minimize bank erosion and possibly promote benching. The locations of two meander bends are noted in figure 22 by the letters A and B. One meander bend (A) 1,800 feet upstream from the bridge has rapidly migrated to the left (east) approximately 720 feet, or an average of 16.0 feet per year between 1960 and 2005, and vegetation has established on the right point-bar surface. Another gradual meander bend (B) 5,000 feet downstream from the bridge also has rapidly migrated to the left (east) approximately 820 feet, or an average of 18.2 feet per year between 1960 and 2005, and vegetation has established on the right point-bar surface. The upper part of this meander bend did not migrate as rapidly as the lower end, effectively straightening out the meander.

Various historical ground photographs were scanned for 08098290 Brazos River near Highbank. On October 15, 1965, the daily mean streamflow was 524 cubic feet per second, and a photograph taken that day from the right bank just downstream from the bridge shows relatively low-flow conditions, gently sloping grassy banks, and concrete bridge piers in the channel (fig. 23A at end of report). A repeat photograph taken on April 1, 2008, shows relatively low-flow conditions (daily mean streamflow was 955 cubic feet per second), a densely vegetated left bank, and exposed sand deposits adjacent to the concrete bridge piers (fig. 23B).

Two historical photographs were taken on March 31, 1964, from the bridge looking upstream and downstream. The upstream photograph (fig. 23C) shows a gently sloping left grassy bank, a slightly sloped right bank with scattered trees, an open mid-channel bar, and isolated slabs of locally derived bedrock. The downstream photograph (fig. 23D) shows a slightly sloped left grassy bank with isolated trees and a slightly sloping and densely vegetated right bank. A repeat photograph looking upstream from the bridge on April 1, 2008, shows much denser vegetation on the left and right banks and slightly steeper slopes. The mid-channel bar still occupies the same position (fig. 23E). A repeat photograph looking downstream from the bridge on April 1, 2008, also shows much denser vegetation on the left bank and similar vegetation density on the right bank (fig. 23F).

The measurement site is along a straight reach between two meander bends and the cross-sectional geometry generally is symmetrical (fig. 24 at end of report). Along with moderate and high flows, a number of low-flow measurements were made from the bridge and an opportunity was afforded to assess channel-bed stability from these cross sections. Historical cross sections for low flows indicate channel-bed incision of about 1 foot between 1979 and 2002 (fig. 24A). Historical cross sections for moderate flows corroborate evidence from low-flow measurements, indicating about 1 foot of channel-bed incision between 1972 and 2004 (fig. 24B). Although historical cross sections for high flows indicate about 1 foot of channel-bed incision between 1975 and 1991 (fig. 24C), it is likely that the 1991 flow, the highest magnitude for the five measurements, temporarily scoured the channel bed to a relatively low elevation, possibly to the shale bedrock. This interpretation is supported by a rebound of channel-bed

elevation in 1997. The relatively minor amount of channel-bed incision, as well as similar bed elevations from low to high flows, indicates that bedrock along the channel bed controls incision at this location. Further, relatively rapid channel migration rates in the vicinity continuously supply sediment, partly offsetting the reduction of sediment loads caused by upstream impoundments. Evidence from low-, moderate-, and high-flow cross sections indicate channel-bank positions are very stable for the period of record.

Computations of selected hydraulic properties for historical cross sections of the Brazos River near Highbank are listed in table 17 at end of report. An increase in hydraulic depth and cross-sectional area through time for moderate-flow cross sections is associated with an increase in mean flow velocity and decrease in flow resistance (Froude number). Channel incision is not indicated, however, by high-flow cross sections. Constant width and slightly fluctuating hydraulic depths for high-flow cross sections indicate relative channel stability since the 1970s.

08106500 Little River near Cameron, Texas

The Little River near Cameron, Tex., streamflow-gaging station (08106500) is located at a bridge along U.S. Highway 77/190 (fig. 25 at end of report), and the gravel- and sand-bed river (table 1) is a major tributary of the lower Brazos River. Streamflow measurements at the site began in November 1916 and continue to present (2009) (table 1); at least 18 stage-discharge rating curves have been used (table 6) for the period of record. Stage-discharge rating curve implementation dates are not digitally available prior to 1995, and no interpretations are made here using their frequency of adjustment. Stage-discharge relations determined from field measurements between October 1922 and the present (2009) show considerable variability and an overall pattern of degradation since the 1960s (fig. 26 at end of report). After 1990, a change in slope for stage-discharge relations at about 2,000 cubic feet per second indicates aggradation is occurring for low flows up to about 2,000 cubic feet per second and degradation is occurring for higher flows. The reason for this discrepancy is unknown, but historical cross sections presented for this station provide a possible morphologic explanation. The bridge at this site was finished in 2005 (table 7) and its construction over several years might have affected one cross section digitized in October 2003. Measurement section distances were changed in the late 1970s, thus two sequences of historical cross sections are provided.

One historical aerial photograph from 1951 was georeferenced and compared to a 2004 DOQQ in the vicinity of the gaging station (fig. 27 at end of report). One of the more evident changes since 1951 is the considerable growth of vegetation in the floodplain adjacent to the river channel, which is expected to increase flow resistance and possibly cause floodplain sedimentation rates to increase. The locations of five meander bends are noted in figure 27 by the letters A, B, C, D, and E. One meander bend (A) 3,300 feet upstream from the bridge has migrated to the right (south) approximately 165 feet, or an average of 3.1 feet per year between 1951 and 2004, and has migrated downstream approximately 100 feet. The meander bend (B) immediately downstream, or 2,500 feet upstream from the bridge, has migrated to the left (north) approximately 250 feet (average of 4.7 feet per year between 1951 and 2004) and downstream approximately 250 feet. The meander bend (C) closest to the gaging station, or 1,000 feet upstream from the bridge, was reduced in length by a neck cutoff, an event common to meandering rivers (fig. 25A). The neck cutoff locally steepens the channel slope and can (1) temporarily increase sediment loads downstream, and (2) cause cross-sectional adjustment immediately upstream and for some distance downstream. A former meander bend (D) 900 feet downstream from the bridge straightened to the right by migrating approximately 260 feet, or an average of 4.9 feet per year between 1951 and 2004. Finally, the meander bend (E) 1,500 feet downstream from the bridge has migrated to the left approximately 250 feet, or an average of 4.7 feet per year between 1951 and 2004. Observations based on comparison of the 1951 aerial photograph and 2004 DOQQ provide much information for understanding channel geometry and planform variability through time. Channel geometry and planform variability along the reach of Little River near Cameron was apparently driven by lateral migration, neck cutoff processes, and associated establishment of vegetation.

The measurement site is along a short, straight reach between two meander bends (fig. 25A) and the cross-sectional geometry generally is symmetrical with a thalweg closest to the left bank (fig. 28 at end of report). Between 1949 and 1975, the channel gradually migrated to the left about 30 feet, or an average of 1.2 feet per year, and incised the channel bed adjacent to the left bank about 5 feet (fig. 28A,B). The right bank was basically stable during this time, with some evidence of sediment deposition along its upper edge by 1975. Between 1981 and 2001, considerable incision lowered the channel bed by about 7 feet (fig. 28C,D). If both sets of measurements are combined for the period 1949 to 2001, Little River has incised its channel bed by no less than 12 feet, or an average of 0.23 feet per year. An apparent aggradation phase between 2001 and 2003 likely resulted from bridge construction activity and not natural causes. The progressive channel incision at this location probably is related to reduced sediment loads as a result of upstream impoundments, including Belton Lake, Stillhouse Hollow Lake, Lake Georgetown, and Granger Lake (fig. 1). Planform characteristics, however, indicate that this reach of Little River is conspicuously sinuous relative to adjacent reaches, which can result from subtle tectonic anomalies affecting local channel adjustment processes. Additionally, a high-magnitude flood with a peak flow of 116,000 cubic feet per second on December 21, 1991, might have initiated an upstream-migrating knickpoint of channel-bed incision that passed the measurement location between January 1992 and April 1993. Finally, high-flow cross sections indicate the channel migrated to the right about 15 feet between 1989 and 2001

(fig. 28D), or about 1.2 feet of migration per year during this period.

Computations of selected hydraulic properties for historical cross sections of Little River near Cameron are listed in tables 18 and 19 at end of report. The highly variable mean velocity for high flows during 1949 to 1975 is related to the simplification of assigning uniform Manning's *n* values for flows within the banks and overbank. Because Manning's *n* values will differ greatly within banks and overbank, mean flow velocity values based on computations that did not include overbank flow probably are more accurate. An increase in hydraulic depth and cross-sectional area through time for moderate- and high-flow cross sections is associated with progressive incision of the channel bed. Mean flow velocity values at a constant stage, however, are variable but generally increase as the channel bed is lowered.

08108700 Brazos River at State Highway 21 near Bryan, Texas

The Brazos River at SH 21 near Bryan, Tex., streamflow-gaging station (08108700) is located at a bridge (fig. 29 at end of report), and this reach is a sand-bed river (table 1) meandering through a wide (approximately 6 miles) alluvial valley. The gaging station was established in 1993 (table 1) as a replacement for 08109000 Brazos River near Bryan (4.8 miles downstream), because of structural problems associated with the cableway at the original gage. Seven stage-discharge rating curves have been used (table 6) for the period of record and adjustments are primarily because of temporary shifts in sand-bar positions. Stage-discharge relations determined from field measurements indicate little to no overall adjustment during the relatively short period of record (fig. 30 at end of report). The bridge at this site has been in place since 1986, therefore no channel adjustments are attributed to construction activity (table 7).

The measurement site is at the upper end of a straight reach and the cross-sectional geometry generally is symmetrical (fig. 31 at end of report). Historical cross sections for moderate flows indicate very little change between 1993 and 2004 (fig. 31A), with possibly some lateral migration to the left and limited channel-bed incision of about 0.5 foot. Historical cross sections for high flows support the moderate-flow evidence, indicating no substantial channel adjustments between 1992 and 2007 (fig. 31B), with some vertical growth of a channel bar near the left bank between 1992 and 1997. Apparent degradation of this bar in 2007 probably is attributed to temporary scour by the relatively high flow (76,800 cubic feet per second) measured on May 29, 2007.

Computations of selected hydraulic properties for historical cross sections of the Brazos River at SH 21 near Bryan are listed in table 20 at end of report. Hydraulic properties for moderate and high flows show little variation through time and thereby support an interpretation of relative channel stability. A slight increase in hydraulic depth and cross-sectional area for moderate flows is associated with a slight increase in mean velocity, which provides some evidence of channel incision.

08109000 Brazos River near Bryan, Texas

The Brazos River near Bryan, Tex., streamflow-gaging station (08109000) is a discontinued station 4.8 miles downstream from its replacement, 08108700 Brazos River at SH 21 near Bryan (fig. 29A); the sand-bed river (table 1) meanders through a wide alluvial valley (approximately 6 miles wide) in this vicinity. Streamflow measurements at the site began in August 1899 and were discontinued in September 1993 (table 1); at least nine stage-discharge rating curves have been used (table 6) for the period of record. Stage-discharge rating curve implementation dates are not digitally available prior to 1983, and no interpretations are made here using their frequency of adjustment. Stage-discharge relations determined from field measurements indicate progressive channel degradation during the period of record (fig. 32 at end of report). Disturbance associated with the construction of the Texas SH 21 bridge in 1986 (table 7) might have delivered minor quantities of sediment 4.8 miles downstream to the site.

One historical aerial photograph from 1957 was georeferenced and compared to a 2006 DOQQ in the vicinity of the gaging station (fig. 33 at end of report). One of the more evident changes since 1957 is the considerable growth of vegetation along the channel banks and point-bar surfaces, which is expected to minimize erosion and possibly promote deposition of sediment along the banks and bar surfaces. The locations of three meander bends are noted in figure 33 by the letters A, B, and C. One meander bend (A) 8,800 feet upstream from the discontinued station was eroded along the upper part of its right bank and rapidly migrated 790 feet (average of 16.1 feet per year between 1957 and 2006), and vegetation has established on the left point-bar surface. Another meander bend (B) 2,000 feet upstream from the discontinued station also has rapidly migrated to the left (east) approximately 750 feet (average of 15.4 feet per year between 1957 and 2006), and the bend has reduced its wavelength from about 2,000 to 1,300 feet at the apex. One meander bend (C) 3,300 feet downstream from the discontinued station has not migrated, but vegetation has encroached on the left point-bar surface and on a longitudinal bar along the right side of the channel immediately downstream from the meander apex.

Various historical ground photographs were scanned for 08109000 Brazos River near Bryan. A February 5, 1954, photograph taken from the left bank just downstream from the gage's stilling well shows low-flow conditions (daily mean streamflow of 409 cubic feet per second), an open to slightly wooded left bank, and a gradually sloping, open right point-bar surface (fig. 34A at end of report). Another historical photograph from March 10, 1971 (daily mean streamflow of 294 cubic feet per second), continues to show an open to slightly wooded left bank, but benching of sediment on the

right point-bar surface has slightly increased the slope to the channel (fig. 34B). A repeat photograph taken on April 2, 2008, shows flow conditions slightly less than the long term mean for this date (daily mean streamflow of 2,190 cubic feet per second), a steeper and more densely vegetated left bank compared to the photographs from 1954 and 1971, with vegetation that blocked the view of the stilling well in 2008, and dense vegetation on the right point-bar surface, which has resulted in considerable benching of sediment and a steeper point-bar surface to the channel (fig. 34C).

The measurement site is between two large meander bends; cross-sectional geometry is slightly asymmetrical, with the thalweg near the steep left channel bank (fig. 35 at end of report). Historical cross sections for moderate flows (fig. 35A) show thalweg incision of about 1.5 feet and relative channel-bed stability on the right side between 1962 and 1985. About 15 feet of lateral erosion on the lower left bank also is detected in moderate-flow cross sections, or an average of about 0.65 foot per year between 1962 and 1985. Unlike the historical moderate-flow cross sections, historical high-flow cross sections (fig. 35B) do not indicate channel-bed incision, probably attributed to considerable scour of the sand bed during high flows and possibly extending down to a more resistant surface. The deep thalweg incision for the extreme high-flow measurement in December 1991 (161,500 cubic feet per second) can be associated with unusually high flow velocity and bed shear stress (table 21), and the extreme flow conditions compounded the inherent difficulty of cableway measurements and associated errors at such extreme-magnitude flows. High-flow cross sections also indicate vertical deposition of sediment on the right side of the channel that causes a steeper right-bank angle, probably resulting from the aforementioned vegetation encroachment on this side of the river. Further, about 20 feet of upper left bank erosion between 1961 and 1991 is shown in figure 35B, which resulted in structural problems with gaging-station infrastructure and required the eventual relocation of this site upstream to 08108700 Brazos River at SH 21 near Bryan. The detection of minor thalweg incision in moderate-flow cross sections (greater than 5,000 and less than 10,000 cubic feet per second) and the lack of evidence for incision in high-flow cross sections of the Brazos River near Bryan substantiates that moderate flows are best suited for assessments of channel-bed stability for sand-bed and high-energy gravel-bed rivers that are known to scour and fill during high flows.

Computations of selected hydraulic properties for historical cross sections of the Brazos River near Bryan are listed in table 21. Hydraulic properties for moderate flows show a slight overall increase in hydraulic depth and associated cross-sectional area and mean velocity, related to the minor channel incision observed in historical cross sections since 1962 (fig. 35A). Hydraulic properties for high flows, excluding the extreme-magnitude 1991 flood, show a gradual reduction in channel width, resulting from benching on the right bank, and increase in hydraulic depth since 1961. The reduction in the width-to-depth ratio through time offsets adjustments of cross-sectional area and mean velocity, which are variable through time. The complementary increases of hydraulic depth for moderate and high flows have increased values of depth-dependent shear stress.

08110325 Navasota River above Groesbeck, Texas

The Navasota River above Groesbeck, Tex., streamflow-gaging station (08110325) is at a water-treatment facility about 1.1 miles downstream from Springfield Lake, but the site for moderate- and high-flow measurements is at the SH 14 bridge only 0.15 mile downstream from the lake (fig. 36A,B at end of report). This fine sand- and silt-bed river (table 1), a major tributary of the Brazos River, is confined and relatively straight between Springfield Lake and the gaging station. Streamflow measurements at the site began in June 1978 and continue to present (2009) (table 1). Only two stage-discharge rating curves have been used (table 6) for the period of record; stage-discharge relations determined from field measurements indicate stable channel dimensions during the period of record (fig. 37 at end of report). The bridge at this site has been in place since 1960, thus no channel adjustments are attributed to construction activity (table 7).

One historical aerial photograph from 1968 was geo-referenced and compared to a 2006 DOQQ in the vicinity of the gaging station (fig. 38 at end of report). In general, vegetation growth along the river and on surrounding lands has increased since 1968, which is expected to increase flow resistance and possibly promote benching and floodplain sedimentation. No planform changes are detected along the straight reach of the river downstream from Springfield Lake, and few changes would be expected as a result of the confined valley setting.

The measurement site is along a straight reach and the cross-sectional geometry is highly symmetrical (fig. 39A,B at end of report). A channel-in-channel morphology is evident, with a relatively narrow and deep low-flow channel that conveys low and normal flows, set within a larger flood channel that conveys high flows. It is likely that this geometry is either related to a previous episode of channel incision associated with greatly reduced sediment loads that are now effectively trapped in Springfield Lake, or possibly related to channel dredging operations near the bridge. Historical cross sections for moderate flows indicate very little change between 1979 and 2004 (fig. 39A). The apparent thalweg aggradation and sediment benching along the left and right channel margins for high flows actually is temporary scour of the channel boundary during the relatively high-magnitude flow in May 1979 (26,800 cubic feet per second). Moderate flow cross-sectional geometry before and after this high flow remains constant and again warrants that caution should be used when interpreting cross-sectional change using high-flow measurements.

Computations of selected hydraulic properties for historical cross sections of the Navasota River above Groesbeck are listed in table 22 at end of report. Hydraulic properties for high flows show a wider channel with a greater cross-sectional area in 1979, which is explained by temporary scour expected for the higher flow on this date. Because of the break in slope between the lower channel and the upper high-flow channel (fig. 39B), hydraulic depth is lower at a stage of 5 feet than it is at a stage of zero.

08110500 Navasota River near Easterly, Texas

The Navasota River near Easterly, Tex., streamflow-gaging station (08110500) is located at a bridge along U.S. Highway 79 (fig. 40 at end of report); the sand- and silt-bed river (table 1), a major tributary of the lower Brazos River, is about 20 miles downstream from Lake Limestone, a reservoir impounded in 1978. Streamflow measurements at the site began in April 1924 and continue to present (2009) (table 1); at least 12 stage-discharge rating curves have been used (table 6) for the period of record. Stage-discharge rating curve implementation dates are not digitally available prior to 1987, and no interpretations are made here using their frequency of adjustment. Stage-discharge relations determined from field measurements show two distinct episodes of channel degradation: (1) the 1940s, and (2) the late 1970s and 1980s (fig. 41 at end of report). A second bridge at this site was constructed in 1959 and reconstructed in 1981 (table 7) and those activities are likely to have affected cross-sectional geometry. Measurement section distances were changed with the 1959 construction, therefore, two sequences of historical cross sections are provided. Further, streamflow in two overflow channels (anabranches) has consistently been measured, thereby affording an opportunity to investigate cross-sectional adjustment of floodplain channels, which are common in the lower Navasota River subbasin (Phillips, 2009). An anabranch is a separate channel that has diverged from the main channel and rejoins the stream somewhere downstream; it is a discrete, semi-permanent channel that may be the same size as the main channel or smaller, thereby distinguishing it from channel braids that are not discrete and may be highly ephemeral (Osterkamp, 2008). Anabranches along the Navasota River are abandoned main channel courses resulting from upstream avulsions that occur when the main channel is abandoned in favor of a more hydraulically efficient flow path through the alluvial valley. These former channel courses fill in with sediment through time, but many are semi-active for years following the avulsion and convey a large proportion of streamflow during floods. For discussion of the Navasota River, anabranches should be considered as former positions of the main channel.

One historical aerial photograph from 1958 was georeferenced and compared to a 2004 DOQQ in the vicinity of the gaging station (fig. 42 at end of report). A detectable change since 1958 is the considerable growth and density of vegetation near the channel and in the floodplain, which is expected to promote floodplain sedimentation. Meanders of the left anabranch are visible in the 1958 aerial photograph but are obscured by vegetation in the 2004 DOQQ. Likewise, meanders and cutoffs of the main channel are more easily discerned in 1958 than in 2004, when vegetation obscures the channel just upstream from the bridge crossing.

Various historical ground photographs were scanned for 08110500 Navasota River near Easterly. Although not consistently taken from the same vantage point, photographs looking upstream on June 7, 1934 (fig. 43A at end of report), December 1952 (fig. 43B), and April 1, 2008 (fig. 43C), show considerable change in the channel through time. In 1934, a weir was located just downstream from the bridge, and a gently sloping open left bank contrasts with a relatively steep wooded right bank upstream from the bridge. By 1952, the weir was gone, the channel had slightly migrated to the right, considerable accretion of sediment covered the lower one-half of the leftmost (right side of the photograph) bridge piers, and vegetation along the channel had mostly been removed. From first glance, one might suspect a recent flood was responsible for the condition of the channel in 1952, but annual peak streamflow was mostly low for the previous 6 years. The weir probably was destroyed during the May 2, 1944, flood with a peak flow of 60,300 cubic feet per second. By 2008, a third bridge replaces the older bridge, vegetation has reestablished along the channel banks, sediment has been deposited along the channel margins, and a reduction in channel dimensions has resulted. A December 5, 1941, photograph taken from the left bank just upstream from the bridge shows low-flow conditions (daily mean streamflow of only 6.8 cubic feet per second), wooden piers and decking of the old bridge, and an undulating right bank devoid of vegetation (fig. 43D). A repeat photograph taken on April 1, 2008, during normal-flow conditions (daily mean streamflow of 59 cubic feet per second), shows the replacement bridge built in 1981, wooden piers at the base of the right bank that are remnants of the older bridge shown in the 1941 photograph, and denser vegetation and less undulation along the right bank (fig. 43E). A July 22, 1985, photograph taken from the left bank just downstream from the bridge shows low-flow conditions (daily mean streamflow of 2.8 cubic feet per second) and a contracted channel with gradual opening to wooded left and right banks that cover the base of the older bridge’s piers (fig. 43F). A repeat photograph taken on April 1, 2008 (fig. 43C), shows that the right bank has eroded away from the concrete bridge pier and that vegetation density along the banks in 1985 and 2008 is similar. This series of photographs qualitatively indicates that between the 1930s and 1950s riparian vegetation removal and increased sedimentation, probably caused by land-use practices in the subbasin, resulted in lateral channel activity and considerable benching of sediment along the channel margins. Between the 1950s and 2008, vegetation was reestablished along the channel margins and sedimentation continued, resulting in a reduction of conveyance capacity. Minor fluctuations in channel geometry for the past 20 years or more probably are attributed to variable flood magnitudes and frequencies.

The measurement site is on a relatively straight reach between numerous meanders (fig. 40). Historical cross sections for low flows between 1932 and 1952 (fig. 44A at end of report) show approximately 3 feet of channel incision and about 25 feet of migration to the right (west), or an average migration of 1.2 feet per year. Considerable benching of sediment on the left channel margin occurred between 1932 and 1938, and topographic irregularities filled in as thalweg incision and slow lateral migration continued until 1952. Historical cross sections for high flows between 1932 and 1957 reinforce the thalweg incision and slow lateral migration that was indicated by low-flow measurements, and also show that one swale (station 640 feet) in the floodplain adjacent to the right channel bank filled in with sediment between 1932 and 1938 (fig. 44B). Also, one large floodplain swale (station 1,150 feet) adjacent to the left channel bank was filled in with about 10 feet of sediment by 1944, but was scoured again to its previous level by 1957. The high-flow cross sections also show that small natural levees at the tops of both banks grew vertically by about 0.5 foot by 1957. Bankfull channel width of high-flow cross sections between 1932 and 1957, inferred from sharp breaks in slope between the channel and relatively flat floodplain, was consistently about 200 feet. The contraction of the bankfull channel width during the early 1960s persisted in 1974, after which a gradual expansion of width and area occurred. Moderate-flow cross sections for 1978 and 1991 show another geometric adjustment of the channel (fig. 44C). The steep left and right banks evident in 1978 were lower and more gradually sloped by 1991, possibly related to 1981 bridge reconstruction. Channel-bed incision in the 1978 and 1991 cross sections was similar. Moderately high-flow cross sections show migration of the thalweg to the right side of the channel between 1965 and 1974 followed by a slight rebound to the left by 1997 (fig. 44D). Bankfull channel width contracted to only 90 feet by 1965, roughly one-half the width of 1957. Although it is likely that the 1959 bridge construction strongly influenced this change, a rebound of bankfull channel width to about 140 feet by 1997 has not fully compensated for the dramatic reduction of cross-sectional area during the early 1960s. The recent expansion of width occurred by erosion of the tops of both banks, resulting in a more gradual transition from the floodplain to the channel. Between 1965 and 2000, the high-flow cross sections show about 1.5 feet of channel incision, which occurred during a period of overlap when the channel migrated to the left between 1984 and 2000 (fig. 44D,E). Cross-sectional geometry in 2000 was symmetrical and relatively deep for its width (fig. 44E), which is common when fluvial sediment is very fine grained. A summary of channel adjustment for the main channel is as follows: (1) activity was at its greatest between 1932 and 1957, when channel-bed incision and lateral migration to the right occurred alongside sediment deposition on the channel margins and at the tops of both banks; (2) bankfull channel width contracted to one-half its former width during the early 1960s, likely in part because of bridge construction in 1959; (3) channel-bank angles were gradually decreased between 1975 and 2000 and the channel thalweg migrated to the right until the mid-1970s, when it reversed direction and migrated to the left by 2000; (4) slight thalweg incision occurred between 1965 and 2000; and (5) adjustment of the contemporary Navasota River occurs mostly through changes in channel width resulting from sediment deposition or erosion along the channel margins, as opposed to channel incision and lateral migration, which were more active processes in the early 20th century.

Anabranches are relatively confined as they pass under the roadway through narrow bridges, but can be assessed to determine if they maintain their activity through time by analyzing their patterns and rates of sedimentation. A relatively large left anabranch (approximately 300 feet wide) of the Navasota River near Easterly shows some lateral activity between 1932 and 1957 as the thalweg shifted from the right to the left between 1944 and 1957, but overall bed elevation has not changed (fig. 45A at end of report). Between 1965 and 2000, the anabranch was constricted by about 50 feet because of the 1959 bridge construction, and eventually lowered much of its bed by about 2 feet (fig. 45B), indicating that it has continued to convey high flows. A smaller, symmetrical right anabranch had very stable dimensions between 1932 and 1957 (fig. 46A at end of report), but has aggraded since that time (fig. 46B), probably as a result of artificial changes to conveyance during the bridge construction in 1959 and reconstruction in 1981 (table 7). Decreases in channel cross-sectional area between 1965 and 2000 might indicate that over time, decreasing volumes of flow are being conveyed by this anabranch.

Computations of selected hydraulic properties for historical cross sections of the Navasota River near Easterly are listed in tables 23 and 24 at end of report. Hydraulic properties for low and high flows between 1932 and 1957 reflect channel incision as hydraulic depth and cross-sectional area increase for a given stage. Beginning in the early 1960s, the relatively high mean velocity reflects a contraction of the channel to a narrow and deep geometry, followed by a rebound to a wider channel with a lower mean velocity by the mid-1980s.

08110800 Navasota River at Old Spanish Road near Bryan, Texas

The Navasota River at Old Spanish Road near Bryan, Tex., streamflow-gaging station (08110800) is located at a bridge (fig. 47A,B at end of report). The sand- and silt-bed river (table 1), a major tributary of the lower Brazos River, typically meanders through an open to wooded floodplain in this vicinity, but is straight adjacent to the bridge. The straight reach appears to have been artificially constructed (fig. 47A,B), most likely to increase hydraulic efficiency of high flows at the bridge. The gaging station was established in 1997 (table 1) as a replacement for 08111000 Navasota River near Bryan because of channel avulsion and accessibility issues at the latter station. Seven stage-discharge rating curves have been used (table 6) for the period of record, possibly

indicating a geomorphically unstable channel. Stage-discharge relations determined from field measurements indicate some channel degradation during the short period of record (fig. 48 at end of report). The bridge at this site has been in place since 1956 and, therefore, no channel adjustments are attributed to construction activity (table 7).

The measurement site is along a straight reach and the cross-sectional geometry is symmetrical (fig. 49 at end of report). Steep banks have maintained a stable position through time, but about 1 foot of channel-bed incision occurred between 1997 and 2003, thereby explaining the frequent adjustments of stage-discharge rating curves (table 6). Channel incision commonly is associated with artificially straightened reaches because local channel slope, and thereby bed shear stress, increases when the river distance between two points is shortened, causing bed erosion.

Computations of selected hydraulic properties for historical cross sections of the Navasota River at Old Spanish Road near Bryan are listed in table 25 at end of report. Hydraulic properties indicate channel stability between 1997 and 2003, and hydraulic depth does not increase, as would be expected for an actively incising channel. This can be attributed to a small topographic convexity on the left bank that developed and compensated for the observed decrease in channel-bed elevation.

08111000 Navasota River near Bryan, Texas

The Navasota River near Bryan, Tex., streamflow-gaging station (08111000) is a discontinued station downstream from its replacement, 08110800 Brazos River at Old Spanish Road near Bryan. The Navasota River near Bryan meanders through an open to wooded floodplain (fig. 50 at end of report); this sand- and silt-bed river (table 1) is a major tributary of the lower Brazos River. Streamflow measurements at streamflow-gaging station 08111000 began in January 1951 and were discontinued in March 1997 (table 1); at least 13 stage-discharge rating curves were used (table 6) for the period of record. Stage-discharge rating curve implementation dates are not digitally available prior to 1982, so interpretations of channel adjustment on the basis of rating curve changes were not made. Stage-discharge relations determined from field measurements indicate progressive channel degradation during the period of record (fig. 51 at end of report). Historical streamflow measurements were made from the U.S. Highway 190 bridge; construction of the bridge in 1959 (table 7) affected cross-sectional geometry of the river channel. Two anabranches have consistently been measured, thereby affording an opportunity to investigate cross-sectional adjustment of floodplain channels, which are common in the lower Navasota River subbasin.

One historical aerial photograph from 1949 was georeferenced and compared to a 2004 DOQQ in the vicinity of the gaging station (fig. 52 at end of report). The most apparent change since 1949 is that the Navasota River switched to a new western course at a point of avulsion just upstream from the bridge and gaging station, which resulted in an abandoned channel and gradual cessation of flow to the gaging-station infrastructure. Another apparent change since 1949 has been vegetation removal in the floodplain downstream from the gaging station, which is expected to reduce resistance to overbank flows.

Various historical ground photographs were scanned for 08111000 Navasota River near Bryan. An August 27, 1975, photograph looking upstream from the U.S. Highway 190 bridge shows normal-flow conditions (daily mean streamflow of 33 cubic feet per second), a steep and exposed lower right bank with dense vegetation near the top of the bank, and a vegetated left bank (fig. 53A at end of report). Although not taken from the bridge crossing, an April 1, 2008, photograph looking upstream from the left bank downstream from the bridge shows a similarly open lower right bank with dense vegetation above the channel (fig. 53B). However, the channel shown in figure 53B had become an abandoned segment by April 1, 2008, and the water was not flowing. By 2008, the channel had reoccupied an anabranch (fig. 53C) and the daily mean streamflow on April 1, 2008, was 147 cubic feet per second.

The Navasota River near Bryan measurement site is along a meandering reach and the cross-sectional geometry is relatively narrow (bankfull width approximately 100 feet), deep (1993 bankfull depth approximately 11 feet), and mostly symmetrical, with a thalweg adjacent to the left bank (fig. 54 at end of report). Historical cross sections for moderately high flows (fig. 54A) show an episode of rapid channel-bed aggradation, about 4 feet between 1958 and 1965, related to bridge construction in 1959 and followed by a period of degradation from 1965 through 1993. The aggradational episode also coincides with the dramatic decrease in channel width upstream at 08110500 Navasota River near Easterly (fig. 44B,D), also likely associated with bridge construction in 1959. Since 1965, the channel readjusted by incising its bed about 2 feet. Additionally, the floodplain elevation increased by about 2 feet in some locations between 1958 and 1965 and, unlike the channel bed, has not readjusted since that time. Despite the substantial vertical adjustments of the river to bridge construction activities, lateral position appears to be relatively stable, with only about 5 feet of constriction from the right bank. Historical cross sections for high flows (fig. 54B) substantiate aggradation from moderately high flows.

Anabranch channels are relatively confined as they pass under the roadway through narrow bridges; by analyzing the patterns and rates of sedimentation in the anabranches over time, it can be determined if they maintain their conveyance function during high flows. A relatively wide anabranch (approximately 200 feet wide) of the Navasota River near Bryan had a very stable cross-sectional configuration between 1965 and 1993, with only slight channel-bed incision adjacent to the right bank (fig. 55A at end of report). The channel bed of a formerly smaller (1965 width approximately 125 feet), narrow anabranch was initially incised between 1974 and 1984, with more rapid incision progressing until 1993 (fig.

55B). Total channel-bed incision between 1974 and 1993 was about 7 feet, and is associated with this overflow channel becoming the main channel following an upstream avulsion.

Computations of selected hydraulic properties for historical cross sections of the Navasota River near Bryan are listed in table 26 at end of report. Hydraulic properties for moderately high-flow and high-flow cross sections reflect channel aggradation associated with the 1959 bridge construction, followed by gradual incision since that time. The apparently wide channel for the May 8, 1990, high-flow measurement is an artifact related to the low density and wide spacing of data points rather than channel adjustment processes.

08111500 Brazos River near Hempstead, Texas

The Brazos River near Hempstead, Tex., streamflow-gaging station (08111500) is located at a bridge along U.S. Highway 290 (fig. 56 at end of report). Compared to other sites on the lower Brazos River, the sand-bed channel near Hempstead (table 1) meanders through a relatively narrow (approximately 2.5 miles) alluvial valley. Streamflow measurements at the Hempstead site began in October 1938 and continue to present (2009) (table 1); at least 11 stage-discharge rating curves have been used (table 6) for the period of record. Although rating curves are not digitally available prior to 1976, the lengthy duration of two rating curves since that date would appear to indicate relative channel stability at this location. Stage-discharge relations determined from field measurements, however, indicate an overall degradational pattern for the period of record (fig. 57 at end of report), with much of the adjustment during the 1990s and 2000s. Much of the period of record between 1950 and 1980, however, is absent from figure 57. The bridge at this site was reconstructed in 1972 (table 7) and might have affected cross-sectional channel geometry. Because measurement section distances were changed in 1949 with the construction of a cableway upstream from the bridge and again in 1974 with the reconstruction of the bridge, three sequences of historical cross sections are provided.

Various historical ground photographs were scanned for 08111500 Brazos River near Hempstead. A December 15, 1975, photograph looking downstream from the U.S. Highway 290 bridge shows low-flow conditions (daily mean streamflow of 728 cubic feet per second) and a moderately sloping and lightly wooded right bank (fig. 58A at end of report). A repeat photograph taken at the gaging station on April 2, 2008, shows normal-flow conditions (daily mean streamflow of 3,260 cubic feet per second), an open base of the right bank, and denser vegetation at the top of the right bank (fig. 58B).

The measurement site is between two gradual meander bends and the cross-sectional geometry varies from a slightly to strongly asymmetrical form (fig. 59 at end of report), with much of the shape dependent on changes in measurement locations. Historical cross sections for moderate and high flows between 1939 and 1949 (fig. 59A,B) show that the formation of an instream bench along the right bank was associated with about 15 feet of channel-bed incision toward the left bank. The deposition of material along the right bank modified the symmetrical form of the channel and must have resulted from construction activities because more than 15 vertical feet of the right channel bank remained in place above the deposit, indicating that the typical bank caving processes do not explain the bench. Additionally, sediment deposition on the upper one-half of the left bank and erosion of the left bank near the bed resulted in a steeper bank angle by 1949. Historical cross sections for moderate and high flows measured at the cableway show the channel-bed elevation increased about 9 feet between 1950 and 1956, and then decreased by about 8 feet between 1956 and 1960 (fig. 59D,E). These considerable changes in bed elevation for a relatively brief time period might be the result of downstream sand-bar migration into and out of the measurement section, scour-and-fill processes associated with individual flow magnitudes, continuation of direct human disturbance to the channel at this site, or a combination of these factors. Further, the decrease in channel-bed elevation during the late 1950s is partly explained by scour associated with the May 1957 flood, which had the highest peak streamflow (143,000 cubic feet per second) on record at this gaging station. Historical cross sections for moderate and high flows between 1980 and 2000 indicate about 6 feet of thalweg incision, with most of the incision occurring between 1981 and 1991 (fig. 59E,F), although stage-discharge rating curves were not frequently updated during this time (table 6). Most bank positions appear to be stable during this time, although deposition of sediment on the right bank between 1981 and 1987 might be attributed to the aforementioned increase in vegetation density at this location. In summary, cross-sectional geometry of the Brazos River near Hempstead has shifted considerably between 1939 and 2000. Some of these adjustments result from human activity, including instream modification and bridge construction, and others from scour during a range of floods. Slow channel incision appears to be the dominant long-term process at this location, but a lack of data during the 1960s and 1970s along with frequent changes in the measurement locations confounds the assessment of geomorphic processes. The relatively confined alluvial valley usually indicates that bedrock is relatively close to the surface, suggesting further channel incision will also be slow. At this station, Dunn and Raines (2001) show that water-surface elevation declined about 1.5 feet at a discharge of 5,000 cubic feet per second since 1938, supporting an interpretation of slow channel incision for the period of record.

Computations of selected hydraulic properties for historical cross sections of the Brazos River near Hempstead are listed in tables 27–29 at end of report. Hydraulic properties for moderate-flow and high-flow cross sections reflect channel-bed incision associated with human activity between 1939 and 1949, evidenced by an increase in hydraulic depth, cross-sectional area, and mean velocity. An increase in hydraulic depth overcompensated for a reduction of channel width at the base of the right bank, resulting in the considerable increase in

cross-sectional area. Hydraulic properties for moderate-flow and high-flow cross sections for the period 1950 to 1960 are variable and associated with frequent adjustments of channel-bed elevation during this time. Finally, hydraulic properties for moderate-flow and high-flow cross sections for the period 1980 to 2000 are less variable than previous years.

08114000 Brazos River at Richmond, Texas

The Brazos River at Richmond, Tex., streamflow-gaging station (08114000) is located at a bridge along U.S. Highway 90A (fig. 60 at end of report), and the sand-bed river (table 1) meanders through the upper part of the alluvial-deltaic plain. Although a few intermittent streamflow measurements were made between 1903 and 1906, routine streamflow measurements began in October 1922 and have continued to present (2009) (table 1). During high flows, even below bankfull, considerable flow is diverted upstream to the sinuous Oyster Creek and other drainage features across the alluvial-deltaic plain. Oyster Creek is located a few miles to the east of the Brazos River and was a former channel position of the Brazos River, flowing from upstream of Richmond to the Gulf of Mexico; other sinuous drainage features flow roughly parallel to the Brazos River across the alluvial-deltaic plain. At least 15 stage-discharge rating curves have been used (table 6) for the period of record. Although rating curves are not digitally available prior to 1984, five updates after this date likely indicate channel adjustment processes have been active since 1984. In addition, stage-discharge relations determined from field measurements indicate progressive channel degradation since the 1970s (fig. 61 at end of report). The period of record prior to 1975 was not digitally available for figure 61. The westbound and eastbound bridges at this site were constructed in 1965 and 1989 (table 7), respectively, and might have affected cross-sectional channel geometry. Before late 1957, measurements were made from a cableway 270 feet downstream from the gage. Since 1957, measurements have been made from the eastbound bridge. For this reason, two sequences of historical cross sections are provided.

One historical aerial photograph from 1952 was georeferenced and compared to a 2005 DOQQ for the area near the gaging station 08114000 Brazos River at Richmond (fig. 62 at end of report). Since 1952, vegetation along the channel banks has grown and increased in density in the vicinity of the station, which is expected to minimize erosion and possibly promote deposition of sediment along the banks, bar surfaces, and floodplain. The location of one meander bend is noted in figure 62 by the letter A. The meander bend (A) just upstream from the station has narrowed by about 65 feet as the result of sediment deposition along the right bank, possibly enhanced by engineered bank-stabilization. Further, the upper end of this meander bend about 2,000 feet upstream from the station has migrated to the left about 200 feet, or an average of 3.8 feet per year between 1952 and 2005. The point bar of this meander, on the right channel margin, has been covered by vegetation and effectively serves as the right bank. The vegetation on the point bar might trap sediment during moderately high flows, contributing to ongoing narrowing of the meander bend.

Various historical ground photographs were scanned for 08114000 Brazos River at Richmond. An August 10, 1965, photograph looking upstream from the eastbound bridge shows normal-flow conditions (daily mean streamflow of 4,240 cubic feet per second), a steep and exposed right bank with scattered lobes of concrete rip-rap, and a pier for the westbound bridge (fig. 63A at end of report). A repeat photograph taken on August 7, 2008, shows low-flow conditions (daily mean streamflow of 549 cubic feet per second), a vegetated right bank, and sediment deposits that cover the base of the bridge pier (fig. 63B). These observations substantiate evidence from aerial photographic comparison that the channel has narrowed by about 65 feet because of deposition along the right channel margin. Although not useful for identification of geomorphic changes below bankfull stage, a photograph was taken on May 21, 1965, looking downstream from the cableway during high-flow conditions (daily mean streamflow of 88,800 cubic feet per second) (fig. 63C). A photograph looking downstream from the eastbound bridge on August 7, 2008, shows the recent condition of the channel (fig. 63D).

The measurement site is at the downstream end of a meander bend; the cross-sectional geometry varies from symmetrical (fig. 64A,B at end of report) to slightly asymmetrical with a left point bar sharply descending to the thalweg near the right cutbank side of the channel (fig. 64C,D). Historical cross sections for moderate and high flows between 1934 and 1957 (fig. 64A,B) are symmetrical because the cableway measurement was farther downstream from the meander bend apex; helicoidal flow, a corkscrew-spiraling flow that promotes meander bend asymmetry (Thompson, 1986), is less pronounced with increasing distance from the apex. Although channel-bed elevations are relatively stable during this time, the channel migrated to the right about 40 feet, or an average of 1.7 feet per year, and the left bank first retreated to the left then back to the right. The sequence of migration illustrated by moderate- and high-flow cross sections occurred in the following chronological order: (1) the right bank retreated by erosion, increasing cross-sectional area; (2) channel-bed sediment was deposited at the base of the left bank, resulting in a gradual transverse slope of the channel bed; and (3) a wedge of sediment along the right bank grew vertically, but had not completed its growth by 1957. Historical cross sections for moderate and high flows between 1957 and 2004 show an asymmetrical configuration because of the close proximity to the meander bend apex, which is associated with strong helicoidal flow and thalweg scour near the cutbank (fig. 64C,D). Cross-sectional adjustment for this time frame is complex and associated with apparent stabilization efforts on the right bank, bridge construction activities, and upstream controls including reductions in sediment transport. Between 1957 and the late 1970s, considerable accretion of sediment on the left

channel margin occurred simultaneously with erosion of the right bank, resulting in overall migration of the channel to the right, a steeper left bank, and an overall reduction in cross-sectional area. These changes to cross-sectional geometry probably are partly associated with bridge construction in 1965. No measurement data were available for the Brazos River at Richmond gaging station from the Federal Archives for the 1960s and early 1970s, so the effects of the 1965 bridge construction were difficult to ascertain. During the 1980s, the left bank eroded and retreated about 100 feet, but retained its steep descent to the thalweg. Between 1991 and 1993, material apparently was added to the right bank to prevent continued migration toward Richmond, amounting to about 35 feet of lateral contraction toward the left. Between 1993 and 2004, incision of approximately 5 feet occurred along most of the channel bed, with only the right thalweg remaining relatively unaffected. The overall result of channel adjustments between the late 1950s and mid-2000s is a narrower, deeper channel with steeper banks. At this station, Dunn and Raines (2001) show that water-surface elevations are variable through time, with a sharp decline between 1944 and 1955, then a sharp increase between 1955 and 1959, followed by a gradual decline until the early 1980s, and finally a sharp decline to 1990. Overall, the water-surface elevation declined about 3.5 feet at a discharge of 5,000 cubic feet per second since 1934, thereby supporting an interpretation of gradual channel incision for the entire period of record.

Computations of selected hydraulic properties for historical cross sections of the Brazos River at Richmond are listed in tables 30 and 31 at end of report. Hydraulic properties for moderate-flow cross sections reflect channel migration processes between 1934 and 1955, evidenced by fluctuation in channel width. High-flow hydraulic properties during this time show an increase in channel width and a decrease in hydraulic depth; fluctuation in mean velocity is mostly related to flow magnitude during the measurement. Hydraulic properties for moderate-flow cross sections between 1957 and 1998 fluctuate, but an increase in channel width, hydraulic depth, cross-sectional area, and mean velocity after 1993 reflect active channel enlargement processes during that time. Hydraulic properties for high-flow cross sections between 1958 and 2004 show a decrease in channel width coupled with an increase in hydraulic depth, indicating the development of a narrower, deeper channel.

08116650 Brazos River near Rosharon, Texas

The Brazos River near Rosharon, Tex., streamflow-gaging station (08116650) is located at a bridge along Texas FM 1462 (fig. 65 at end of report), and the sand-bed river (table 1) meanders through the upper part of the alluvial-deltaic plain. Streamflow measurements at the site began in April 1967 and continue to present (2009) (table 1); at least 10 stage-discharge rating curves have been used (table 6) for the period of record. Although rating curves are not digitally available prior to 1988, four updates since this date likely indicate contemporary channel adjustment. Stage-discharge relations determined from field measurements indicate progressive channel degradation since the 1980s (fig. 66 at end of report). The bridge at this site has been in place since 1965, so the channel adjustments since the 1980s were not caused by construction activity (table 7). Before 1976, high-flow measurements were made from the upstream side of the bridge, but most high-flow measurements since then are made from the downstream side of the bridge, thus two sequences of high-flow historical cross sections are provided.

One historical aerial photograph from 1958 was georeferenced and compared to a 2005 DOQQ in the vicinity of the gaging station (fig. 67 at end of report). Since 1958, vegetation has generally grown and become denser along the channel and on point bars, which is expected to minimize erosion and possibly promote deposition of sediment along the banks and bar surfaces. The locations of three meander bends are noted in figure 67 by the letters A, B, and C. One meander bend (A) 3,200 feet upstream from the station has migrated downstream about 410 feet, or an average of 8.7 feet per year between 1958 and 2005, with the erosion occurring along the left bank. Further, a good example of a crevasse-splay deposit is shown in the eastern (left) floodplain of this meander bend in 1958, indicating overbank flow and deposition at this location. Downstream at the gage and meander bend (B), the channel boundaries show the result of vegetation encroachment on the left point bar. Another meander bend (C) 2,800 feet downstream from the station has migrated toward the left about 260 feet, or an average of 5.6 feet per year between 1958 and 2005.

Various historical ground photographs were scanned for 08116650 Brazos River near Rosharon. An April 2, 1967, photograph looking upstream from the right bank shows low-flow conditions (daily mean streamflow of 50 cubic feet per second), a steeply sloping and exposed right bank, an open laterally extensive point bar with a recently deposited bench at the transition to the wooded eastern (left) floodplain, and a bridge pier near the base of the right bank (fig. 68A at end of report). It is uncertain if the pier was originally designed to have exposed pilings at its base, but a high-magnitude flood in May 1965 (peak discharge of 98,800 cubic feet per second upstream at 08114000 Brazos River at Richmond) might have scoured below the designed base of the bridge pier. A repeat photograph taken on August 7, 2008, shows low-flow conditions (daily mean streamflow of 463 cubic feet per second), a steeply sloping and vegetated right bank, and a vegetated bench along the left point-bar surface (fig. 68B). An August 28, 1973, photograph looking upstream from the FM 1462 bridge shows low-flow conditions (487 cubic feet per second), a steeply sloping and exposed right bank with some rip-rap at its base near the bridge, and a vegetated bench on the left point-bar surface (fig. 68C). A repeat photograph taken on August 7, 2008, shows a steeply sloping and vegetated right bank with additional rip-rap and numerous pilings at its base, a completely vegetated

bench on the left point-bar surface, and migration of the lower point bar upstream (fig. 68D). An August 28, 1973, photograph looking downstream from the FM 1462 bridge shows a steeply sloping and exposed right bank, an open lower point-bar surface at the left channel margin, and a recently deposited bench at the transition to the wooded eastern (left) floodplain (fig. 68E). A repeat photograph taken on August 7, 2008, shows more vegetation along the right bank adjacent to the bridge and a completely vegetated and elevated point-bar surface at the left channel margin (fig. 68F). All recent photographs indicate the channel width is narrower as a result of bench development on the left point-bar surface and subsequent encroachment of vegetation.

The measurement site is near the apex of a meander bend; cross-sectional geometry is asymmetrical, with the thalweg near the steep right channel bank (fig. 69 at end of report). Historical cross sections for a channel survey and two high flows between 1967 and 1976 (fig. 69A) show about 6 feet of thalweg incision and considerable sediment deposition on the formerly gradual left bank, resulting in a steeper angle to the thalweg. Historical cross sections for moderate flows between 1976 and 1997 (fig. 69B) show that about 4.5 feet of channel-bed incision occurred simultaneously with contraction of the right bank by about 40 feet, probably because of bank stabilization efforts and vegetation encroachment at the bridge. Historical cross sections for high flows between 1986 and 2000 (fig. 69C) generally support the channel adjustments inferred from moderate-flow cross sections, showing about 2 feet of channel-bed incision and limiting the time frame of bank deposition to the mid-1980s. In total, historical cross sections indicate that about 10.5 feet of thalweg incision occurred between 1967 and 2000, probably as a result of: (1) hydraulic adjustments associated with the bridge construction; (2) benching of sediment on the left point-bar surface; (3) stabilization efforts along the right bank; and (4) possible instream sand mining activities along the river (Dunn and Raines, 2001). At this station, Dunn and Raines (2001) show that the water-surface elevation declined only about 2 feet at a discharge of 5,000 cubic feet per second since 1969, indicating that most of the channel incision at this location occurred between 1967 and 1969. It is plausible that altered hydraulic patterns associated with the 1965 bridge construction, coupled with a high-magnitude flood in May 1968 (peak streamflow of 79,900 cubic feet per second) resulted in a substantial amount of the channel-bed incision observed by Dunn and Raines (2001).

Computations of selected hydraulic properties for historical cross sections of the Brazos River near Rosharon are listed in tables 32 and 33. Hydraulic properties for high-flow cross sections between 1975 and 1976 show the condition of the channel following a period of channel incision and channel narrowing. Hydraulic properties for moderate-flow cross sections between 1976 and 1997 reflect active channel incision and contraction of the right bank, which were accompanied by increases in hydraulic depth, cross-sectional area, mean velocity, and shear stress for a given stage. Hydraulic properties for high-flow cross sections between 1986 and 2000 show an initial decrease in channel width and increase in mean velocity by 1991, followed by an increase in hydraulic depth. The adjustments of cross-sectional geometry during this period, however, do not result in substantial changes to cross-sectional area.

Summary

The U.S. Geological Survey (USGS), in cooperation with the Texas Water Development Board, completed a retrospective analysis of channel geometry and estimated hydraulic properties at selected USGS streamflow-gaging stations in the lower Sabine and lower Brazos River Basins in Texas and Louisiana. Adjustments of planform and cross-sectional channel geometry, as well as associated changes in flow hydraulics, are important factors to consider for assessments of aquatic habitat condition and function. Morphologic and ecological assessments are required for the Texas Instream Flow Program; an understanding of historical changes resulting from upstream impoundments, land use, instream modifications, and flow variability are imperative to the success of the program. This report documents historical channel adjustment and estimates of selected hydraulic values and is intended to provide practitioners with (1) a procedural framework to use USGS streamflow data and other sources to quantify changes in channel morphology during the period of streamflow-gaging-station record, and (2) information on patterns of channel change in the aforementioned river basins.

Various methods were used to assemble information necessary to assess morphologic adjustments in the Sabine River, Brazos River, and selected tributaries. The primary sources of information were hard-copy USGS discharge measurement notes, which are detailed tables completed in the field that record intermittent measurements of cross-sectional width, flow depth, and flow velocity. The weighted mean gage heights, as well as individual measures of cross-sectional width and flow depth, were used to reconstruct cross-sectional geometry for selected dates throughout the period of record of the gaging station, and historical cross-section elevations were adjusted to contemporary values, if necessary, to account for arbitrary gage-datum changes. The technique can be used when streamflow measurements are made at a consistent cross section through time, such as the upstream side of a bridge or a cableway. It is problematic when streamflow measurements are made by wading, and cross-section locations vary along the reach.

When depth and velocity measurement locations are changed along a cross section, the results for a previous time series of geometric measurements are inconsistent with one that follows. This can occur when a bridge is reconstructed, a cableway is abandoned for another location, or cross-sectional measurement location marks are re-painted on a bridge rail, among other reasons. Interpretations of cross-sectional

adjustment through time must consider temporary scour-and-fill processes active during the time of measurement, which commonly occur in sand-bed and high-energy gravel-bed rivers. For this reason, cross sections measured at moderate and low flows probably represent the most accurate assessments of channel adjustment, because high flows can temporarily scour the channel bed. An optimal streamflow measurement for assessment of channel adjustment would be a moderate flow that does not scour the channel bed, but that also has a water-surface elevation that delimits the majority of the channel banks, thereby defining the entire channel. For most rivers in this investigation, the optimal flow was between 5,000 and 10,000 cubic feet per second, which is less than bankfull discharge at most stations. Additional caution applies to instream modifications at the measurement location, notably bridge-construction activities, because the hydraulics of contracted flow at many bridges likely will result in cross-sectional channel adjustment. For this reason, cross sections at cableways probably render more accurate assessments of natural channel adjustment and flow hydraulics than bridges. Likewise, cross sections at old bridges are better suited for comparison to present (2009) conditions than bridges that have recently been constructed. Finally, consideration should be given to hydraulic and other boundary conditions associated with gaging station locations. Gaging stations are strategically located to minimize complexities associated with streamflow measurement, often in confined locations with relatively stable channels that might not be representative of conditions along the majority of the river's length.

Other techniques used in this investigation include estimation of flow hydraulics for historical cross sections, analyses of stage-discharge relations of field measurements, and comparison of historical and contemporary aerial and ground photographs. Flow hydraulic properties were computed for historical cross sections using the Manning's *n* slope-area procedure. Channel slope was determined using 10-meter digital elevation models (DEMs), and the Manning's *n* flow-resistance value was adjusted for each cross section to closely match the measured streamflow for that date. For measurements that included multiple overflow channels, the streamflow used for hydraulic computations was constrained to the channel, or channels, of interest and not the total streamflow. Analyses of stage-discharge relations of digitally available field measurements for the period of record were done to complement and reinforce interpretations of channel adjustment made from historical cross sections. To investigate planform channel condition and migration rates, historical aerial photographs were scanned, georeferenced, and compared with contemporary DOQQs. Finally, historical ground photographs of the river channel were scanned and two trips were made to take replicate photographs that closely resemble the historical images.

The Sabine River downstream from Toledo Bend Reservoir has slightly adjusted during historical time, and records available for this study extend back to the 1930s for one gaging station. Toledo Bend Reservoir is not a flood-control impoundment and the regular occurrence of high-magnitude floods since its completion in 1966 nullifies explanations of geomorphic change based on flood hydrology alone. Relatively minor channel incision, related to sediment trapping in Toledo Bend Reservoir, is detected at the uppermost gaging station, 08026000 Sabine River near Burkeville, Tex., however channel-bed elevations downstream appear to be relatively stable. One notable exception was an episode of channel-bed aggradation at 08028500 Sabine River near Bon Wier, Tex., in the 1930s. Relatively low rates of lateral channel migration, less than an average of 1 foot per year, are shown for the stations near Burkeville and Bon Wier, but only are quantified from streamflow-measurement data and not aerial photography, which would provide more evidence for lateral activity over a longer reach than that observed at the measurement section. Overall, the Sabine River near Ruliff, along with its distributaries, appears to have the most stable channel configuration. Some fluctuations in channel-bed elevations at these stations are likely associated with scour-and-fill processes, especially at high flows, or downstream channel-bar migration, common to sand-bed rivers. Hydraulic variable adjustments reflect changes in channel geometry through time.

The Brazos River downstream from Waco, Tex., also has shown geomorphic adjustment during historical time; records available for this study extend back to the 1920s for one gaging station and to the 1930s for two other gaging stations. Channel adjustments along the Brazos River are not entirely explained by reductions in flood frequency and magnitude associated with flood-control impoundments, although flood magnitudes have decreased downstream from Waco, especially at the uppermost gaging stations used in this study. Since the 1960s, various lines of evidence show that point-bar deposits have grown vertically as a result of vegetation encroachment and sediment deposition, referred to as benching. These changes result in a steeper angle between the point-bar surface and the thalweg, which reduces cross-sectional area and promotes thalweg incision. Channel-bed incision is detected at all gaging stations along the Brazos River, and the depth of incision is greatest in the lowermost gaging stations, 08114000 Brazos River at Richmond and 08116650 Brazos River near Rosharon, with the latter showing about 10 feet of incision since 1967. This high value, however, probably is partly associated with considerable sediment deposition as a result of 1965 bridge construction and subsequent incision of that sediment. One episode of channel-bed aggradation, likely associated with upstream dam construction, is detected at 08096500 Brazos River at Waco, Tex., during the late 1920s and 1930s. Although benching and channel incision could be inferred as a stagnation of active lateral processes, evidence shows that many reaches of the Brazos River have actively developing point bars, lateral migration, and localized widening trajectories. For example, relatively high rates of lateral channel migration (greater than an average of 10 feet per year) were computed for the Brazos River between Waco and Hempstead, and lower rates (less than an average of 10 feet per year) were computed downstream from Hempstead. The sediment

removed from the floodplain at cutbanks of actively migrating bends and added to the river by tributaries adequately offsets sediment trapped by upstream reservoirs, and might be the supply for vertical accretion of downstream point bars. As with the Sabine River, hydraulic variable adjustments reflect changes in channel geometry through time.

Channel adjustment patterns and rates of change differed for two tributaries of the Brazos River—Little River and Navasota River. Historical cross sections of Little River, a gravel- and sand-bed channel, show considerable channel incision of about 12 feet over the last 50 years, which is probably attributed to reduced sediment loads resulting from various upstream impoundments. The Navasota River, a sand- and silt-bed channel, has a complex history of adjustment, which is complicated by bridge construction and avulsion activities at measurement locations. For example, the Navasota River near Easterly, Tex. (08110500), actively migrated and lowered its channel bed until the 1960s, when bridge construction contracted the bankfull width to one-half its previous width. Since that time, the channel has slowly adjusted its bank slopes and thalweg elevation, but has not restored its condition prior to 1960. Another example is the Navasota River near Bryan, Tex. (08111000), which aggraded about 4 feet as a result of 1959 bridge construction and, subsequently, slowly incised its bed by about 2 feet until an upstream avulsion re-routed the streamflow to a former overflow channel.

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