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Base Flow (1966–2005) and Streamflow Gain and Loss (2006) of the Brazos River, McLennan County to Fort Bend County, Texas, 2006

Scientific Investigations Report 2007–5286

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

Cover: U.S. Geological Survey field technician deploying discharge measurement equipment at Hidalgo Falls on the Brazos River near Navasota, Texas, March 8, 2006 (photograph by Jimmy Hopkins, U.S. Geological Survey).

Base Flow (1966–2005) and Streamflow Gain and Loss (2006) of the Brazos River, McLennan County to Fort Bend County, Texas

By Michael J. Turco, Jeffery W. East, and Matthew S. Milburn

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Conversion Factors and Datum

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)

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

°F=(1.8×°C)+32

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

Water year is defined as the 12-month period October 1 through September 30 and is designated by the calendar year in which it ends.

Datum

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

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Base Flow (1966–2005) and Streamflow Gain and Loss (2006) of the Brazos River, McLennan County to Fort Bend County, Texas, 2006

By Michael J. Turco, Jeffery W. East, and Matthew S. Milburn

Abstract

During 2006–07, the U.S. Geological Survey (USGS), in cooperation with the Texas Water Development Board, did a study to quantify historical (water years 1966–2005) base flow and streamflow gains and losses from two streamflow-measuring surveys (March and August 2006) in the Brazos River from McLennan County to Fort Bend County, Texas. The Brazos River is hydraulically connected to the Brazos River alluvium aquifer, which in turn is hydraulically connected to several underlying aquifers, the outcrops of which occur in laterally adjacent layers generally parallel to the coast (major aquifers, Carrizo-Wilcox and Gulf Coast, and minor aquifers, Queen City, Sparta, and Yegua-Jackson). Hydrograph separation was done using the USGS computer program Hydrograph Separation and Analysis with historical streamflow from 10 USGS gaging stations, three on the Brazos River and seven on selected tributaries to the Brazos River. Streamflow data for computation of gains and losses were collected in March 2006 from 36 sites on the Brazos River and 19 sites on 19 tributaries to the Brazos River; and in August 2006 from 28 sites on the Brazos River and 16 sites on tributaries. Hydrograph separation and associated analyses indicate an appreciable increase in base flow as a percentage of streamflow in the reach of the Brazos River that crosses the outcrops of the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers compared to that in the adjacent upstream reach (on average from about 43 percent to about 60 percent). No increase in base flow as a percentage of streamflow in the reach of the Brazos River crossing the Gulf Coast aquifer compared to that in the adjacent upstream reach was indicated. Streamflow gains and losses computed for March 2006 for 35 reaches defined by pairs of sites on the Brazos River indicated that five reaches were verifiably gaining streamflow (computed gain exceeded potential flow measurement error) and none were verifiably losing streamflow. Four of the five gaining reaches are in the outcrop areas of the Carrizo-Wilcox and Yegua-Jackson aquifers. The results of the synoptic gain and loss surveys are consistent with the results of the base-flow analysis of historical streamflow. Appreciable increases in streamflow, apparently the result of increases in base flow, occur in the reach of the Brazos River that crosses the outcrops of the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers.

Introduction

The Brazos River alluvium aquifer is an important resource to water users in the Brazos River Basin from McLennan County to Fort Bend County, Texas (fig. 1). As demands on the resource increase in the future, the Brazos River alluvium aquifer likely will become more important. Quantification of base flow in the Brazos River and the exchange of water between the Brazos River and the underlying Brazos River alluvium aquifer could assist water managers and planners responsible for the long-term sustainability of surface- and ground-water resources in the area.

Slade and others (2002) identified 31 previous studies in which streamflow gain and loss data were collected in the Brazos River, which extends across Texas from southeastern New Mexico to the Gulf of Mexico (fig. 1). However, none of those studies were done in the reach of the river that flows through the area of the Brazos River alluvium aquifer (the reach that defines the area of this study). General qualitative descriptions of base flow in segments of the study area were reported by the Texas Board of Water Engineers (1960):

- Area between Waco and the northern Falls County line—Geologic formations can be expected to make extremely small contributions to base flow of the Brazos River.
- Area between the northern Falls County line and Bryan—Geologic formations can be expected to make large contributions to base flow of the Brazos River.
- Area between Bryan and Hempstead—Geologic formations can be expected to make small contributions to base flow of the Brazos River.

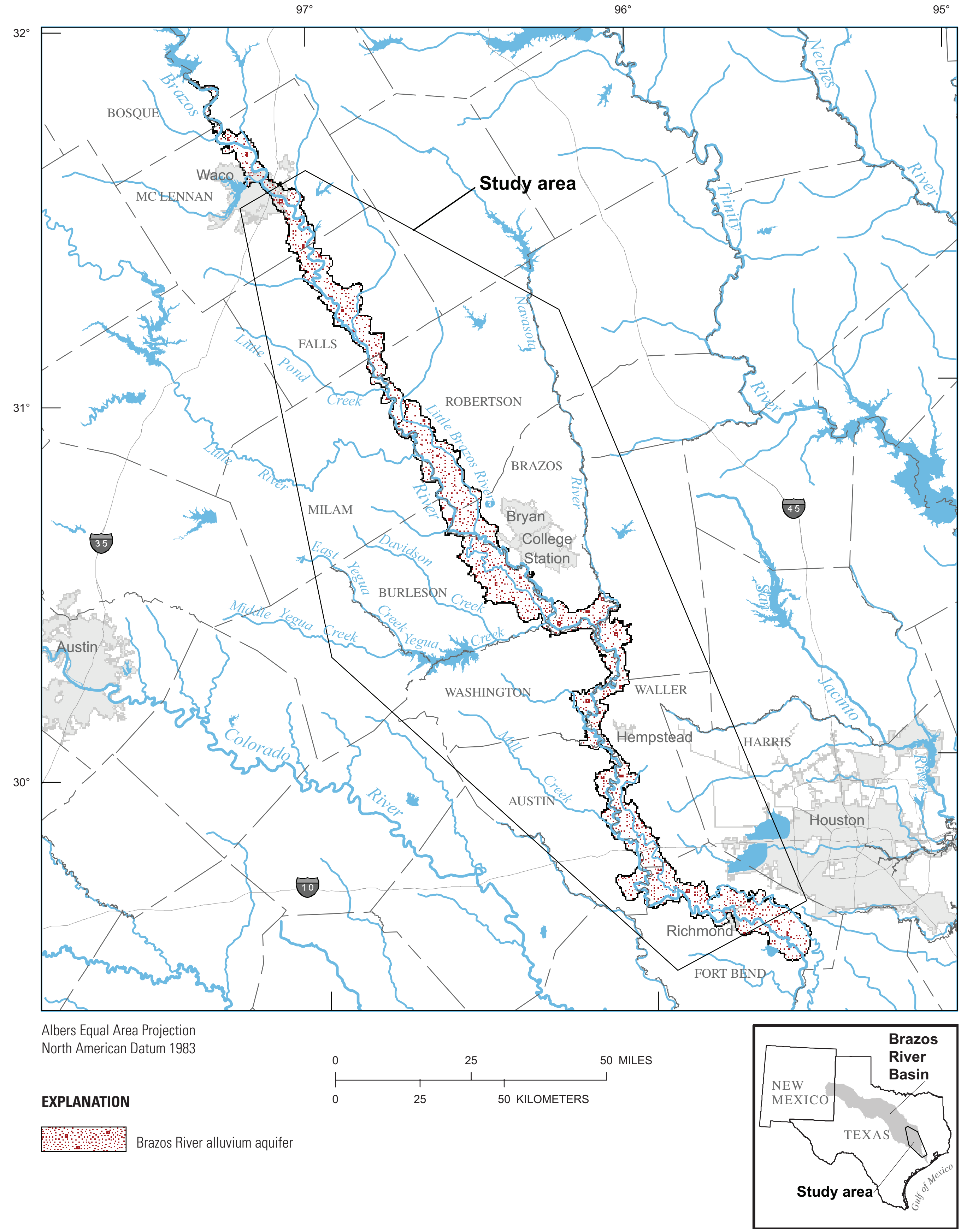

Figure 1. Study area, Brazos River, and extent of Brazos River alluvium aquifer, McLennan County to Fort Bend County, Texas.

- Area between Hempstead and Richmond—Geologic formations can be expected to make moderate contributions to base flow of the Brazos River.

During 2006–07, the U.S. Geological Survey (USGS), in cooperation with the Texas Water Development Board (TWDB), did a study to quantify base flow and streamflow gains and losses in the Brazos River from McLennan County to Fort Bend County. Of particular interest were potential gains and losses in the river where it flows across the outcrop areas of the Carrizo-Wilcox aquifer, the Queen City aquifer, the Sparta aquifer, and the Yegua-Jackson aquifer (fig. 2). These outcrop areas are essentially coincident with the area between the southern Falls County line and Bryan that, according to the Texas Board of Water Engineers (1960), is expected to make large contributions to base flow of the Brazos River.

Purpose and Scope

The purpose of this report is to document the results of base-flow analysis (hydrograph separation) of historical (water years 1966–2005 [October 1965 through September 2005]) streamflow and two synoptic streamflow gain and loss surveys of the Brazos River from McLennan County to Fort Bend County, Texas, in March and August 2006. Methods of data collection and analysis are described. Results of hydrograph separation based on available historical data for three sites on the Brazos River and seven sites on tributaries to the Brazos River are presented. Streamflow gains and losses based on flow data collected from 55 sites on the Brazos River and selected tributaries during the two synoptic surveys are presented, and the respective gaining and losing reaches are identified. Water-quality properties (temperature and specific conductance) were collected as a part of the March 2006 survey and are included in the report, but those data were not used in the analysis of gains and losses.

Description of Study Area

The study area encompasses a 310-mile reach of the Brazos River from Waco in McLennan County to Richmond in Fort Bend County (fig. 1) and includes selected inflow tributaries along the reach. The major tributaries are the Little River, Little Brazos River, Yegua Creek, Navasota River, and Mill Creek. Average annual rainfall (1971–2000) at College Station is 39.67 inches (National Weather Service, 2007). Five real-time USGS streamflow-gaging stations are on the Brazos River in the study area (fig. 2):

1. 08096500 Brazos River at Waco, Tex. (site B1, fig. 2)
2. 08098290 Brazos River near Highbank, Tex. (site B6, fig. 2)
3. 08108700 Brazos River at State Highway 21 near Bryan, Tex. (site B14, fig. 2)
4. 08111500 Brazos River near Hempstead, Tex. (site B26, fig. 2)
5. 08114000 Brazos River at Richmond, Tex. (site B36, fig. 2)

Daily mean streamflow (1941–2006) ranged from 2,147 cubic feet per second at the Brazos River at Waco to 7,532 cubic feet per second at the Brazos River at Richmond (U.S. Geological Survey, 2007).

The Brazos River is hydraulically connected to the Brazos River alluvium aquifer. The alluvium aquifer is composed of fine to coarse sand, gravel, silt, and clay, the distribution of which varies from place to place (Cronin and others, 1963). Beds or lenses of sand and gravel grade laterally into vertically finer or coarser material. In general, the finer material is in the upper part of the aquifer. The thickness of the aquifer throughout most of its extent is less than 100 feet (Shah and others, 2007, sheet 4).

Underlying the Brazos River alluvium aquifer in laterally adjacent layers generally parallel to the coast are two major aquifers, Carrizo-Wilcox and Gulf Coast, and three minor aquifers, Queen City, Sparta, and Yegua-Jackson (Texas Water Development Board, 2007) (fig. 2). The Gulf Coast aquifer is actually an aquifer system, the principal aquifers of which are the Chicot, Evangeline, and Jasper (not differentiated in this report). Upstream from the outcrop of the Carrizo-Wilcox aquifer, the Brazos River alluvium aquifer is underlain by rocks not characterized as part of a major or minor aquifer by the TWDB. Like the Brazos River alluvium aquifer, each of the underlying aquifers is composed of interbedded sand, clay, gravel, and silt in varying amounts (Ashworth and Hopkins, 1995; Ryder and Ardis, 2002). The underlying aquifers are distinguished from one another in large part by the stratigraphic units of the rocks composing the aquifers and the relative positions of the units.

The underlying aquifers are hydraulically connected to the Brazos River alluvium aquifer, as indicated by potentiometric-surface maps of the Carrizo-Wilcox, Queen City, and Sparta aquifers (Garza and others, 1987). The approximate potentiometric-surface map of the Carrizo-Wilcox aquifer for 1980 of Garza and others (1987) in the aquifer outcrop shows U-shaped potentiometric contours, closed upstream and relatively large, across the Brazos River. Similarly, the approximate potentiometric-surface map of the Sparta-Queen City aquifer (Garza and others [1987] combined the Queen City and Sparta aquifers for mapping) for 1980 in the aquifer outcrop shows U-shaped potentiometric contours, closed upstream, across the Brazos River. The potentiometric-surface maps indicate, in addition to hydraulic connection between the Brazos River, the Brazos River alluvium aquifer, and the underlying aquifers, that the river is gaining water in the aquifer outcrop areas, which is consistent with the Texas Board of Water Engineers (1960) qualitative description of the river gaining base flow in the reaches crossing the aquifer outcrops. Although no potentiometric surface for the Yegua-Jackson aquifer is available, and no potentiometric-surface maps

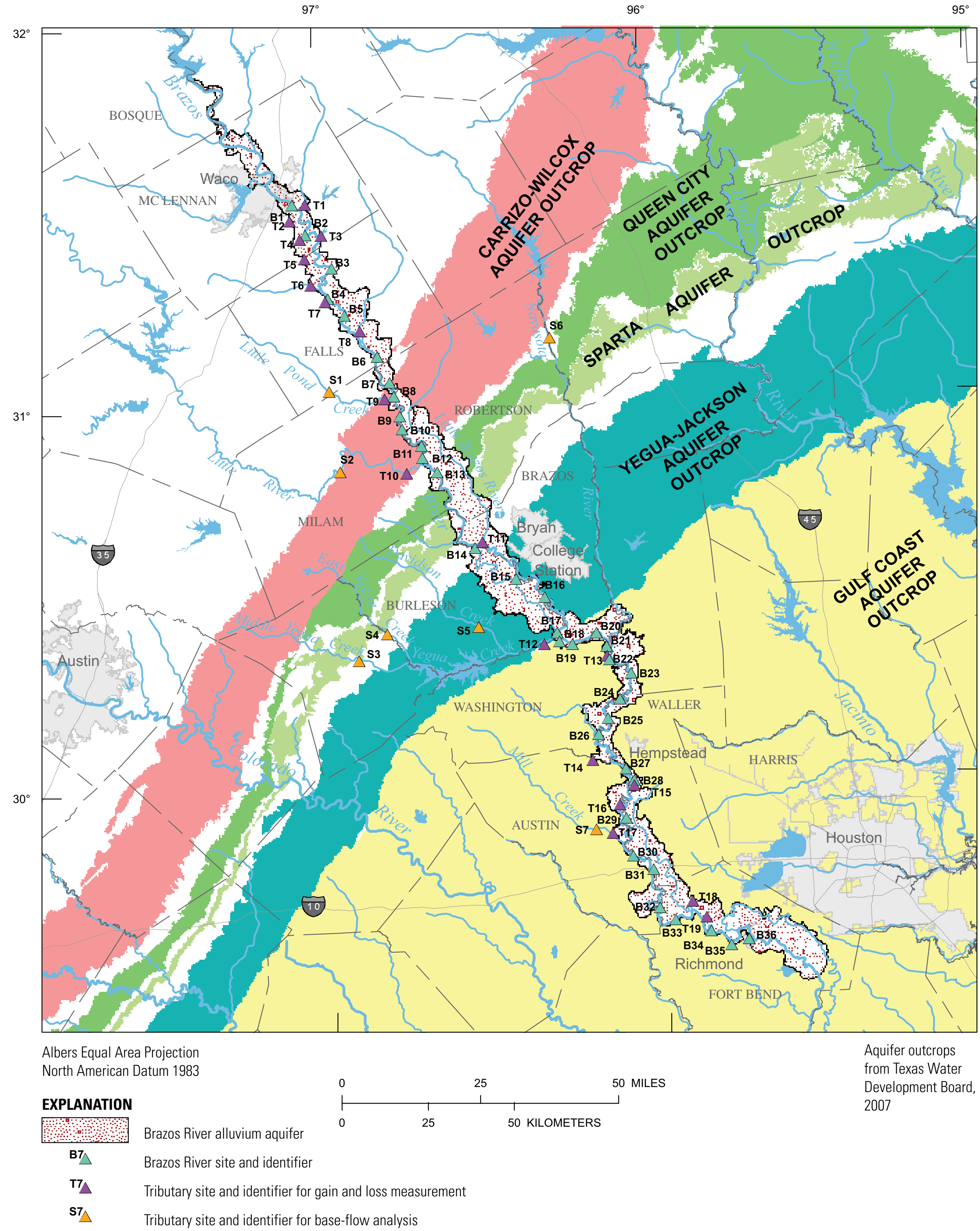

Figure 2. Brazos River alluvium aquifer, McLennan County to Fort Bend County, Texas; outcrops of underlying aquifers; and data-collection sites.

constructed using shallow wells in the outcrops of the Chicot, Evangeline, and Jasper aquifers are known to exist, hydraulic connection between those aquifers, the Brazos River alluvium aquifer, and Brazos River are assumed.

Acknowledgments

The authors acknowledge the contributions of Barney Austin, Robert Mace, and Ali Chowdhury of the Texas Water Development Board during the planning of this study. Additionally, the authors acknowledge staff of the Brazos River Authority who assisted in identifying appropriate streamflow-measuring sites and in collecting data. The authors thank the numerous property owners who allowed access to measuring sites.

Methods

Hydrograph separation using historical streamflow was done to estimate base flow. Streamflow data collection and streamflow gain and loss computation were done to estimate streamflow gains and losses in the reach of the Brazos River from McLennan County to Fort Bend County.

Hydrograph Separation

Hydrograph separation is the process of separating measured streamflow into components resulting either from direct surface runoff or from ground-water discharge (base flow). Hydrograph separation was done using the USGS computer program Hydrograph Separation and Analysis (HYSEP) (Sloto and Crouse, 1996). The data used in HYSEP were historical (water years 1966–2005) streamflow from 10 USGS gaging stations, three on the Brazos River and seven on selected tributaries to the Brazos River (table 1). The HYSEP program makes the hydrograph separation process objective by removing inconsistencies inherent in manual methods. Daily mean streamflow for each station was input to the HYSEP program. Output from the program includes the two components of the annual mean streamflow—annual mean surface runoff and annual mean base flow. Additionally, HYSEP provides the base-flow index (BFI), which is the ratio of the annual mean base flow to the annual mean streamflow. The BFI was used as a means to graphically compare streamflows (hydrographs) from the three Brazos River stations. The graphical comparisons indicate whether the reach between two stations is gaining or losing flow.

Wahl and Wahl (1995) states that caution should be used in applying hydrograph separation to data for short-term storms or for sites where streamflow is affected by upstream regulation, such as reservoir releases. The Brazos River in the study area is affected by regulation. Therefore, after using HYSEP to make hydrograph separation computations, the results were analyzed and judgments made regarding whether rises were from storm runoff or from reservoir releases. When judged necessary, HYSEP program input was adjusted by varying the runoff-timing parameter, and the program was rerun. This iterative process was continued until the results were deemed reasonable (that is, periods of reservoir releases were categorized by HYSEP as storm runoff).

Streamflow Data Collection

Streamflow data for computation of gains and losses were collected from the Brazos River and 19 tributaries to the Brazos River during March 6–10, 2006, and during August 10–18, 2006. The study was separated into two periods to collect streamflow data that were representative of two distinct hydrologic conditions. March is usually wetter than August and demand on water resources (pumpage from the river, the alluvium aquifer, and underlying major and minor aquifers) is relatively low. August is usually drier and demand on water resources is relatively high.

During the March data-collection period, streamflow was measured at 55 sites, 36 on the Brazos River and 19 on tributaries (fig. 2; table 2). During the August data-collection period, streamflow measurements were made at 44 of the 55 sites, 28 on the Brazos River and 16 on tributaries. Water temperature and specific conductance also were measured during the March data-collection period at 53 and 52 sites, respectively.

Table 1. U.S. Geological Survey streamflow-gaging stations on the Brazos River and selected tributaries, McLennan County to Fort Bend County, Texas, that provided data for hydrograph separation, water years 1966–2005 (October 1965 through September 2005).

[USGS, U.S. Geological Survey]

Site identifier (fig. 2)	USGS station number	USGS station name	Contributing drainage area (square miles)
B6	08098290	Brazos River near Highbank, Tex.	20,870
S1	08098300	Little Pond Creek near Burlington, Tex.	23.0
S2	08106500	Little River near Cameron, Tex.	7,065
S3	08109700	Middle Yegua Creek near Dime Box, Tex.	236
S4	08109800	East Yegua Creek near Dime Box, Tex.	244
S5	08110100	Davidson Creek near Lyons, Tex.	195
S6	08110500	Navasota River near Easterly, Tex.	968
B26	08111500	Brazos River near Hempstead, Tex.	34,314
S7	08111700	Mill Creek near Bellville, Tex.	376
B36	08114000	Brazos River at Richmond, Tex.	35,541

Table 2. Sites on the Brazos River and selected tributaries, McLennan County to Fort Bend County, Texas, at which measurements for streamflow gain and loss computation were made, March and August 2006.

[USGS, U.S. Geological Survey; SH, State Highway; --, not applicable; CR, County Road, FM, Farm Road; IH, Interstate Highway]

Site identifier (fig. 2)	USGS station number	USGS station name	Latitude (degrees minutes seconds)	Longitude (degrees minutes seconds)	Distance upstream from mouth (miles)
B1	08096500	Brazos River at Waco, Tex.	313209	0970423	401
T1	313210097015800	Tehuacana Creek at SH 6 near Waco, Tex.	313210	0970158	--
T2	312934097045300	Flat Creek at CR 3400 near Robinson, Tex.	312934	0970453	--
B2	312723097020000	Brazos River near Robinson, Tex.	312723	0970200	390
T3	312715096590800	Monas Creek at FM 1860 near Riesel, Tex.	312715	0965908	--
T4	312639097030500	Castleman Creek near Robinson, Tex.	312639	0970305	--
T5	312335097022100	Bull Hide Creek at FM 434 near Golinda, Tex.	312335	0970221	--
B3	312201096572200	Brazos River near Golinda, Tex.	312201	0965722	375
T6	311927097011700	Cow Bayou below FM 434 near Chilton, Tex.	311927	0970117	--
B4	08097500	Brazos River near Marlin, Tex.	311718	0965810	364
T7	311645096584400	Deer Creek at SH 320 near Marlin, Tex.	311645	0965844	--
B5	311437096551300	Brazos River at FM 712 near Marlin, Tex.	311437	0965513	359
T8	311204096523300	Mussel Run Creek near Highbank, Tex.	311204	0965233	--
B6	08098290	Brazos River near Highbank, Tex.	310802	0964929	346
B7	310354096472000	Brazos River below FM 1373 near Baileyville, Tex.	310354	0964720	338
B8	310143096463800	Brazos River above Pond Creek near Baileyville, Tex.	310143	0964638	335
T9	310120096481700	Pond Creek at FM 2027 near Baileyville, Tex.	310120	0964817	--
B9	305836096453800	Brazos River at FM 979 near Calvert, Tex.	305836	0964538	329
B10	305630096451400	Brazos River near Calvert, Tex.	305630	0964514	326
B11	305349096414800	Brazos River at Big Bend near Calvert, Tex.	305349	0964148	317
B12	305158096414500	Brazos River at FM 485 near Hearne, Tex.	305158	0964145	314
T10	304932096443900	Little River at CR 263 near Gause, Tex.	304932	0964439	--
B13	08108500	Brazos River at Valley Junction, Tex.	304938	0963905	309
B14	08108700	Brazos River at SH 21 near Bryan, Tex.	303736	0963238	286
T11	08108990	Little Brazos River at SH 21 near Bryan, Tex.	303827	0963116	--
B15	08109500	Brazos River near College Station, Tex.	303233	0962521	269
B16	302932096201600	Brazos River at Batts Ferry near Wellborn, Tex.	302932	0962016	258
B17	302355096181000	Brazos River near FM 159 near Clay, Tex.	302355	0961810	243
T12	302208096203500	Yegua Creek at FM 50 near Clay, Tex.	302208	0962035	--
B18	302230096175000	Brazos River near FM 1955 near Clay, Tex.	302230	0961750	241
B19	302200096152900	Brazos River at Rogers Plantation near Millican, Tex.	302200	0961529	239
B20	302342096110400	Brazos River near FM 159 near Millican, Tex.	302342	0961104	233
B21	302134096091800	Brazos River at SH 105 near Washington, Tex.	302134	0960918	228
T13	302003096091400	Navasota River below SH 105 near Washington, Tex.	302003	0960914	--
B22	301927096085300	Brazos River below Navasota River near Washington, Tex.	301927	0960853	226
B23	301713096050000	Brazos River at Old River Road near Courtney, Tex.	301713	0960500	219
B24	301313096071200	Brazos River near FM 2726 near Courtney, Tex.	301313	0960712	209
B25	301014096092700	Brazos River near FM 1736 near Hempstead, Tex.	301014	0960927	202
B26	08111500	Brazos River near Hempstead, Tex.	300744	0961115	194
T14	300343096123300	Caney Creek at FM 1371 near Hempstead, Tex.	300343	0961233	--
B27	300217096063400	Brazos River at SH 159 near Hempstead, Tex.	300217	0960634	179
B28	300024096050500	Brazos River near FM 1887 near Hempstead, Tex.	300024	0960505	176
T15	295936096051100	Clear Creek near FM 1887 near Hempstead, Tex.	295936	0960511	--
T16	295637096075400	Piney Creek at FM 331 near Burleigh, Tex.	295637	0960754	--

Table 2. Sites on the Brazos River and selected tributaries, McLennan County to Fort Bend County, Texas, at which measurements for streamflow gain and loss computation were made, March and August 2006—Continued.

Site identifier (fig. 2)	USGS station number	USGS station name	Latitude (degrees minutes seconds)	Longitude (degrees minutes seconds)	Distance upstream from mouth (miles)
B29	295431096064800	Brazos River at FM 529 near Burleigh, Tex.	295431	0960648	162
T17	295211096091900	Mill Creek at FM 331 near Burleigh, Tex.	295211	0960919	--
B30	294830096054400	Brazos River at FM 1458 at San Felipe, Tex.	294830	0960544	147
B31	294617096021200	Brazos River at IH–10 near Brookshire, Tex.	294617	0960212	140
B32	294017096011400	Brazos River at FM 1093 at Simonton, Tex.	294017	0960114	125
B33	293820095583200	Brazos River at FM 1489 near Simonton, Tex.	293820	0955832	117
T18	294107095551800	Bessies Creek at FM 1093 near Fulshear, Tex.	294107	0955518	--
T19	293835095525600	Jones Creek at Bois du Arc Road near Fulshear, Tex.	293835	0955256	--
B34	293621095521300	Brazos River at CR near FM 359 near Rosenberg, Tex.	293621	0955213	103
B35	293403095483700	Brazos River at FM 723 near Rosenberg, Tex.	293403	0954837	97
B36	08114000	Brazos River at Richmond, Tex.	293456	0954527	92

Discrete measurements of streamflow were made using USGS methods described in Rantz and others (1982). Where conditions allowed (water depths generally less than 3 feet), streams were waded and velocity measurements were made using rod-mounted acoustic meters (Sontek/YSI, Inc., 2007). In all other instances, boat-mounted acoustic Doppler current profilers were used to measure streamflow, as described in Oberg and others (2005). In-place measurements of water temperature and specific conductance were made using methods described by Wilde and Radtke (1998).

Streamflow Gain and Loss Computation

Streamflow gains and losses over the course of a stream are measured indirectly by computing the differences in streamflow between sites along the stream. Sources of gains or losses between two sites (which define a reach), in addition to ground-water inflow or outflow through the streambed, include tributary inflow, diversions, return flows, and evaporation. Using these factors, streamflow gain or loss in the reach is computed as

$$G = Q_D - Q_U - I + D - R + E, \tag{1}$$

where

- G = streamflow gain or loss (ground-water inflow or outflow);
- Q_D = measured streamflow at the downstream boundary of the reach;
- Q_U = measured streamflow at the upstream boundary of the reach;
- I = measured inflows from tributaries;
- D = measured outflows (diversions) from the reach;
- R = return flows to the reach; and
- E = evaporation. (Units of all variables are cubic feet per second.)

During this study, numerous tributary inflows and one diversion were measured directly. However, return flows and evaporation were not measured, and those components were excluded from equation 1. The magnitude of error associated with these exclusions is believed to be minor when compared to potential errors associated with the flow measurements.

For this report, a stream reach is classified as verifiably gaining or losing only when the difference between streamflows at the upstream and downstream measuring sites that define the reach is greater than the potential error associated with the flow measurements. Measurement error is based on the rating of the streamflow measurement (excellent, good, fair, or poor) by the streamgager (Sauer and Meyer, 1992). The rating is based on factors such as cross-section uniformity, velocity homogeneity, streambed conditions, and other factors that affect the accuracy of the measurement. Measurements rated excellent are believed to be within 2 percent of the actual flow, good are believed to be within 5 percent, fair are believed to be within 8 percent, and poor are believed to differ from the actual flow by more than 8 percent. The potential errors associated with each pair of streamflow measurements for a given reach were summed to obtain the potential composite error for comparison with the computed gain or loss.

Base Flow

The results of hydrograph separation for three streamflow-gaging stations on the Brazos River, 08098290 Brazos River near Highbank (site B6, fig. 2), 08111500 Brazos River near Hempstead (site B26, fig. 2), and 08114000 Brazos River at Richmond (site B36, fig. 2) for water years 1966–2005 are shown in figure 3 and listed in table 3. At the Highbank station, base flow as a percentage of streamflow ranged from a high of about 59 percent in 1990 to a low of about 30 percent

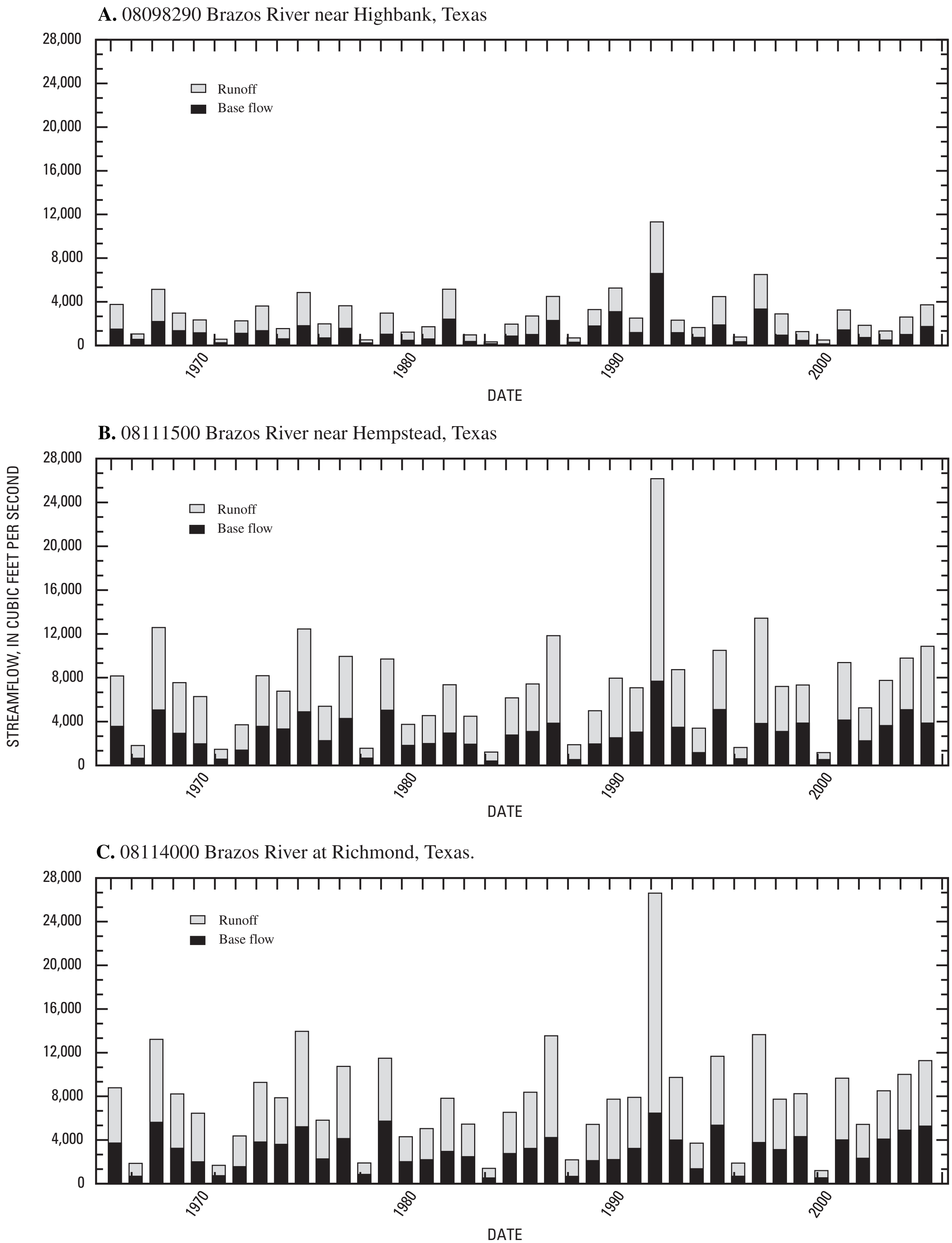

Figure 3. Base flow and runoff components of streamflow, 1966–2005, from hydrograph separation for (A) 08098290 Brazos River near Highbank, Texas; (B) 08111500 Brazos River near Hempstead, Texas; and (C) 08114000 Brazos River at Richmond, Texas.

Table 3. Results of hydrograph separation for 08098290 Brazos River near Highbank, Texas, 08111500 Brazos River near Hempstead, Texas, and 08114000 Brazos River at Richmond, Texas, 1966–2005.

[Q, annual mean streamflow; ft^3/s, cubic feet per second; BF, base-flow component; RO, runoff component; BFI, base-flow index (defined as BF/Q)]

Water year	08098290 Brazos River near Highbank, Tex.				08111500 Brazos River near Hempstead, Tex.				08114000 Brazos River at Richmond, Tex.			
	Q (ft^3/s)	BF (ft^3/s)	RO (ft^3/s)	BFI	Q (ft^3/s)	BF (ft^3/s)	RO (ft^3/s)	BFI	Q (ft^3/s)	BF (ft^3/s)	RO (ft^3/s)	BFI
1966	3,759	1,503	2,255	0.40	8,156	4,596	3,560	0.56	8,792	5,066	3,726	0.58
1967	1,051	565	485	.54	1,822	1,164	658	.64	1,866	1,187	679	.63
1968	5,144	2,195	2,950	.43	12,593	7,534	5,059	.60	13,226	7,597	5,629	.57
1969	2,963	1,354	1,610	.46	7,546	4,619	2,927	.61	8,218	4,974	3,245	.60
1970	2,337	1,161	1,176	.50	6,286	4,312	1,973	.69	6,459	4,453	2,006	.68
1971	572	244	328	.43	1,466	893	573	.61	1,678	941	737	.56
1972	2,253	1,109	1,144	.49	3,703	2,308	1,396	.62	4,374	2,807	1,566	.64
1973	3,611	1,355	2,257	.38	8,186	4,616	3,570	.56	9,282	5,464	3,818	.59
1974	1,552	611	941	.39	6,776	3,447	3,329	.51	7,876	4,266	3,611	.54
1975	4,853	1,815	3,038	.37	12,452	7,560	4,829	.61	13,956	8,735	5,221	.63
1976	1,980	693	1,287	.35	5,400	3,137	2,263	.58	5,817	3,540	2,277	.61
1977	3,643	1,568	2,075	.43	9,958	5,674	4,284	.57	10,740	6,601	4,139	.61
1978	517	233	284	.45	1,564	898	666	.57	1,894	1,038	856	.55
1979	2,970	1,031	1,940	.35	9,722	4,691	5,031	.48	11,487	5,749	5,738	.50
1980	1,218	474	744	.39	3,741	1,917	1,823	.51	4,307	2,284	2,023	.53
1981	1,711	593	1,118	.35	4,541	2,546	1,995	.56	5,053	2,852	2,201	.56
1982	5,150	2,414	2,736	.47	7,360	4,403	2,957	.60	7,829	4,871	2,958	.62
1983	970	363	607	.37	4,491	2,551	1,940	.57	5,462	2,982	2,480	.54
1984	329	162	167	.49	1,216	817	399	.67	1,403	881	522	.63
1985	1,959	865	1,094	.44	6,159	3,384	2,775	.55	6,540	3,775	2,765	.58
1986	2,697	1,002	1,695	.37	7,434	4,332	3,101	.58	8,379	5,144	3,235	.61
1987	4,494	2,298	2,196	.51	11,850	7,997	3,853	.67	13,546	9,318	4,228	.69
1988	690	296	395	.43	1,888	1,350	538	.71	2,184	1,506	678	.69
1989	3,289	1,787	1,502	.54	4,985	3,020	1,966	.61	5,436	3,318	2,118	.61
1990	5,265	3,103	2,162	.59	7,951	5,426	2,525	.68	7,742	5,528	2,214	.71
1991	2,503	1,182	1,321	.47	7,088	4,052	3,035	.57	7,914	4,680	3,233	.59
1992	11,319	6,599	4,720	.58	26,170	18,484	7,685	.71	26,619	20,153	6,466	.76
1993	2,319	1,170	1,149	.50	8,731	5,249	3,482	.60	9,733	5,727	4,006	.59
1994	1,646	736	911	.45	3,399	2,233	1,166	.66	3,718	2,351	1,366	.63
1995	4,474	1,881	2,594	.42	10,508	5,409	5,099	.51	11,676	6,313	5,363	.54
1996	774	346	429	.45	1,638	1,027	611	.63	1,885	1,201	684	.64
1997	6,497	3,337	3,160	.51	13,437	9,607	3,830	.72	13,656	9,880	3,776	.72
1998	2,892	951	1,941	.33	7,207	4,114	3,094	.57	7,735	4,616	3,119	.60
1999	1,273	470	804	.37	7,336	3,467	3,869	.47	8,251	3,940	4,311	.48
2000	506	150	356	.30	1,175	640	536	.54	1,201	667	534	.56
2001	3,253	1,428	1,825	.44	9,390	5,252	4,139	.56	9,662	5,653	4,009	.58
2002	1,849	726	1,122	.39	5,249	3,004	2,244	.57	5,435	3,102	2,333	.57
2003	1,336	499	837	.37	7,758	4,123	3,634	.53	8,515	4,432	4,083	.52
2004	2,605	1,000	1,605	.38	9,805	4,717	5,089	.48	10,115	4,580	5,535	.45
2005	3,719	1,738	1,982	.47	10,877	7,017	3,861	.65	11,280	6,944	4,336	.62

in 2000. At the Hempstead station, base flow as a percentage of streamflow ranged from a high of about 72 percent in 1997 to a low of about 47 percent in 1999. At the Richmond station, base flow as a percentage of streamflow ranged from a high of about 76 percent in 1992 to a low of about 48 percent in 1999.

The compositions of streamflow at the Highbank and Hempstead gaging stations were compared graphically using BFI values (tables 3, 4). BFI values for the Brazos River near Highbank were graphed relative to corresponding BFI values for the Brazos River near Hempstead (fig. 4A). This graph shows that for each water year, the BFI value for the Brazos River near Hempstead is greater than the corresponding BFI value for the Brazos River near Highbank, which indicates that a larger percentage of the mean annual flow at the downstream gage (Hempstead) than at the upstream gage (Highbank) is composed of base flow.

The graph of BFI values in figure 4A does not reflect the effect of tributary inflows in the reach between the Highbank and Hempstead stations. To include the effect of tributary inflows, the results of hydrograph separation (annual mean base flow and streamflow) for tributary sites (stations) S1–S6 (fig. 2) were summed and added to those from the Brazos River near Highbank (table 4). The sum of drainage areas for these six stations is 8,731 square miles, which accounts for about 65 percent of the intervening drainage area between the Brazos River near Highbank and the Brazos River near Hempstead stations. The BFI values for the Highbank and tributary stations combined were graphed relative to corresponding BFI values for the Brazos River near Hempstead (fig. 4B). The graph including the effect of tributary inflows is very similar to that without the effect of tributary inflows, again indicating that more of the mean annual flow at the downstream gage (Hempstead) is composed of base flow.

Data to quantify the potential effects on historical streamflows of diversions, return flows, or other anthropogenic activities are not available. To assess whether these factors have affected historical streamflows, BFI values were graphed relative to time. Figure 4C shows a time series of BFI values for the Brazos River near Hempstead station, and figure 4D shows time series of BFI values for the Brazos River near Highbank station and for the Highbank station plus tributary stations. Visual examination of these time-series graphs does not indicate any discernible trends. To verify the visual result, Mann-Kendall trend tests (Helsel and others, 1992) were run on the time series; no significant trends were indicated (at the .05 level of significance) (p-value = .49 for the Brazos River near Hempstead time series [fig. 4C], p-value = .70 for the Brazos River near Highbank time series [fig. 4D], p-value = .83 for the Brazos River near Highbank plus tributary stations time series [fig. 4D]).

The same process was applied to compare the compositions of streamflow at the Brazos River near Hempstead and Brazos River at Richmond gaging stations (fig. 5; table 3). Again, annual BFI values for the two gages were compared graphically (fig. 5A). This graph shows that for each water year, the BFI value for the Brazos River at Richmond is on average about the same as the corresponding BFI value for the Brazos River near Hempstead, which indicates that the percentage of the mean annual flow that is base flow at the downstream gage (Richmond) is not noticeably different from that at the upstream gage (Highbank).

One USGS streamflow-gaging station is on a tributary that enters the Brazos River in the reach between the Hempstead and Richmond stations (site S7, table 1). The drainage area for this station is 376 square miles, or about 31 percent of the intervening drainage area between the Brazos River near Hempstead and Brazos River at Richmond stations. Figure 5B shows the graph of BFI values for the Brazos River near Hempstead plus the tributary station relative to the BFI values for the Brazos River at Richmond. The relation in this graph is similar to that of the BFIs without the effect of the tributary (fig. 5A), although it appears slightly biased toward a larger percentage of base flow in streamflow at the Hempstead station than at the Richmond station. Time series of BFI values for the Brazos River at Richmond station (fig. 5C) and for the Brazos River near Hempstead station and the Brazos River near Hempstead station plus the tributary station (fig. 5D) do not show discernible trends, which likely indicates diversions, return flows, or other anthropogenic activities have not measurably affected streamflow in the reach during 1966–2005. Mann-Kendall trend tests run on the time series indicated no significant trends at the .05 level of significance (p-value = .29 for the Brazos River at Richmond time series and p-value = .77 for the Brazos River near Hempstead plus one tributary station time series).

Hydrograph separation and graphical evidence from BFI values indicate appreciably more base flow as a percentage of streamflow at the Hempstead station (about 60 percent on average) than at the Highbank station (about 43 percent on average). The reach of the Brazos River between the two stations crosses the outcrops of the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers, the probable source of the additional base flow. This result is consistent with indications of a gaining reach on potentiometric-surface maps of the Carrizo-Wilcox and Queen City-Sparta aquifers of Garza and others (1987) and with the Texas Board of Water Engineers (1960) qualitative description of the river gaining base flow in the reach, as noted previously in the “Description of Study Area” section. Hydrograph separation and graphical evidence from BFI values also indicate no increase in base flow as a percentage of streamflow in the reach of the Brazos River crossing the Gulf Coast aquifer (Chicot, Evangeline, and Jasper aquifers) compared to that in the adjacent upstream reach. Base flow as a percentage of streamflow at the Richmond station is essentially the same as that at the Hempstead station (about 60 percent on average).

Streamflow Gain and Loss

Daily mean streamflow of the Brazos River at three stations during the March and August 2006 surveys (08096500

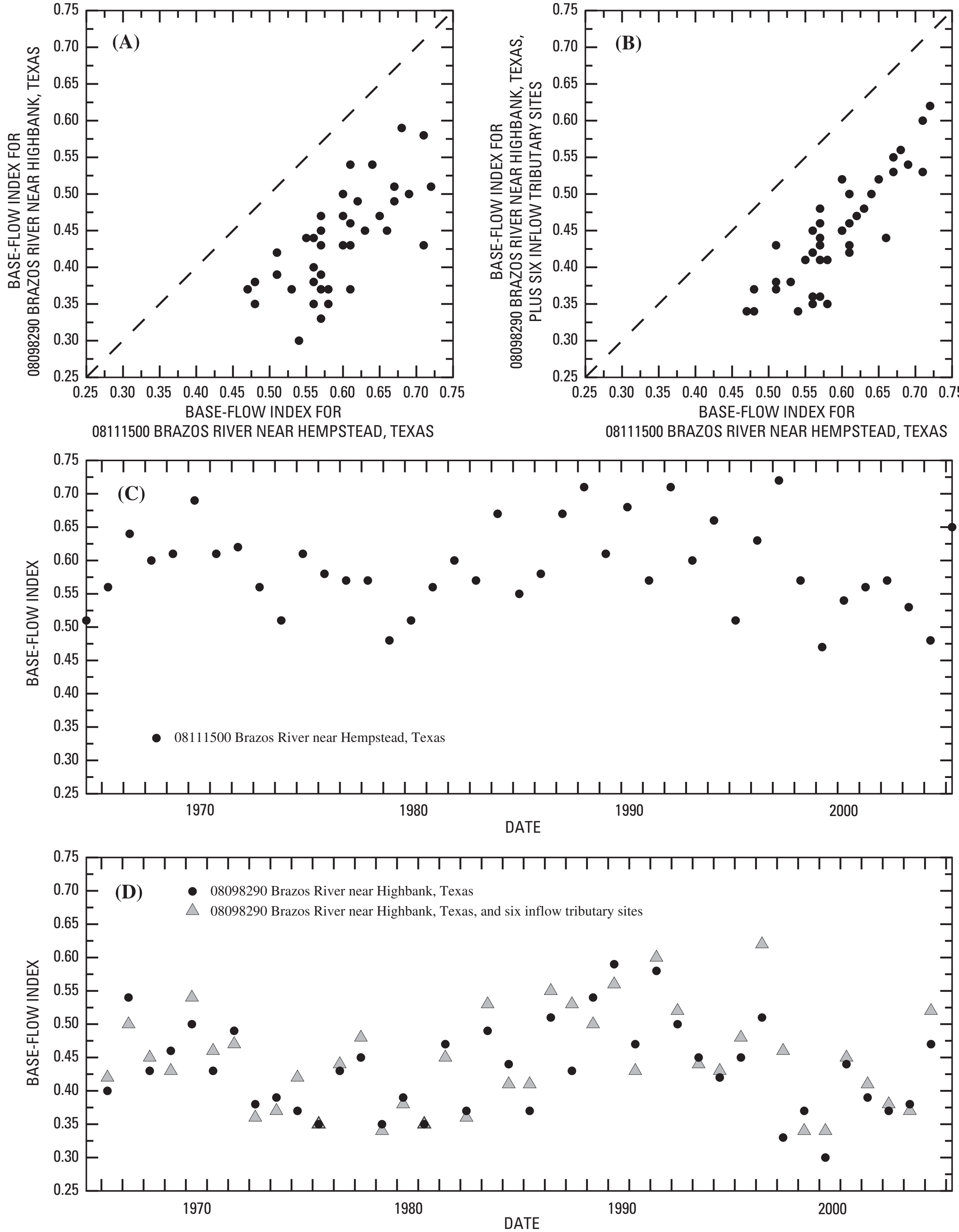

Figure 4. (A) Relation between annual base-flow index for 08098290 Brazos River near Highbank, Texas, and for 08111500 Brazos River near Hempstead, Texas; (B) relation between annual base-flow index for 08098290 Brazos River near Highbank, Texas, plus six inflow tributary sites, and for 08111500 Brazos River near Hempstead, Texas; (C) time series of annual base-flow index for 08111500 Brazos River near Hempstead, Texas, 1966–2005; and (D) time series of annual base-flow index for 08098290 Brazos River near Highbank, Texas, 1966–2005, and for 08098290 Brazos River near Highbank, Texas, plus six inflow tributary sites, 1966–2005.

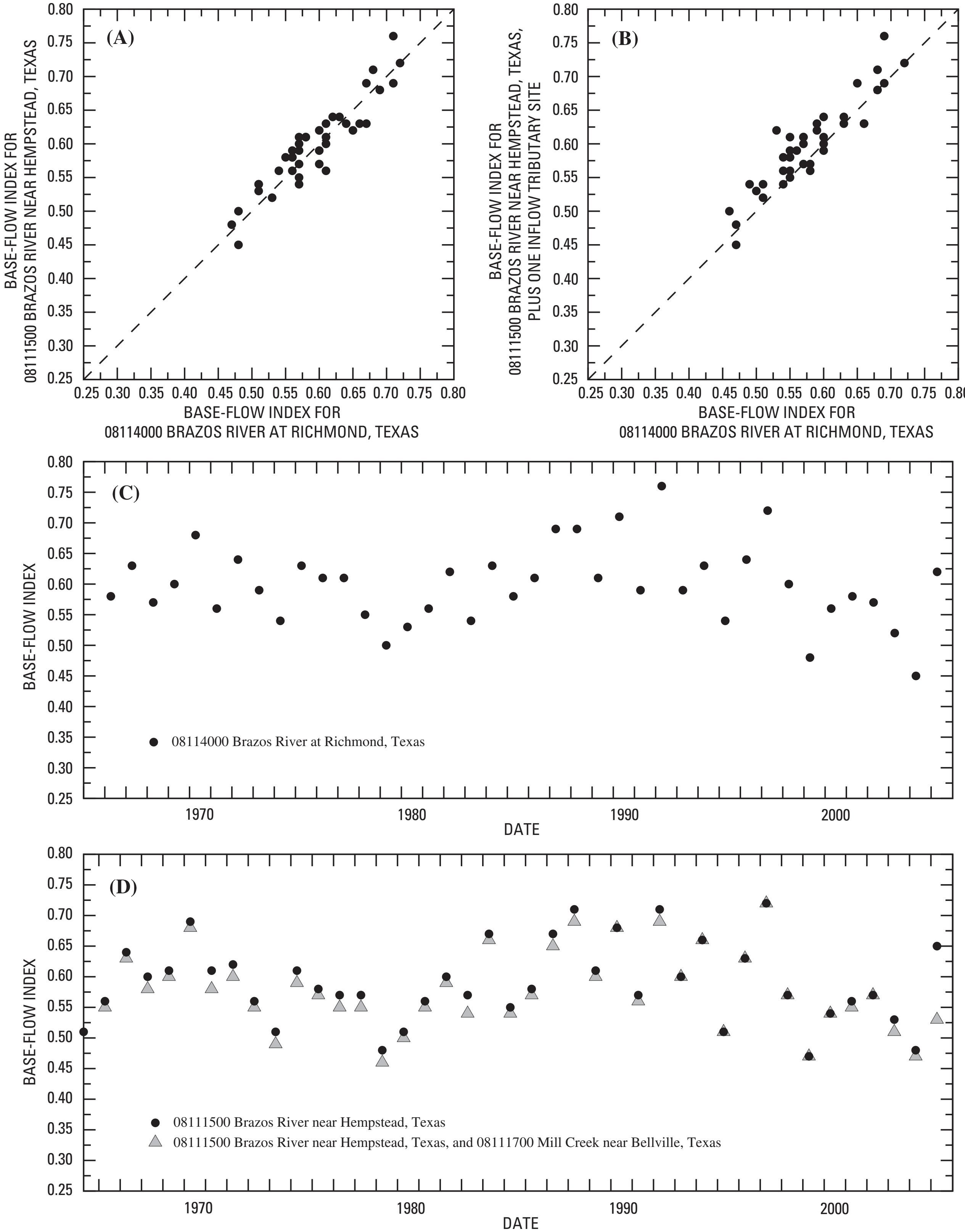

Figure 5. (A) Relation between annual base-flow index for 08111500 Brazos River near Hempstead, Texas, and for 08114000 Brazos River at Richmond, Texas; (B) relation between annual base-flow index for 08111500 Brazos River near Hempstead, Texas, plus one inflow tributary site, and for 08114000 Brazos River at Richmond, Texas; (C) time series of annual base-flow index for 08114000 Brazos River at Richmond, Texas, 1966–2005; and (D) time series of annual base-flow index for 08111500 Brazos River near Hempstead, Texas, 1966–2005, and for 08111500 Brazos River near Hempstead, Texas, plus one inflow tributary site, 1966–2005.

Table 4. Results of hydrograph separation for 08098290 Brazos River near Highbank, Texas, plus six inflow tributary sites, 1966–2005; and 08111500 Brazos River near Hempstead, Texas, plus one inflow tributary site, 1966–2005.

[Q, annual mean streamflow; ft^3/s, cubic feet per second; BF, base-flow component; RO, runoff component; BFI, base-flow index (defined as BF/Q)]

Water year	08098290 Brazos River near Highbank, Tex., plus six inflow tributary sites[1]				08111500 Brazos River near Hempstead, Tex., plus one inflow tributary site[2]			
	Q (ft^3/s)	BF (ft^3/s)	RO (ft^3/s)	BFI	Q (ft^3/s)	BF (ft^3/s)	RO (ft^3/s)	BFI
1966	6,822	2,852	3,970	0.42	8,334	4,643	3,690	0.56
1967	1,538	776	762	.50	1,844	1,170	674	.63
1968	9,581	4,300	5,281	.45	12,937	7,567	5,370	.58
1969	5,158	2,199	2,959	.43	7,812	4,677	3,135	.60
1970	4,999	2,716	2,283	.54	6,425	4,347	2,077	.68
1971	1,013	470	543	.46	1,545	910	635	.59
1972	3,176	1,506	1,671	.47	3,889	2,340	1,548	.60
1973	5,778	2,100	3,679	.36	8,591	4,680	3,911	.54
1974	3,966	1,473	2,493	.37	7,182	3,522	3,660	.49
1975	9,858	4,127	5,731	.42	12,902	7,666	5,236	.59
1976	4,099	1,436	2,662	.35	5,580	3,179	2,400	.57
1977	7,184	3,174	4,010	.44	10,431	5,757	4,674	.55
1978	887	423	463	.48	1,661	923	738	.56
1979	5,943	2,047	3,896	.34	10,351	4,776	5,575	.46
1980	2,440	923	1,517	.38	3,892	1,961	1,931	.50
1981	3,464	1,222	2,242	.35	4,689	2,574	2,116	.55
1982	6,376	2,881	3,496	.45	7,583	4,438	3,145	.59
1983	2,417	879	1,538	.36	4,765	2,591	2,173	.54
1984	590	314	275	.53	1,273	839	433	.66
1985	3,654	1,495	2,160	.41	6,320	3,423	2,896	.54
1986	5,535	2,282	3,253	.41	7,671	4,380	3,291	.57
1987	8,886	4,856	4,030	.55	12,240	8,063	4,177	.66
1988	1,297	691	606	.53	2,003	1,379	625	.69
1989	4,295	2,142	2,154	.50	5,061	3,038	2,023	.60
1990	7,122	4,018	3,104	.56	7,979	5,440	2,539	.68
1991	4,495	1,937	2,557	.43	7,357	4,088	3,270	.56
1992	20,987	12,523	8,464	.60	26,836	18,593	8,243	.69
1993	5,174	2,700	2,475	.52	8,731	5,249	3,482	.60
1994	2,636	1,169	1,467	.44	3,399	2,233	1,166	.66
1995	7,552	3,216	4,335	.43	10,508	5,409	5,099	.51
1996	1,237	592	645	.48	1,638	1,027	611	.63
1997	11,872	7,344	4,527	.62	13,437	9,607	3,830	.71
1998	5,701	2,614	3,087	.46	7,207	4,114	3,094	.57
1999	4,067	1,389	2,678	.34	7,336	3,467	3,869	.47
2000	853	289	564	.34	1,175	640	536	.54
2001	6,591	2,936	3,655	.45	9,571	5,294	4,277	.55
2002	3,993	1,649	2,345	.41	5,342	3,032	2,310	.57
2003	3,819	1,472	2,347	.39	8,216	4,191	4,024	.51
2004	5,332	1,979	3,353	.37	10,081	4,784	5,297	.47
2005	8,235	4,293	3,942	.52	11,065	7,065	3,999	.64

[1] Sites S1–S6 (fig. 2, table 1).

[2] Site S7 (fig. 2, table 1).

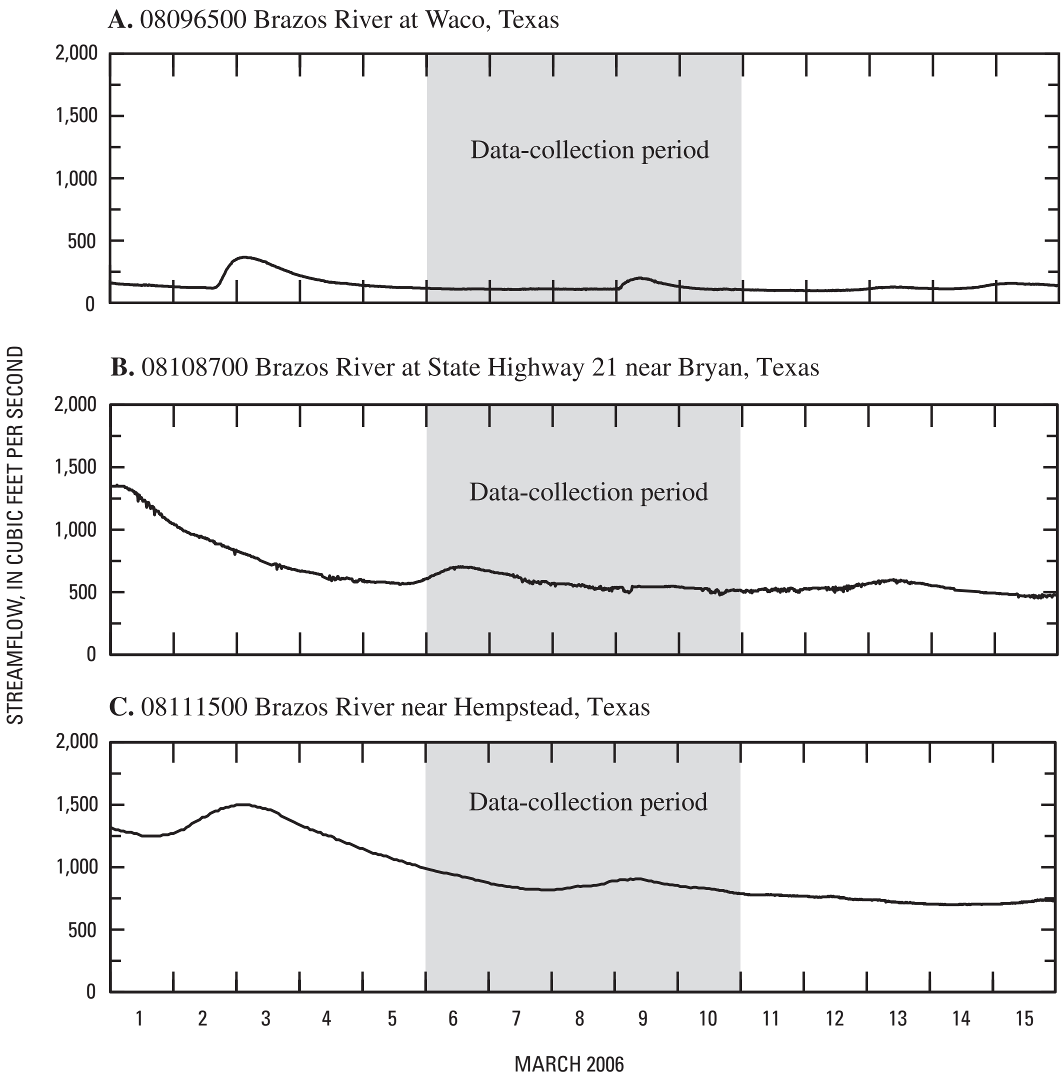

Figure 6. Daily mean streamflow for March 1–15, 2006, at (A) 08096500 Brazos River at Waco, Texas; (B) 08108700 Brazos River at State Highway 21 near Bryan, Texas; and (C) 08111500 Brazos River near Hempstead, Texas.

Brazos River at Waco, 08108700 Brazos River at State Highway 21 near Bryan, and 08111500 Brazos River near Hempstead) (figs. 6, 7) was relatively stable, except at the Waco station during the August survey. At the Waco station, streamflow was affected most days during the August survey by releases from upstream reservoirs for hydroelectric power generation.

Measurements of streamflow at the 36 sites along the main stem of the Brazos River from the March survey (table 5) are graphed relative to downstream distance in figure 8. Streamflow increases from upstream to downstream except at the downstream end of the study reach. An appreciable increase in Brazos River flow (173 cubic feet per second) occurred between sites B12 and B13 (table 5), the reach bracketing the confluence with Little River, the largest tributary. Another large increase in flow (258 cubic feet per second) occurred between sites B15 and B16 (river miles 269–258, fig. 8) that is not a result of tributary inflow.

Measurements of streamflow at 28 of the 36 sites along the main stem of the Brazos River from the August survey (table 6) are graphed relative to downstream distance in figure 9. The graph shows the same general pattern of increasing streamflow from upstream to downstream, except at the downstream end of the study reach, as in the March survey, although the minimum flows at the upstream end are larger and the maximum flows toward the downstream end are lower. Larger minimum flows at the upstream end of the study reach likely are the result of releases from upstream reservoirs (fig. 7); and lower maximum flows likely are the result of generally drier conditions in August. Little River inflow was substantially less than in the March survey, and the increase in flow between sites B15 and B16 (table 6) also was substantially less than in the March survey.

Streamflow gains and losses for reaches defined by pairs of sites on the Brazos River were computed for 35 reaches during the March survey (table 7) and for 27 reaches

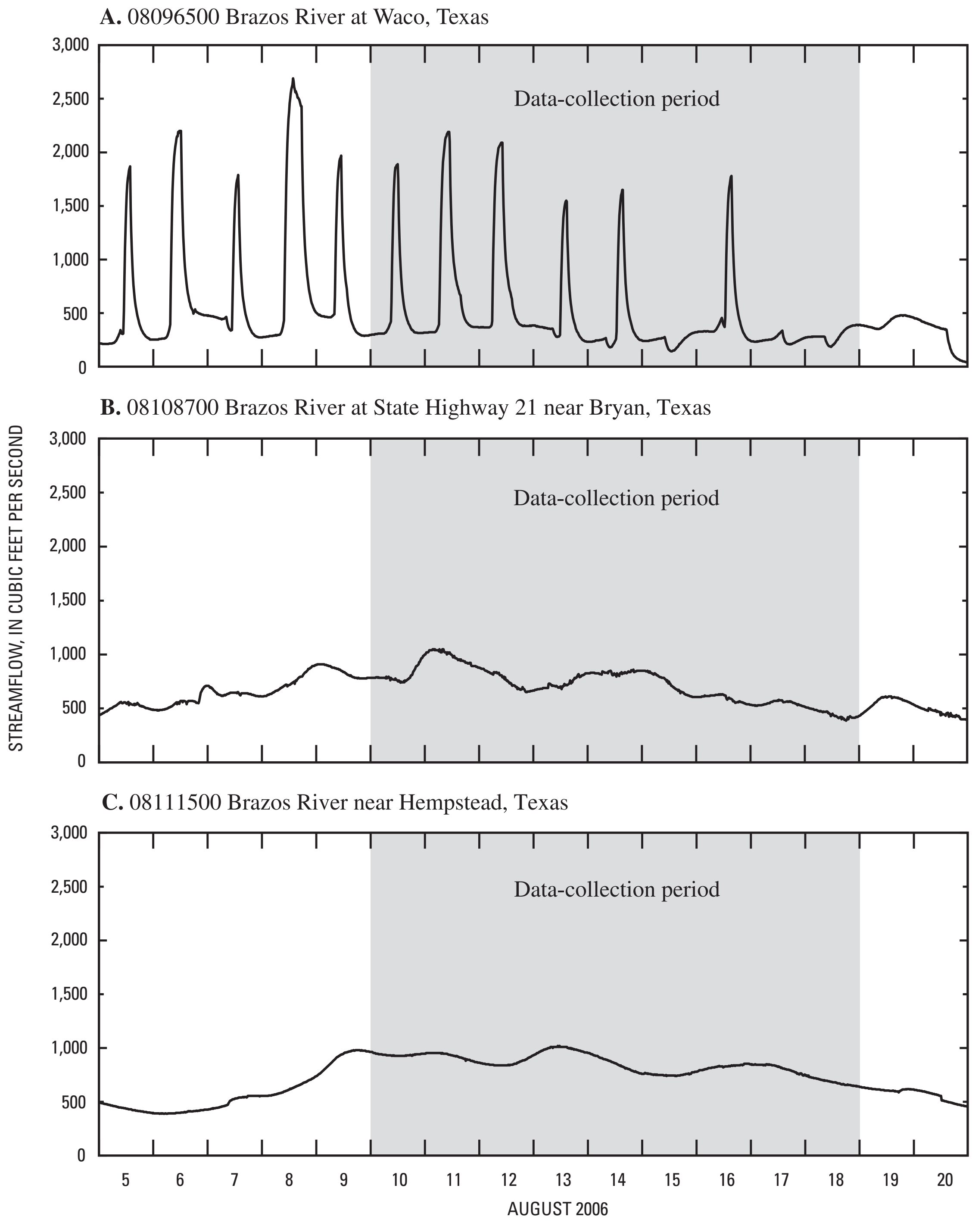

Figure 7. Daily mean streamflow for August 5–20, 2006, at (A) 08096500 Brazos River at Waco, Texas; (B) 08108700 Brazos River at State Highway 21 near Bryan, Texas; and (C) 08111500 Brazos River near Hempstead, Texas.

during the August survey (table 8). Also listed is the potential error for each pair of measurements used to compute a gain or loss. Only gains or losses in reaches for which the difference between upstream and downstream measurements exceeds the potential measurement error are considered verified. Based on this criterion, five of 35 stream reaches were verifiably gaining streamflow and none were verifiably losing streamflow during the March survey (fig. 10). Four of the five gaining reaches are in the outcrop areas of the Carrizo-Wilcox and Yegua-Jackson aquifers. The reach gaining the most flow (B15–B16, 258 cubic feet per second) is in the Yegua-Jackson aquifer outcrop. No reason is known for the gaining reach at Waco, which is not in an aquifer outcrop.

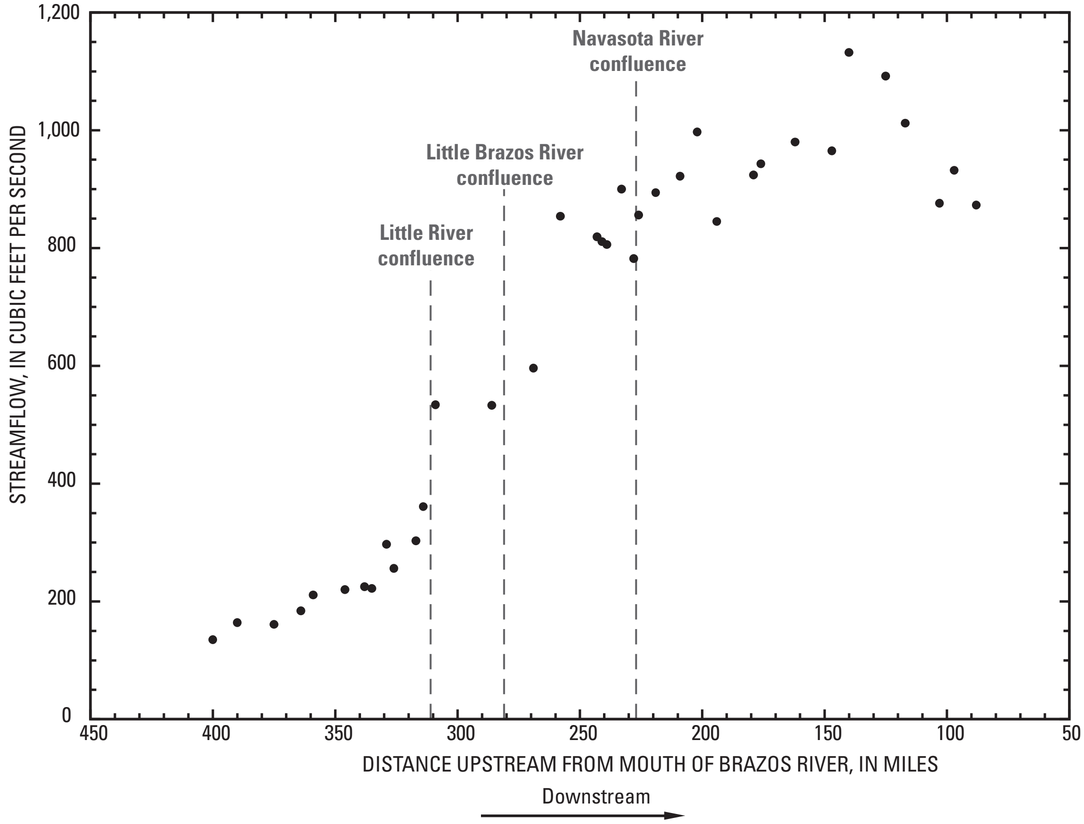

Figure 8. Instantaneous streamflow at 36 sites on the Brazos River, McLennan County to Fort Bend County, Texas, March 6–10, 2006.

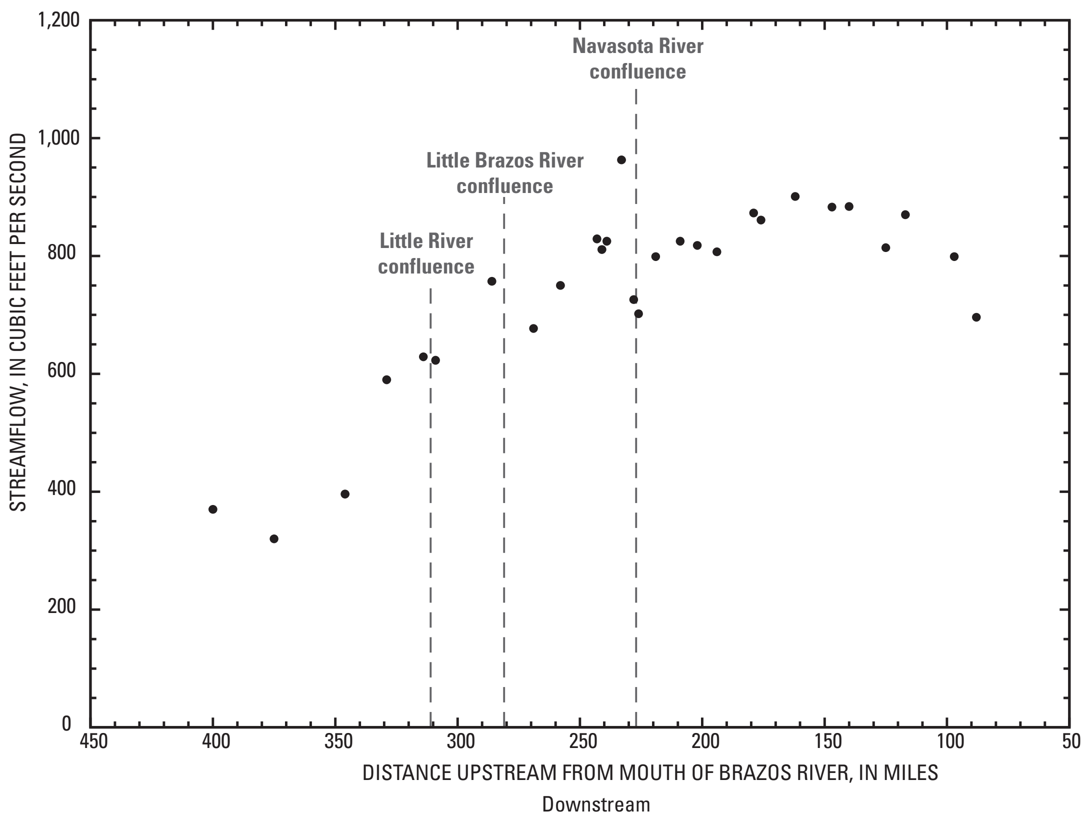

Figure 9. Instantaneous streamflow at 28 sites on the Brazos River, McLennan County to Fort Bend County, Texas, August 10–18, 2006.

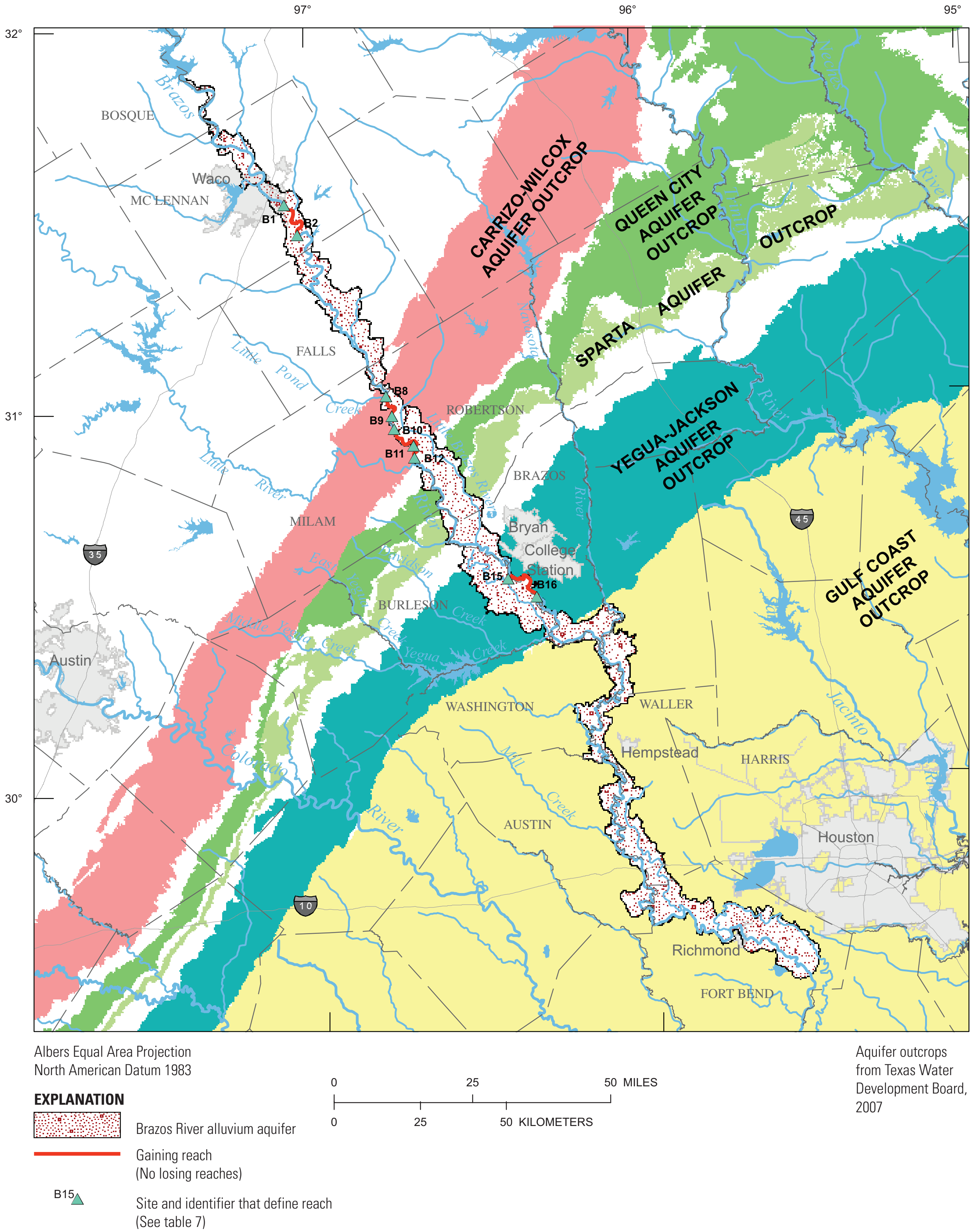

Figure 10. Reaches of the Brazos River, McLennan County to Fort Bend County, Texas, identified as gaining or losing streamflow, March 6–10, 2006.

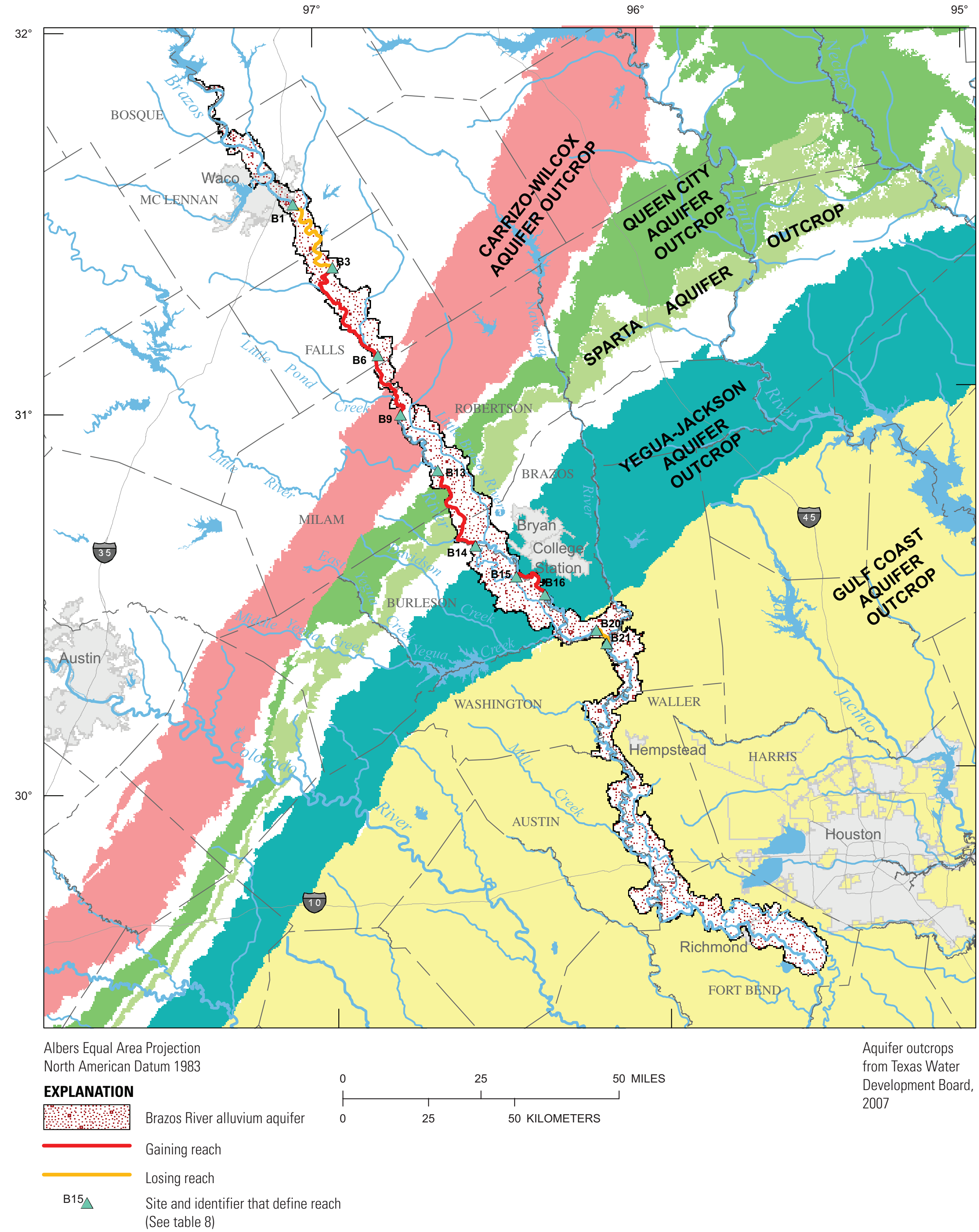

Figure 11. Reaches of the Brazos River, McLennan County to Fort Bend County, Texas, identified as gaining or losing streamflow, August 10–18, 2006.

For the August survey, four stream reaches were verifiably gaining streamflow and two were losing streamflow (fig. 11). Because some measurement sites in the March survey were not used in the August survey, the number of reaches defined by site pairs is 27, and thus some reaches are longer than those of the March survey. Although the August survey reaches are not everywhere comparable to the March survey reaches, the gaining reaches of the August survey generally match those of the March survey—occurring mostly in the outcrops of the aquifers. The reach gaining the most flow (B6–B9, 194 cubic feet per second) (fig. 11) begins upstream from the outcrop of the Carrizo-Wilcox aquifer and contains the relatively short gaining reach defined by sites B8 and B9 (fig. 10) in the outcrop of the Carrizo-Wilcox aquifer from the March survey. The reach gaining the second-most flow (B13–B14, 134 cubic feet per second) is in the outcrops of the Queen City and Sparta aquifers; that reach was not a gaining reach in the March survey. The reach defined by sites B15 and B16 in the Yegua-Jackson aquifer outcrop, which had the largest gain during the March survey, gained 73 cubic feet per second during the August survey. No reasons are known for the streamflow losses that occurred in the reach defined by sites B1 and B3 at the upstream end of the study reach and in the reach defined by sites B20 and B21 in the outcrop of the Gulf Coast aquifer.

The results of the synoptic gain and loss surveys are consistent with the results of the base-flow analysis (hydrograph separation) of historical streamflow and with the findings of Garza and others (1987) and the Texas Board of Water Engineers (1960). Appreciable increases in streamflow, apparently the result of increases in base flow, occur in the reach of the Brazos River that crosses the outcrops of the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers. The gain and loss surveys also yielded no evidence for appreciable streamflow gains or losses in the outcrop of the Gulf Coast aquifer, except for the relatively large, unexplained loss (237 cubic feet per second) in the reach defined by sites B20 and B21 in the August survey.

Table 5. Instantaneous streamflow, water temperature, and specific conductance for sites on the Brazos River and selected tributaries, McLennan County to Fort Bend County, Texas, March 6–10, 2006.

[USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; °C, degrees Celsius; μS/cm, microsiemens per centimeter at 25 °C; --, not available; SH, State Highway; CR, County Road; FM, Farm Road; IH, Interstate Highway]

Site identifier (fig. 2)	USGS station name	Date	Streamflow, instantaneous (ft^3/s)	Water temperature (°C)	Specific conductance (μS/cm)
B1	Brazos River at Waco, Tex.	March 8, 2006	133	--	--
T1	Tehuacana Creek at SH 6 near Waco, Tex.	March 6, 2006	.107	18.0	755
T2	Flat Creek at CR 3400 near Robinson, Tex.	March 6, 2006	.802	19.3	384
B2	Brazos River near Robinson, Tex.	March 3, 2006	162	20.7	2,580
T3	Monas Creek at FM 1860 near Riesel, Tex.	March 7, 2006	.168	17.2	727
T4	Castleman Creek near Robinson, Tex.	March 7, 2006	.439	23.8	704
T5	Bull Hide Creek at FM 434 near Golinda, Tex.	March 7, 2006	1.00	18.7	925
B3	Brazos River near Golinda, Tex.	March 7, 2006	159	21.7	2,240
T6	Cow Bayou below FM 434 near Chilton, Tex.	March 7, 2006	2.87	19.2	652
B4	Brazos River near Marlin, Tex.	March 9, 2006	182	21.7	2,050
T7	Deer Creek at SH 320 near Marlin, Tex.	March 7, 2006	1.06	20.5	854
B5	Brazos River at FM 712 near Marlin, Tex.	March 9, 2006	209	23.0	1,850
T8	Mussel Run Creek near Highbank, Tex.	March 7, 2006	1.59	20.4	1,400
B6	Brazos River near Highbank, Tex.	March 9, 2006	218	21.3	1,860
B7	Brazos River below FM 1373 near Baileyville, Tex.	March 9, 2006	223	19.4	2,090
B8	Brazos River above Pond Creek near Baileyville, Tex.	March 9, 2006	220	20.8	2,140
T9	Pond Creek at FM 2027 near Baileyville, Tex.	March 9, 2006	.180	21.1	2,470
B9	Brazos River at FM 979 near Calvert, Tex.	March 6, 2006	295	18.9	2,470
B10	Brazos River near Calvert, Tex.	March 7, 2006	254	21.7	2,410
B11	Brazos River at Big Bend near Calvert, Tex.	March 7, 2006	301	20.5	2,400

Table 5. Instantaneous streamflow, water temperature, and specific conductance for sites on the Brazos River and selected tributaries, McLennan County to Fort Bend County, Texas, March 6–10, 2006—Continued.

Site identifier (fig. 2)	USGS station name	Date	Streamflow, instantaneous (ft^3/s)	Water temperature (°C)	Specific conductance (µS/cm)
B12	Brazos River at FM 485 near Hearne, Tex.	March 6, 2006	359	21.1	2,240
T10	Little River at CR 263 near Gause, Tex.	March 6, 2006	239	22.2	659
B13	Brazos River at Valley Junction, Tex.	March 7, 2006	532	20.6	1,660
B14	Brazos River at SH 21 near Bryan, Tex.	March 10, 2006	531	20.0	1,630
T11	Little Brazos River at SH 21 near Bryan, Tex.	March 10, 2006	35.6	20.3	794
B15	Brazos River near College Station, Tex.	March 10, 2006	594	20.6	1,550
B16	Brazos River at Batts Ferry near Wellborn, Tex.	March 7, 2006	852	21.0	1,360
B17	Brazos River near FM 159 near Clay, Tex.	March 7, 2006	817	23.0	1,510
T12	Yegua Creek at FM 50 near Clay, Tex.	March 7, 2006	5.26	23.0	747
B18	Brazos River near FM 1955 near Clay, Tex.	March 7, 2006	809	24.2	1,500
B19	Brazos River at Rogers Plantation near Millican, Tex.	March 7, 2006	804	22.0	1,700
B20	Brazos River near FM 159 near Millican, Tex.	March 7, 2006	898	21.7	1,930
B21	Brazos River at SH 105 near Washington, Tex.	March 8, 2006	780	20.3	1,950
T13	Navasota River below SH 105 near Washington, Tex.	March 8, 2006	93.0	20.5	566
B22	Brazos River below Navasota River near Washington, Tex.	March 8, 2006	854	20.4	1,810
B23	Brazos River at Old River Road near Courtney, Tex.	March 8, 2006	892	21.7	--
B24	Brazos River near FM 2726 near Courtney, Tex.	March 8, 2006	920	21.8	1,790
B25	Brazos River near FM 1736 near Hempstead, Tex.	March 8, 2006	995	22.7	1,740
B26	Brazos River near Hempstead, Tex.	March 9, 2006	843	21.4	1,740
T14	Caney Creek at FM 1371 near Hempstead, Tex.	March 8, 2006	1.80	23.0	589
B27	Brazos River at SH 159 near Hempstead, Tex.	March 9, 2006	922	20.8	1,730
B28	Brazos River near FM 1887 near Hempstead, Tex.	March 9, 2006	941	23.5	1,510
T15	Clear Creek near FM 1887 near Hempstead, Tex.	March 9, 2006	8.84	21.5	456
T16	Piney Creek at FM 331 near Burleigh, Tex.	March 8, 2006	3.58	26.5	199
B29	Brazos River at FM 529 near Burleigh, Tex.	March 9, 2006	978	22.5	1,750
T17	Mill Creek at FM 331 near Burleigh, Tex.	March 9, 2006	20.8	22.0	513
B30	Brazos River at FM 1458 at San Felipe, Tex.	March 8, 2006	963	21.4	1,860
B31	Brazos River at IH–10 near Brookshire, Tex.	March 8, 2006	1,130	22.4	1,830
B32	Brazos River at FM 1093 at Simonton, Tex.	March 8, 2006	1,090	23.3	1,790
B33	Brazos River at FM 1489 near Simonton, Tex.	March 9, 2006	1,010	22.6	1,820
T18	Bessies Creek at FM 1093 near Fulshear, Tex.	March 8, 2006	2.48	24.2	320
T19	Jones Creek at Bois du Arc Road near Fulshear, Tex.	March 9, 2006	1.00	--	--
B34	Brazos River at CR near FM 359 near Rosenberg, Tex.	March 9, 2006	874	22.9	1,790
B35	Brazos River at FM 723 near Rosenberg, Tex.	March 9, 2006	930	24.1	1,730
B36	Brazos River at Richmond, Tex.	March 9, 2006	871	24.2	1,520

Table 6. Instantaneous streamflow for sites on the Brazos River and selected tributaries, McLennan County to Fort Bend County, Texas, August 10–18, 2006.

[Negative discharge indicates irrigation pumpage from the Brazos River. USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; SH, State Highway; CR, County Road; --, not available; FM, Farm Road; IH, Interstate Highway]

Site identifier (fig. 2)	USGS station name	Date	Streamflow, instantaneous (ft^3/s)
B1	Brazos River at Waco, Tex.	August 10, 2006	370
T1	Tehuacana Creek at SH 6 near Waco, Tex.	August 10, 2006	0
T2	Flat Creek at CR 3400 near Robinson, Tex.	August 10, 2006	.500
B2	Brazos River near Robinson, Tex.	--	--
T3	Monas Creek at FM 1860 near Riesel, Tex.	August 10, 2006	.020
T4	Castleman Creek near Robinson, Tex.	August 10, 2006	0
T5	Bull Hide Creek at FM 434 near Golinda, Tex.	--	--
B3	Brazos River near Golinda, Tex.	August 10, 2006	320
T6	Cow Bayou below FM 434 near Chilton, Tex.	--	--
B4	Brazos River near Marlin, Tex.	--	--
T7	Deer Creek at SH 320 near Marlin, Tex.	August 10, 2006	0
B5	Brazos River at FM 712 near Marlin, Tex.	--	--
T8	Mussel Run Creek near Highbank, Tex.	August 11, 2006	1.00
B6	Brazos River near Highbank, Tex.	August 11, 2006	396
B7	Brazos River below FM 1373 near Baileyville, Tex.	--	--
B8	Brazos River above Pond Creek near Baileyville, Tex.	--	--
T9	Pond Creek at FM 2027 near Baileyville, Tex.	August 11, 2006	0
B9	Brazos River at FM 979 near Calvert, Tex.	August 14, 2006	590
B10	Brazos River near Calvert, Tex.	--	--
B11	Brazos River at Big Bend near Calvert, Tex.	--	--
B12	Brazos River at FM 485 near Hearne, Tex.	August 14, 2006	629
T10	Little River at CR 263 near Gause, Tex.	August 14, 2006	61.1
B13	Brazos River at Valley Junction, Tex.	August 15, 2006	623
B14	Brazos River at SH 21 near Bryan, Tex.	August 15, 2006	757
T11	Little Brazos River at SH 21 near Bryan, Tex.	August 15, 2006	8.03
B15	Brazos River near College Station, Tex.	August 16, 2006	677
B17	Brazos River near FM 159 near Clay, Tex.	August 16, 2006	829
T12	Yegua Creek at FM 50 near Clay, Tex.	August 16, 2006	6.59
B18	Brazos River near FM 1955 near Clay, Tex.	August 16, 2006	811
B19	Brazos River at Rogers Plantation near Millican, Tex.	August 16, 2006	825
B20	Brazos River near FM 159 near Millican, Tex.	August 16, 2006	963
B21	Brazos River at SH 105 near Washington, Tex.	August 17, 2006	726
T13	Navasota River below SH 105 near Washington, Tex.	--	--
B22	Brazos River below Navasota River near Washington, Tex.	August 17, 2006	702
B23	Brazos River at Old River Road near Courtney, Tex.	August 17, 2006	799
B24	Brazos River near FM 2726 near Courtney, Tex.	August 17, 2006	825
B25	Brazos River near FM 1736 near Hempstead, Tex.	August 17, 2006	818
B26	Brazos River near Hempstead, Tex.	August 17, 2006	807

Table 6. Instantaneous streamflow for sites on the Brazos River and selected tributaries, McLennan County to Fort Bend County, Texas, August 10–18, 2006—Continued.

Site identifier (fig. 2)	USGS station name	Date	Streamflow, instantaneous (ft^3/s)
T14	Caney Creek at FM 1371 near Hempstead, Tex.	August 17, 2006	0
B27	Brazos River at SH 159 near Hempstead, Tex.	August 18, 2006	873
B28	Brazos River near FM 1887 near Hempstead, Tex.	August 18, 2006	861
T15	Clear Creek near FM 1887 near Hempstead, Tex.	August 17, 2006	3.33
T16	Piney Creek at FM 331 near Burleigh, Tex.	August 17, 2006	.07
B29	Brazos River at FM 529 near Burleigh, Tex.	August 18, 2006	901
T17	Mill Creek at FM 331 near Burleigh, Tex.	August 17, 2006	3.84
B30	Brazos River at FM 1458 at San Felipe, Tex.	August 17, 2006	883
B31	Brazos River at IH–10 near Brookshire, Tex.	August 17, 2006	884
B32	Brazos River at FM 1093 at Simonton, Tex.	August 17, 2006	814
B33	Brazos River at FM 1489 near Simonton, Tex.	August 17, 2006	870
T18	Bessies Creek at FM 1093 near Fulshear, Tex.	August 18, 2006	0
T19	Jones Creek at Bois du Arc Road near Fulshear, Tex.	August 18, 2006	-106
B34	Brazos River at CR near FM 359 near Rosenberg, Tex.	--	--
B35	Brazos River at FM 723 near Rosenberg, Tex.	August 18, 2006	799
B36	Brazos River at Richmond, Tex.	August 18, 2006	696

Table 7. Streamflow gains and losses computed for 35 reaches on the Brazos River, McLennan County to Fort Bend County, Texas, March 6–10, 2006.

[Bold font indicates gain or loss that is greater than potential measurement error for that particular reach. mi, miles; ft^3/s, cubic feet per second; --, not applicable]

Site identifier (fig. 2)	Distance between downstream and upstream sites (mi)	Streamflow, instantaneous (ft^3/s)	Measured inflow between downstream and upstream sites (ft^3/s)	Difference in streamflow between downstream and upstream sites (ft^3/s)	Gain or loss in streamflow between downstream and upstream sites (ft^3/s)	Potential measurement error between downstream and upstream sites (ft^3/s)
B1	--	133	--	--	--	--
	11		0.91	29.0	**28.1**	23.6
B2		162				
	15		1.61	-3.00	-4.61	20.9
B3		159				
	11		2.87	23.0	20.1	22.5
B4		182				
	5		1.06	27.0	25.9	31.3
B5		209				
	13		1.59	9.00	7.41	27.6
B6		218				
	8		0	5.00	5.00	28.7
B7		223				
	3		0	-3.00	-3.00	35.4
B8		220				
	6		0.18	75.0	**74.8**	47.1
B9		295				
	3		0	-41.0	-41.0	42.2
B10		254				
	9		0	47.0	**47.0**	27.8

Table 7. Streamflow gains and losses computed for 35 reaches on the Brazos River, McLennan County to Fort Bend County, Texas, March 6–10, 2006—Continued.

Site identifier (fig. 2)	Distance between downstream and upstream sites (mi)	Streamflow, instantaneous (ft^3/s)	Measured inflow between downstream and upstream sites (ft^3/s)	Difference in streamflow between downstream and upstream sites (ft^3/s)	Gain or loss in streamflow between downstream and upstream sites (ft^3/s)	Potential measurement error between downstream and upstream sites (ft^3/s)
B11		301				
	3		0	58.0	**58.0**	43.8
B12		359				
	5		239	173	-66.0	71.3
B13		532				
	23		0	-1.00	-1.00	85.0
B14		531				
	17		35.6	63.0	27.4	90.0
B15		594				
	11		0	258	**258**	116
B16		852				
	15		0	-35.0	-35.0	134
B17		817				
	2		5.26	-8.00	-13.3	130
B18		809				
	2		0	-5.00	-5.00	129
B19		804				
	6		0	94.0	94.0	136
B20		898				
	5		0	-118	-118	134
B21		780				
	2		93.0	74.0	-19.0	105
B22		854				
	7		0	38.0	38.0	140
B23		892				
	10		0	28.0	28.0	145
B24		920				
	7		0	75.0	75.0	153
B25		995				
	8		0	-152	-152	164
B26		843				
	15		1.80	79.0	77.2	158
B27		922				
	3		0	19.0	19.0	149
B28		941				
	14		12.4	37.0	24.6	154
B29		978				
	15		20.8	-15.0	-35.8	155
B30		963				
	7		0	167	167	167
B31		1,130				
	15		0	-40.0	-40.0	178
B32		1,090				
	8		0	-80.0	-80.0	168
B33		1,010				
	14		3.48	-136	-139	151
B34		874				
	6		0	56.0	56.0	144
B35		930				
	5		0	-59.0	-59.0	144
B36		871				

Table 8. Streamflow gains and losses computed for 27 reaches on the Brazos River, McLennan County to Fort Bend County, Texas, August 10–18, 2006.

[Bold font indicates gain or loss that is greater than potential measurement error for that particular reach. mi, miles; ft^3/s, cubic foot per second; --, not applicable]

Site identifier (fig. 2)	Distance between downstream and upstream sites (mi)	Streamflow, instantaneous (ft^3/s)	Measured inflow between downstream and upstream sites (ft^3/s)	Difference in streamflow between downstream and upstream sites (ft^3/s)	Gain or loss in streamflow between downstream and upstream sites (ft^3/s)	Potential measurement error between downstream and upstream sites (ft^3/s)
B1	--	370	--	--	--	--
	26		0.52	-50.0	**-50.5**	34.5
B3		320				
	29		1.00	76.0	**75.0**	35.8
B6		396				
	17		0	194	**194**	49.3
B9		590				
	15		0	39.0	39.0	61.0
B12		629				
	5		61.1	-3.00	-64.1	81.3
B13		623				
	23		0	134	**134**	87.7
B14		757				
	17		8.03	-80.0	-88.0	92.0
B15		677				
	11		0	73.0	**73.0**	71.3
B16		750				
	15		0	79.0	79.0	104
B17		829				
	2		6.59	-18.0	-24.6	131
B18		811				
	2		0	14.0	14.0	131
B19		825				
	6		0	138	138	143
B20		963				
	5		0	-237	**-237**	135
B21		726				
	2		0	-24.0	-24.0	114
B22		702				
	7		0	97.0	97.0	120
B23		799				
	10		0	26.0	26.0	130
B24		825				
	7		0	-7.00	-7.00	131
B25		818				
	8		0	-11.0	-11.0	130
B26		807				
	15		0	66.0	66.0	134

Table 8. Streamflow gains and losses computed for 27 reaches on the Brazos River, McLennan County to Fort Bend County, Texas, August 10–18, 2006—Continued.

Site identifier (fig. 2)	Distance between downstream and upstream sites (mi)	Streamflow, instantaneous (ft^3/s)	Measured inflow between downstream and upstream sites (ft^3/s)	Difference in streamflow between downstream and upstream sites (ft^3/s)	Gain or loss in streamflow between downstream and upstream sites (ft^3/s)	Potential measurement error between downstream and upstream sites (ft^3/s)
B27		873				
	3		0	-12.0	-12.0	139
B28		861				
	14		3.40	40.0	36.6	141
B29		901				
	15		3.84	-18.0	-21.8	143
B30		883				
	7		0	1.00	1.00	141
B31		884				
	15		0	-70.0	-70.0	136
B32		814				
	8		0	56.0	56.0	135
B33		870				
	20		-106	-71.0	-35.0	134
B35		799				
	5		0	-103	-103	120
B36		696				

Summary

During 2006–07, the U.S. Geological Survey (USGS), in cooperation with the Texas Water Development Board (TWDB), did a study to quantify base flow and streamflow gains and losses in the Brazos River from McLennan County to Fort Bend County, Texas. This report documents the results of base-flow analysis (hydrograph separation) of historical (1966–2005) streamflow and two synoptic streamflow gain and loss surveys of the Brazos River from McLennan County to Fort Bend County, Texas, in March and August 2006.

The study area encompasses a 310-mile reach of the Brazos River from Waco in McLennan County to Richmond in Fort Bend County and includes selected inflow tributaries along the reach. The Brazos River is hydraulically connected to the Brazos River alluvium aquifer. Underlying the Brazos River alluvium aquifer in laterally adjacent layers generally parallel to the coast are two major aquifers, Carrizo-Wilcox and Gulf Coast, and three minor aquifers, Queen City, Sparta, and Yegua-Jackson. Upstream from the outcrop of the Carrizo-Wilcox aquifer, the Brazos River alluvium aquifer is underlain by rocks not characterized as part of a major or minor aquifer. The underlying aquifers are hydraulically connected to one another and to the Brazos River alluvium aquifer, as indicated by 1980 potentiometric-surface maps of the Carrizo-Wilcox, Queen City, and Sparta aquifers that show U-shaped potentiometric contours, closed upstream, across the Brazos River.

Hydrograph separation was done using the USGS computer program Hydrograph Separation and Analysis (HYSEP). The data used in HYSEP were historical (water years 1966–2005) streamflow from 10 USGS gaging stations, three on the Brazos River and seven on selected tributaries to the Brazos River. Streamflow data for computation of gains and losses were collected during March 6–10, 2006, from 36 sites on the Brazos River and 19 sites on 19 tributaries to the Brazos River; and during August 10–18, 2006, from 28 sites on the Brazos River and 16 sites on tributaries. HYSEP provides the base-flow index (BFI), which is the ratio of the annual mean base flow to the annual mean streamflow. The BFI was used as a means to graphically compare streamflows (hydrographs) from the three Brazos River stations. The graphical comparisons indicate whether the reach between two stations is gaining or losing flow.

Streamflow gains and losses for reaches defined by adjacent pairs of Brazos River measurement sites were computed as streamflow at the downstream site minus streamflow at the upstream site minus inflows from tributaries (plus a diversion for one reach). For this report, a stream reach is classified as verifiably gaining or losing only when the difference between

streamflows at the upstream and downstream measuring sites that define the reach is greater than the potential error associated with the flow measurements.

Hydrograph separation and graphical evidence from BFI values indicate an appreciable increase in base flow as a percentage of streamflow in the reach of the Brazos River that crosses the outcrops of the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers compared to that in the adjacent upstream reach (on average from about 43 percent to about 60 percent). This result is consistent with indications of a gaining reach on 1980 potentiometric-surface maps of the Carrizo-Wilcox and Queen City-Sparta aquifers. Hydrograph separation and graphical evidence from BFI values also indicate no increase in base flow as a percentage of streamflow in the reach of the Brazos River crossing the Gulf Coast aquifer compared to that in the adjacent upstream reach.

Streamflow gains and losses computed for March 2006 for 35 reaches defined by pairs of sites on the Brazos River indicated that five reaches were verifiably gaining streamflow and none were verifiably losing streamflow. Four of the five gaining reaches are in the outcrop areas of the Carrizo-Wilcox and Yegua-Jackson aquifers. The reach gaining the most flow (258 cubic feet per second) is in the Yegua-Jackson aquifer outcrop. For the August survey, four stream reaches were verifiably gaining streamflow and two were losing streamflow. Although the August survey reaches are not everywhere comparable to the March survey reaches, the gaining reaches of the August survey generally match those of the March survey—occurring mostly in the outcrops of the aquifers. The reach gaining the most flow (194 cubic feet per second) begins upstream from the outcrop of the Carrizo-Wilcox aquifer and ends in the outcrop of that aquifer. The reach gaining the second-most flow (134 cubic feet per second) is in the outcrops of the Queen City and Sparta aquifers.

The results of the synoptic gain and loss surveys are consistent with the results of the base-flow analysis (hydrograph separation) of historical streamflow. Appreciable increases in streamflow, apparently the result of increases in base flow, occur in the reach of the Brazos River that crosses the outcrops of the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers. The gain and loss surveys also yielded no evidence for appreciable streamflow gains or losses in the outcrop of the Gulf Coast aquifer, except for one relatively large, unexplained loss (237 cubic feet per second) in the August survey.

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