Flow Modifications and Geomorphic Thresholds in the Lower Brazos River

Texas Water Development Board
Contract Number 1248311367

FINAL REPORT

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Executive Summary

The goal of this study was to identify potential thresholds with respect to geomorphic changes in response to changes in flow regimes and sediment supply, in the lower Brazos River, Texas, from Waco to the Gulf of Mexico. Major findings and outcomes are listed below.

•Six geomorphic zones (river styles) between Waco and Bryan were identified, to complement the 30 zones previously identified from Bryan to the Gulf of Mexico.

•Threshold stages and discharges were identified for six Brazos River gaging stations corresponding to thalweg connectivity, bed inundation, low and high ranges of high sub-banktop flows, channel-floodplain connectivity (CFC), and overbank flooding. Channel-floodplain connectivity occurs at flows significantly below flood levels throughout the study area. Higher sub-banktop and CFC flows are uniformly greater than mean or median flows, and in most of the study area flows necessary to achieve CFC are less than typical annual maximum daily mean flows.

•Threshold discharges were identified for six Brazos River gaging stations corresponding to estimated thresholds for sandy bedform mobility, medium gravel mobility, specific stream power, and cohesive-bank channel instability. These thresholds have variable relationships to mean, median, and maximum flows in the historical record.

•Soil series mapped along the banks of the lower Brazos River were identified, and critical shear stresses identified based on plasticity indices. However, these are useful only as indicators of relative resistance, as the actual critical shear stress is underestimated. Because of the complex spatial pattern of soils, geomorphic-zone scale assessments of bank resistance based on these data are not feasible. However, this information can be used in conjunction with soil map data to identify potential high- and low-resistance sites at a local scale.

•A significant number of wetland depressions and floodplain lakes in the Brazos River valley bottoms are associated with tributaries, paleochannels, or depressional features for which the primary source of runoff is adjacent uplands rather than the Brazos River.

•The 36 geomorphic zones of the lower Brazos were examined with respect to the presence of mid-channel islands, inset floodplains, abandoned channel water bodies and the flow thresholds identified with these features determined.

•The flow-channel fitness model was applied to the study area to illustrate its use in predicting geomorphic responses to changes in discharge, slope, and sediment inputs.

•Nomographs were produced allowing estimation of potential changes in shear stress and stream power, for ranges of slopes, depths, and discharges relevant to the lower Brazos.

The thresholds for thalweg connectivity are essentially always maintained (based on the historical flow record) in the lower Brazos, but discharges somewhat in excess of bed inundation are required to prevent excessive silt and clay accumulation. In most cases, thresholds for mobility of channel sediments are regularly exceeded (based on the historical record), and thresholds for channel instability are mostly exceeded often enough to preserve the Brazos' character as an actively laterally-migrating channel.

CHAPTER 1
INTRODUCTION AND OVERVIEW

Introduction

This study seeks to identify potential thresholds with respect to geomorphic changes in response to changes in flow regimes and sediment supply, and estimate the degree of flow change necessary to result in exceedance of the thresholds. In this way the geomorphic impacts (and associated ecological impacts and engineering and management ramifications) of instream flow changes can be assessed. The study area is the Brazos River of central Texas, from just downstream of Waco to the Gulf of Mexico.

Rivers and other geomorphic systems are often governed by thresholds, defined as the point at which a system's behavior changes. Geomorphic thresholds fall into three broad categories:

•Force:resistance thresholds relate to the force or power driving change to the resistance to change. For example, mean boundary shear stress in a stream channel vs. the shear strength of the channel boundary determines whether a given flow results in channel erosion.

•Relative rate thresholds are connected to the comparative rates of linked processes. For instance, the rate at which sediment is deposited on a floodplain vs. the rate of erosional removal of sediment from floodplain storage determines the net increase or decrease in alluvial sediment storage.

•Storage capacity thresholds relate to finite capacities to store or absorb inputs of mass and/or energy, or to limits of growth. For instance, key thresholds in the storage of sediment within channels may lead to avulsions (c.f. Jerolmack and Mohrig, 2007; Phillips 2011a).

Most of the thresholds considered here are of the first and third type. Force:resistance thresholds are often associated with fundamental geomorphic changes in river channels. Especially important are thresholds related to the relationship between sediment supply to channels and the ability of flows to transport that sediment. Examples include critical shear stress and stream power relative to sediment transport, bed mobility and bank erosion. Storage capacity thresholds include those related to channel capacities (where exceedance determines factors such as channel-floodplain connectivity) and discharges or stages necessary to inundate specific landforms and aquatic or riparian habitats.

Study Area

The study area is the Brazos River from the Texas Highway 6 crossing on the south side of Waco to the river mouth. The Brazos River is the largest entirely in Texas, with a drainage area of about 118,000 km^2 (45,560 mi^2), and a river length of more than 1,900 km (1,180 mi) from its headwaters in New Mexico to the Gulf of Mexico at Freeport (Figure 1).

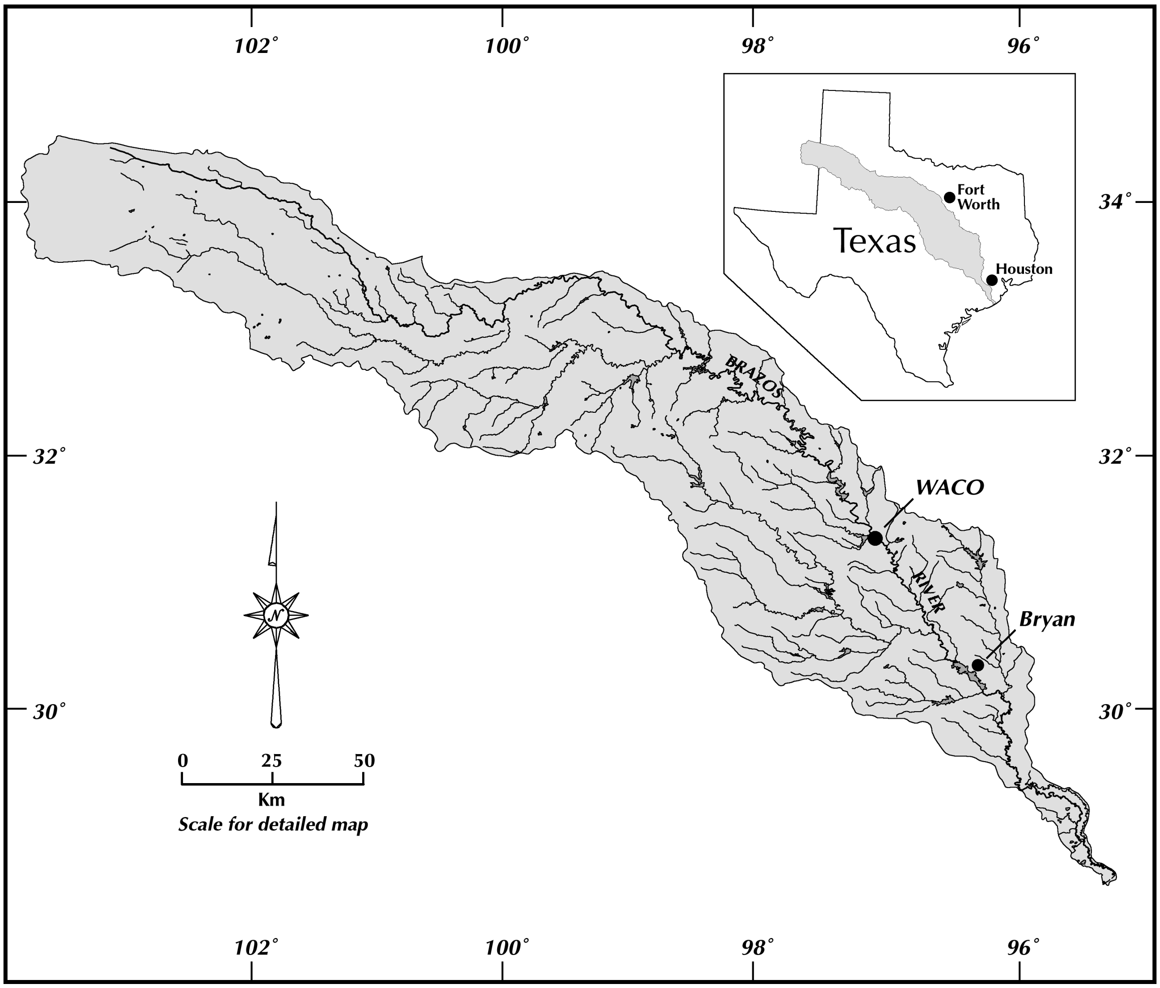


Figure 1. Brazos River basin.

The climate of the lower Brazos area is generally humid subtropical. Mean annual precipitation is about 990 mm (39 in) in Brazos County, and 1,320 (52 in) near the Gulf of Mexico in Brazoria County. Precipitation occurs year-round, but summer droughts and low-flow periods are common, due to the high evapotranspiration during this period.

Temperature normals for College Station are broadly representative of the area as a whole. Average daily maximum temperatures range from 35° C (95° F) in August to 14⁰ (57° F) in January, with an annual mean daily high of 25.5°C (78° F). Average daily minima are 23° in July and August and 4° in January, with an annual mean of 14⁰ C (73, 39, and 57 °F, respectively).

The lower Brazos River (along with the Sabine, Neches, lower Trinity, and San Jacinto) drain the portion of Texas with a humid subtropical climate and mean annual precipitation of 750 to 1300 mm yr^{-1} (30 – 51 in yr^{-1}). Watersheds are dominated by agricultural land uses (particularly grazing). Channel substrates are generally sandy to muddy and quite mobile, but in some cases bedrock is exposed, or covered by only a thin (<1 m or 3.3 ft) veneer of alluvial sediment.

The coastal plain portion of the Brazos River is a meandering stream with evidence of active Quaternary, historical, and recent channel migration. The lower reaches are often characterized by yazoo-style tributaries representing former trunk channel courses. The valleys are inset into pre-Quaternary materials, with the modern channels typically incised into Pleistocene terrace deposits.

Like other regional rivers, the Brazos has experienced several episodes of cutting, filling, channel migration, extension, and contraction due to Quaternary sea level and climate changes (Alford and Holmes, 1985; Blum et al. 1995; Morton et al. 1996; Rodriguez et al., 2005; Waters and Nordt, 1995). This history is important in determining contemporary river behavior. For example, the Brazos River is incised into Pleistocene alluvial terraces, the elevation, morphology, and composition of which influence the modern river (Blum et al., 1995; Waters and Nordt, 1995).

Nordt et al. (1994) inferred late Pleistocene and Holocene climate change in the region from vegetation changes reflected in stable carbon isotopes in alluvial deposits and soils. Conditions in the late Pleistocene appear to have been cooler and moister than at any other time in the past 15 ka. Between 11 and 8 ka, a transition to warmer and drier Holocene conditions is inferred. In the mid-Holocene (~8 – 6 ka), expansion of warmer, drier conditions occurred, followed by a shift to a cooler and wetter regime about 4 ka. (Nordt et al., 1994).

River Styles

A geomorphic categorization of the Brazos River valley from the SH 21 bridge near Bryan to Freeport was developed by Phillips (2006; 2007a), resulting in identification of 30 different river styles or geomorphic zones. This geomorphic zonation was extended upstream to Waco using the same methods and criteria described in Phillips (2006; 2007a), identifying six additional zones along this 212 km reach. These are shown in Table 1 and Figure 2, and key geomorphic characteristics are shown in Table 2.

Table 1. Geomorphic reaches of the Brazos River from Waco to near Bryan. Landmarks and latitude, longitude (lat-long) coordinates refer to the downstream end of the reach. River styles and geomorphic reaches for the river from SH 21 near Bryan to the Gulf of Mexico are described in earlier reports (Phillips 2006; 2007a).

Reach	**Length** (km, mi)	**Lat-Long**	**Landmark**	**River Style**
Highway 6 at Waco to Golinda	32.05 19.91	31.3997, -96.9945	Meander bend east of Golinda, west of Perry	Unconfined meandering
Golinda to near Highway 7	29.58 18.38	31.3027, -96.9875	2.73 channel km upstream of Highway 7 bridge	Unconfined strongly meandering
Near highway 7 to Robertson County	39.04 24.26	31.1065, -96.8287	Intersection of Falls, Milam, & Robertson County lines	Partly confined low sinuosity
Robertson County to Little Brazos Diversion	14.17 8.80	31.0488, -96.7669	Diversion channel, Brazos to Little Brazos River, east of Baileyville	Partly confined meandering
Little Brazos Diversion to Little River	45.08 28.01	30.8419, -96.6779	Brazos-Little River confluence	Partly confined meandering with paleochannel
Little River to SH 21	51.75 32.16	30.6280, -96.5443	State Highway 21 bridge west of Bryan	Confined meandering, with paleochannel

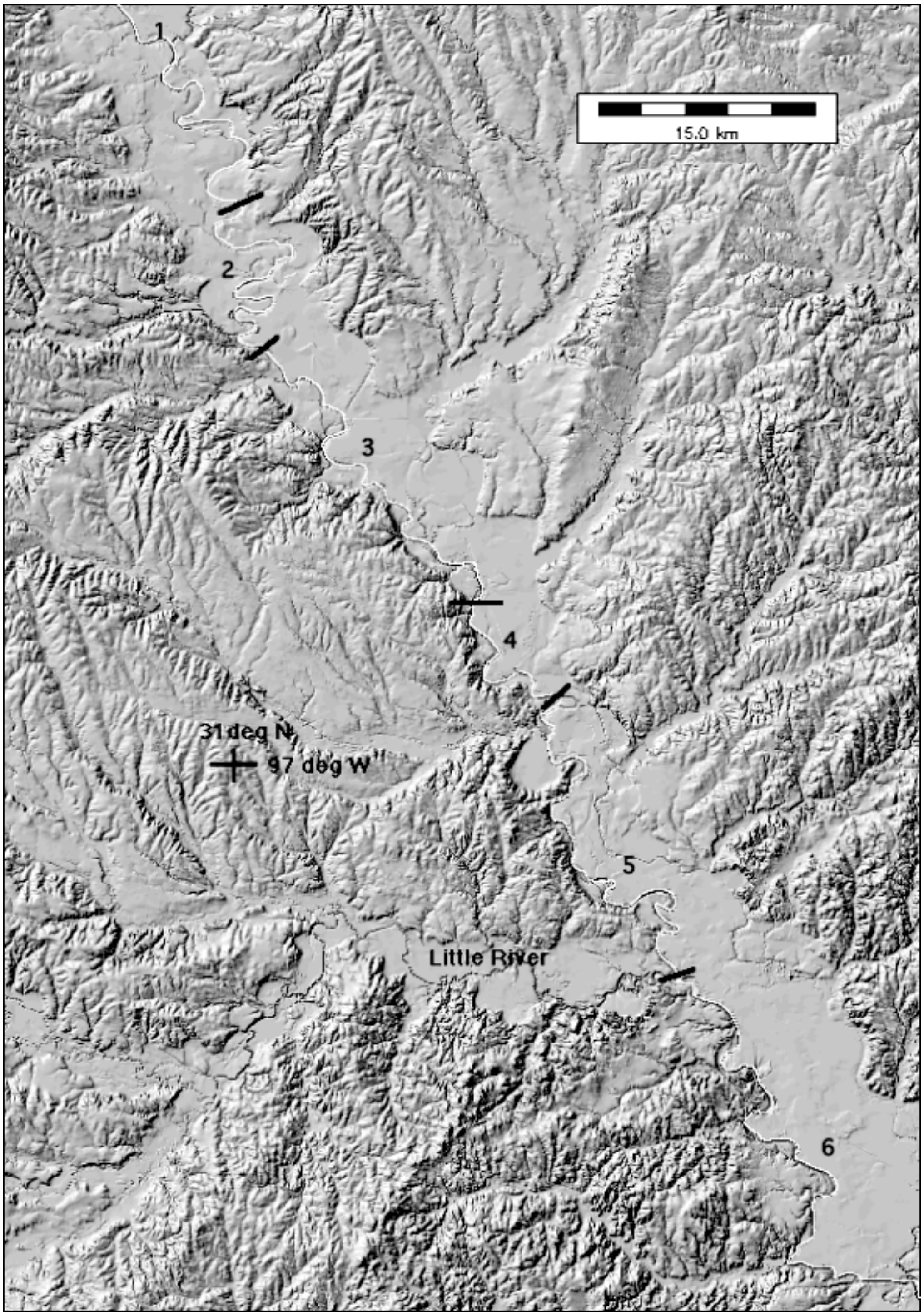


Figure 2. Shaded relief map (20X vertical exaggeration), Brazos River valley from Highway 7 at Waco to Highway 21 near Bryan. Black lines demarcate geomorphic zones as follows (see Table 1): 1 = Waco to Golinda; 2 = Golinda to near highway 7; 3 = near highway 7 to Robertson Co. ; 4 = Robertson Co. to Little Brazos diversion; 5 = Little Brazos diversion to Little River; 6 = Little River to SH 21.

Table 2. Geomorphic characteristics of Brazos River geomorphic zones, Waco to Bryan.

Reach	Slope	Sinuosity	Valley confinement	Channel-floodplain connectivity	Other features
Highway 6 at Waco to Golinda	0.0002760	1.84	unconfined	Moderate due to relatively frequent overbank flow	McClennan Falls; Lake Creek Lake Fault near downstream end
Golinda to Highway 7	0.0003277	2.65	unconfined	Moderate due to numerous meander scar depressions	Evidence of at least two avulsions (one continues to following reach)
Highway 7 to Robertson County	0.0005256	1.46	partly confined	Moderate due to numerous meander scar depressions & paleochannel	Evidence of several avulsions & paleochannel fragments; Falls of the Brazos
Robertson County to Little Brazos Diversion	0.0000419	1.63	partly confined	Low due to infrequent overbank flow & few valley bottom depressions	Hardin Slough paleochannel
Little Brazos Diversion to Little River	0.0002357	1.84	partly confined	Moderate due to Little Brazos connections	Little Brazos River a Yazoo Channel
Little River to SH 21	0.0002335	1.68	confined	High due to frequent Little Brazos backflooding	River mostly pinned to right (west) valley side

The Brazos River in the Waco-Bryan reach is incised, but less so than downstream of SH 21. As in the rest of the study area, the river is a meandering single-thread channel, though sinuosity varies from less than 1.5 to 2.65. From about 30 km downstream of Waco, paleochannels of various types, resulting from meander cutoffs and avulsions, are more common. These exist in various stages of development, from active tributary-occupied channels to infilled meander scars. A major tributary, the Little River, enters on the west (right) side of the valley, defining the boundary between the fifth and sixth zones. A major paleochannel resulting from a Holocene avulsion, the Little Brazos River, parallels the Brazos in the lower two zones and joins the river near SH 21.

CHAPTER TWO
HYDROLOGICAL ANALYSES

Methods

Six gaging stations maintained by the U.S. Geological Survey and cooperating agencies exist along the Brazos River within the study area (Table 3). Flow records from these stations were analyzed to determine critical or threshold flow levels.

Table 3. US Geological Survey gaging Stations used in this study. Datum refers to the elevation of the gage above mean sea level; date is the beginning of regular recording at the site. Slope is derived from digital elevation model data and is the slope used in shear stress and stream power calculations for the site.

Name	*Location*	*Number*	*Drainage area (km^2)*	*Datum (m)*	*Date*	*Slope*
Waco	SH 6, south side of Waco	08096500	51,782	106.5	1898	0.0002000
Highbank	FM 413	08098290	54,053	110.0	1965	0.0005000
Bryan	SH 21 W of Bryan	08108700	101,137	57.7	1993	0.0002000
Hempstead	US 290 W of Hempstead	08111500	113,649	33.5	1938	0.0009967
Richmond	US 90	08114000	116,827	8.7	1903	0.0001000
Rosharon	FM 1462 nr Brazos Bend State Park	08116650	117,428	~0	1967	0.0001800

Asquith et al. (2007a) and Asquith and Heitmuller (2008) conducted extensive analyses of discharge records from Texas gaging stations, including those shown in Table 3. They determined key flow statistics and probabilities for each station, based on the entire period of record. However, the periods of record are variable, with measurements commencing at various dates from 1898 to 1993. The longer periods of record include periods both before and after major dams on the Brazos River upstream of the study area, and on tributaries such as Yegua Creek. Thus separate analyses of mean daily flows were conducted to determine flow regimes characteristic of the past 20 to 30 years. For the Waco, Highbank, Hempstead, and Richmond stations the period analyzed was January 1, 1983 through December 31, 2012. Due to later establishment of the gaging station and missing data, respectively, the periods for the Bryan and Rosharon stations were 1993-2012 and 1984-2012.

The field measurements data for each gaging station was used to identify critical flow levels. For each available set of measurements, the following data were extracted, along with the date and time: gage height (GH, ft), discharge (Q, $ft^3\ sec^{-1}$), width (W, ft), cross-sectional area (A, ft^2), and mean velocity (V, ft sec^{-1}). From these mean depth D was calculated as A/W. A representative channel slope S for each gaging station was determined from digital elevation model data using River Tools™. For the latter the upstream slope (channel leading into the gage site) was used. The reach of consistent slope closest to the station was used, provided there was a minimum channel distance of 10 km.

Mean boundary shear stress ($N\ m^{-2}$) for each measurement was calculated as

$$\tau = \gamma\ R\ S, \qquad (1)$$

with hydraulic radius *R* assumed to be equal to *D*. As width-depth ratios were in all cases >10, this is considered a reasonable assumption. The specific gravity g is assumed constant, with a value of 9810.

Specific stream power (power per unit channel width, sometimes referred to as unit stream power) was determined by

$$\omega = \gamma\ Q\ S/W. \qquad (2)$$

SI units were used for shear stress and stream power calculations (*Q:* $m^3 sec^{-1}$*; D, W: m*).

For each data set, the following pairwise relationships were examined to identify major changes or inflections in the relationship:

GH vs. Q, W, D, V, τ, ω
Q vs. W, D, V, τ, ω

In many cases the *GH vs. Q* relationship (the rating curve) is not consistent over time. In these cases the measurements from the most recent rating curve indicated in the USGS data were used.

In addition to identifying inflection points in the relationships, flows associated with the following thresholds were identified:

1. Threshold shear stress for gravel mobility. This is set at 5.8 $N\ m^{-2}$, based on the critical threshold for entrainment of medium gravel in the widely used Shields entrainment function (see discussion in Church, 2006).

2. Threshold velocity for mobility of sandy bedforms. A value of 0.35 $m\ sec^{-1}$ was established by Carling et al. (2000) for the threshold of incipient motion of fluvial sand dunes in the Rhine River. This velocity falls within the range of values for bed stage transitions reported by Robert and Uhlman (2001) from experimental data. The 0.35 $m\ sec^{-1}$ threshold is above the critical shear velocity for individual grains of sand and very fine gravel given by Fischenich (2001).

3. Critical specific stream power threshold (10 $W\ m^{-2}$). This is based on thresholds of transport and/or channel change identified at approximately this value identified

in several studies of bed load transport, fluvial energy expenditure, and channel morphological change (Williams, 1983; Ferguson, 2005; Petit et al., 2005; Kale and Hire, 2007).

4. Threshold shear stress for channel instability for alluvial streams with tight clay or alluvial silt banks (12.68 N m^{-2}; Fischenich, 2001).

For each of items 1-4 the discharge associated with the critical value was determined for each station, and the associated gage height determined from the rating curve.

Key stages for overbank flow and flood effects were determined from National Weather Service (NWS) flood stage information in the advanced hydrologic prediction systems. Information for the study area gages is available via the West Gulf River Forecast Center (http://www.srh.noaa.gov/wgrfc/). In addition, digital elevation model (DEM) data for valley bottom areas in the vicinity of gaging stations was examined to estimate stages at which inundation of key geomorphic features is likely to occur.

The probability for mean daily flows to exceed the identified thresholds can be determined visually from graphs presented by Asquith and Heitmuller (2008). An example is shown in Figure 3. However, these are based on the entire period of record, and may differ from those based on recent decades. The latter were determined from daily mean flows using the standard formula for recurrence interval, $RI = (n + 1)/m$, where n is the number of daily values, and m is the rank of the discharge. RI in days was converted to years by dividing by 365.25. The daily probability is the inverse of RI in days.

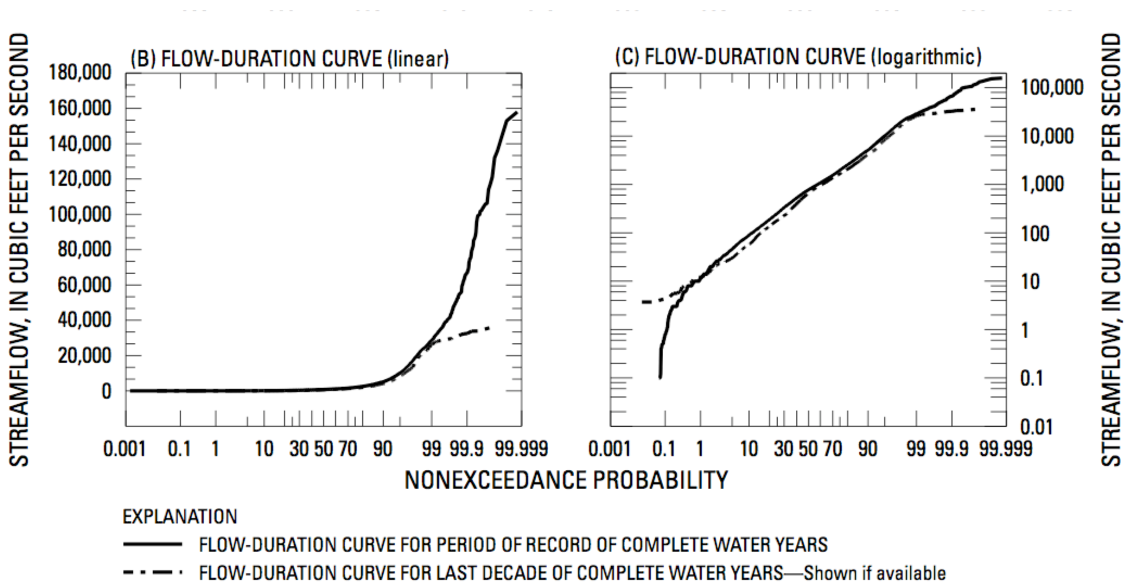


Figure 3. Nonexceedance probabilities for mean daily discharges for the Brazos River at Waco (from Asquith and Heitmuller, 2008).

General Results

Mean and median flows increase, as expected, in the downstream direction. Maximum and minimum flows also generally decline, though this pattern does not hold between the two downstream-most stations. L-statistics from Asquith ejt al. (2007a) are uniformly less than mean and median mean daily flows, indicating relatively low flow variability (very high variability would be indicated by L-values greater than the means or medians).

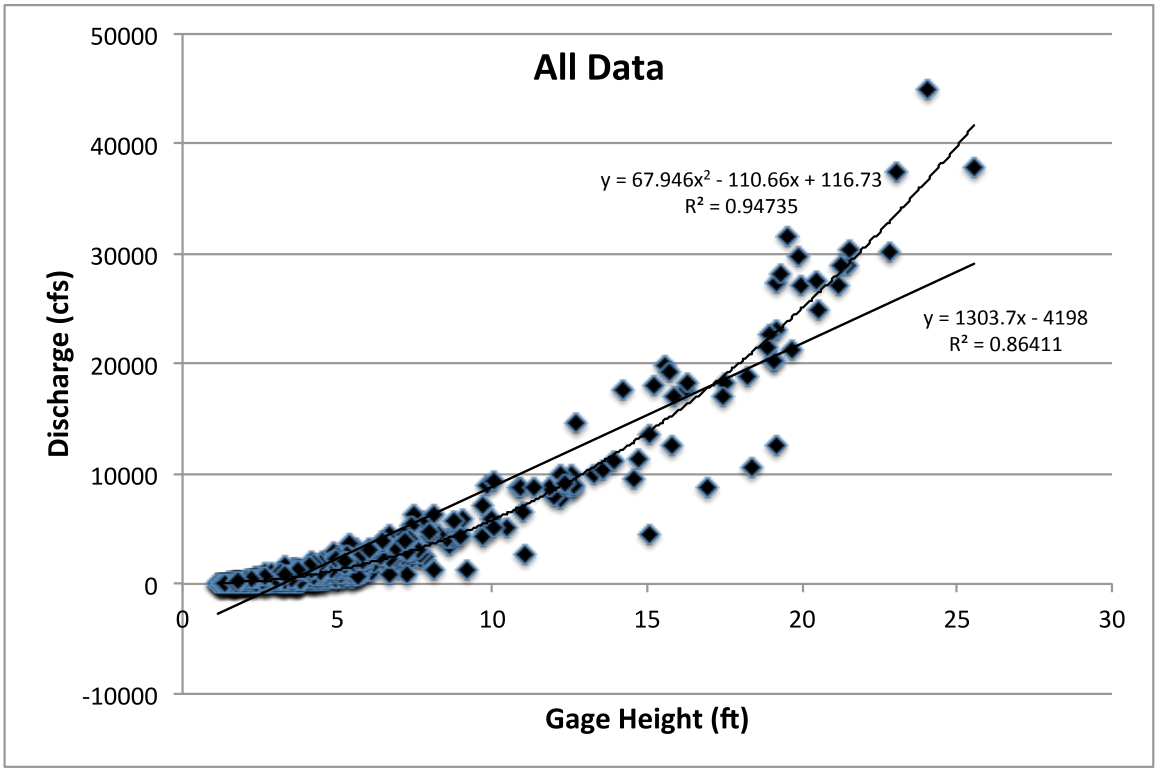
Stream power and shear stress are both a function of slope, with stream power also directly related to discharge, and shear stress to mean depth. Velocity is indirectly linked to slope and depth, and is also influenced by roughness. Thus the relative thresholds of shear stress (for gravel movement and for channel instability), specific stream power (10 N m^{-2}), and velocity (for sand bedform movement) vary between the stations. At the Waco and Rosharon stations the two shear stress thresholds were the lowest and highest among the four, though at Rosharon both the gravel and sandy bedform mobility levels are attained the vast majority of the time. At Highbank, Bryan, and Richmond the velocity threshold occurs most frequently (lowest discharges), and the channel instability shear stress threshold least often (at Richmond, essentially never). The stream power critical value is associated with higher flows than the gravel mobility shear stress threshold at all sites. The key velocity for sandy bedform motion is associated with lower flows than the stream power threshold for most sites, the exception being Hempstead. At the latter site, both shear stress thresholds are nearly always exceeded (see discussion below).

Overbank flow is most common at the Rosharon and Richmond sites, and least common at Bryan and Highbank, with Waco and Hempstead intermediate. Backwater flooding or other forms of channel-floodplain connectivity occurs at sub-flood levels at five gaging stations (Waco, Highbank, Bryan, Hempstead, and Richmond). This is most pronounced at Bryan, where backwater flooding of the Little Brazos begins at a discharge of just over 21 percent of the NWS flood stage. At Waco, discharges of less than half that associated with flood stage achieve some connectivity with floodplain depressions, and at Hempstead floodplain depressions downstream are connected at flows well below bankfull. At Richmond, a discharge of 86 percent of flood stage results in channel-floodplain connectivity (CFC), while at Rosharon, stages approximating NWS flood levels are required. However, at the latter (and at Richmond), such connectivity increases very rapidly once banktop stages are reached.

With respect to correlations among hydraulic variables, in some cases relationships among gage height, discharge, and other variables were consistent over the entire data set of field measurements. In other cases these relationships changed over time, as reflected in changing rating curves. Figure 4, for example, shows the *Q vs. GH* relationships for the Waco stage for the entire data set, and for the most recent rating curve.

At lower flows, a threshold could be detected representing flows inundating the entire river bed, as opposed to low flows confined to thalwegs, pools, and other lower areas. This often showed up as a sharp inflection in relationships between gage height and flow width. In the case of Waco, for example (Figure 5), width increases very rapidly with stage, from about 50 to 300 feet, as stage goes from about 2 to 4 feet. From there width is relatively constant with stage up to a gage height of about 17 feet, where another increase occurs as channel shelves (small inset floodplains) become inundated. Similar phenomena occur at the Highbank, Richmond, and Rosharon stations. The Bryan station shows a rapid increase in width with stage at the lowest stages (up to about 6 ft), and a more gradual increase thereafter. At Hempstead, width is highly variable (from 190 to about 340 ft) at low stages (gage heights of 10-12’), and consistently around 300’ up to a stage of 24 to 30’, at which point width increases gradually due to drowning of channel shelves.

In the following sections the gaging stations are discussed individually.



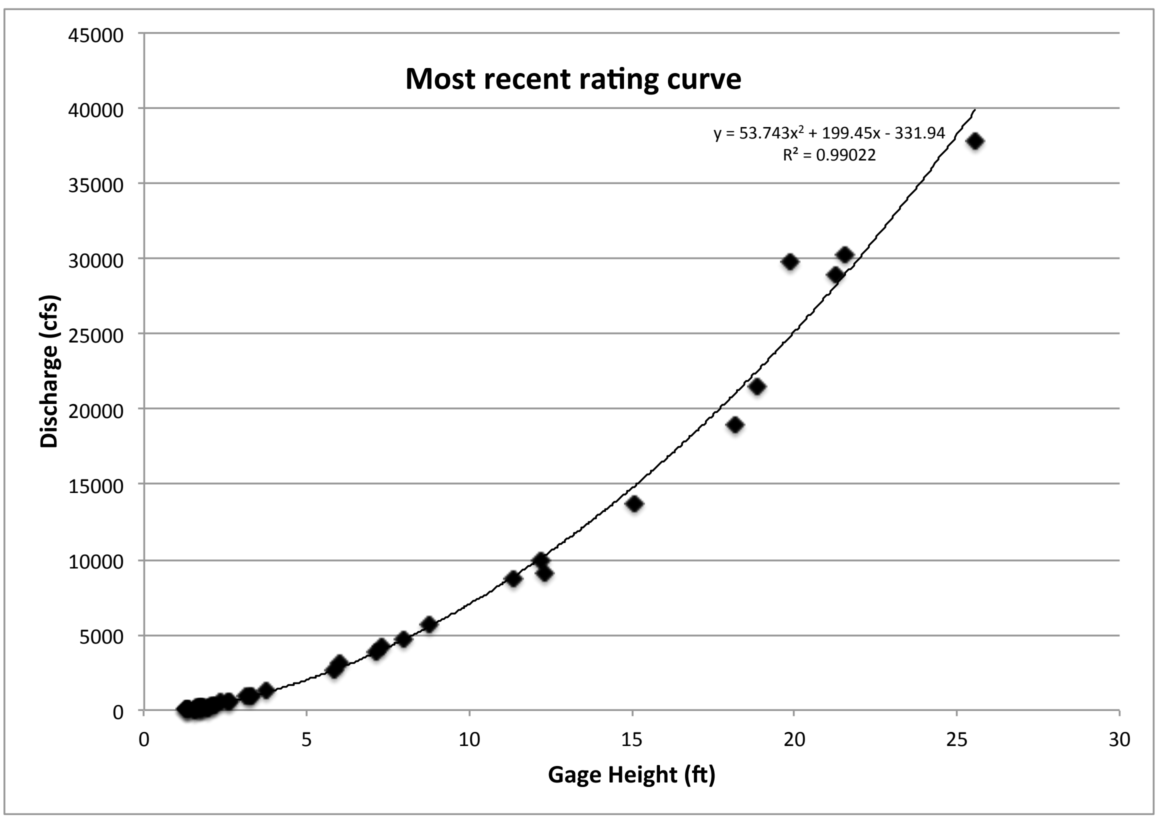


Figure 4. Stage (gage height) vs. discharge relationships for the Waco gaging station.

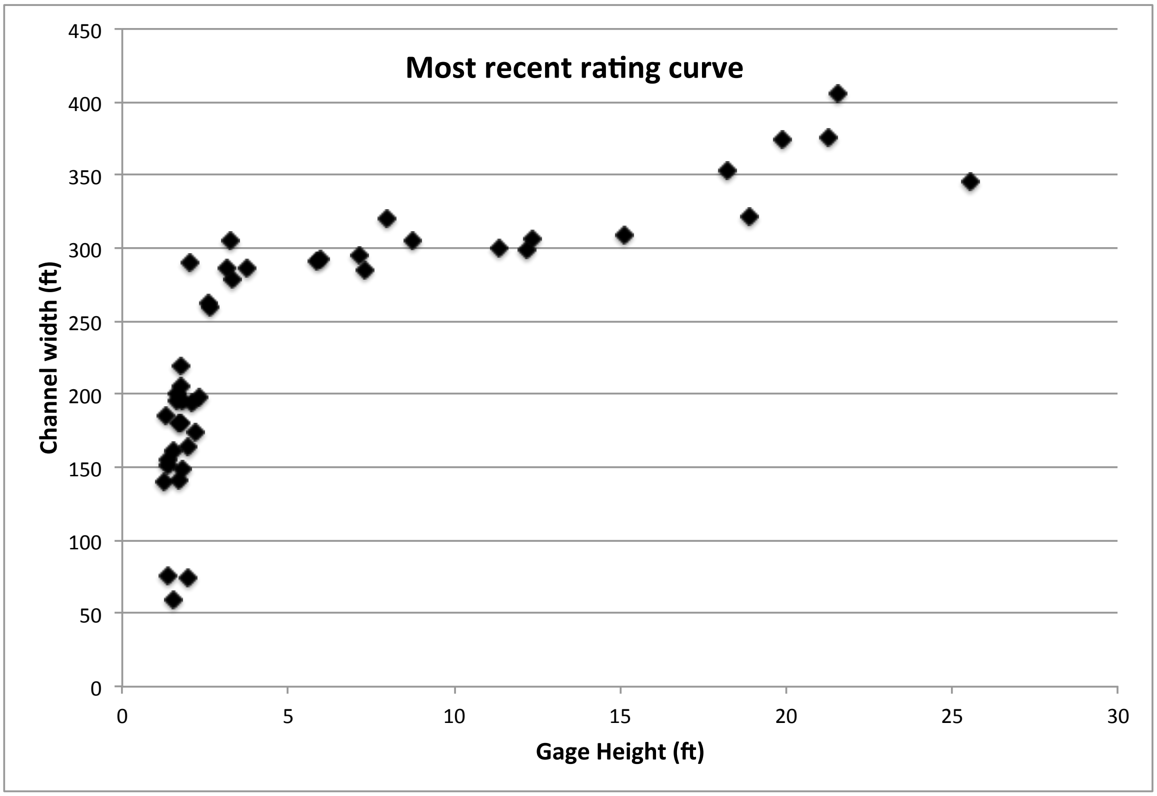


Figure 5. Gage height vs. flow width relationship for the Waco gaging station.

Results by Gaging Station

Waco

Since the mid 1960s flows of the Brazos at Waco have been influenced by upstream reservoirs--most directly by Lake Waco, where impoundment began in February, 1965. To avoid confounding effects of pre- and post-impoundment regimes, only field measurements from 3 March 1965 onward were used (N=393).

Average flows at Waco are on the order of 2,000 cfs, with typical annual high flows of 30,000 to 40,000 cfs, and minima of <100 cfs (Asquith et al., 2007a). Asquith et al. (2007a) show a significant downward trend in the annual maximum. The flow regime for the 1983-2012 period is summarized in Table 4. Note that here and subsequently, the median discharge is also the flow that has a 50% probability of being exceeded on any given day.

Table 4. Flow statistics for the Brazos River near Waco, based on mean daily flows, 1983-2012. Q1 and Q1 low, respectively, are the high and low flows with a recurrence interval of one year, and Q10 the 10-year flood.

	Mean	Median	Q1	Q1 low	Q10
Discharge ($ft^3\ sec^{-1}$)	2,207	750	33,600	4.1	36,400
Discharge ($m^3\ sec^{-1}$)	62.5	21.2	951.0	0.1	1030.7

Threshold flow levels are shown in Table 5. A discharge of about 750 cfs is necessary to achieve full bed inundation, and about 3,500 cfs for the threshold of gravel mobility. Nearly 7,000 cfs is required for the threshold velocity for sandy bedform movement, about 8,400 for the specific stream power threshold, and nearly 11,000 cfs to achieve the threshold shear stress for channel instability. All of these are sub-banktop flows, and all are associated with daily exceedance probabilities of at least 4 percent or more based on the historical record. Flow approaching 15,000 cfs is associated with stages necessary to inundate small inset floodplains, and of about 21,000 cfs to trigger channel-floodplain connectivity downstream. These are sub-banktop flows with probabilities of about 2 percent or more. Threshold stages for flooding are associated with discharges of >44,000 cfs, and have daily exceedance probabilities of <0.01 percent (Table 5).

Table 5. Threshold flow levels for the Brazos River at Waco. Items shown in **bold** represent the identified stage or discharge threshold value and units, with other values determined from the rating curve and/or unit conversions.

Gage hgt, ft (m)	*Q, cfs (cms)*	*Daily prob. (%)*	*Comments*
3 (0.91)	750 (14)	50	Transition from narrow, higher velocity flow; inundation of entire bed. Below this level increased flow primarily by higher velocity; strong influence by bedforms and detailed bed topography.
4 (1.22)	1,413 **(40)**	32	Transition: roughly constant unit stream power with discharge to this point; then increases more rapidly
7 (2.14)	3,532 **(100)**	14	Threshold shear stress for gravel mobility (5.8 N m^{-2})
9.8 (3.0)	6,890 **(195)**	7	Threshold velocity for sandy bedform mobility (0.35 m sec^{-1})
11 (3.35)	8,365 (237)	6	Associated with threshold specific stream power value of 10 W m^{-2}
12.5 (3.82)	10,604 **(300)**	4	Threshold shear stress for channel instability (12.68 N m^{-2})
15 (4.57)	14,750 (418)	3	Inundation of small inset floodplain
18 (5.50)	20,670 (585)	2	Channel-floodplain connectivity downstream (approximate)
27 (8.23)	44,230 (1253)	<0.01	NWS minor flooding
30 (9.14)	54,020 (1530)	<0.01	NWS moderate flooding
38 (11.58)	84,850 (2403)	<0.01	NWS major flooding

Highbank

The Highbank area comes by its name honestly; the river is strongly incised in this vicinity. Observations back to at least 1913 show only two overbank flow events. Average flows are about 2,800 cfs, and the typical annual maximum just under 36,000 cfs (Table 6).

Table 6. Flow statistics for the Brazos River near Highbank, based on mean daily flows, 1983-2012. Q1 and Q1 low, respectively, are the high and low flows with a recurrence interval of one year, and Q10 the 10-year flood.

	Mean	Median	Q1	Q1 low	Q10
Discharge (ft^3 sec^{-1})	2,791	924	35,900	30	51,900
Discharge (m^3 sec^{-1})	79.0	26.2	1016.6	0.8	1469.6

Threshold flow levels are shown in Table 7. Relatively steep slope and flow confinement leads to relatively high velocities, and a minimal stage associated with a discharge of only about 350 cfs to achieve sandy bedform mobility. However, this would occur only in the thalweg. Velocity continues to increase rapidly with gage height up to 6 ft (5,000 cfs) before increasing more slowly and erratically with discharge. The gravel mobility threshold is only slightly greater, and $\omega = 10$ N m^{-2} occurs at about 8,000 cfs. The estimated channel instability threshold is linked to a discharge of about 15,000 cfs. All of these have occurred at least four percent of the time in the historical record.

Because of the high banks and incised channel, stages necessary to inundate inset floodplains and valley bottom depressions are rare ($p < 0.01$), and flood stage is even rarer, requiring flows approaching 100,000 cfs (Table 7).

Table 7. Threshold flow levels for the Brazos River near Highbank. Items shown in **bold** represent the identified stage or discharge threshold value and units, with other values determined from the rating curve and/or unit conversions

Gage hgt, ft (m)	*Q, cfs (cms)*	*Daily prob. (%)*	*Comments*
>3	353 **(10)**	77	Threshold velocity for mobility of sandy bedforms (0.35 m sec^{-1}); bed inundation
4 (1.22)	2,000 (56.6)	28	Inundation of lower, unvegetated channel banks
6 (1.83)	5,000 (141)	13	Below this level increased flow primarily by higher velocity; strong influence by bedforms and detailed bed topography. Based on gage height vs. velocity relationship.
6.1 (1.86)	5,085 **(144)**	13	Threshold shear stress for gravel mobility (5.8 N m^{-2})
7.8 (2.38)	8,051 **(228)**	8	Associated with threshold specific stream power value of 10 W m^{-2}
11.3 (3.44)	14,725 **(417)**	4	Threshold shear stress for channel instability (12.68 N m^{-2})
32 **(9.75)**	78,500 (2223.1)	<0.01	Channel-floodplain connectivity; flow to inset floodplains & valley bottom depressions
35 (10.67)	91,100 (2580)	<0.01	NWS minor flooding
38 (11.58)	104,500 (2959.4)	<0.01	NWS moderate flooding
40 (12.19)	113,900 (3225.6)	<0.01	NWS major flooding

Bryan

The Brazos River gaging station at SH 21 west of Bryan is near the confluence with the Little Brazos River, and the Little River also joins the Brazos between the Highbank and Bryan stations. The median daily discharge here is significantly less than the mean of about 4,800 cfs (Table 8).

Table 8. Flow statistics for the Brazos River near Bryan, based on mean daily flows, 1993-2012. Q1 and Q1 low, respectively, are the high and low flows with a recurrence interval of one year, and Q10 the 10-year flood.

	Mean	Median	Q1	Q1 low	Q10
Discharge ($ft^3\ sec^{-1}$)	4,790	1,390	58,900	143	76,700
Discharge ($m^3\ sec^{-1}$)	135.6	39.4	1667.9	4.0	2171.9

Threshold flow levels are shown in Table 9. Bed inundation occurs at <500 cfs, and sandy bedform mobility at about 2,000 cfs. The threshold for gravel mobility occurs at about 4,200 cfs, which is achieved in mean daily flows about 27 percent of the time. The specific stream power threshold and the initiation of backwater flooding in the Little Brazos occur at similar discharges just under 16,000 cfs, which occur about 8 percent of the time. More significant backwater flooding of the Little Brazos is associated with a discharge of about 39,000 cfs. NWS flood stages are rarely achieved ($p < 0.01$) (Table 9), and only two stages above 48 ft have ever been recorded.

Table 9. Threshold flow levels for the Brazos River near Bryan. Items shown in **bold** represent the identified stage or discharge threshold value and units, with other values determined from the rating curve and/or unit conversions

Gage hgt, ft (m)	*Q, cfs (cms)*	*Daily prob. (%)*	*Comments*
6 (1.83)	469 (13)	88	Bed inundation; rapid increase of width with stage to this point; more gradual at higher stages
11 (3.4)	2,120 **(60)**	40	Threshold velocity for sandy bedform mobility (0.35 m sec^{-1})
12.1 (3.69)	4,240 **(120)**	27	Threshold shear stress for gravel mobility (5.8 N m^{-2})
21 (6.40)	15,600 (442)	8	Backwater flooding up Little Brazos River
21.2 (6.46)	15,900 **(450)**	8	Associated with threshold specific stream power value of 10 W m^{-2}
26 (7.92)	25,000 (709)	4	Approximate inflection in gage height vs. velocity relationship. Above this level limited increase in velocity.
29 (8.84)	31,780 **(900)**	2	Threshold shear stress for channel instability (12.68 N m^{-2})
32 (9.75)	39,300 (1112)	1	Significant backwater flooding up Little Brazos River
43 (13.11)	73,800 (2090)	<0.1	NWS minor flooding
48 (14.63)	93,000 (2635)	<0.01	NWS moderate flooding
54 (16.46)	118,900 (3365)	<0.01	NWS major flooding

Hempstead

Mean and median discharges at Hempstead are in the range of 7,200 and to 2,500 cfs, respectively, with typical annual maxima >70,000 (Table 10). The Navasota River and Yegua Creek are major tributaries with confluences between Bryan and Hempstead.

Table 10. Flow statistics for the Brazos River near Hempstead, based on mean daily flows, 1983-2012. Q1 and Q1 low, respectively, are the high and low flows with a recurrence interval of one year, and Q10 the 10-year flood.

	Mean	Median	Q1	Q1 low	Q10
Discharge (ft^3 sec^{-1})	7,251	2,530	72,900	290	111,010
Discharge (m^3 sec^{-1})	205.3	71.6	2064.3	8.2	3143.5

The Hempstead station occurs within a bedrock controlled section of the lower Brazos River valley, and slopes are the steepest of any gaging station. Width/depth ratios, though all >10, are also significantly lower than at other stations. As a result, nearly all discharges exceed the thresholds for gravel mobility and channel instability of cohesive sediment channels, though actual instability is not prevalent because of the bedrock control. Only four of about 850 field measurements show shear stresses <10 N m^{-2}.

For discharges up to about 1,700 cfs, depth increases rapidly with discharge, with the relationship flattening at this point. The ω = 10 and sandy bedform thresholds are at 3,200 and 4,700 cfs, respectively. At a discharge of about 18,000 cfs flooding of inset channel shelves occurs, and flood stage requires >90,000 cfs, with daily mean flows reaching this level about 0.1% of the time (Table 11).

Table 11. Threshold flow levels for the Brazos River near Hempstead. Items shown in **bold** represent the identified stage or discharge threshold value and units, with other values determined from the rating curve and/or unit conversions.

Gage hgt, ft (m)	*Q, cfs (cms)*	*Daily prob. (%)*	*Comments*
10 (3.05)	<1000 (<28.32)	>81	Bed inundation
12 (3.66)	1,652 (46.8)	63	Depth increases steeply with gage height to here; then flattens
13.6 (4.14)	3,172 **(90)**	45	Associated with threshold specific stream power value of 10 W m^{-2}
15 (4.57)	4,670 (132)	36	Threshold velocity for mobility of sandy bedforms (0.35 m sec^{-1})
24 (7.31)	18,049 (511.1)	11	Width approximately constant, then increases with stage; flooding of channel shelf and floodplain depressions downstream.
50 (15.24)	93,119 (2367)	<0.1	NWS minor flooding
53 (16.15)	105,263 (2981)	<0.05	Widespread floodplain inundation
55 (16.8)	113,759 (3222)	<0.02	Major lowland flooding

Richmond

Discharge does not increase greatly between Hempstead and Richmond, as there are no large tributaries between the two stations. Also within this reach, the Bessie's Creek/Oyster Creek drainage (occupying the former Brazos River channel abandoned after an avulsion about 1,500 years ago; Taha and Anderson, 2008) conveys some of the runoff that would otherwise contribute to Brazos River flow. Flood peaks are somewhat depressed because at flows approaching 75,000 cfs, cross-valley flow to the Oyster Creek system occurs. Average flows are about 7,700 cfs, and annual maxima about 74,000 (Table 12).

Table 12. Flow statistics for the Brazos River at Richmond, based on mean daily flows, 1983-2012. Q1 and Q1 low, respectively, are the high and low flows with a recurrence interval of one year, and Q10 the 10-year flood.

	Mean	Median	Q1	Q1 low	Q10
Discharge ($ft^3\ sec^{-1}$)	7,729	2,900	74,100	247	92,000
Discharge ($m^3\ sec^{-1}$)	218.9	82.1	2098.3	7.0	2605.1

The vertical datum of the Richmond gage is <9 masl, and the slope is about 1/10 that at Hempstead. Thresholds for sandy bedform movement and gravel mobility are correspondingly higher, associated with flows of approximately 6,400 and 21,000 cfs, respectively (Table 13). To achieve the channel instability threshold shear stress of 12.68 N m^{-2} with a slope of 0.0001, a depth of 12.93 m would be required. Nearly 980 field measurements show a maximum depth of 11 m. Extrapolation of the discharge vs. mean depth relationship indicates a flow approaching 100,000 cfs would be required to achieve the critical depth—but as cross-valley flow occurs at discharges of 75,000 cfs or greater, this is extremely unlikely.

Table 13. Threshold flow levels for the Brazos River at Richmond. Items shown in **bold** represent the identified stage or discharge threshold value and units, with other values determined from the rating curve and/or unit conversions

Gage hgt, ft (m)	*Q, cfs (cms)*	*Daily prob. (%)*	*Comments*
14.5 (4.4)	6,390 **(180)**	32	Threshold velocity for movement of sandy bedforms (0.35 m sec^{-1})
21 (6.4)	15,791 (447)	14	Velocity increases steeply with stage until this point, then flattens
24.1 (7.3)	21,120 **(600)**	9	Threshold shear stress for gravel mobility (5.8 N m^{-2})
36.4 (11.1)	47,630 **(1350)**	2	Associated with threshold specific stream power value of 10 W m^{-2}
46.1 (14.1)	74,590 (2113)	0.3	Backwater flooding of tributaries, flow to Oyster Creek
48 (14.6)	80,450 (2265)	0.1	Flood stage
49.8 (15.2)	86,280 (2443)	0.07	Massive lowland flooding

At a stage of about 21 ft (~16,000 cfs) the rate of velocity increase with flow is somewhat reduced, apparently due to increased roughness on upper banks. Channel floodplain connectivity and flood stage occur at about 75,000 and 80,000 cfs (Table 13).

The relationship between discharge and sediment transport at the Richmond gage was analyzed by Hudson (2010), who identified a discharge of about 53,000 $ft^3\ sec^{-1}$ as the "most effective" discharge. The latter is defined as that which transports the greatest total mass of sediment over time.

Rosharon

Comparison of Table 14 below with Table 12 shows that mean and annual maximum flows increase only slightly from Richmond to Rosharon, and the 10-year flood value, and annual minimum actually decrease. Asquith et al. (2007a) show that the L-scale increases somewhat, indicating greater variability at Rosharon. The datum of the Rosharon gage is at sea level, and overbank flows in the Richmond-Rosharon reach and downstream are more common than upstream of Richmond. Flow into the Oyster Creek system, and water storage in floodplain depressions is common at discharge of about 55,000 cfs or greater, accounting for the diminution of peaks in this reach.

Table 14. Flow statistics for the Brazos River near Rosharon, based on mean daily flows, 1984-2012. Q1 and Q1 low, respectively, are the high and low flows with a recurrence interval of one year, and Q10 the 10-year flood.

	Mean	Median	Q1	Q1 low	Q10
Discharge ($ft^3\ sec^{-1}$)	8,124	3,090	75,500	91	83,200
Discharge ($m^3\ sec^{-1}$)	230.0	87.5	2137.9	2.6	2356.0

The low elevation of the river bed at Rosharon ensures that bed inundation is nearly constant, and the consistently high mean depths (average = 3.43 m = 11.2 feet) coupled with a slope approaching that of the Bryan and Waco stations ensures that the thresholds for gravel and sandy bedform movement are nearly always achieved (Table 15). The specific stream power of 10 W m^{-2}, however, requires a discharge of nearly 18,000 cfs, and the channel instability threshold occurs at about 35,000 cfs (Table 15).

Table 15. Threshold flow levels for the Brazos River near Rosharon. Items shown in **bold** represent the identified stage or discharge threshold value and units, with other values determined from the rating curve and/or unit conversions.

Gage hgt, ft (m)	*Q, cfs (cms)*	*Daily prob. (%)*	*Comments*
4 (1.2)	35 (1)	>99	Inflection in gage height vs. width relationship (bed inundation)
6.3 (1.9)	400 **(11)**	94	Threshold shear stress for gravel mobility (5.8 N m^{-2})
11.7 (3.6)	3,533 **(100)**	47	Threshold velocity for sandy bedform movement (0.35 m sec^{-1})
24.5 (7.5)	17,630 **(500)**	13	Threshold specific stream power of 10 W m^{-2}
31 (9.4)	28,380 (804)	7	Inflection in gage height vs. velocity relationship (increased roughness; flooding of channel shelf)
34.6 (10.5)	35,370 **(1000)**	5	Threshold shear stress for channel instability (12.68 N m^{-2})
43 (13.1)	54,580 (1545)	1.7	Flood stage
50.8 (15.5)	64,000 (1812)	0.9	Cross-floodplain flow to Oyster Creek

CHAPTER THREE
SOILS AND BANK RESISTANCE

Introduction

Soil surveys conducted by the U.S. Department of Agriculture represent a wealth of environmental and geotechnical information that is readily available at a detailed spatial scale of 1:24,000 or finer. This data source can potentially be leveraged into useful information for instream or environmental flow management (and river and wetland management more generally). This is the case for Texas, where detailed soil maps are generally available.

Several properties of stream bank materials influence their resistance to erosion, including shear strength, density, and texture or particle size. One that has been widely used in stream bank erosion studies is the liquid and plastic limits, from which the critical shear stress necessary for erosion can be estimated. The Atterberg limits indicate the moisture content at which a dry, brittle soil begins to behave as a plastic solid (plastic limit), and at which the material takes on properties of a viscous liquid. The plasticity index is the difference between the liquid and plastic limits.

Smerdon and Beasley (1961) examined the relationships between several soil properties (plasticity index, dispersion ratio, mean particle size, and percent clay) and critical shear stress (Pa) for bed failure in flume studies, finding that plasticity index (PI) gave the best results. The relationship is

$$\tau_c = 0.16 \, PI^{0.84}. \qquad (3)$$

Clark and Wynn (2007) found that this method consistently underestimates τ_c, but also found that eq. (3) produces results similar to other predictive methods, and that most of the latter also produce underestimates. Therefore this index does provide a reasonable index of *relative* erodibility based on soil properties alone, though it is not a good predictor of actual shear stress values at the moment of failure or erosion, which depend also on non-soil factors (e.g., morphology, vegetation cover, root reinforcement) and on both physical and chemical interactions between the fluid and the soil. Note also that failure occurs when critical shear stresses are exceeded locally; these may be different from the mean boundary shear stresses computed from eq. (3).

Methods

Soil mapping units adjacent to the Brazos River and comprising the banks were determined from the USDA Web Soil Survey database (http://websoilsurvey.nrcs.usda.gov). The dominant bank soil mapping units were identified for each geomorphic zone, along with other more rarely occurring bank soils. The mapping units consist of soil series or phases thereof, and soil complexes (a spatial mosaic of two or more series). In one case, older data from the Fort Bend County survey also includes "sandy alluvial land," a type of mapping unit known as a land type.

For each soil series included in the mapping unit the plastic index was determined from the USDA National Cooperative Soil Survey Soil Characterization database (http://soils.usda.gov/survey/nscd/index.html). These are given as ranges to reflect variability within soil series. Where, as is often the case, the PI is not uniform vertically, the PI values associated with the subsoil (or the thickest subsoil horizons) were used, assuming that this was more likely to be impinged on by flow than the surface horizons. From these values the critical shear stress was estimated using eq. (3). Other properties of the soils were also recorded, including taxonomy, typical landscape or geomorphic settings, dominant subsoil texture, and drainage class.

Results

River bank soil types, by geomorphic zones, are shown in Table 16. Taxonomic information on included soil series, along with texture, drainage, and geomorphic interpretations, are given in Table 17, and Table 18 shows the plastic index range and associated τ_c estimates for the dominant soils. These are generally consistent with conventional fluvial geomorphic wisdom that sandy floodplain soils (such as the Gaddy, Kiomatia, and Yahola series) are more erodible, while clay-rich soils (e.g., Brazoria, Ships) have greater resistance.

Table 16. Soil mapping units along the banks of the Brazos River, by geomorphic zones or reaches. The first six reaches are described in chapter 1. The "GR" designations for others refer to geomorphic reaches identified in Phillips (2007a).

Reach	**Dominant soil mapping units**	**Other soils**
Waco to Golinda (WB1)	Yahola loam; Gaddy loamy fine sand; Yahola/Gaddy complex	Weswood silty clay loam
Golinda to near Highway 7 (WB2)	Weswood sandy loam; Yahola loam; Gaddy loamy fine sand	Ships clay
Highway 7 to Robertson County (WB3)	Gaddy loamy fine sand; Yahola loam; Weswood sandy loam; Ships clay	Weswood silty clay loam & silt loam
Robertson County to Little Brazos diversion (WB4)	Gaddy loamy fine sand; Yahola loam; Weswood silty clay loam; Ships clay; Highbank silty clay loam	
Little Brazos diversion to Little River (WB5)	Gaddy loamy fine sand; Yahola loam; Weswood silty clay loam; Ships clay; Highbank silty clay loam	
Little River to SH 21 (WB6)	Weswood silty clay loam; Gaddy loamy fine sand; Yahola fine sandy loam; Ships clay; Highbank silty clay loam; Coarsewood silt loam	Burleson clay
SH 21 to Thompson's Creek (GR 1)	Highbank silt loam; Coarsewood silt loam; Ships clay; Weswood silty clay loam; Weswood/Yahola complex; Yahola fine sandy loam	Burleson clay
Thompson's Creek to SH 60 (GR 2)	Highbank silt loam; Ships clay; Weswood silty clay loam; Weswood/Yahola complex; Yahola fine sandy loam	Coarsewood silt loam; Burleson clay
SH 60 to Yegua Creek (GR 3, 4)	Highbank silt loam; Ships clay; Weswood silty clay loam; Weswood/Yahola complex; Yahola fine sandy loam	Burleson clay
Yegua Creek to Navasota River (GR 5, 6)	Kiomatia/Norwood complex; Oklared/Norwood complex; Clemville silt loam; Brazoria clay	Crockett fine sandy loam; Norwood silt loam; Trinity clay
Navasota River to New Year Creek (GR 7, 8)	Oklared/Norwood complex; Clemville silt loam; Crockett fine sandy loam; Norwood silt loam; Kiomatia/Norwood complex; Trinity clay; Oklared very fine sandy loam; Brazoria clay	Belk clay; Sumpf clay; Asa silt loam
continued on	*following page*	

New Year Creek to SH 529 (GR 9, 10)	Brazoria clay; Oklared/Norwood complex; Oklared very fine sandy loam	Sumpf clay; Clemville silt loam
SH 529 to Simonton (GR 11, 12, 13, 14, 15)	Oklared very fine sandy loam; Oklared/Norwood complex; Brazoria clay	Clemville clay; Silawa loamy fine sand; Kenney loamy fine sand; Norwood silty clay loam
Simonton to Allens Creek (GR 16)	Brazoria Clay	Asa/Pledger complex; Clemville fine sandy loam; Kenney loamy fine sand
Allens Creek to Richmond (GR 17, 18, 19)	Sandy alluvial land; Brazoria clay; Norwood silt loam & silty clay loam; Clemville fine sandy loam & silt loam	Asa/Pledger complex; Kenney loamy fine sand; Pledger clay; Asa fine sandy loam
Richmond to Rabbs Ridge oil field (GR 20, 21)	Sandy alluvial land; Brazoria clay; Clemville fine sandy loam, silt loam, & silty clay loam	Asa/Pledger complex; Pledger clay; Asa silty clay loam; Norwood silt loamd & silty clay loam; Sumpf clay
Rabbs Ridge oil field to Harris Reservoir (GR 22, 23, 24, 25)	Norwood silt loam	
Harris reservoir to Middle Bayou (GR 26, 27)	Norwood silt loam	Brazoria clay; Asa silt loam
Middle Bayou to Cutoff Lake (GR 28)	Norwood silt loam; Pledger clay; Clemville silty clay loam	
Cutoff Lake to Freeport ship channel (GR 29)	Norwood silt loam; Brazoria clay	Sumpf clay
Freeport ship channel to Gulf of Mexico (GR 30)	Norwood silt loam; Brazoria clay; Ijam clay	Surfside clay; Vebsco clay; Veston silty clay loam

Table 17. Dominant river bank soil series of the lower Brazos River. Taxonomy is according to the USDA classification system. Texture codes are: CL = clay loam; LS = loamy sand; SCL = sandy clay loam; SiCL = silty clay loam; SiL = silt loam; SL = sandy loam. Drainage codes are: MWD = moderately well drained; PD = poorly drained; SED = somewhat excessively drained; VPD = very poorly drained; WD = well drained.

Series	*Taxonomy*	*Dominant subsurface texture*	*Drainage*	*Geomorphic interpretation*
Asa	Fine-silty, mixed, superactive, hyperthermic Fluventic Hapludolls	CL	WD	Floodplains; flood plains of the lower Colorado and Brazos Rivers. The soils formed in calcareous, reddish, stratified loamy alluvium derived mainly from Permian redbed sediments
Belk	Fine, mixed, active, thermic Entic Hapluderts	clay, SiL	WD	Floodplains; vertic clays overlying loamy stratified alluvium
Brazoria	Very-fine, smectitic, hyperthermic Chromic Hapluderts	clay	MWD	Floodplains; alkaline clayey alluvial sediments
Burleson	Fine, smectitic, thermic Udic Haplusterts	clay	MWD	Pleistocene stream terraces
Clemville	Fine-silty, mixed, superactive, hyperthermic Fluventic Eutrudepts	SiC	WD	Floodplains; stratified, calcareous, silty and clayey alluvium
Coarsewood	Coarse-silty, mixed, superactive, calcareous, thermic Udic Ustifluvents	SiL	WD	Floodplains; soil formed in stratified, calcareous, loamy alluvium along channel levees of rivers and streams draining soils that formed in Permian Age sediments, mainly along the Brazos and Colorado Rivers
Gaddy	Sandy, mixed, thermic Udic Ustifluvents	LS, sand	SED	Floodplains; sandy Holocene alluvium
Highbank	Fine, mixed, active, thermic Udertic Haplustepts	SiC, clay	WD	Brazos River floodplains; loamy and clayey alluvium
Ijam	Fine, smectitic, nonacid, hyperthermic Vertic Fluvaquents	clay	PD	Alkaline, saline, clayey sediments dredged or pumped from the floor of rivers, bays, and canals or from marshes in construction of canals or waterways
continued	*on following*	*page*		

Kiomatia	Sandy, mixed, thermic Typic Udifluvents	sand	WD	Floodplains; andy alluvium with thin strata of finer materials
Norwood	Fine-silty, mixed, superactive, hyperthermic Fluventic Eutrudepts	SiL; SL	WD	Floodplains; stratified, calcareous, loamy alluvium of mixed origin. Buried clay Ab; SL Bwb's
Oklared	Coarse-loamy, mixed, active, calcareous, thermic Typic Udifluvents	SL	WD	Floodplains of streams draining mainly from Permian and Pennsylvanian age; calcareous loamy and sandy alluvium.
Pledger	Very-fine, smectitic, hyperthermic Typic Hapluderts	clay	MWD	Floodplains; recent calcareous, reddish stratified clayey and silty alluvium
Ships	Very-fine, mixed, active, thermic Chromic Hapluderts	clay	MWD	Floodplains; reddish and brownish clayey alluvial sediments
Silawa	Fine-loamy, siliceous, semiactive, thermic Ultic Haplustalfs	SCL, SL, LS	WD	Pleistocene stream terraces
Sumpf	Very-fine, mixed, active, thermic Aeric Endoaquerts	clay	VPD	Abandoned river channels on floodplains; alkaline clayey alluvial sediments.
Surfside	Very-fine, smectitic, hyperthermic Vertic Endoaquolls	clay	VPD	Low terraces, coast prairie; calcareous clayey recent alluvium less than 10 feet above sea level
Trinity	Very-fine, smectitic, thermic Typic Hapluderts	clay	MWD	Floodplains; calcareous clayey alluvium
Weswood	Fine-silty, mixed, superactive, thermic Udifluventic Haplustepts	SiL, SiCL	WD	Floodplains; buried SiCL 2Bwb's & 3Ab silty clay
Yahola	Coarse-loamy, mixed, superactive, calcareous, thermic Udic Ustifluvents	SL	WD	Floodplains in the Central Rolling Red Prairies (MLRA-80A). Calcareous loamy alluvium from Permian and Pleistocene age sediments.

Table 18. Range of plasticity index, and minimum and maximum shear stress associated with the lower and upper values (Pa) for Brazos River bank soils. NP = nonplastic.

Series	*Plasticity index*	τ_c *min*	τ_c *max*
Asa	6-27	0.72	2.55
Belk	NP-8		0.92
Brazoria	32-52	2.94	4.42
Burleson	34-54	3.09	4.56
Clemville	22-50	2.15	4.28
Crockett	15-42	1.56	3.70
Gaddy	NP-18		1.81
Highbank	35-50	3.17	4.28
Ijam	35-55	3.17	4.63
Kenney	7-20	0.82	1.98
Kiomatia	NP-5		0.62
Norwood	7-26	0.82	2.47
Oklared	NP-10		1.11
Pledger	22-39	2.15	3.47
Ships	35-50	3.17	4.28
Silawa	NP-18		1.81
Sumpf	35-55	3.17	4.63
Surfside	35-70	3.17	5.68
Trinity	30-60	2.79	4.99
Weswood	5-22	0.62	2.15
Yahola	NP-10		1.11

Table 19 was produced by examining the range of estimated τ_c for the stronger and weaker bank soils mapped in each reach. This assigns qualitative ratings of resistance from low to very high on the basis of the following ranges of τ_c: very low = 0 to 0.75; low = 0.75 to 1.5; moderate = 1.5 to 2.5; high = 2.5 to 4; very high = > 4. Given that τ_c is only a relative estimate of resistance, and the range of plastic index values for each soil, these qualitative ratings better reflect the nature of the information.

Each reach contains relatively lower and high resistance bank materials, such that rating the geomorphic zones as a whole is difficult. However, there are a few reaches that might be considered potential "hot spots" of bank erosion and lateral channel migration due to lower resistance: Waco to Highway 7, and Yegua Creek to the Navasota River. A few others are clearly more resistant than the norm; most notably the lowermost two reaches. In the other cases there is typically a wide range of resistance, such that potential hot spots would need to be identified on the sub-reach scale. Results do suggest the viability of using soil maps to identify low-resistance bank areas, such as those mapped as sandy alluvial land, and the Gaddy, Komatia, Oklared, Silawa, and Yahola series. Also, the most highly resistant soils are likely to resist and retard erosion and lateral migration, and thus may form loci of potential channel change where they occur in patchy or discontinuous distributions (e.g., Brazoria, Burleson, Clemville, Highbank, Ijam, Ships, and Trinity series). Resistance of the most common river bank soils along the lower Brazos River is shown in Figure 6. The "sandy alluvial land" mapped in Fort Bend County is comparable to the Oklared series.

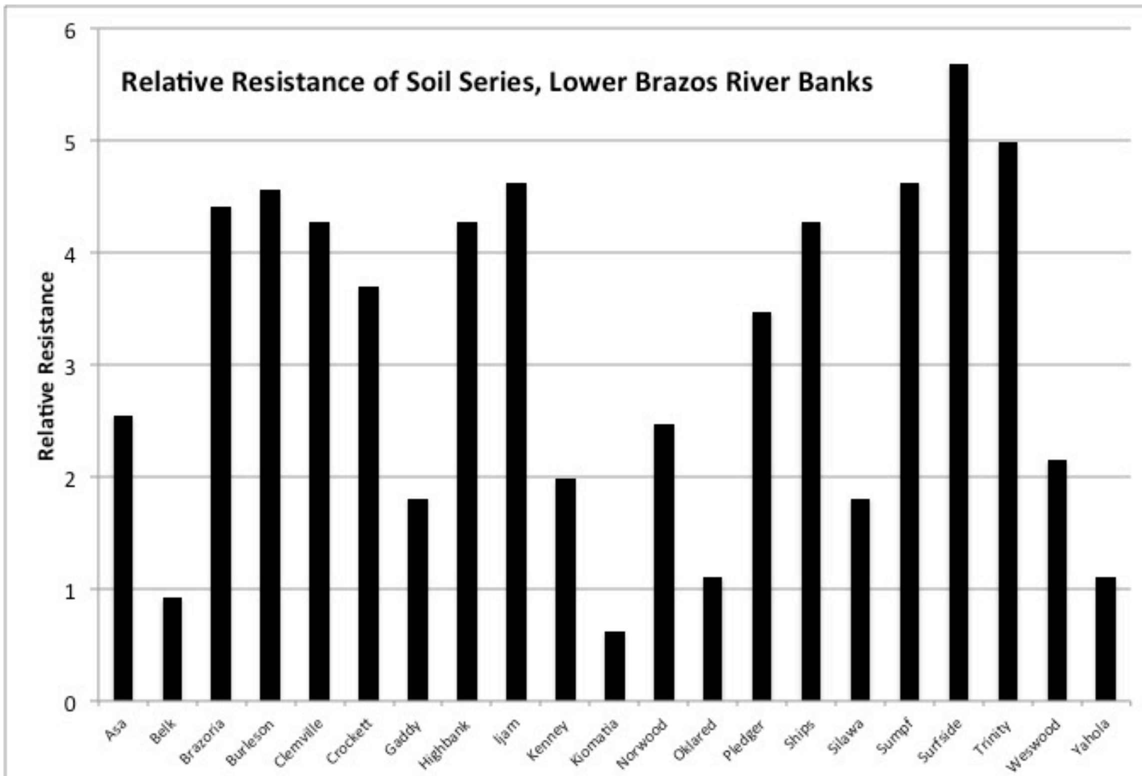


Figure 6. Relative erosion resistance of river bank soils, based on the maximum critical shear stress shown in Table 18. The "sandy alluvial land" mapping unit is similar to the Oklared series in this regard.

Table 19. Resistance of river bank soils to erosion. See text for explanation of ratings.

Reach	**Relative resistance, stronger soils**	**Relative resistance, weaker soils**
Waco to Golinda	low to moderate	very low to low
Golinda to Highway 7	low to very high	very low to low
Highway 7 to Robertson County	high to very high	very low to moderate
Robertson County to Little Brazos diversion	high to very high	very low to moderate
Little Brazos diversion to Little River	high to very high	very low to moderate
Little River to SH 21	high to very high	very low to moderate
SH 21 to Thompson's Creek (GR 1)	high to very high	very low to moderate
Thompson's Creek to SH 60 (GR 2)	high to very high	very low to moderate
SH 60 to Yegua Creek (GR 3, 4)	high to very high	very low to moderate
Yegua Creek to Navasota River (GR 5, 6)	low to moderate	very low to low
Navasota River to New Year Creek (GR 7, 8)	moderate to very high	very low to moderate
New Year Creek to SH 529 (GR 9, 10)	high to very high	very low to moderate
SH 529 to Simonton (GR 11, 12, 13, 14, 15)	high to very high	very low to moderate
Simonton to Allens Creek (GR 16)	high to very high	low to high
Allens Creek to Richmond (GR 17, 18, 19)	moderate to very high	very low to moderate
Richmond to Rabbs Ridge oil field (GR 20, 21)	moderate to very high	very low to moderate
Rabbs Ridge oil field to Harris Reservoir (GR 22, 23, 24, 25)	moderate	low
Harris reservoir to Middle Bayou (GR 26, 27)	moderate to high	low
Middle Bayou to Cutoff Lake (GR 28)	moderate to very high	low to moderate
Cutoff Lake to Freeport ship channel (GR 29)	high to very high	low to moderate
Freeport ship channel to Gulf of Mexico (GR 30)	high to very high	low to moderate

CHAPTER FOUR
DISCHARGE THRESHOLDS

Critical Flow Stages

Previous work on instream flows in Texas cites five key discharge levels or stages (Figure 7). First is thalweg connectivity. This is the minimum level of flow necessary to connect pools within the channel to maintain some downstream water flow, and provide some opportunity for movement of aquatic biota. The next highest critical stage is associated with bed inundation, the water level necessary to submerge all bedforms, aquatic habitats, and channel bottom area between the lower banks on both sides of the channel. The third key stage is called high sub-banktop, and is defined as the maximum flow contained entirely within the channel banks, as defined by the morphological bank tops. Fourth is the flow necessary to create channel floodplain-connectivity, which for practical purposes can be defined as a flux or exchange of flow between the river channel and floodplain depressions (sloughs, oxbows, lakes, etc.). Because this may occur due to occupation of high flow subchannels, flow through gaps in the natural levee, or backwater flooding of tributaries, the channel-floodplain connectivity stage may be less than that for overbank flooding. The latter is the stage associated with general overtopping of levees and floodplain inundation. Thresholds associated with these critical stages in the lower Brazos River are summarized in Table 20 and discussed below.

Table 20. Estimated discharges (cfs) for thresholds of thalweg connectivity (TC), bed inundation (BI), high sub-banktop (HSB), channel-floodplain connectivity (CFC), and overbank flooding (OvB).

Gaging Station	*TC*	*BI*	*HSB*	*CFC*	*OvB*	*Mean*[1]	*Min*[1]	*Max*[1]
Waco	<700	750	14,750 to 44,000	20,670	44,230	2,020	53	27,500
Highbank	<300	350	17,500 to 78,000	78,500	91,100	2,800	136	29,800
Bryan	<400	470	25,000 to 73,000	39,300	73,800	3,070	343	34,900
Hempstead	<700	<1,000	18,000 to 93,000	39,200	93,100	6,280	574	50,600
Richmond	50	1,200[2]	10,000 to 80,000	52,000	80,400	7,220	643	56,200
Rosharon	<35	35	28,400 to 54,000	32,000	54,600	7,780	506	51,400

[1]Median annual mean, minimum, and maximum discharge from Asquith et al. (2007a).
[2]Highly variable over the period of record; this is based on rating curve 16, 2012.

Figure 7. Key flow stages illustrated using the channel of Hardin Slough, a Brazos River tributary. The thalweg connectivity stage would be less that the water level shown in the photo, which at the time was slightly above bed inundation stage.

Thalweg Connectivity

Thalweg connectivity seems to be maintained across the entire range of historic flows in the lower Brazos. No evidence of near-zero or negative (upstream flux) velocities was discovered in the surface water measurements for any of the Brazos gaging stations examined in this study, or other evidence of discontinuous flows. A U.S. Geological Survey study of the occurrence of zero-flow at Texas gaging stations also did not identify any zero-flow events in the lower Brazos (Asquith et al., 2007b).

Bed inundation

Based on the historic record from gaging stations, bed inundation stages occur nearly always in the lowermost reaches (Richmond and Rosharon gaging stations) and at the Highbank station, and at least 87 to 88 percent of the time at Hempstead and Bryan. At Waco, discharges necessary to achieve bed inundation tend to be exceed this threshold about 50 percent of the time.

However, the gaging stations are located at bridges, and bridge crossings are not necessarily representative. Road builders tend to choose sites with narrower alluvial valleys, if possible, and relatively narrow channel segments. Other things being equal, bed inundation will occur less frequently where channel width:depth ratios are greater (e.g., Figure 8).

Figure 8. Brazos River in the Golinda to Highway 7 reach at a stage below bed inundation on Feb. 4, 2012. On this day flows at the upstream gage at Waco and the downstream station at Highbank were entirely above the bed inundation threshold.

High Sub-Banktop

At the gaging station sites banktop flow stages can be based on National Weather Service flood stages. The high range of high sub-banktop flows is therefore slightly less than the discharge associated with flood stage. The lower range of high sub-banktop (recognizing that "high" merely identifies flows above bank inundation and mean or median discharges, and fully inundating the lower banks) was estimated from inflection points of discharge vs. width relationships. For example, at the Rosharon gaging station the discharge vs. width relationship reaches a width of about 400 ft at a discharge of a bit less than 30,000 ft^3 sec^{-1} (Figure 9), and then levels off before rising again at banktop flow levels. This indicates full inundation of the lower banks and is taken as the lower range of the higher sub-banktop flows.

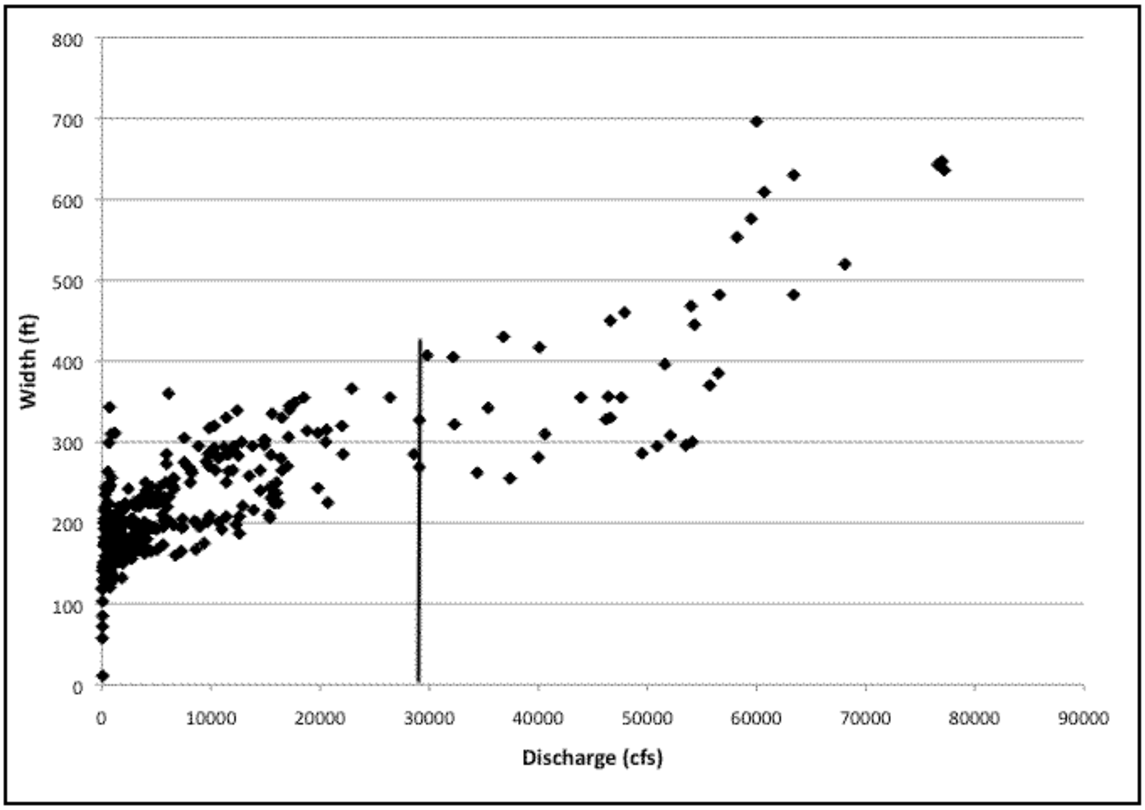


Figure 9. Discharge-width relationship for the Rosharon gaging station. Straight line indicates the identified lower end of high sub-banktop flows. The graph includes all field measurement data; the most recent rating curve suggests the inflection point is associated with a discharge of about 28,400 $ft^3 sec^{-1}$.

A very large range of flows can occur between higher and lower sub-banktop flows, ranging by a factor of nearly twofold at Rosharon to more than fivefold at Hempstead (Table 20). Note, however, that even the lower end of high sub-banktop flows are greater, often much greater, than mean or median discharges.

The lower Brazos River is mainly incised, and in many areas alluvial surfaces have developed within the incised banks (Figure 10). The terminology and specific nature of these surfaces varies, including point bars, floodplains or inset floodplains, and channel shelves. The elevation of the more-or-less flat upper surfaces of these features in incised channels is (in humid-regional perennial alluvial streams) associated, or assumed to be associated, with discharges with a recurrence interval of 1 to 2 years (Harrelson et al., 1994; Stream Team, 2012). The elevation of these inset features is often referred to as "bankfull" flow. Thus, use of the term "banktop" in this report to refer to the actual morphological channel boundaries.

Figure 10. Brazos River near Downsville, looking downstream. Note the elevations of the island surface (middle left) and inset floodplain surface (upper left) relative to the banktop in the foreground.

At five sites from Waco to the US 79/190 bridge, field measurements showed elevation differences between the top of inset floodplains or upper point bar surfaces to be (in upstream-downstream order), 2.65, 4.40, 4.00, 2.25, and 6.00 meters (7.4 to 19.7 ft). From Bryan to Brazoria, a number of field measurements conducted in conjunction with earlier projects (Phillips, 2006; 2007a) showed differences of 2 to 8 m (7 to 26 ft) in elevation between inset floodplain surfaces and morphological bank tops.

Channel-Floodplain Connectivity

Hydrological connectivity between the active river channel and the floodplain—particularly depressional areas—can occur via overbank flooding, crevasse-type flow through gaps in natural levees, activation of high-flow subchannels, backwater flooding of tributaries, and groundwater flux. Flows or stages necessary to initiate channel-floodplain connectivity are less than overbank flood stage at all gaging stations, and occur within the range of high sub-bankfull discharge at all sites except Highbank (Table 20).

Some floodplain depressions on the lower Brazos are fed primarily by tributary flow and local runoff rather than Brazos River flow. This is discussed in separate section below.

Overbank Flood

Overbank flood flows are associated with exceedance of the channel capacity and overtopping of natural levees and the morphological bank tops. An upstream-downstream gradient exists in the frequency of such flows. At Waco and Highbank, the probability of mean daily flows equaling or exceeding this level is <0.01%, and at Bryan and Hempstead <0.1%. At Richmond this rises to 0.1%, and at Rosharon to 1.7%.

Hydrology of Floodplain Depressions

Depressional areas in the Brazos River bottomlands include paleochannels of the Brazos River and its tributaries. Some of these are active channels occupied by contemporary tributary streams. Others are semiactive, conveying water during high river flows and wet periods, or are lakes with standing water. Others are only occasionally inundated, or convey flow only during major floods. These paleochannels include oxbow lakes or swamps, and sloughs or billabongs. Hudson (2010) identified 45 oxbow lakes along the lower 350 km (217 mi) of the Brazos valley, with a total area of more than 5 km^2 or 1.9 mi^2 (mean 0.113 km^2), and more than 2 km^2 (0.8 mi^2) of other floodplain lake types.

Depressions also include morphological flood basins associated with Pleistocene meander scars (Sylvia and Galloway, 2006; Phillips, 2007a), swales between alluvial ridges, and artificial pits (from stock ponds or sand mining, for example). The hydrologic status of these ranges from perennially flooded lakes to occasionally inundated.

Potential water sources for these depressions include local precipitation, runoff, and water table rise; river flooding; river surface flow via high-flow subchannels, crevasses, or backwater flooding; tributary flow; and water table rise due to high river stages. Studies of abandoned channel water bodies (oxbows and sloughs) along the lower Guadalupe and Sabine Rivers show considerable variety in the type and frequency of connectivity with the river (Hudson, 2010; Phillips, 2011b), and an inventory of channel reaches abandoned by avulsions in the lower Brazos, Navasota, Trinity, Neches, and Sabine Rivers shows active, semi-active, tributary-occupied, ponded, and infilled segments all in close proximity (Phillips, 2009).

Detailed study of three lower Brazos oxbow lakes by Chowdhury et al. (2010) showed that two are connected to the river more than once a year, on average, and the third is rarely connected, even during large floods. Osting et al. (2004) examined the connectivity of six Brazos oxbows downstream of the Bryan area, including the three studied by Chowdhury et al. (2010). Three of the six were determined to connect with the Brazos more than once per year, one at least every two years, one about every 4.5 years, and one only during very large floods. Oxbow lakes are geomorphically dynamic, and infill at varying rates, depending on the geomorphic situation. Specific examples for the lower Brazos River are described by Hudson (2010) and Giardino and Lee (2012).

Examination of topographic data and aerial imagery suggests that many of the valley-bottom depressions of all types in the lower Brazos River are supplied primarily by local or tributary runoff rather than river flow. For example, the depressions shown in Figures 11 and 12 regularly receive flow from tributaries on the adjacent uplands, and infrequently to very rarely from the Brazos. This appears to particularly be the case for the Pleistocene meander scar depressions on the valley sides (e.g., Figure 13). However, it is not exclusive to these features—some oxbows and sloughs are tributary-occupied, with those inputs being the major water source (e.g., Figure 14).

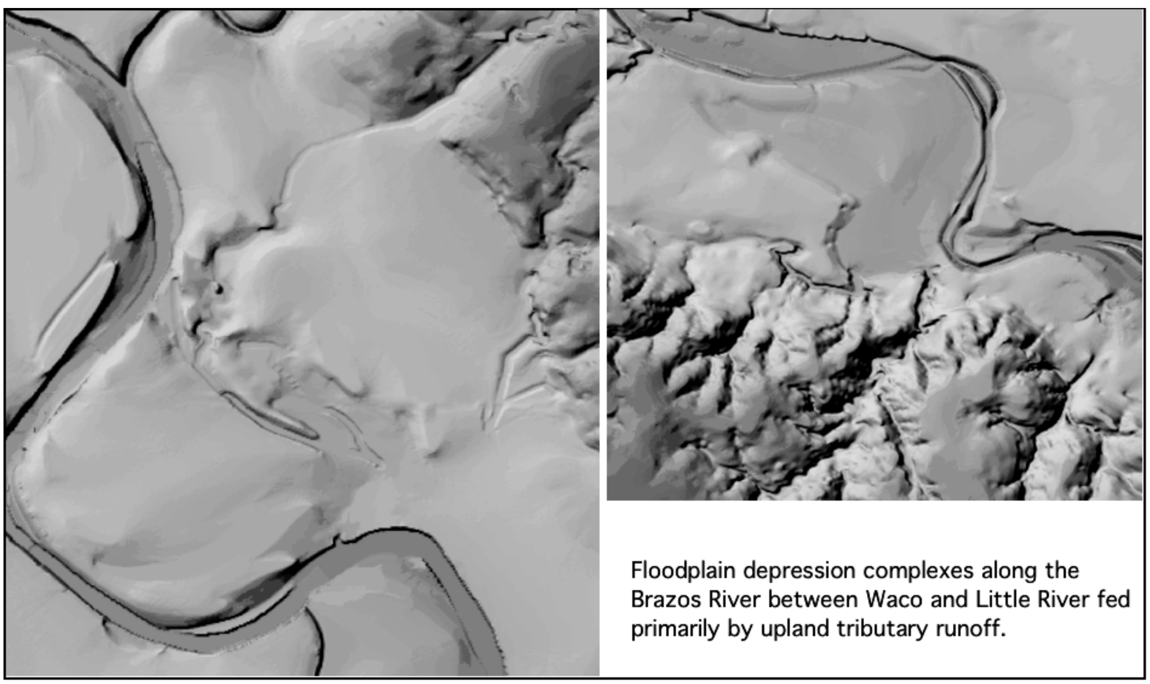


Figure 11. Floodplain depressions fed by tributary input. On the left, the depression at the center of the image receives regular tributary input, but only occasional backwater flooding at its lower end from the River. On the right, the valley-side depression at the image center regularly receives runoff from adjacent uplands and tributaries, but only rare overbank floods supply river water.

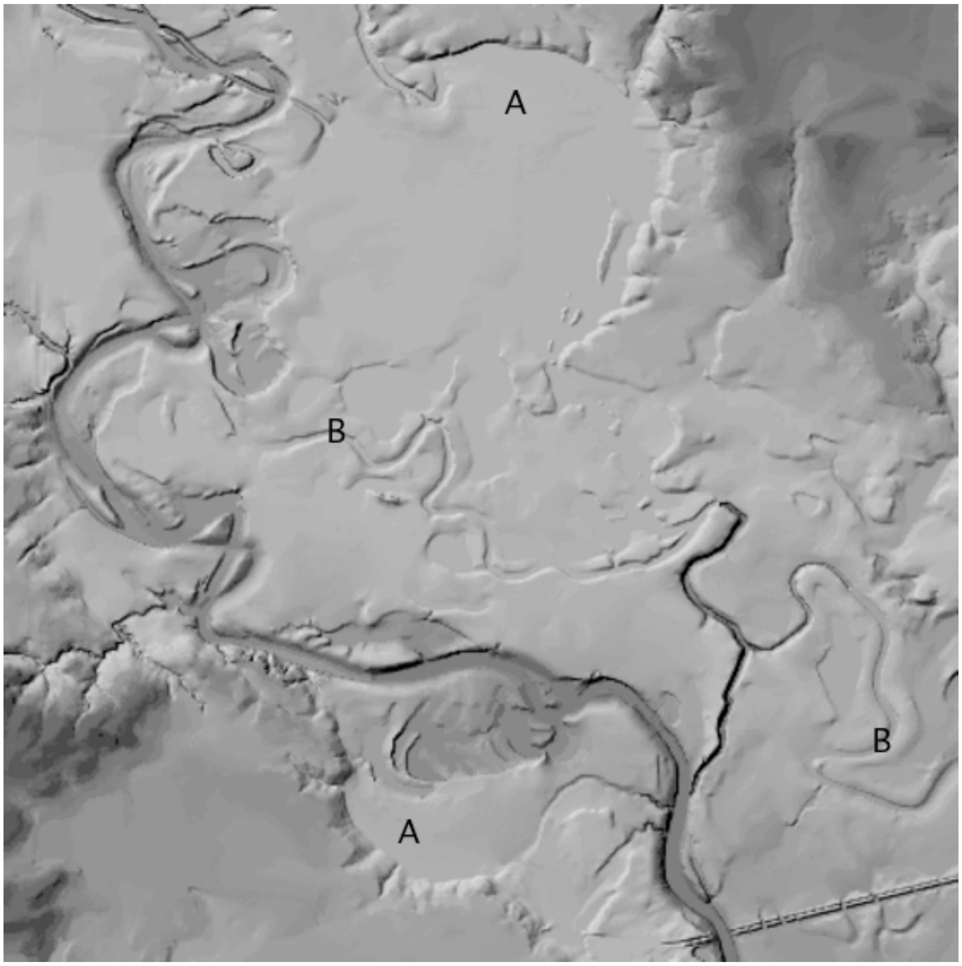


Figure 12. Shaded relief of Brazos River valley near San Felipe. Locations marked *A* are Pleistocene meander depressions that collect runoff from adjacent uplands. *B* indicates Brazos River paleochannels occupied by Bessie's Creek and Oyster Creek.

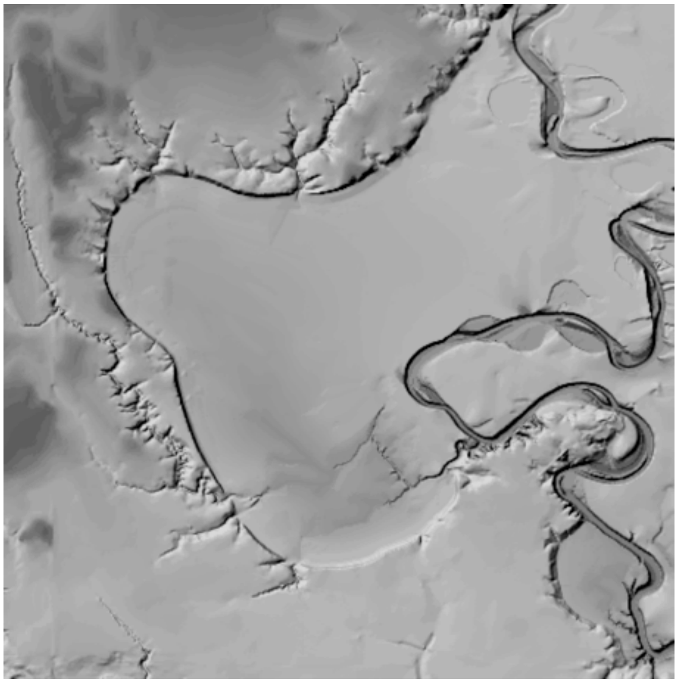


Figure 13. Valley side paleomeander depression near Simonton. Much of the depression is at a lower elevation than the Brazos River bank tops. Note the incised upland tributaries draining to the depression with no obvious connection to the river.

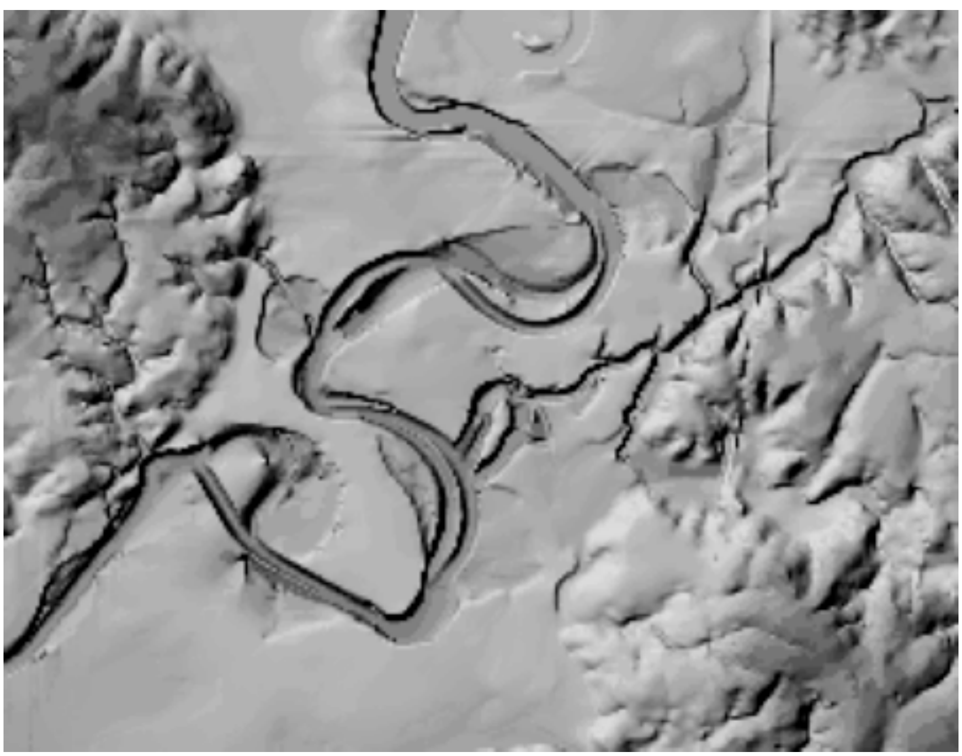


Figure 14. Shaded relief of oxbow fed primarily by tributary (Beason Creek), downstream of Hempstead.

Geomorphic zones from the Little Brazos diversion to Bryan are characterized by the presence of the Little Brazos River occupying a Brazos River paleochannel. The Little Brazos receives runoff from a number of tributaries on the left (east) side of the valley, but also some flow from the Brazos through the diversion channel. Field observations in 2012 confirmed steady flow from the Brazos toward the Little Brazos via the diversion. There is also connectivity via backflooding of the lower Little Brazos. Because the Brazos River is adjacent to the opposite (right or west) valley wall in most of these reaches, and overbank flooding is very rare, floodplain depressions are more likely to receive water input from the Little Brazos system than from the main river.

From Bryan to the Navasota River there also exist long stretches of Brazos River paleochannels in various stages of activity, such as Big Creek. This reach includes at least one oxbow supplied primarily by the Brazos (Osting et al., 2004; Chowdhury et al., 2010). However, given the elevation of the paleochannels above the modern Brazos, the lack of a well-defined connection from the river to these features, and the rarity of overbank flow at Bryan, local groundwater flux and tributary inputs must be the major water source for depressions other than the oxbows (Figure 15).

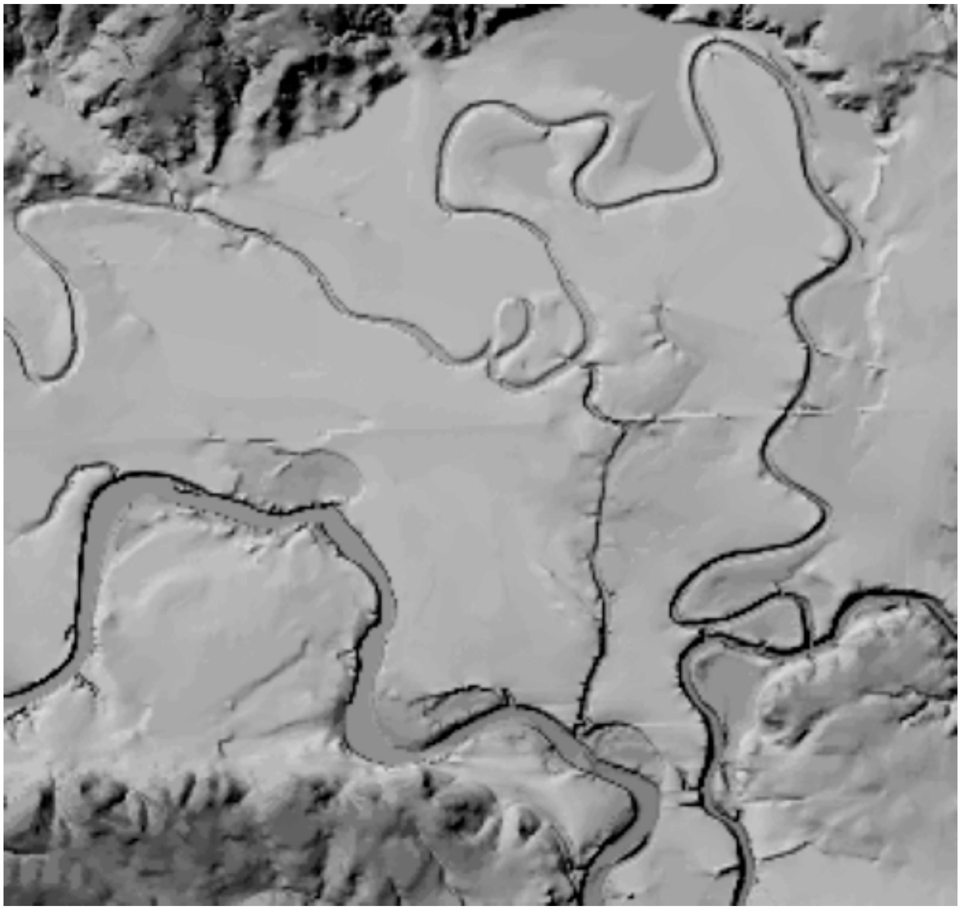


Figure 15. Shaded relief of the Big Creek area along the Brazos River between College Station and Navasota. Big Creek (a former Brazos River channel) is the primary source of water for many floodplain depressions.

In the geomorphic zones from about San Felipe (SH 529) to approximately Brazoria, the Brazos is paralleled by the Bessie's Creek/Oyster Creek system, occupying a Brazos paleochannel. Figure 16 shows, for example, that the elevation of Brazos River levees is often greater than that of the paleochannels.

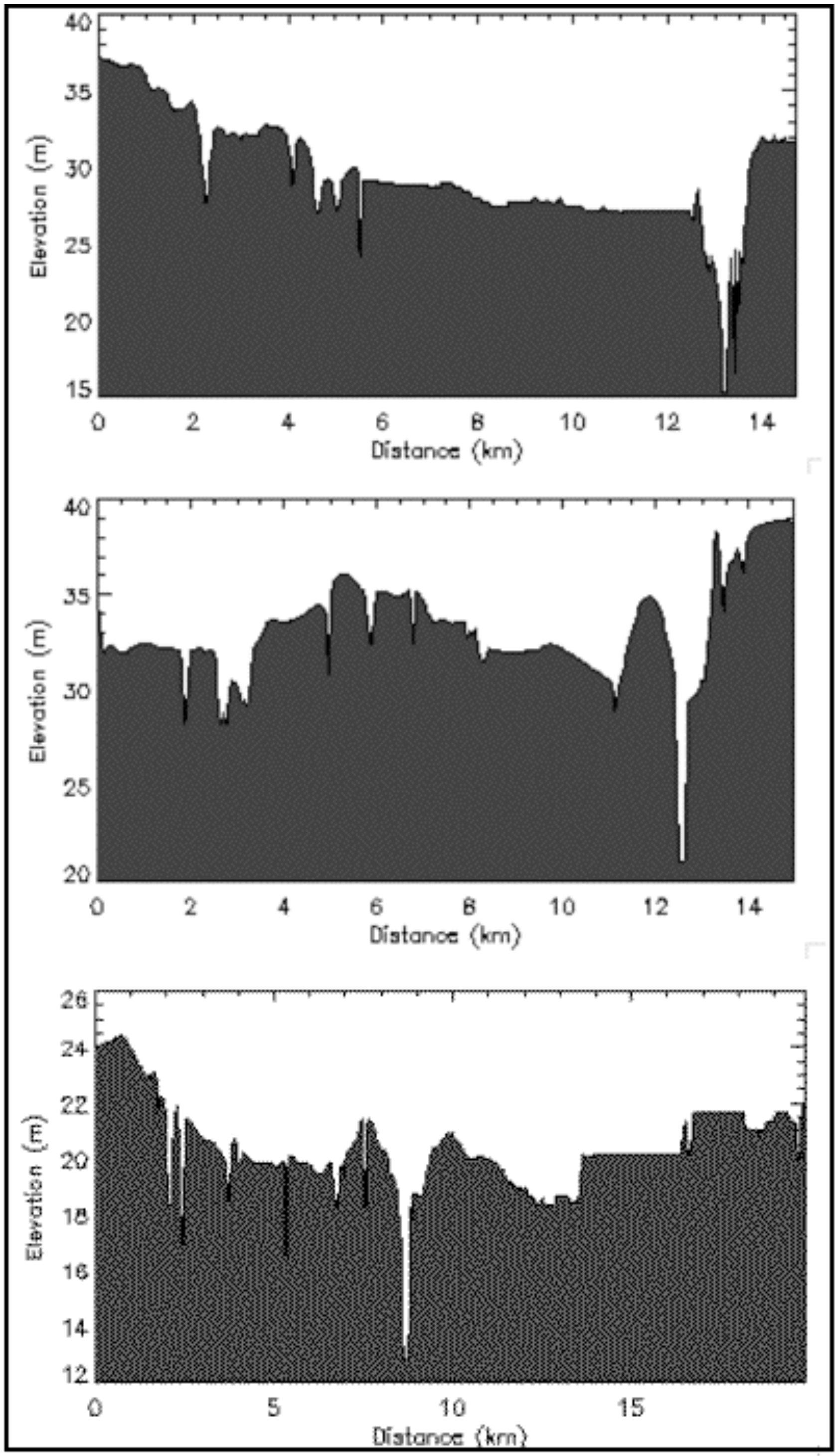


Figure 16. Cross-sections of the lower Brazos River valley. Top to bottom: north to south near Rosenberg; northeast to southwest near Orchard; northeast to southwest near Thompsons. In each case the narrow depressions are channels. The deepest is the Brazos River; the others are mainly associated with Oyster Creek and related paleochannels.

Other than the six oxbows studied by Oosting et al. (2004) and Chowdhury et al. (2010), there is little or no information on water sources for the valley-bottom depressions of the lower Brazos. Further, no stream gaging data exists for the Little Brazos River, Oyster Creek, or other paleochannels to assess flood frequency. Thus the inferences about connectivity and water sources are based on a combination of topographical analysis and *ad hoc* synoptic field observations.

Field measurements of the type conducted by Hudson (2010) for several lower Guadalupe River oxbows, isotopic analyses similar to those of Chowdhury et al. (2010) on the lower Brazos, and field observations during high flows such as those of Phillips (2011b) on the Sabine are needed to confirm and refine these findings. Aerial photography and remotely-sensed imagery may help, particularly in cases where contrast in river and tributary color (presumably related to turbidity and organic acids) allow visual assessment of dominant moisture sources. For example, Figure 17 shows the confluence of the Brazos with Yegua Creek, where it is clear that the creek is the major water source for the depressional area at the confluence. The imagery was acquired on 5 February, 2010, when discharge at the Bryan gaging station upstream and Hempstead downstream was > 30,000 cfs, within the range of high sub-banktop flows. On the same day, an image from downstream of Hempstead shows connectivity with Perry Lake, and apparent backflooding of a tributary (Figure 18), consistent with the fact that the maximum flow at the Hempstead gage for this date and several preceding days reached the channel-floodplain connectivity threshold. Conversely, Figure 19 shows several oxbows, including one immediately adjacent to the channels, with no visible river input.

Figure 17. Google Earth™ image of the confluence of Yegua Creek and the Brazos River.

Figure 18. Google Earth™ image of the Brazos River near Hempstead, with Perry Lake on the right.

Figure 19. Google Earth™ image of the Brazos River near San Felipe.

Force-resistance Thresholds

Key thresholds for movement or transport of various particle sizes or for erosion of various channel materials may be expressed in terms of force *per se* via shear stress, stream power, or critical velocities. Shear stress varies with depth and slope, and is most applicable to estimating thresholds of motion for individual particles or initiation of erosion of specific materials. Stream power varies with discharge and slope, and is best suited for estimates of the total erosive or transport capacity. Velocity is a function of slope, depth, and hydraulic roughness and is related to (among other things) transitions in the state of sand bed channels. The three are related, but not perfectly so. For example, a riffle will have higher velocity and lower depth than an adjacent pool with the same discharge, and the relative water surface slopes may vary with flow conditions.

Magilligan (1992) suggested as specific stream power of about 300 W m^{-2} as a general threshold for catastrophic channel change, and subsequent work has confirmed that as a good approximate value. The historical record of the lower Brazos does not suggest that this has been approached. Thus this threshold represents an extreme event that is likely to be beyond the influence of environmental flow management.

The 10 W m^{-2} specific stream power threshold used here reflects the approximate value at which inflection points occur in relationships between ω and sediment transport and energy dissipation—that is, transport and dissipation increase slowly with stream power up to about 10, and more rapidly thereafter (Williams, 1983; Ferguson, 2005; Petit et al., 2005; Kale and Hire, 2007).

The lower Brazos has occasional rock outcrops in the channel bed, but is classified as a sand-bed channel throughout. The critical shear stress for entrainment of individual sand grains is quite low; more relevant is the movement of the sand bedforms (ripples, dunes, and antidunes) that provide key hydraulic and habitat elements. In this study a threshold value of 0.35 m sec^{-1} was selected, based on the work of Carling et al. (2000) and Robert and Uhlman (2001).

Gravel is present in all but the lowermost reaches of the lower Brazos. Much of the gravel is delivered by erosion of Pleistocene alluvial terraces along the valley walls and within the valley bottom (Phillips, 2007a). A threshold shear stress for gravel mobility was chosen to be 5.8 N m^{-2}, based on the critical threshold for entrainment of medium gravel in the Shields entrainment function.

The guide produced by Fischenich (2001) for design of stable channels identifies a threshold of instability (i.e., bank failure) shear stress of 12.68 N m^{-2} for alluvial streams with tight clay or alluvial silt banks. This is one of the thresholds calculated for this study based on the predominant bank types in the lower Brazos. Of the 20 soil types commonly occurring along the lower Brazos River banks, 15 have subsoil textures of silt loam or finer (Table 17). Note, however, the considerable within-reach variability in bank resistance (Table 19).

The estimated discharge thresholds discussed above are shown for the lower Brazos gaging stations in Table 21. These are estimated based on regression equations relating velocity, shear stress, and specific stream power to discharge (in m^3 sec^{-1}) from the surface water measurements data (as the same slope is used for all stream power and shear stress calculations at a given station, S is not a factor). For example, for Rosharon:

$$V = 0.1904\ LN(Q) - 0.1817$$
$$\tau = 2.3027\ LN(Q) - 4.4096$$
$$\omega = 0.0584\ Q^{0.829}$$

The bank instability threshold is generally highest, except at Hempstead, where the confined valley setting and consistently high depths result in consistently high calculated shear stresses. The velocity threshold is lowest of the thresholds at a given station in three cases (Highbank, Bryan, Richmond), and highest at Hempstead. The gravel mobility shear stress threshold is lowest at the Waco, Hempstead, and Rosharon gages.

Table 21. Discharges ($ft^3\ sec^{-1}$) associated with key thresholds of velocity (V), shear stress (τ), and specific stream power (ω).

Gaging Station	$V \geq 0.35\ m\ sec^{-1}$	$\tau \geq 5.8\ N\ m^{-2}$	$\omega \geq 10\ W\ m^{-2}$	$\tau \geq 12.68\ N\ m^{-2}$
Waco	6,900	3,500	8,400	10,600
Highbank	350	5,100	8,100	14,700
Bryan	2,100	4,200	15,900	31,800
Hempstead	4,700	<1,000	3,200	<1,000
Richmond	6,400	21,100	47,600	>90,000
Rosharon	3,500	400	17,600	35,400

Relative Thresholds

Figures 20-25 show the relative thresholds described above for each gaging station, along with the median mean daily discharge and the median annual maximum mean daily discharge. Note the differing scales on the vertical axes. The thalweg connectivity thresholds are very low at all sites and are not shown.

The higher end of the high sub-banktop discharge is near the overbank flow threshold in all cases, by definition.

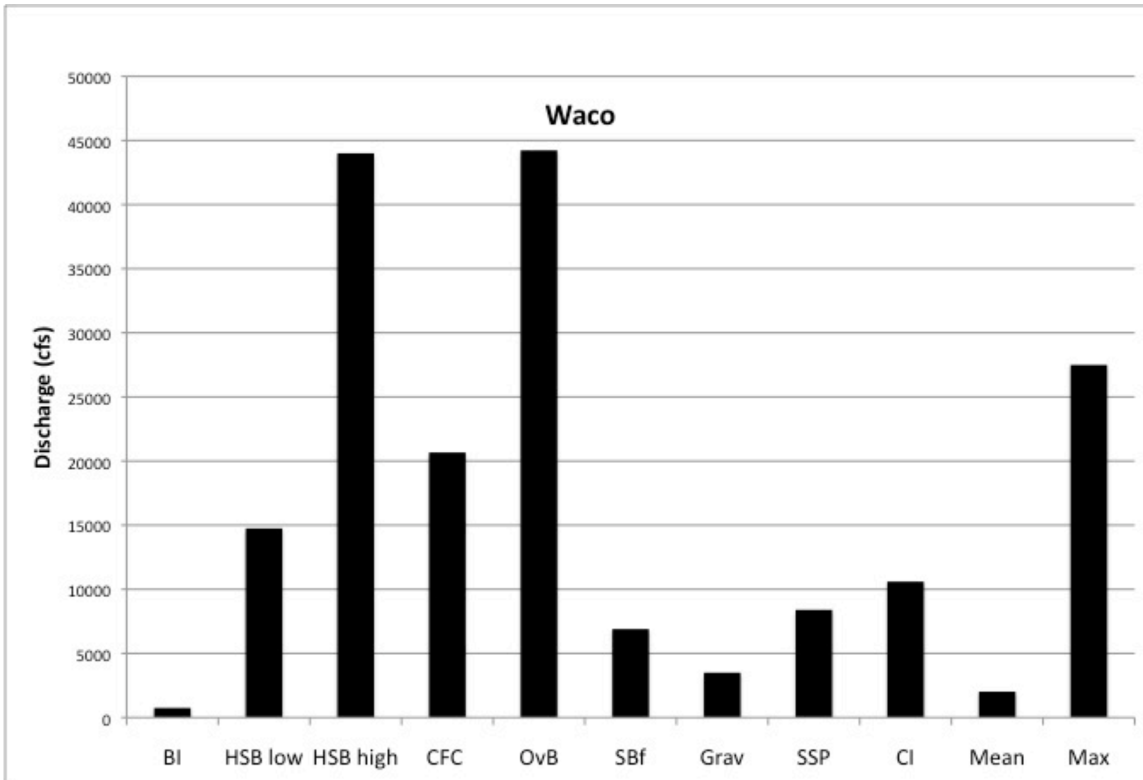


Figure 20. Relative threshold discharges for the Waco gaging station. *BI* = bed inundation; *HSB low, HSB high* = low, high levels for the range of high sub-banktop flows; *CFC* = channel-floodplain connectivity; *OvB* = overbank flooding; *SBf* = velocity for sand bedform mobility; *Grav* = shear stress for gravel mobility; *SSP* = specific stream power; *CI* = channel bank instability; *Mean* = median of mean daily discharges; *Max* = median of annual maximum mean daily discharge (from Asquith et al., 2007a).

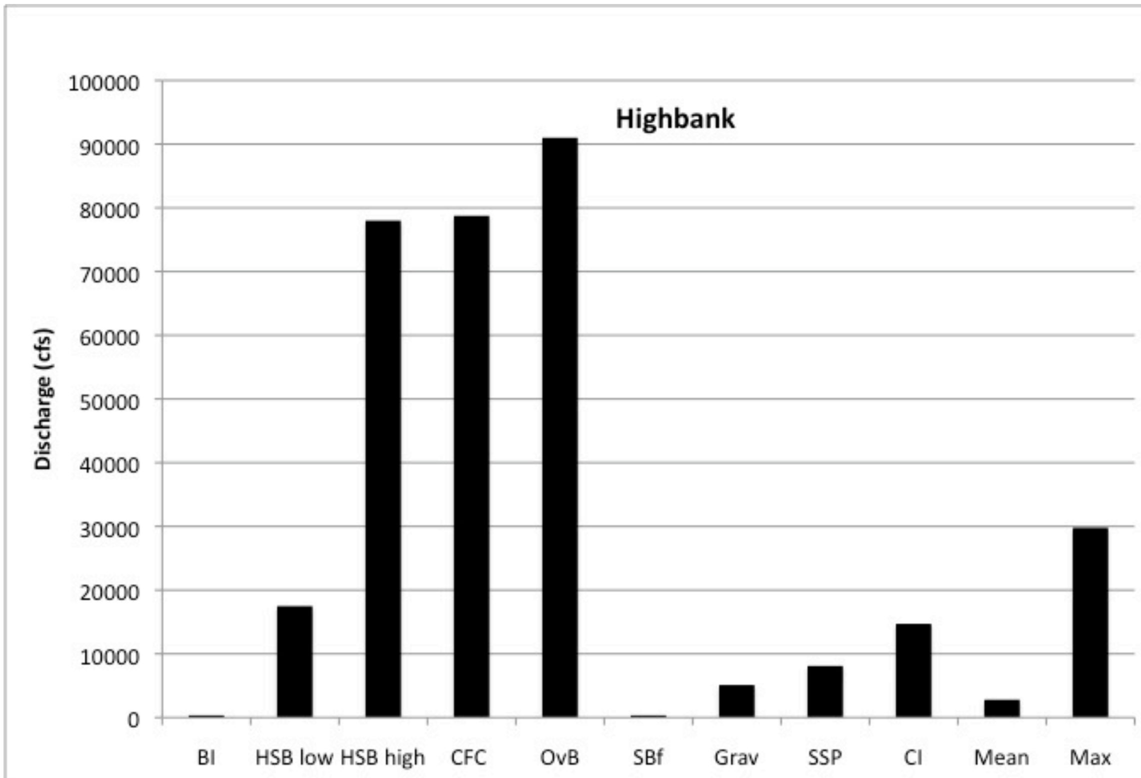


Figure 21. Relative threshold discharges for the Highbank gaging station. See Figure 20 caption for legend.

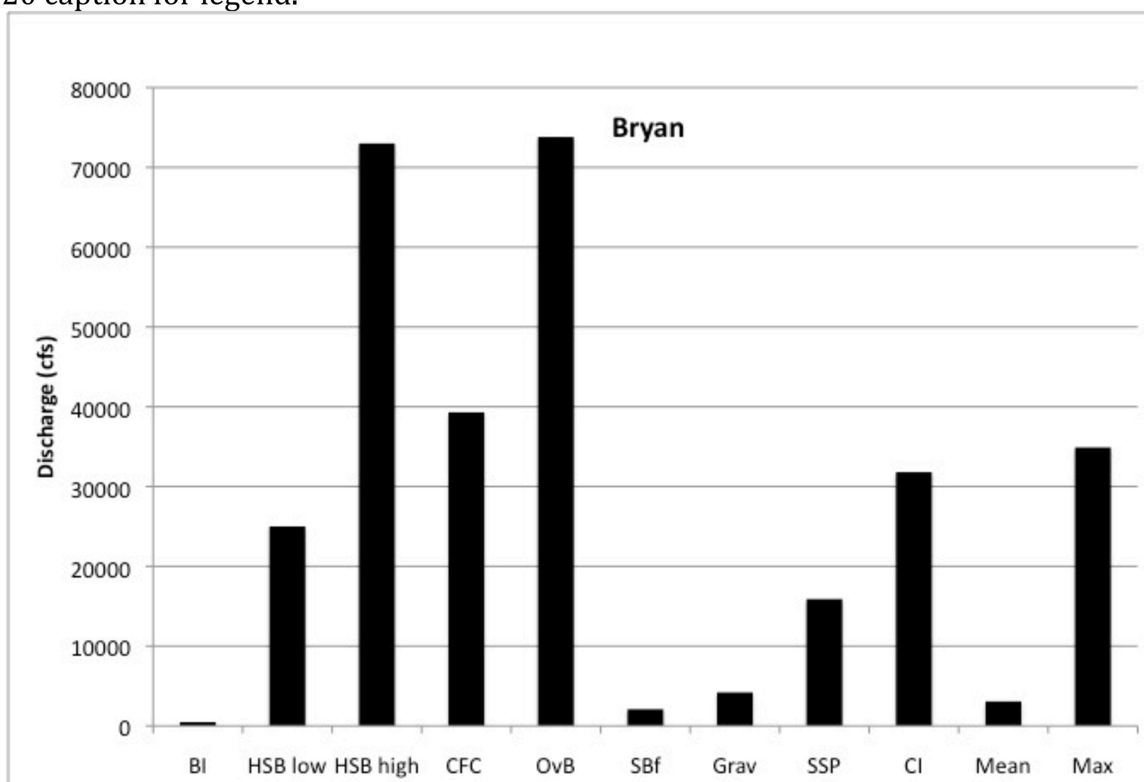


Figure 22. Relative threshold discharges for the Bryan gaging station. See Figure 20 caption for legend.

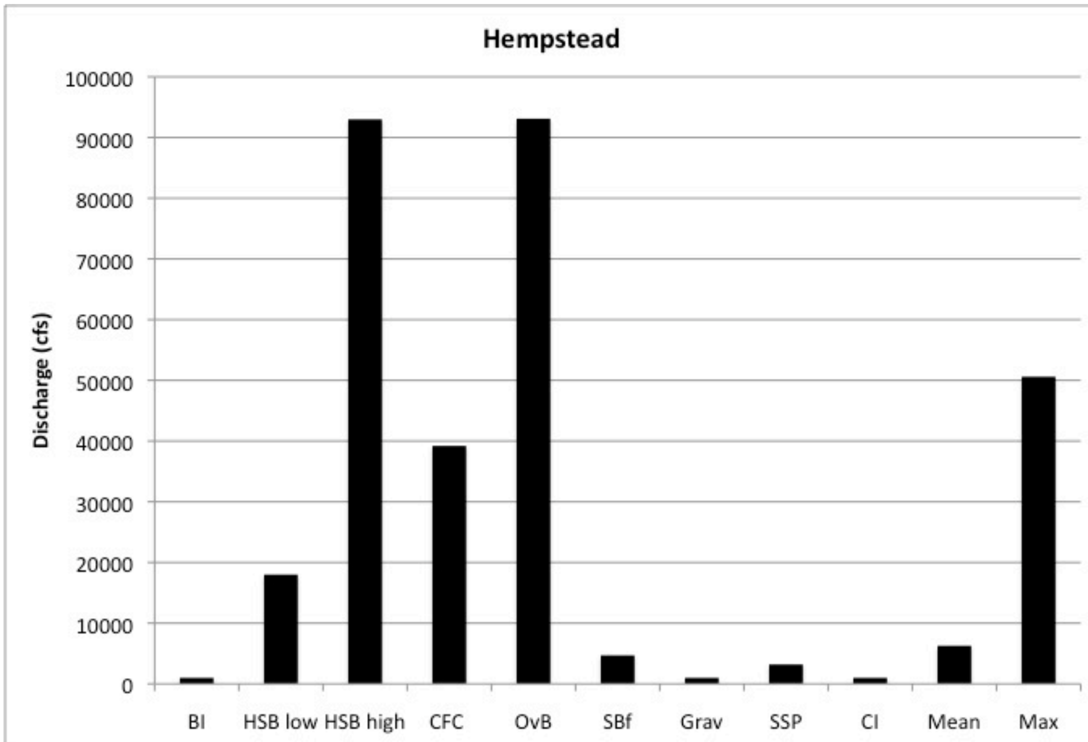


Figure 23. Relative threshold discharges for the Hempstead gaging station. See Figure 20 caption for legend.

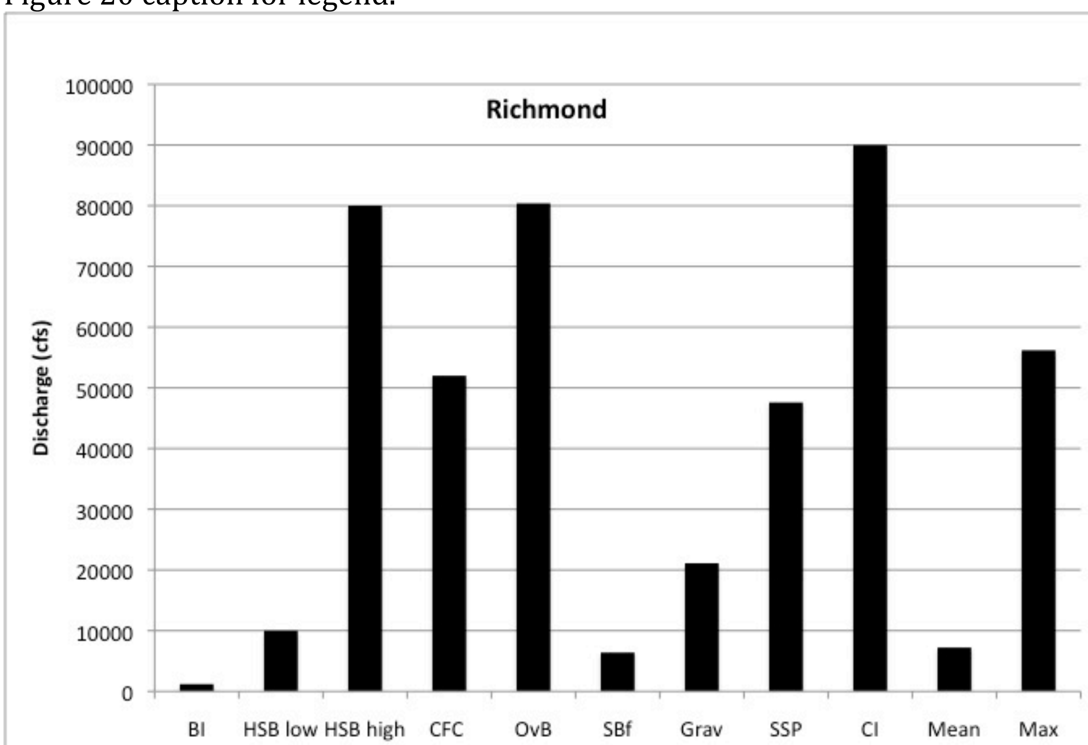


Figure 24. Relative threshold discharges for the Richmond gaging station. See Figure 20 caption for legend.

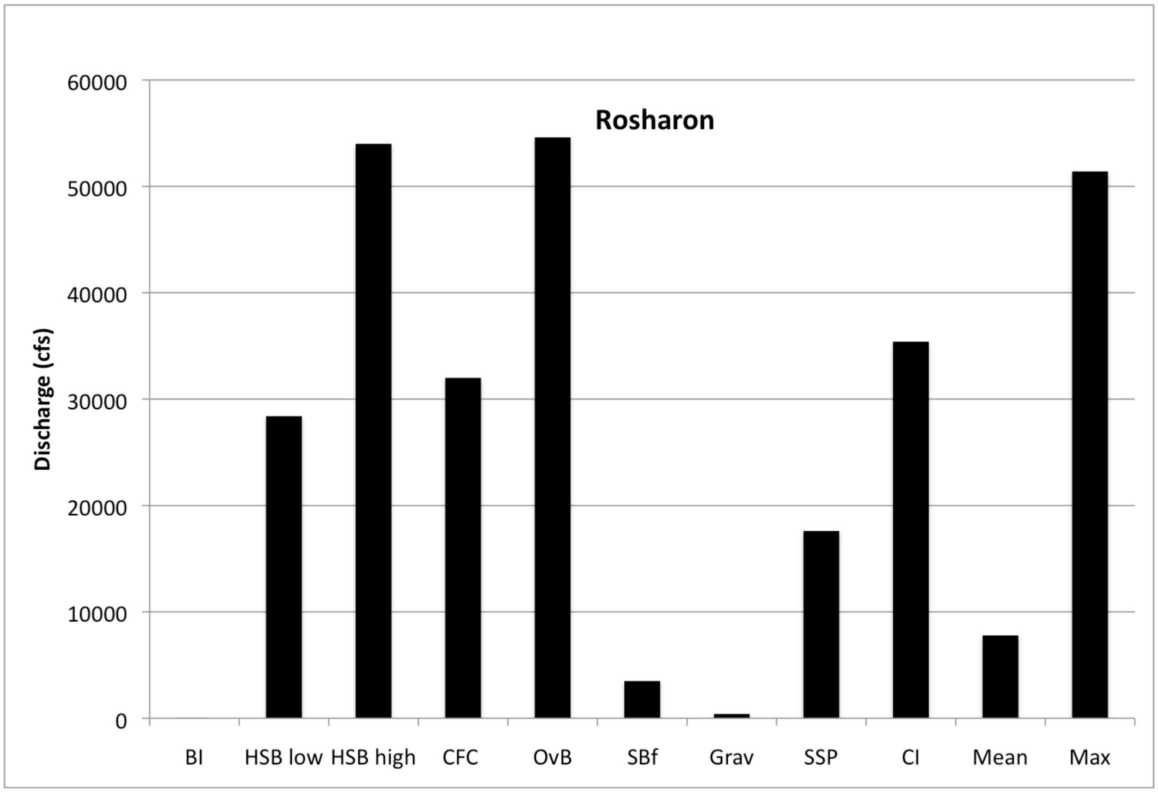


Figure 25. Relative threshold discharges for the Rosharon gaging station. See Figure 20 caption for legend.

Thresholds and Geomorphic Zones

The river styles and geomorphic zones identified in Phillips (2007a), numbered 1-30 from Bryan to the Gulf of Mexico, are assessed here along with the geomorphic zones described in Chapter 1 between Waco and Bryan, numbered WB1 to WB6. Throughout the lower Brazos, river banks—and exposed areas of the bed during low water—often display mud drapes. These are thin, often laminar deposits of silt and clay-sized sediment deposited during falling flow stages. If they persist, these fine-grained deposits fundamentally alter the habitat characteristics of the sandy bed. Thus, frequent bed-inundation flows are necessary to remove these mud drapes.

Zones WB1-WB6 are characterized by sparsely vegetated sand/gravel islands. Some of these are likely ephemeral longitudinal bars, or marginal bars temporarily dissected by flow. However, examination of historical aerial photographs indicates that some of these features are persistent over periods of years to a decade or more, and that the general presence of islands and mid-channel bars is consistent. The limited vegetation cover, and presence of surficial bedforms on bars examined in the field, indicate that these features are inundated at least several times per year, on average. Thus maintenance of these habitats requires relatively frequent flows significantly above the bed inundation stage, and sufficient for sandy bedform mobility *($V \geq 0.35$ m sec^{-1})* and gravel transport *($\tau \geq 5.8$ N m^{-2}).*

Most of the lower Brazos River is incised, and along much of its length inset floodplains in the form of channel shelves and upper point bars have developed. Inundation of these features is roughly associated with the low end of high sub-banktop flows, which should occur on average roughly annually to maintain them. These features are present in every geomorphic zone except 25-30 in the lowermost Coastal Plain.

Abandoned channel water body floodplain lakes (mostly oxbows, but some more linear sloughs) clearly associated with the modern Brazos River (as opposed to tributary streams or Brazos paleochannels) are present in 13 of the geomorphic zones. These are often very important wetland and aquatic habitats. As discussed above, these may be quite variable with respect to their dependence on river discharges for water supply. However, most of these features—as opposed to other types of floodplain depression wetlands—depend at least partly on connectivity with the river. Overbank flood flows are not necessary to achieve connectivity with these features, but flows within the range of high sub-banktop flows (specifically channel-floodplain connectivity thresholds) are required.

The Brazos River valley bottom in many geomorphic zones includes abandoned channel water bodies and wetland depressions associated with Brazos paleochannels now occupied by tributaries. Hydrological connectivity of these features is primarily related to tributary runoff, with Brazos River contributions significant only during relatively rare overbank flood events. These features occur in WB2 and WB3, associated with Hardin Slough and related paleochannels, and in the Little Brazos River area (WB5, WB6). Big Creek, Old River, and other tributary-occupied Brazos paleochannels occur in geomorphic zones 1-5, and the Bessie's Creek/Oyster Creek system and other paleochannels in zones 14-26. In zones 27 to 30 the Oyster Creek system is separated from the main Brazos River valley bottom by a number of urban and industrial land uses.

The valley bottoms also include paleomeander depressions and other floodplain depressions fed primarily by tributary runoff from adjacent uplands. This was judged to be the case when channels could be traced into the depressions but not all the way to the river, or when the depressions were at a lower elevation than the river levees in the vicinity and closer to upland runoff sources than to the Brazos. These features occur in the following zones: WB1-WB3, WB5, 7, 11, 13-15, 19, 22, 25, 26.

Figure 26 summarizes the presence of the features discussed in this section relative to the geomorphic zones.

	WB1	WB2	WB3	WB4	WB5	WB6	1	2	3	4	5	6	7	8	9	10	11	12
Islands	x	x	x	x	x	x												
PB/IFP	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Oxbow/slough							x		x					x		x	x	
Mud drapes	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
FDUR, MDUR	x	x	x		x								x				x	
Paleochannels		x	x		x	x	x	x	x	x	x							

	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Islands																		
PB/IFP	x	x	x	x	x	x	x	x	x	x	x	x						
Oxbow/slough	x		x					x				x	x		x	x	x	
Mud drapes	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
FDUR, MDUR	x	x	x					x		x			x	x				
Paleochannels		x	x	x	x	x	x	x	x	x	x	x	x	x				

Figure 26. Correspondence of mid-channel islands, point bar and channel shelf inset floodplains (PB/IFP), oxbow and slough abandoned channel water body floodplain lakes, mud drapes, floodplain and meander depressions fed primarily by upland runoff (FDUR, MDUR) and paleochannels with the numbered geomorphic zones.

CHAPTER 5
FLOW MODIFICATIONS AND THRESHOLDS

Introduction

Runoff and stream discharge, and stream sediment loads, can be changed by both natural (non-human) and anthropic factors. Natural factors are overwhelmingly dominated by direct and indirect (e.g., vegetation) effects of climate, though it is acknowledged that climate can be influenced by human agency. More proximate human impacts can be divided into direct effects such as water withdrawals or transfers, and the building or removal of impoundments, that directly (and generally purposefully) change the amount, rate, and timing of water and sediment fluxes. Indirect human impacts are primarily in the form of land use and land cover change, which are generally not intended to modify hydrology, but do often profoundly impact the water balance, runoff, sediment production, and surface and ground water flows.

Phillips (2012a) developed a procedure for evaluation of potential geomorphic responses to changes in instream flows specifically for alluvial rivers in Texas (summarized in article form in Phillips, 2012b). The flow-channel fitness model (FCF) is a conceptual and practical model for predicting the qualitative response of alluvial channels to modifications of flow regimes. "Fitness" refers to the size of channels compared to the flows they convey. The predicted behaviors are whether channels experience aggradation, degradation, or relative stability, and whether channel changes are width- or depth-dominated. The model is based on key thresholds of sediment supply vs. transport capacity and shear stress vs. shear strength, and includes transitions among seven possible fitness states. FCF also requires potential changes in sediment supply and water surface or energy grade slope to be accounted for. The FCF model, its background, and assumptions, are described in detail elsewhere (Phillips, 2012a;b).

Flow-Channel Fitness Assessment

As shown in Figure 27, the FCF procedure starts by determining whether the channel capacity is greater than, less than, or equal to a reference flow. The next step is to compare the shear stress of the reference flow to the critical shear stress necessary for channel erosion or instability. If this threshold is exceeded channel enlargement occurs, resulting in increasing underfitness or adjustments toward fitness, depending on the starting point. Otherwise, the stream power of the reference flow is compared to the critical stream power necessary to transport the available sediment (Figure 27). Here the median annual mean daily maximum flow will be used as the reference flow. The somewhat confusing terminology refers to the median value of the maximum mean daily flow for each water year—that is, the daily maximum that has a 50-50 chance of being exceeded in the historical record.

In many rivers this corresponds approximately to a flood event with a recurrence interval of one to two years.

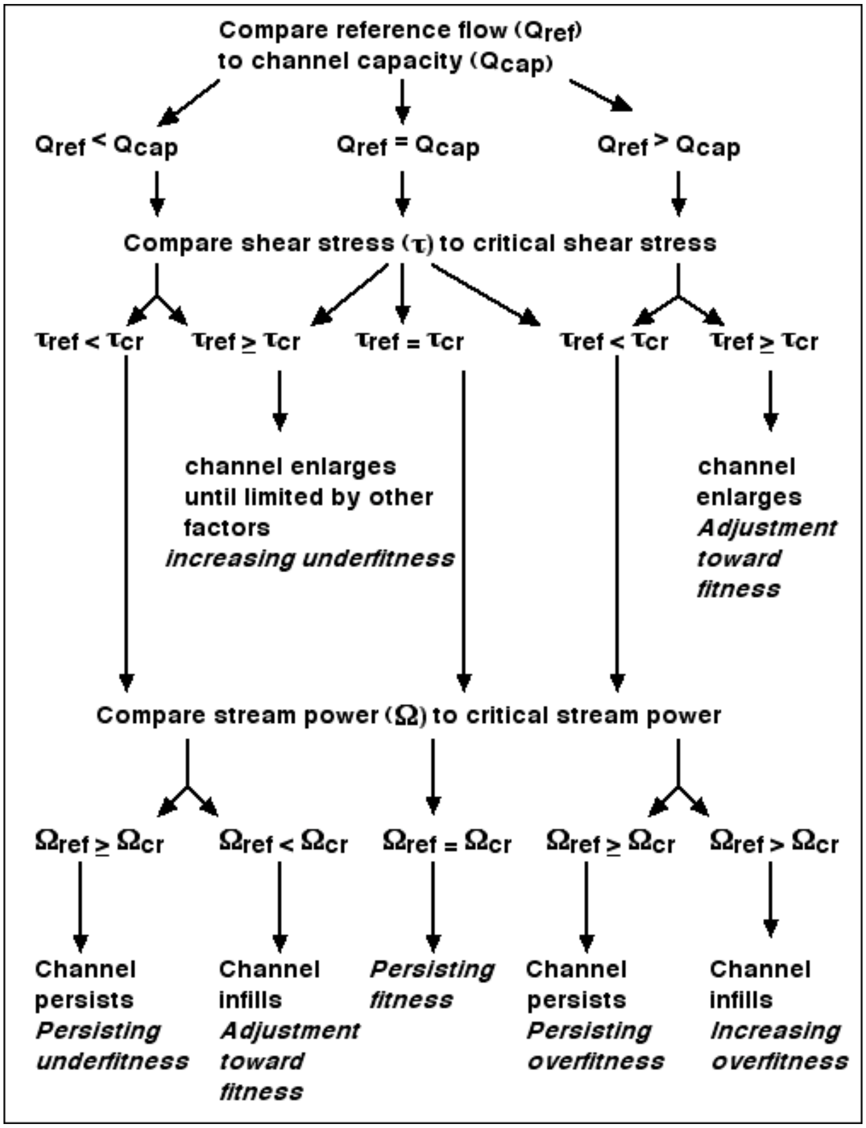


Figure 27. Graphical representation of flow-channel fitness assessment (from Phillips, 2012b).

The reference flow levels for the six gaging stations in the study area are shown in Figure 28. These values are less than the high sub-banktop and overbank flood levels at all stations, and by a large margin at all save Rosharon (see Chapter 2). Thus at all gaging stations the channel is underfit with respect to its ability to convey this flow ($Q_{ref} < Q_{cap}$). This is the case for all geomorphic zones in the study area except zones 25-30.

The flows generally increase downstream, except for Richmond to Rosharon, as discussed in Chapter 2. Between each pair of stations there are significant tributary inputs, but these are particularly prominent between Highbank and Bryan, where the Little River and Little Brazos join the Brazos, and between Bryan and Hempstead, which includes the Brazos confluences with Yegua Creek and the Navasota River. Table 22 relates the geomorphic zones and gaging stations.

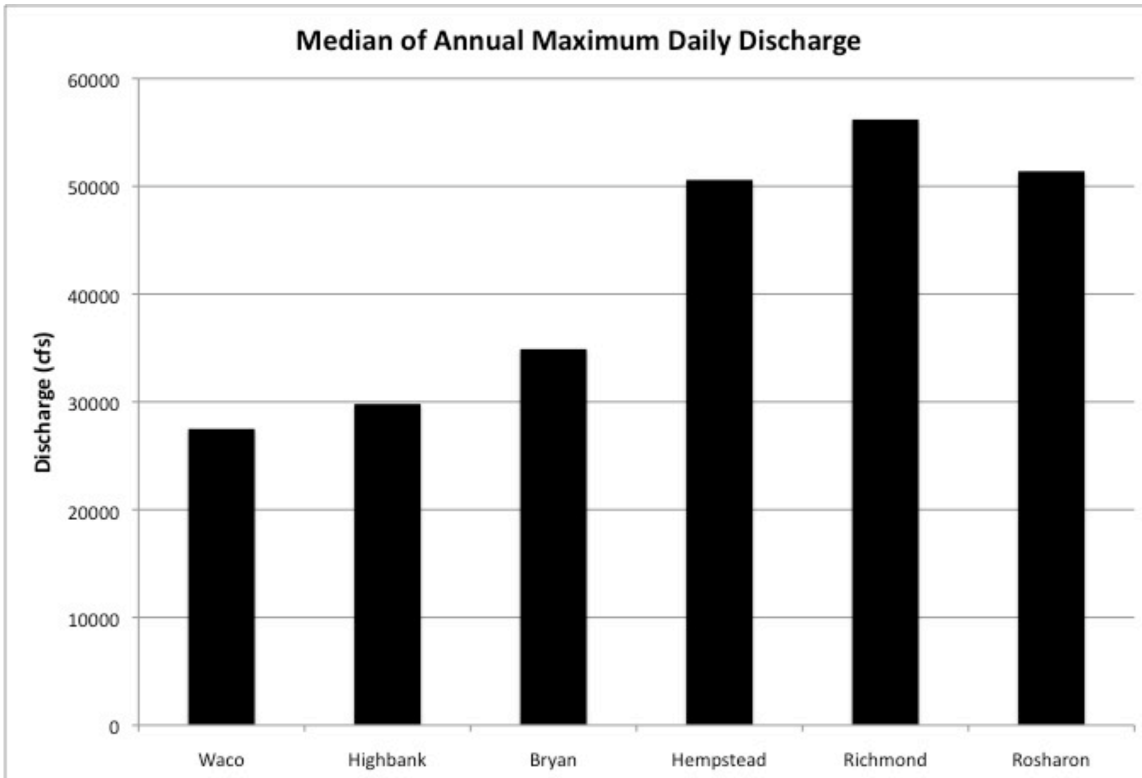


Figure 28. Maximum daily flow with a 50 percent annual chance of exceedance, as calculated by Asquith et al. (2007a).

Table 22. Relationship between geomorphic zones and gaging stations. The nearest upstream station is shown in every case. Where two stations are indicated, the geomorphic zone either includes the second station, or is close enough at its downstream end so that data from the downstream station is likely to be indicative and applicable to the zone.

Geomorphic Zones	*Applicable Gaging Station*
WB1 - 2	Waco
WB3	Waco, Highbank
WB4 - 5	Highbank
WB6	Highbank, Bryan
1 - 7	Bryan
8 – 9	Bryan, Hempstead
10 – 17	Hempstead
18 – 19	Hempstead, Richmond
20 – 21	Richmond
22 – 23	Richmond, Rosharon
24 – 30[1]	Rosharon

[1]Zones 26-30 may be influenced by coastal backwater effects.

The shear stress associated with the reference flow is shown in Figure 29, relative to the $\tau = 12.68$ N m^{-2} threshold for instability of cohesive banks. This threshold is exceeded by the reference flow at Waco, Highbank and Hempstead, and is not exceeded at Richmond. At Bryan and Rosharon the calculated values (12.27 and 12.49, respectively) are close enough to the threshold, given the uncertainties involved, to be considered approximately equal. Thus, for five of the six stations the FCF model leads to "increasing underfitness."

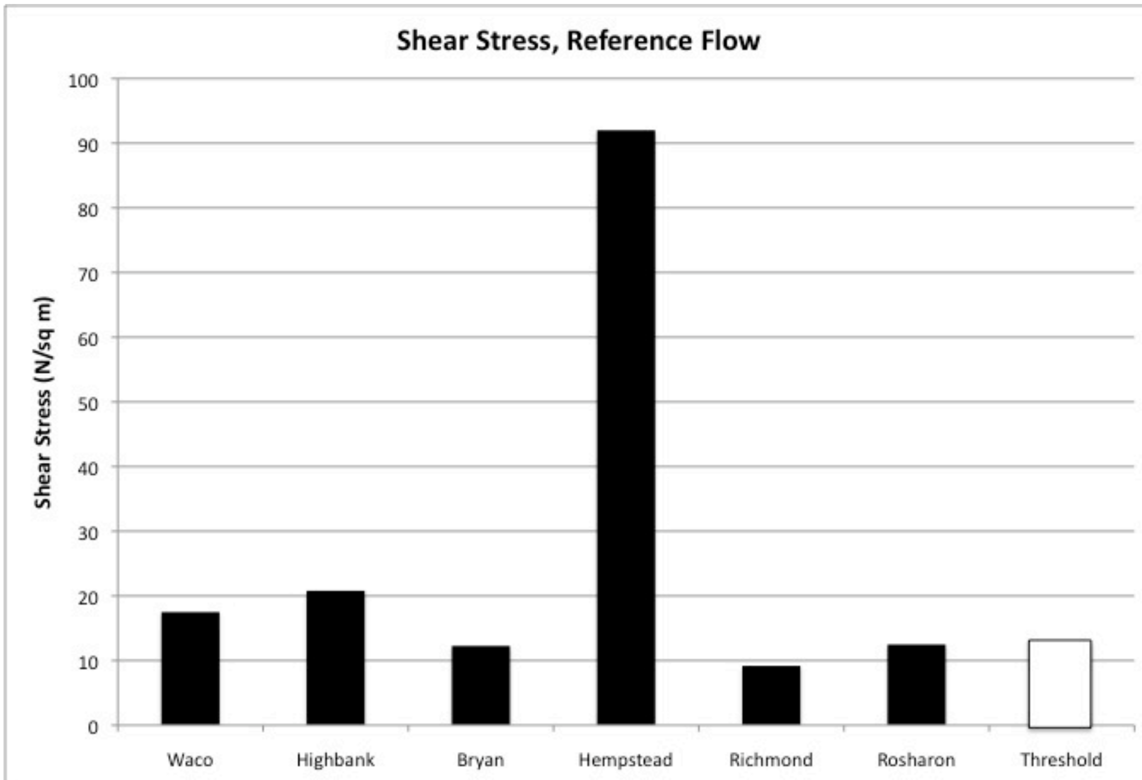


Figure 29. Shear stress for reference flows at Brazos River gaging stations, relative to threshold for channel instability.

The predicted channel enlargement is limited in some specific locations by bedrock outcrops in the channel, or bedrock valley controls, which occur to varying extents in geomorphic zones WB1-WB6, 1-7, and 9-16.

The predicted channel enlargement in the vicinity of the Waco, Hempstead and Rosharon stations is confirmed by the analysis of channel change at these sites by Heitmuller and Greene (2009; see also Dunn and Raines, 2001 re Hempstead). Heitmuller and Greene's (2009) analysis at the Highbank and Bryan stations shows slight channel enlargement, consistent with FCF prediction, limited at Highbank due to bedrock control.

At Richmond, where $\tau_{ref} < \tau_{cr}$, the FCF procedure (Figure 27) proceeds to an examination of sediment supply vs. transport capacity. In general the lower Brazos is transport limited, suggesting $\Omega_{ref} < \Omega_{cr}$, with the FCF predicting infilling and adjustment toward fitness. Consistent with this is the relatively rapid infilling of Old River Lake oxbow just downstream of the gage site. Comparison of aerial photographs between 1995 and 2012 shows channel narrowing both up- and downstream of the gage site, but this may be compensated for by incision deepening the channel. Analysis of data from the gaging station by Dunn and Raines (2001) and Heitmuller and Greene (2009) does not show evidence of a general decrease in channel size, but the evidence is equivocal because of generally complex geomorphic change in the vicinity, and due to modifications of the channel banks at the gage site.

The FCF procedure can be used to explore various scenarios involving changes in Q_{ref}, τ_{ref} and Ω_{ref}, which could be modified as a result of changes in flow and/or slope, and sediment supply, which influences the Ω_{ref} vs. Ω_{cr} relationship. This is described in detail in Phillips (2012a).

Shear Stress and Stream Power

Flow velocity is a complex function of energy grade slope, flow depth or hydraulic radius, and roughness or frictional resistance. However, predictive diagrams can be developed as predictive aids for identifying potential threshold crossings of shear stress and stream power.

Figure 30 shows shear stress vs. depth relationships for several orders of magnitude of slope. Lower Brazos slopes are dominantly in the range of 0.0001 to 0.001, but locally steeper and gentler gradients occur.

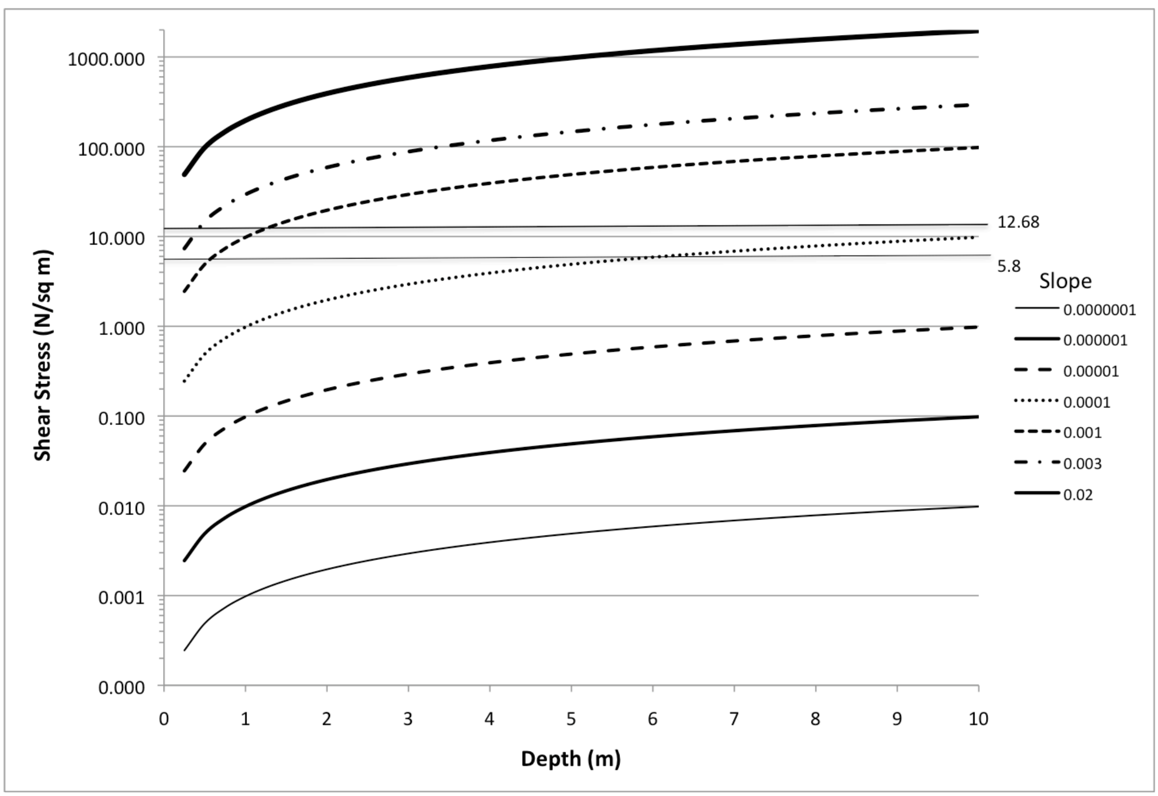


Figure 30. Shear stress/mean depth relationship for several slope gradients. Threshold shear stress values used in this study are highlighted.

Critical stream power thresholds are identified in terms of specific stream power:

$$\omega = \Omega/w = (\gamma\ Q\ S)/w \qquad (4)$$

where Ω is cross-sectional stream power. Ω vs. Q relationships can similarly be calculated for a range of slopes, as shown in Figure 31. The cross-section stream power can be divided by channel width at a site of interest to determine the specific stream power.

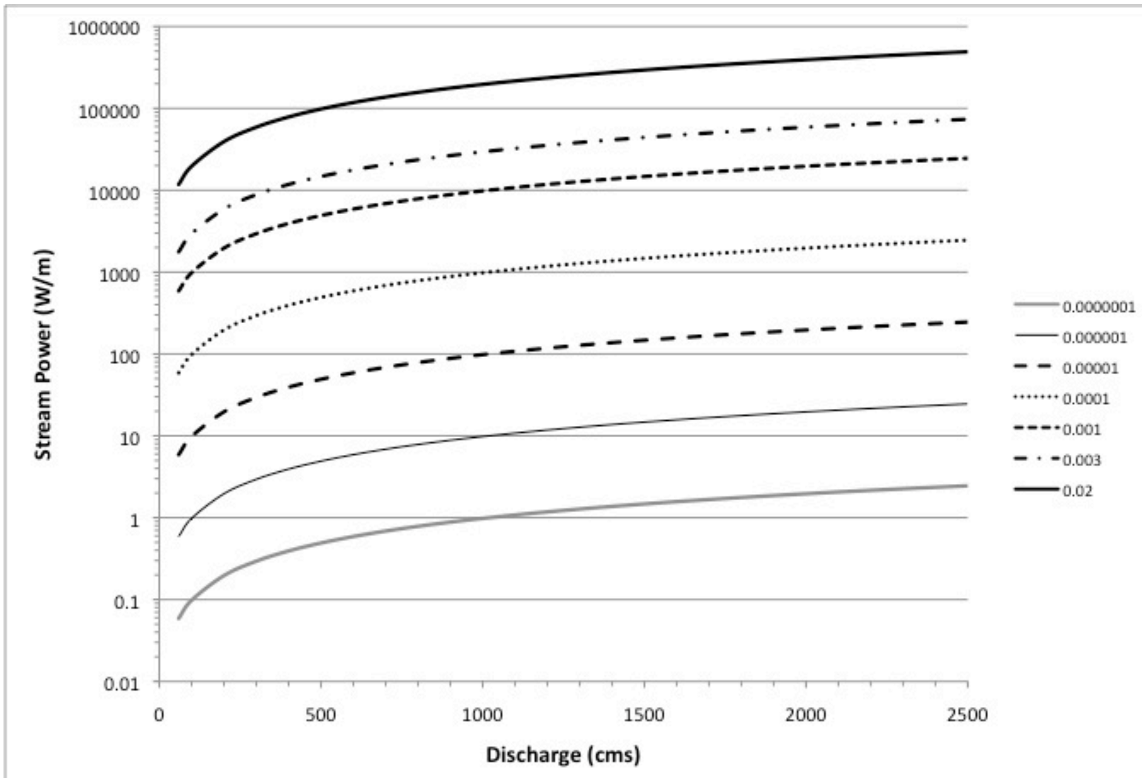


Figure 31. Cross-sectional stream power vs. discharge relationship for several slope gradients. Discharge units are $m^3\ sec^{-1}$ (cms) because these are used in computing stream power (1 cms = 35.31 cfs).

Geomorphic Variability

Any attempt to identify thresholds for geomorphic change must recognize that rivers in general, and alluvial rivers such as the lower Brazos in particular, are dynamic. Lateral migration, changes in sinuosity, meander cutoffs, channel aggradation/degradation, and bar formation and migration are all common in the lower Brazos at time scales of weeks to years. Over longer time scales, avulsions are also common, and both channel and floodplain features may evolve rapidly. Geomorphic thresholds and their associated flows are thus—inevitably—a moving target, and suitable flexibility should be exercised. Geomorphic properties and flow thresholds typically vary a great deal spatially, both between and within geomorphic zones. At any given reach or cross section, landforms and process thresholds are likely to vary significantly over time.

A number of studies have specifically documented geomorphic change and variability in the lower Brazos River (e.g., Waters and Nordt, 1995; Gillespie and Giardino, 1997; Phillips, 2006; 2007a; 2007b; 2009; Sylvia and Galloway, 2006; Heitmuller and Greene, 2009; Giardino and Lee, 2011; 2012).

CHAPTER 6
SUMMARY AND CONCLUSIONS

Major Findings

•Six geomorphic zones (river styles) between Waco and Bryan were identified, to complement the 30 zones previously identified from Bryan to the Gulf of Mexico.

•Threshold stages and discharges were identified for six Brazos River gaging stations corresponding to thalweg connectivity, bed inundation, low and high ranges of high sub-banktop flows, channel-floodplain connectivity (CFC), and overbank flooding. Channel-floodplain connectivity occurs at flows significantly below flood levels throughout the study area. Higher sub-banktop and CFC flows are uniformly greater than mean or median flows, and in most of the study area flows necessary to achieve CFC are less than typical annual maximum daily mean flows.

•Threshold discharges were identified for six Brazos River gaging stations corresponding to estimated thresholds for sandy bedform mobility, medium gravel mobility, specific stream power, and cohesive-bank channel instability. These thresholds have variable relationships to mean, median, and maximum flows in the historical record.

•Soil series mapped along the river banks of the lower Brazos were identified, and critical shear stresses identified based on plasticity indices. However, these are useful only as indicators of relative resistance, as the actual critical shear stress is underestimated. Because of the complex spatial pattern of soils, geomorphic-zone scale assessments of bank resistance based on these data are not feasible. However, this information can be used in conjunction with soil map data to locally identify potential high- and low-resistance sites.

•A significant number of wetland depressions and floodplain lakes in the Brazos River valley bottoms are associated with tributaries, paleochannels, or depressional features for which the primary source of runoff is adjacent uplands rather than the Brazos River.

•The 36 geomorphic zones of the lower Brazos were examined with respect to the presence of mid-channel islands, inset floodplains, abandoned channel water bodies and the flow thresholds identified with these features determined.

•The flow-channel fitness model was applied to the study area to illustrate its use in predicting geomorphic responses to changes in discharge, slope, and sediment inputs.

•Nomographs were produced allowing estimation of potential changes in shear stress and stream power, for ranges of slopes, depths, and discharges relevant to the lower Brazos.

Project Objectives

The project objectives as outlined in the Scope of Work are listed below, and linked to sections of this report relevant to each task.

1. Identify potential discharge and sediment supply-related thresholds related to channel widening and incision (or narrowing and aggradation), bed load mobility, channel-floodplain connectivity, inundation of geomorphic units, and channel change (avulsions or cutoffs).

The key thresholds are identified in chapter 2, and related to individual geomorphic zones in chapter 4.

2. Estimate changes likely to result in threshold exceedances, relative to contemporary flow and sediment regimes.

This objective is met by estimating the critical flows necessary to achieve the thresholds (ch. 2, 5). In all cases flow reductions due to climate change, increased withdrawals, or out-of-basin transfers will result in less frequent achievement of the thresholds. Conversely, increased flow will lead to more frequent threshold exceedance. Potential implications of increased or decreased frequency of threshold exceedances are summarized in Table 23.

Table 23. Potential hydrologic and geomorphic implications of decreased and increased frequencies of critical discharge thresholds.

Threshold	*Decreased frequency*	*Increased frequency*
Thalweg connectivity	Zero-flow	Already exceeded 100% of the time
Bed inundation	Reduced flushing (& increased accumulation) of fine sediments on channel bed	Increased flushing & reduced accumulation of fine sediments on channel bed
High sub-banktop	Reduced flushing (& increased accumulation) of fine sediments on channel banks	Increased flushing & reduced accumulation of fine sediments on channel banks
Channel-floodplain connectivity	Reduced flow to floodplain lakes and wetlands	Increased flow to floodplain lakes and wetlands
Overbank flood	Decreased floodplain accretion	Increased floodplain accretion
Sandy bedform mobility	Decreased bedform mobility; possible channel aggradation, increasing overfitness, & fine sediment accumulations on bed	Increased bedform mobility; possible localized increases in lateral channel migration in low-resistance reaches
Gravel mobility	Decreased mobility of gravel or gravel-armored bars; possible channel aggradation, increasing overfitness	Increased mobility of gravel or gravel-armored bars
Specific stream power	Reduced sediment transport; possible channel aggradation & increasing overfitness	Increased sediment transport; possible channel enlargement & increasing underfitness
Channel instability	Reduced lateral channel migration	Increased lateral channel migration; possible channel enlargement & increasing underfitness

3. Synthesize the threshold discharges and the types of instream flow and sediment supply changes most likely to result in exceedance. The latter include dams, diversions, return flows, land use changes affecting runoff, and climate and hydrometeorological phenomena.

In retrospect this objective is poorly phrased, as it is essentially achieved via objective 2. Synthesis of the overall findings is presented in Chapter 5.

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Scope of Work

SCOPE OF WORK PLAN
Flow Modifications and Geomorphic Thresholds in the Lower Brazos River

Overview

This work plan addresses a cooperative research study of the Brazos River, Texas, downstream of Waco. The study will examine each of the major geomorphic process zones (river styles) previously identified along the river to identify potential thresholds with respect to geomorphic changes in response to changes in flow regimes and sediment supply, and estimate the degree of flow change necessary to result in exceedence of the thresholds. In this way the geomorphic impacts (and associated ecological impacts and engineering and management ramifications) of instream flow changes can be assessed.

Background

Fluvial and other geomorphic systems are typically governed by thresholds, defined as the point at which a system's behavior changes. Geomorphic thresholds fall into three broad categories. Force:resistance thresholds relate to the force or power driving change to the resistance to change. For example, mean boundary shear stress in a stream channel vs. the shear strength of the channel boundary determines whether a given flow results in channel erosion. A second class of thresholds relates to the relative rates of linked processes. For instance, the rate at which sediment is deposited on a floodplain vs. the rate of erosional removal of sediment from floodplain storage determines the net increase or decrease in alluvial sediment storage. The third class of thresholds relates to storage capacity. The storage capacity of subsurface cavities in fluviokarst areas, for instance, determines whether runoff is confined to ground water pathways and storage, as opposed to spillover flooding in surface channels.

Many thresholds in fluvial geomorphology are related to discharge, including depths necessary to inundate specific geomorphic and hydraulic units, and flows required for channel-floodplain connectivity. Especially important are thresholds related to the relationship between sediment supply to channels and the ability of flows to transport that sediment. Examples include critical shear stress and stream power relative to sediment transport, bed mobility and bank erosion.

Modifications to instream water flows and sediment cannot be considered in isolation. Many of the factors resulting in changes in runoff and stream discharge, such as dams and impoundments, vegetation change, and urbanization, may have comparable or even greater impacts on sediment supply. The impact of other flow modifications, such as ground or surface water withdrawals, or flow diversions, are sensitive to the magnitude of flow changes relative to those of sediment supply.

Thus changes in instream flows and sediment supply have the potential to result in the crossing of thresholds and the switching on or off of particular geomorphic phenomena.

Objectives

For each of the river styles or geomorphic zones in the study area:

(1) Identify potential discharge and sediment supply-related thresholds related to channel widening and incision (or narrowing and aggradation), bed load mobility, channel-floodplain connectivity, inundation of geomorphic units, and channel change (avulsions or cutoffs).

(2) Estimate changes likely to result in threshold exceedances, relative to to contemporary flow and sediment regimes.

(3) Synthesize the threshold discharges and the types of instream flow and sediment supply changes most likely to result in exceedences. The latter include dams, diversions, return flows, land use changes affecting runoff, and climate and hydrometeorological phenomena.