Geomorphic Equilibrium in Southeast Texas Rivers

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Preface

This report is based on a study of the geomorphic equilibrium of the coastal plain portions of the Brazos, Trinity, and Sabine Rivers, and of river systems of southeast Texas more generally. River and stream management, assessment, engineering, and classification is often based on concepts of geomorphic equilibrium, and implicit or explicit assumptions that fluvial systems are in, or develop towards, some form of equilibrium. The purpose of this study is to determine the extent to which that is indeed the case in the study area.

The structure of the report is as follows:

•Section 1 provides an introduction to equilibrium theory and concepts in fluvial geomorphology and closely related fields, and to the study area. A regional assessment and synthesis of equilibrium conditions based on published research is given.

•Section 2 is a specific examination of equilibrium with respect to hydraulic geometry in the study area.

•Section 3 examines avulsions in southeast Texas rivers, with emphasis on their geomorphic role in fluvial system evolution, and their relationships to equilibrium and stability.

•Section 4 deals with evidence for equilibrium in the longitudinal profiles of streams within the Brazos, Navasota, Trinity, and Sabine Rivers.

•Section 5 synthesizes the previous sections with respect to the general implications for (assumptions of) geomorphic equilibrium in the region.

Each section except the last is presented as a more-or-less independent paper which can be evaluated independently of the others.

A number of individuals contributed to this work, and I am grateful for their expertise and efforts. Sarah McCormack assisted in fieldwork, data collection and analysis, and background research. Greg Malstaff and Mark Wentzel of the TWDB were instrumental both in getting this project starting, and seeing it through. Responsibility for the content, however, lies entirely with the author.

Section 1
Geomorphic Equilibrium and Fluvial Systems of Southeast Texas

INTRODUCTION

This work addresses the geomorphic equilibrium of the coastal plain portions of the Brazos/Navasota, Trinity, and Sabine Rivers, Texas. Equilibrium concepts are of major theoretical importance in fluvial geomorphology, but also have critical applied implications. River management, assessment, engineering, and classification are often based on concepts of geomorphic equilibrium, and implicit or explicit assumptions that fluvial systems are in, or develop towards, some form of equilibrium.

However, the assumption of equilibrium (or tendencies toward it) is not always valid and is increasingly criticized as a reasonable assumption for models and assessments. Further, equilibrium is variously and sometimes poorly defined. The purpose of this study is to critically review the concept of equilibrium in fluvial systems in general, and in the specific context of southeast Texas. Rigorous definitions of geomorphic equilibrium will be developed and applied to the study rivers, with particular reference to fluvial response to environmental change, and to implications for the Texas Instream Flow Program.

Equilibrium

Dictionary definitions of equilibrium generally denote some notion of balance and stability characterized by equality of distribution, a stable canceling or balancing of forces, or no net change. The term has specific definitions in chemistry, thermodynamics, mathematics, and other fields which may be relevant to geomorphology and hydrology. In this section notions or definitions of equilibrium specific to (fluvial) geomorphology and river engineering will be reviewed. Equilibrium concepts in geomorphology have been extensively critiqued and reviewed elsewhere (e.g., Howard, 1982; Renwick, 1992; Ahnert, 1994; Thorne and Welford, 1994; Bracken and Wainwright, 2006). Rather than revisit these debates, the emphasis here is on the conceptions and use of equilibrium concepts in practice in river science and management.

19 textbooks and general reference works in fluvial geomorphology; river, hydraulic, and sedimentation engineering; fluid mechanics; and water resources were examined for explicit definitions of "equilibrium" and "dynamic equilibrium." In geomorphology, in particular, the latter term is often used to denote a situation whereby a stream or other geomorphic system maintains, or fluctuates around, a steady-state as it responds to external changes. A summary is shown in Table 1.

Table 1. Definitions of "equilibrium" (EQ) and "dynamic equilibrium" (DE) in text and reference works related to fluvial geomorphology and river engineering.

Subject	*Definition*	*Source*
Fluvial Geomorphology	EQ: implies both an adjustability of the channel to changes in independent variables such as load and discharge and a stability in form and profile… as a rule the condition of equilibrium has been observed, measured or thought of in terms of some intermediate timescale.	Leopold et al., 1964: 267
Fluvial Geomorphology	DE: referring to an open system in a steady state in which there is a continuous inflow of materials, but within which the form or character of the system remains unchanged.	Leopold et al., 1964: 267
Fluvial Geomorphology	EQ: characteristic forms, recognizable as statistical averages and associated with single-valued relationships to control variables . . . tendency to develop a recognizable average behavior.	Knighton, 1998: 158-160.
Fluvial Geomorphology	DE: small-scale adjustments are continuously made to maintain an approximate state of balance between processes and forms.	Knighton, 1998: 280
Applied Fluvial Geomorphology	EQ condition implies that stable width, depth, slope, and planform can be expressed as functions of discharge, sediment supply, and bed and bank materials	Brierly & Fryirs, 2005: 72
Geomorphology	DE: given constant climatic and tectonic conditions, the whole landscape will in time become adjusted . . . remain morphologically constant [despite constant loss of material through erosion).	Twidale & Campbell, 2005: 169-170.
Geomorphology	DE: Landforms adapted to present-day conditions.	Rice, 1988: 400
Tectonic Geomorphology	DE implies that, on average over time, the landscape maintains a steady-state form, whereby [landscape properties] fluctuate around long-term mean values.	Burbank & Anderson, 2001: 9-10
Earth Surface Systems	DE: adjustment between the mass available for transport and the energy to transport it . . . a steady-state landscape of roughly constant relief.	Phillips, 1999: 91
Fluid Mechanics	EQ: uniform equilibrium is achieved when the flow properties (d,V) become independent of time and of position along the flow direction	Chanson, 2004: 29
Fluid Mechanics	EQ: as a state in which each particle or portion is at rest or has no velocity with respect to a suitable system of reference…. A stable in which the resulting force on each portion of the fluid is zero	Hunscaker and Rightmire, 1947: 15

River Engineering	EQ: concept originated from the study of stable alluvial canals, which with a mobile bed and earth banks are nonscouring and nonsilting over the operating cycle	Chang, 1988: 7
River Engineering	DE: because of natural discharge variation the true regime or dynamic equilibrium of a natural river may never be attained although each river is constantly adjusting itself towards that direction	Chang, 1988: 7
Sedimentation Engineering	EQ: when the local rate of transport is equal to the supply including the case in which they are both identically zero df(B)/dt is equal to zero and the bed is stable	ASCE, 1977: 48
Sedimentation Engineering	DE: corresponds to an equilibrium for conditions of sediment transport through both the normal and constricted reaches	ASCE, 1977: 61-62
Sedimentation Engineering	DE: according to regime theory the factors in a regime are determined by dynamical laws therefore an in-regime system is one in dynamical equilibrium…. The equilibrium is normally stable, that is, it restores itself after a disturbance, if the causes remain unaffected by the disturbance	Blench, 1966: section 4.9
Fluid/Sediment Mechanics	EQ: quasi-uniform flow = equilibrium flow, in which " the picture of the flow corresponding to a region…does not vary as a function of X (the distance/length of flow) or that it is uniformly distributed along X"	Yalin, 1972: 2
Fluid/Sediment Mechanics	EQ: the amount of sediment coming into the reach is equal to the sediment going out from the same; this is also equal to the sediment transport capacity of the stream for given characteristics of sediment, flow and fluid. Hence the stream bed elevation will not change over a long period of time	Garde and Ranga Raju, 1977: 5
Fluid/ Sediment Mechanics	EQ: many rivers have achieved a state of approximate equilibrium throughout long reaches….considered stable and are known as graded streams by geologists and as poised streams by engineers. However, this does not preclude significant changes over a short period of time or over a period of years	Simons and Senturk, 1977: 40
Fluid Mechanics	EQ/steady state: presumed equilibrium with a chosen flow velocity and a sand supply rate carefully matched	Clifford et al., 1993: 318, 331

Fluid Mechanics	EQ: Equilibrium of alluvial channels implies a balance between incoming and outgoing water discharge and sediment load. Whenever a balance is obtained between incoming and outgoing sediment discharges, the cross-section geometry may locally change as long as the deposition volume with a river reach is equal to the erosion volume	Julien, 2002: 158
Fluvial Systems	DE: over a time-scale of 10-100 yrs the spatial arrangement of patches may change, but the composition of patches within each sector will remain relatively stable, about an average condition	Petts and Amoros, 1996: 270
Water resources	DE: characteristic of the environment by which natural changes occurring over a period of time are countered by natural resilience of the species concerned	Whipple, 1998: 112

In 10 cases the definitions in Table 1 indicate specific criteria for equilibrium, while 10 others make reference to a more general condition or system state. In former case many of these are relevant to specific problems or calculations, but do not imply any general sort of normative condition. Common themes include notions of adjustment, adjustability, or adaptation (7 of 21 entries); of stability or relative constancy of form (11); or of steady-state relationships regarding mass fluxes or input-output linkages (10).

THE EQUILIBRIUM PROBLEM

Despite considerable evidence to the contrary going back more than 30 years (Callander, 1969; Stevens, 1975), geomorphologists—and even more so water resource managers from other backgrounds—have assumed that geomorphic systems in general, and stream channels in particular, are likely to be in "equilibrium." As Table 1 shows, however, even within river science equilibrium is variously defined , despite several attempts to introduce standardization and rigor into equilibrium terminology and the identification of equilibrium states (Ahnert, 1994; Howard, 1982; Thorne and Welford, 1994).

It is often implicitly assumed in fluvial geomorphology that, given sufficient time between disturbances or environmental changes, a fluvial system will reach a state of adjustment with a characteristic form, and that a dynamic steady-state will be maintained. This assumption is particularly common in applied fluvial geomorphology and hydraulic engineering (e.g. Biedenharn and Watson, 1997; Wyzga, 2001; Bledsoe et al., 2002; Toy and Chuse, 2005; Moret et al. 2006). Several classification schemes are based on equilibrium assumptions of this nature, either with respect to specific features such as bed roughness or overall channel state.

In many cases streams do maintain a dynamic steady-state equilibrium, but many do not, either because they are too frequently disturbed, or they are inherently unstable (Renwick, 1992). There is no evidence that stable, steady-state equilibrium stream channels or fluvial systems are notably more common or more "normal" than nonequilibrium states (e.g., Callander, 1969; Stevens et al., 1975; Trimble, 1977; Seminara, 1991; Thornes and Gregory, 1991; Downs, 1995; Vandenberghe, 1995; Bull, 1997; Lane and Richards, 1997; Harbor, 1998; Tooth and Nanson, 2000; Hooke, 2003; 2004; Muto and Swenson, 2005; Phillips et al., 2005).

At this point it is evident that : (1) Not all fluvial systems tend toward a steady-state equilibrium, even when not subjected to major disturbances for extended periods; (2) Equilibria in fluvial systems are sometimes unstable; and (3) Multiple possible equilibria may exist, rather than a single characteristic state or form.

The National Academy of Sciences review of instream flow science and the Texas Instream Flow Program recognizes that classic equilibrium concepts do not apply to flood-dominated west Texas Rivers (NAS, 2005: 23; 91), but is otherwise firmly grounded in equilibrium orthodoxy. Channel assessment is framed in terms of identifying whether a channel is in dynamic equilibrium or disequilibrium (41); not even recognizing the possibility of nonequilbrium systems.

Like many uses of the term in hydrology, geomorphology, and ecology, the NAS (2005) report is not specific in what is meant by "equilibrium," but it can be deduced from table 5-1 (93) that in the view of the committee equilibrium channels are not significantly aggrading, incising, or widening. This is in practice quite unlikely, particularly in the study area where the rivers have always gone through episodes of aggradation, incision, and channel migration that vary in the upstream-downstream direction, and in response to local boundary conditions (Alford and Holmes, 1985; Blum et al. 1995; Morton et al. 1996; Phillips, 2003; 2007a; Phillips, et al. 2004; 2005; Rodriguez et al., 2005; Waters and Nordt, 1995).

Equilibrium is sometimes used loosely in connection with the concept of relaxation time—the time required for the most rapid initial adjustments to a change or disturbance to be completed. It appears that the NAS (2005) perception of "equilibrium" may be partly in this vein, in essence recommending that managers should consider the extent to which a river section is still responding rapidly to a change (for example, channel scour downstream of a dam), or whether that response has slowed down or ceased. That notion is also clear in the model for quantification of equilibrium in incised channels of Bledsoe et al. (2002), which is based on an incised channel passing through all stages of an evolutionary sequence originally proposed by Schumm et al. (1984).

TYPES OF EQUILIBRIUM

This project employs three increasingly restrictive concepts and related definitions of geomorphic equilibrium:

1. *Relaxation Time:* a fluvial system is in equilibrium if it has completed its response to a given disturbance or environmental change. This is the weakest concept of equilibrium, implying only that a response has had time to be completed.

2. *Characteristic Form:* this stronger concept implies relaxation time equilibrium, with the additional criterion that the system achieves (or at least moves toward) a form or state which is adjusted to its environmental constraints and contexts. This has traditionally been interpreted in terms of a more-or-less universal equilibrium form (for instance a concave-up longitudinal profile).

3. *Steady-State*: This, the strongest form of equilibrium, implies that the characteristic form is stable in response to all but very large perturbations, and self-maintaining.

Relaxation time equilibrium (RTE) has no particular theoretical implications, as it implies only that changes in response to a disturbance or to new boundary conditions have run their course, or at least slowed to negligible rates. In an applied perspective, notions of RTE are typically employed to define the domain of applicability of particular models, techniques, or assumptions. Bledsoe et al.'s (2002) models of stable slopes in "quasi-equilibrium" incised channels, for instance, are to be applied where the channel evolution sequence of Schumm et al. (1984) has reached its final stage, implying RTE.

Characteristic form equilibrium (CFE) implies a high degree of predictability in terms of morphological responses to change or disturbance. If this form of equilibrium is present, similar responses to similar forcings should occur where the environmental controls are reasonably consistent, such as within the study area. CFE also implies that models, simulations, management standards, and restoration targets can be based on normative conditions.

If a system with CFE is also self-maintaining and stable to small perturbations, steady-state equilibrium (SSE) is present. This form of equilibrium is inherent in the concept of the graded river and "dynamic equilibrium" as described by Hack (1960). The graded or (steady-state) equilibrium river profile, for example, adjusts its slope to the given discharge so that it can just transport the sediment supplied to it, without large or long-term aggradation or degradation. Even more than CFE, SSE implies that fluvial systems evolve toward a single self-maintaining state, and that there exists a "normal," expected condition.

RTE may be assessed in two ways. Direct assessment involves determining whether a particular response has indeed slowed substantially or ceased. Scour of the Trinity River downstream of Livingston Dam, for instance, has reached its limits with respect to downstream propagation, and bedrock in the channel limits the rate of future incision, implying RTE for this response (Phillips et al., 2005). Historical assessment involves the synthesis of observational, process, morphological, stratigraphic, and paleoenvironmental evidence to determine the relaxation time of responses relative to the frequency of a given disturbance. There has apparently been ample time for valley filling and subsequent terrace formation, for instance, in response to sea level change, relative to the time scale of transgressions and regressions, implying RTE (e.g., Blum et al. 1995; Morton et al., 1996; Rodriguez et al., 2005).

For disturbances that are discrete in time (e.g., dam construction), the progress of adjustments can be directly assessed. For ongoing or long-lasting changes (e.g., sea level) the characteristic time scales or rates of changes and adjustments can be compared. Formally, RTE can be said to exist where

$$(t-t_d)/t_r \geq 1 \quad \text{or} \tag{1}$$

$$t_r/F_d > 1 \tag{2}$$

where t is time of observation, t_d is the time of disturbance, t_r relaxation time, and F_d the frequency of the change or disturbance in question.

CFE necessitates similarity of responses for similar sets of environmental controls, and regional consistency of form-process relationships. The presence of multiple equilibria or modes of adjustments indicates that CFE is not present. For instance, if an increase in sinuousity in response to sea level rise, or a decrease in lateral channel migration in response to flow reduction, has a reaction time rapid enough relative to the changes, then CFE would also require that these responses be consistent in reaches with similar environmental constraints. Thus, in formal terms the necessary and sufficient conditions for CFE are satisfaction of eq. (1) or (2), and

$$S = f(\mathbf{x}) \approx \text{constant} \tag{3}$$

where S is the state of the fluvial system (as represented, for instance, by the longitudinal profile, planform, etc.), and **x** a vector representing a given set of environmental controls.

The most stringent form (SSE) can be based on a direct determination of whether steady-state is present, given that RTE and CFE occur. For example, a graded stream or steady-state fluvial sediment system means that sediment delivered to the channel at least roughly corresponds to sediment export from the drainage basin, such that little or no long-term net changes in sediment storage occur (Trimble, 1977; Phillips, 1986). SSE could imply a simple situation where

$$dS/dt = d\mathbf{x}/dt \approx 0 \tag{4}$$

More commonly, as $d\mathbf{x}/dt \approx 0$ is unrealistic, the implication is that

$$\delta x_i(t) = \mathbf{c}\, e^{\lambda t};\ \boldsymbol{\lambda} < 0, \tag{5}$$

where $\delta x_i(t)$ represents a perturbation of component x at time t, **c** is a vector constant normalizing initial conditions, and $\boldsymbol{\lambda}$ are the Lyapunov exponents of the system, which are equivalent to the (real parts of the) eigenvalues of the Jacobian interaction matrix. In geomorphological practice, this can be cast in terms of methods for determining convergent or divergent development of fluvial (and other geomorphic) systems, enabling determination of whether any λ are positive, indicating instability and no SSE. A more full and general explanation is given by Phillips (2006), and an application is given in section 3 of this report.

OBJECTIVES AND METHODS

Objectives

The specific study objectives outlined in the Scope of Work are to:

(1) Determine, for the geomorphic processes and changes described below, the general equilibrium conditions of the river study reaches as a whole, and of critical transition zones and environmentally sensitive areas, according to the relaxation time, characteristic form, and steady-state criteria described above.

(2) Determine the equilibrium status of the study rivers with respect to three geomorphic processes or phenomena:
(a) Channel and valley aggradation/degradation;
(b) Upstream-downstream variation in dominant sediment transport and depositional regimes; and
(c) Channel cross-sectional changes (hydraulic geometry).

(3) Determine the equilibrium status of the study rivers with respect to three general types of change:
(a) Holocene sea level fluctuations;
(b) Downstream effects of dams and reservoirs; and
(c) Changes in flow regimes associated with climate change, land use, and water withdrawals or redistributions.

(4) Assess the viability of equilibrium assumptions with respect to water resource management in the study area.

Methods

Recent and ongoing studies by the author in the Brazos/Navasota, Trinity, Sabine rivers provides a great deal of background on geomorphic responses to a variety of environmental changes in the region. In addition, a number of other geomorphological and stratigraphic studies have been conducted in the region in the last 20 years or so. These provide a basis for addressing objectives (1) – (3) above. Section 5 will address objective (4).

Table 2 shows a matrix of the three general geomorphic phenomena and three forcings or changes addressed here, with the available published work. All the indicated references are refereed research papers; additional data, information, and interpretations are available in a number of technical reports to the Texas Water Development Board (see http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp).

Table 2. Published studies forming the basis for equilibrium assessments of rivers in southeast Texas.

	Channel/valley aggradation	*Sediment transport/deposition regime*	*Hydraulic Geometry*
Sea Level	Rodriguez et al. 2005 Phillips & Slattery 2007b Phillips 2007 Taha & Anderson 2007	Rodriguez et al. 2005 Phillips & Slattery, 2007a Phillips & Slattery 2007b Phillips 2007 Taha & Anderson 2007	Rodriguez et al. 2005 Phillips et al. 2005 Phillips & Slattery 2007b Phillips 2007
Dams	Phillips 2003 Phillips 2001 Phillips et al. 2004 Phillips & Musselman 2003	Hudson & Mossa 1997 Dunn & Raines 2001 Phillips 2003 Phillips 2001 Phillips & Marion 2001 Phillips et al. 2004 Phillipa & Musselman 2003	Dunn & Raines 2001 Phillips 2003 Phillips et al. 2005
Flow regimes	Waters & Nordt 1995 Phillips 2003 Phillips 2001 Sylvia & Galloway 2006	Waters & Nordt 1995 Hudson & Mossa 1997 Dunn & Raines 2001 Phillips 2003 Phillips 2001 Phillips & Slattery, 2007a	Alford & Holmes 1985 Waters & Nordt 1995 Phillips 2003 Phillips et al. 2005 Sylvia & Galloway 2006

STUDY AREA

The study area (figures 1, 2) includes the southeast Texas coastal plain from the Brazos River to the Sabine River on the Louisiana border. The climate is humid subtropical, and the topography ranges from virtually flat in the coastal marshes to gently rolling. Soils—as might be expected in such a large area—are quite variable. The oldest and most strongly weathered soils are Paleudults and Kandiudults on Tertiary and older Quaternary uplands, but Vertisols, Alfisols, and Mollisols are common in smectitic parent materials and those with significant carbonate contents. A variety of recent, poorly developed Inceptisols and Entisols occur on floodplains, deltas, and coastal wetlands.

Figure 1. Major rivers of Texas draining to the Gulf of Mexico. The lower Brazos/Navasota, Trinity, and Sabine Rivers are the focus of this study.

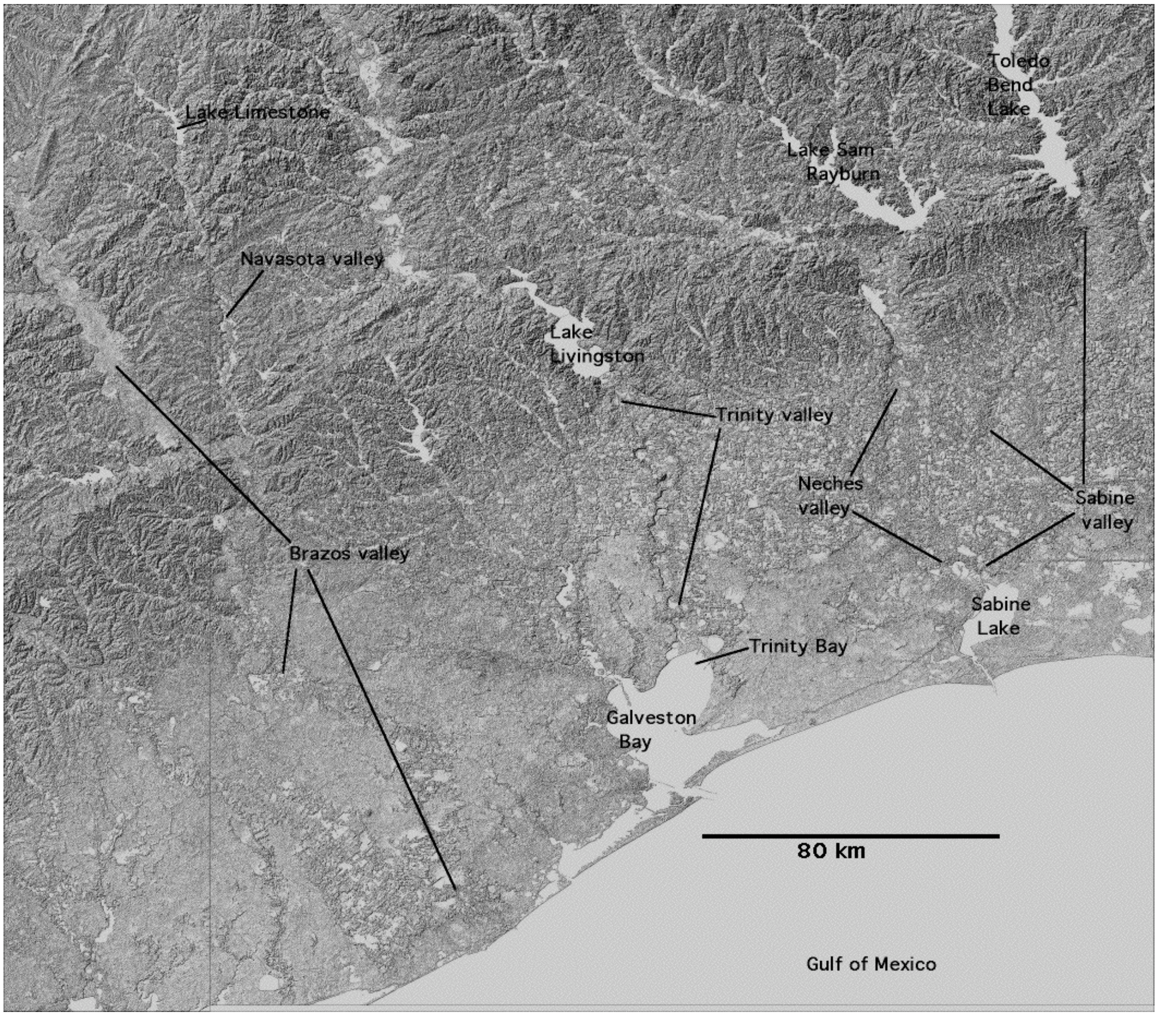

Figure 2. Shaded relief map of the study area derived from 90-m shuttle radar topography mission (SRTM) data. The major river valleys and other key features are identified.

The Quaternary geologic framework is of most significance to this study, so it will be described in some detail.

Quaternary Geology

The uppermost portions of the studied Brazos, Navasota, and Neches reaches are in Tertiary coastal and marine formations, but otherwise the entire study area is in Quaternary material. Recent reviews and syntheses of the Quaternary geologic framework and sea level history of the region (and some of the controversies pertaining thereto) are provided by Blum et al. (2002) and Otvos (2005). Recent research on the role of antecedent topography and recent geologic and sea level history on current forms, processes, and evolution are given for the Brazos River by Sylvia and Galloway (2006), Phillips (2007b), and Taha (2007; Taha and Anderson, 2007); for the Navasota by

Phillips (2007b); for the Trinity by Rodriguez et al. (2005) and Phillips and Slattery (2007a;b); and for the Sabine by Phillips (2007a; Phillips and Slattery, 2007c).

The study rivers are flanked by modern floodplains and flights of several Pleistocene Terraces. The oldest and highest are the Beaumont terrace (correlative with the Prairie surface in Louisiana). Dates for the Prairie-Beaumont formation in Louisiana and Texas reviewed by Otvos (2005) range from 33 to 195 Ka. Otvos' (2005) analysis places the deposition of the Beaumont terraces in Texas, which are 50 to 100 km wide from the coast, at 74 to 116 Ka--broadly consistent with Blum et al. (1995) and Thomas and Anderson (1994).

Below the Beaumont surface and often merging into the modern floodplain are a series of up to three alluvial terraces. These are typically referred to as Deweyville, though they are no longer interpreted as part of a single terrace system (Blum et al., 1995; Morton et al., 1996). In most locations "at least two" (Blum and Price, 1998), or three (Blum et al., 1995; Morton et al., 1996; Rodriguez et al., 2005) separate "Deweyville" surfaces are recognized, though not always exposed at the surface. Where exposed, the lowest of these terraces are only slightly higher than the modern floodplain (Alford and Holmes, 1985; Blum et al., 1995; Rodriguez et al., 2005). Aerial photographs show obvious palaeomeanders in the Trinity, Neches, and Sabine valleys, expressed as swampy depressions or meander scrolls. These occur on the Deweyville surfaces, with radii of curvature and amplitudes suggesting significantly larger palaeodischarges than at present (Alford and Holmes, 1985; Blum et al., 1995). Cuspate indentations in the valley wall of the Brazos, where most of the Deweyville terraces are buried, are also associated with these higher paleodischarges (Sylvia and Galloway, 2006).

In the Sabine River Alford and Holmes (1985) date the undifferentiated Deweyville surfaces at 4-9 ka. In the Colorado River, Texas, Blum and Price (1998) place the deposition of the Eagle Lake Alloformation, youngest of the group, from 20 to 14 Ka, followed by incision from 14-12 Ka, and then Holocene valley fill. The three Deweyville surfaces are designated (youngest to oldest) the Fredonia, Sandjack, and Merryville alloformations by the Louisiana Geological Survey (Heinrich et al., 2002).

Otvos' (2005: 102) chronology for the Sabine River indicates entrenchment from about 100 to 50 Ka, and aggradation, producing two terraces, from 40 to 20 Ka. Then followed entrenchment from 20 to 18 Ka and aggradation from 18 to 2 Ka (Otvos, 2005: 102). The Sabine and Trinity systems were connected during lower sea level stands on what is now the continental shelf, and the Neches, which now flows into Sabine Lake, was a Sabine River tributary. Thomas et al. (1994) reckon the oldest incision of the Trinity-Sabine system at about 110 Ka. Blum et al. (1995) associate the incision of the Beaumont surfaces with marine oxygen isotope stage 5 (115 to 75 Ka). Several stages of aggradation, degradation, and lateral migration, degradation, and aggradation occurred within those incised valleys during isotope stages 4, 3, and 2 glacials as channels flowed to shorelines further out on the current continental shelf (Blum et al., 1995; Morton et al., 1996). The variations in shelf slope and antecedent morphology associated with those Pleistocene events are directly related to along-strike variability in Holocene coastal retreat rates between Louisiana and Galveston Bay (Rodriguez et al., 2004)—and by extension, to fluvial responses.

Morton et al.'s (1996) analysis suggests Trinity River incision sometime after 13 Ka, followed by aggradation triggered by sea level rise and progressive onlap and burial of Deweyville surfaces sometime during isotope stage 1, from about 10 Ka. This is consistent with analyses of offshore and estuarine sediments, which indicate that Galveston Bay began forming initially by flooding of incised valleys about 8 Ka, with subsequent, apparently rapid inundation of valleys creating the approximate modern version of Galveston Bay about 4 Ka (Anderson et al., 1992). Rodriguez et al. (2005) identified flooding surfaces in Galveston Bay from decreases in sedimentation rates and changes from delta plain to central estuarine basin facies in cores. Formation of these surfaces dates to 8.2 and 7.7 Ka, at depths matching the elevations of relatively flat alluvial terraces.

According to Waters and Nordt (1995) the lower Brazos River was a competent meandering stream from 18 to 8.5 ka, leaving thick coarse lateral accretion deposits (such as those associated with Deweyville terraces) as it migrated across the floodplain. At about 9 to 9.4 ka a transition to an underfit stream incised into those deposits and dominated by vertical accretion occurred .

RESULTS

Results of the analysis of the literature are presented in terms of the changes or forcing functions, based on the results of the studies shown in Table 2.

Sea Level

Details of the history of Quaternary sea level change in the Gulf of Mexico region are subject to debate (e.g., Blum et al., 2002; Otvos, 2005), but the effects of base level changes in the alluvial sedimentary record are clear from studies of the Colorado, Brazos, and Trinity/Neches/Sabine river systems (Blum et al., 1995; Morton et al., 1996; Blum and Price, 1998; Rodriguez et al., 2005; Blum and Aslan, 2006; Taha and Anderson, 2007). These effects include cycles or episodes of incision and aggradation, floodplain formation and subsequent abandonment (terrace formation), backstepping of deltaic sequences, and migration of avulsion nodes. This history—and the ability to recognize these effects in the sedimentary record—suggest that channel/valley aggradation (degradation) patterns and sediment transport/deposition regimes can be considered to be in relaxation time equilbrium with effects of sea level change.

Research dealing with effects of sea level (and antecedent morphology related to sea level change) on the modern topography, morphology, and processes, however, reveals considerable variety in forms and responses (Aslan and Blum, 1999; Rodriguez et al., 2004; Phillips, 2003; 2007a; Phillips, et al. 2004; Phillips and Slattery, 2006; 2007b). This is reflected in fundamental differences in infilling of incised valleys, delta form and development, avulsion regimes, convergent-divergent network characteristics, and the relative importance of planform vs. profile responses to base level change. Thus characteristic form equilibrium is not present in the region.

The absence of CFE precludes the existence of SSE. More general theoretical treatments of the stability of sediment budgets and transfer regimes in coastal plain rivers are given elsewhere (Phillips, 1987; Phillips and Gomez, 2007).

Dams

Studies of dam effects on the downstream geomorphology of southeast Texas Rivers have been conducted for the Sabine, Trinity, and Brazos Rivers, Loco Bayou (Angelina/Neches River basin), and Yegua Creek (Brazos basin). In the Brazos, results suggest changes in flow regimes following construction of major dams upstream, and some evidence of a decline in lateral migration, but no evidence of changes in sediment transport to the lower basin (Gillespie and Giardino, 1997; Hudson and Mossa, 1997; Dunn and Raines, 2001). This may be in part because dams are the main channel are well upstream of the lower Brazos study area.

Studies directly examining morphological effects downstream of dams in the region have generally found a "hungry water" scour zone downstream of the dam, which extends relatively short distance ($\leq$ 55 km) downstream, and limited impacts on sediment transport or storage further downstream, due to a combination of sediment supplied by bed and bank erosion in the scour zone, tributary and local sediment inputs downstream of the dams, and the fact that the systems were transport-limited and overloaded with sediment (relative to transport capacity) before dam construction (Phillips, 2001; 2003; Phillips, et al. 2004; 2005; Phillips and Marion, 2001; Phillips and Musselman, 2003). In the lowermost Trinity and Sabine Rivers the effects of Holocene sea level, antecedent topography, and inherently limited stream power overwhelm the potential effects of any upstream change in sediment supply, including dams (Phillips, et al., 2004; 2005; Phillips, 2007a; Phillips and Slattery, 2007a; 2007b). This, plus the fact that incision is generally down (or close) to resistant bedrock, suggests that further downstream propagation of dam effects is unlikely and RTE has been achieved.

Given the multiple modes of adjustment documented at specific cross-sections, CFE cannot be assumed at this scale (Phillips, et al. 2005). However, the general characteristic form of a scour zone terminated by a zone where other controls overwhelm upstream influences could be considered a characteristic form at a broader scale. This implies that SSE may be a possibility at a broad reach scale, but not at a cross-section scale.

The Toledo Bend (Sabine), Lake Livingston (Trinity), and Lake Nacogdoches (Bayou Loco) reservoirs are hydropower or water supply impoundments, and the first two have limited impacts on long-term flow regimes or peak flows (Phillips, 2003; Wellmeyer et al., 2005). Lake Nacogdoches and Loco Bayou have no flow records, but given the design of the lake and permitted operations, it is likely that the impoundment does not affect peak flows, but does substantially reduce flows during dry periods (Phillips, 2001). Flood control impoundments generally have greater impacts on downstream flow regimes, particularly peak flows. The geomorphic effects of the Sam Rayburn reservoir, a major flood control lake on the Angelina/Sabine River, have not been examined. However, Chin et al. (2002) studied effects of Lake Somerville, a flood control reservoir, on a tributary of the lower Brazos (Yegua Creek). They found that the effects of the dam diminished downstream, consistent with the other studies, but due to major reductions in peak flows, the chief response was aggradation within the channel.

Flow Regimes

The major long-term changes in flow regime are due to climate change associated with Quaternary glacial/interglacial cycles, while on the shorter term more transitory climate changes (e.g., droughts, wet periods) and human agency are the major influences on flow regimes. The latter include land use changes which affect runoff responses, water withdrawals, and interbasin transfers.

The available morphological, stratigraphic, and paleoenvironmental evidence shows that the study rivers have responded to major Quaternary climate changes, and that in some respects these are reflected in characteristic forms, such as the disparity between channel dimensions and meander amplitudes between the modern rivers and those which deposited the Deweyville terraces and associated palaeomeanders (e.g. Alford and Holmes, 1985; Blum et al., 1995; Waters and Nordt, 1996; Sylvia and Galloway, 2006).

Relaxation time equilibrium seems likely, based on observations of relatively rapid responses to changes in flow regimes downstream of dams (Phillips, 2001; Chin et al., 2002; Wellmeyer et al., 2005) and in channel responses to flow diversions (Phillips, 2007a; Phillips and Slattery, 2007c; see also section 3). The evidence is insufficient to evaluate CFE, but general regional evidence suggests that multiple modes of adjustment to similar changes in flow occur, and that CFE (and thus SSE) is unlikely (c.f, Friedman, et al., 1998; Wellmeyer, et al. 2005; section 3). Further, evidence within the region shows that responses of tributaries may be out of phase with those of the trunk river (Nordt, 2004; Musselman, 2006), at least implying that contemporary CFE cannot be assumed within a river system.

Summary

Based on the review above, a general assessment of the likelhihood of the various forms of equilibrium with respect to the three forcings discussed above (sea level, dams, and flow regimes) can be made for the three responses of channel and valley aggradation (or degradation) patterns, the sediment transport and deposition regime, and hydraulic geometry (Table 3).

Table 3. The likelihood of relaxation time, characteristic form, and steady-state equilibrium (RTE, CFE, SSE) with respect to various forcings and responses, as discussed above. A question mark indicates that field evidence is insufficient, and thus a significantly higher degree of uncertainty.

	Channel/valley aggradation	Sediment transport/deposition regime	Hydraulic Geometry
Sea Level	RTE: yes CFE: no SSE: no	RTE: yes CFE: no SSE: no	RTE: yes CFE: no SSE: no
Dams	RTE: yes CFE: yes/no* SSE: no?	RTE: yes CFE: yes/no* SSE: no?	RTE: yes CFE: no SSE: no
Flow regimes	RTE: yes CFE: no? SSE: no?	RTE: yes CFE: no? SSE: no?	RTE: yes? CFE: no SSE: no

*yes for reach scale; no for cross-section scale

DISCUSSION AND CONCLUSIONS

The analysis above, based on published work and summarized in Table 2, indicates that the weakest form of equilibrium (RTE) is probably common and a reasonable assumption in the study area. The stronger forms—CFE and SSE—are far less likely.

While useful, however, the analysis suffers from both uncertainty of evidence and scale-contingent conclusions. Further, the rivers of southeast Texas (like those elsewhere) are subjected simultaneously to effects of base level change, dams, climate change, land use, tectonics, and other factors.

Thus separate analyses were conducted for three separate phenomena. One, hydraulic geometry, is a common issue for all rivers and a key concern for almost any geomorphic, hydrologic, engineering, or ecological analysis of a fluvial system, and operates over time scales ranging from virtually instantaneous to decades. The second, avulsions, is a phenomenon known to be important in the region. The general controls of avulsions, and their frequency of occurrence, indicate that this phenomena is critical over time scales of decades to a few thousand years. The third, longitudinal profiles, is believed to reflect the long-term geological evolution of river systems, but is also overprinted with the effects of geologically recent, and historical, changes.

Those analyses will be presented in sections 2-4 as more-or-less independent analyses, with section 5 presenting a synthesis.

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Section 2
Hydraulic Geometry

HYDRAULIC GEOMETRY

Hydraulic geometry involves the interactions between discharges in a stream channel and the channel itself, and is concerned with how changes in discharge are accommodated at a given cross-section. Hydraulic geometry is therefore a canonical example of mutual adjustments in fluvial systems, and is thus directly relevant to classical concepts of dynamic steady-state equilibrium in geomorphology. Singh's (2003) review of hydraulic geometry theories illustrates the pervasiveness of equilibrium concepts as both an analytical assumption and as an underlying epistemological notion. However, others have critiqued hydraulic geometry models based on assumptions of steady-state and stability in both theoretical and applied contexts (e.g. Phillips, 1991; Smith et al., 1999). Hydraulic geometry is also important in its own right, due to its importance for making process interpretations based on channel morphology in historical geomorphology and palaeohydrology, and its utility in predicting channel response to imposed flows in process geomorphology, hydrology, hydraulic engineering, and water resource management.

At-a-station hydraulic geometry deals with variations in flow width, depth, and velocity associated with variations in discharge. If the cross-section is fixed, the problem is a straightforward one involving hydraulics of flow resistance and geometry of the channel. But natural channels—particularly in unconsolidated material such as those in the study area—are modifiable and subject to external perturbations of both the channel boundary and flow hydraulics.

The analysis here does not seek to model stable or most probable channel configurations for given discharge. Rather, we examine the broader question of how the channel system responds to changes in system components.

Background and Theory

Leopold and Maddock (1953) developed a well-known set of empirical power functions relating width, depth, velocity, and other variables to power functions of discharge. The three most important are

$$w = aQ^b \tag{1}$$

$$d = cQ^f \tag{2}$$

$$v = kQ^m \tag{3}$$

where w is width of the water surface, d is mean depth, v is mean velocity, Q is discharge, and a, c, k, b, f, and m are coefficients. The continuity equation dictates ack = 1 and b+f+m=1. These and similar relationships for other hydraulic variables fit data well in some instances, but there is no theoretical reason that the equations should be in the form of power functions.

Discharge, width, depth, and velocity are related by the mass continuity equation

$$Q = wdv \tag{4}$$

A change in any variable must be accommodated by an appropriate combination of the other three.

Fluctuations at a cross section may influence more than one variable. Discharge variations may simultaneously affect w, d, and v, for example. Some factors may influence flow indirectly—for example, wood debris may influence velocity indirectly via roughness. The other variables (in addition to Q, w, d, and v) necessary to describe the system are flow resistance and energy grade slope. The addition of these variables, along with the constant of the specific gravity of water (pg), allows a fully-specified, completely-determined system: i.e., every variable can be described as some function of the other variables. Using s to denote energy gradient (commonly approximated as water surface slope), the Darcy-Weisbach friction factor (f) to describe flow resistance, and the Darcy-Weisbach flow resistance equation:

$$Q = wd\ (\rho gRs/f)^{0.5} \tag{5}$$

where hydraulic radius $R = wd/(2d + w)$.

Equation (5) can be rewritten to solve for any variable on the right of the equality.

If other variables are held constant, forecasting channel response to change in any one variable is simple. But as the variables are mutually adjusting, this is unrealistic. Equation systems based on eq. (5) can be solved iteratively for specific cases if the relative rates of change of the variables are known. Such a solution would not allow generalizations, however, because the relative rates of change of variables varies substantially.

Two rationales can be used to collapse the hydraulic geometry system into components of velocity, hydraulic radius, slope, and the friction factor (Phillips, 1990). One, based on rules for system aggregation, will not be discussed here (see Phillips, 1990). Another approach is to identify the minimum number of variables which subsume the variables Q, w, d, v, f, and s. The argument is that the omitted variables (Q, w, d) are subsumed in the included variables. As R is a unique function of w and d. width and depth are represented by hydraulic radius, Any number of combinations of w and d can produce the same R, but the hydraulic influences of w and d are exerted via hydraulic radius. Discharge is a unique function of w, d, and v, so Q is a unique linear function of the product Rv. Because Q, w, and d are subsumed in the variables R and v, the former group may be omitted from the analysis, leaving R, v, f, and s.

The four fundamental hydraulic variables can be linked by rearranging the Darcy-Weisbach equation, with each equation written so that the positive or negative relationships are easily seen from the exponents. Note that qualitatively identical results will be obtained using any flow resistance equation.

$$V = R^{0.5}\, s^{0.5}\, f^{-0.5}\, (pg)^{0.5} \tag{6a}$$

$$s = V^{2}\, R^{-1}\, f^{1}\, (pg)^{-1} \tag{6b}$$

$$R = V^{2}\, s^{-1}\, f^{1}\, (pg)^{-1} \tag{6c}$$

$$f = V^{-2}\, R^{1}\, s^{1}\, (pg)^{1} \tag{6d}$$

The stability of the equation (6) system was tested by Phillips (1990), and shown to be dynamically unstable and chaotic. Unstable hydraulic geometry implies that even the qualitative relationships among the hydraulic variables, not to mention the quantitative links, may not persist in the face of changes in imposed flows or other perturbations to the cross-section. Thus, while equilibrium relationships among the hydraulic variables can be established, qualitatively different equilibria may occur in future flow events.

Instability is manifested in multiple modes of adjustment (MMA), where a mode of adjustment is a specific combination of increases, decreases, or relative constancy of hydraulic variables in response to imposed changes. For example, a reduction in discharge accommodated by a decrease in mean depth and a higher friction factor, while s and V remain constant, would constitute one of many specific modes of adjustment. Second, unstable chaotic behavior implies opposite-from expected behavior. For example, flow resistance equations indicate that if Q decreases, then V, R, and S should decrease and f should increase. However, if the falling Q were accompanied by an increase in velocity, offset by changes in one or more other variables, the decline in V would represent opposite-from-expected behavior.

MMA and opposite-from-expected behavior was shown for data from the Bogue Phalia River, Mississippi by Phillips (1990) and for other rivers by Phillips (1991). Opposite-from-expected behavior and MMA can also be inferred from the data of Simon and Thorne (1996), Ergenzinger (1987), and Brush (1961). Phillips et al. (2005) also found MMA in the response of cross-sections downstream of Livingston Dam on the Trinity River.

Stream gaging and field measurements of discharge are based on Q = Av = wdv, so measurements of w, d, v are available. Measurements of s, f are rarely available. The Froude number can be derived from the commonly available measurements,:

$F = v/(gd)^{0.5}$ (7)

The Froude number distinguishes between tranquil or subcritical ($F<1$) and rapid or critical ($F>1$) flow, and is a key parameter in responses to changing flow conditions. Waves can form during subcritical flow if there is a change in flow conditions, such as encountering an obstacle. When this occurs, the waves created are moving at a speed greater than the oncoming flow; this results in the waves being able to migrate upstream. Such migration of the waves upstream influences the oncoming flow and triggering adjustments. This has been metaphorically described as "warning" the oncoming flow of the downstream change in conditions, enabling the flow to adjust gradually (Wilcox, 2005). During critical flow conditions ($F=1$), a shallow water wave remains almost stationary around an obstruction, and the flow depth is said to be critical. In supercritical flow conditions ($F>1$), flow has a very high velocity and the inertial forces are dominant. In these conditions, any waves created can only move downstream (Simons and Senturk, 1992). Kilgore and Young (1993) also found a very strong relationship between the resistance angle (θ; ratio of vertical to horizontal forces acting on a bed particle) and the Froude number, with $\theta \sim F^2$.

A typical set of field discharge measurements thus provides the following: Q, A, v, w, d, and F. Standard flow resistance and continuity equations show that expected behavior with respect to these variables is that Q, A, v, w, and d should change in the same direction—i.e., an increase in discharge would be accompanied by a an increase in the others, and vice versa. Since velocity varies directly and roughness typically varies inversely with depth (see below), changes in d would be expected to effect the numerator of eq. (7) more than the denominator, thus indicating that F would also be expected to change in the same direction as Q, v, and d (and by extension w and A).

METHODS

The U.S. Geological Survey periodically conducts field measurements at its gaging stations to maintain stage-discharge curves and as a check on automated measurements. These are maintained in databases under the heading "surface water measurements" for each gaging station, and include site measurements of mean velocity, width, and cross-sectional area. The latter is based on width multiplied by mean depth, the latter based on a number of measurements across the channel. Thus mean depth can be computed by $d = A/v$, and as the cross-sections in this study have large w/d rations, $R \approx d$. The Froude number was computed from eq. (7).

Surface water measurements were examined from 11 gaging stations, chosen according to their use in related studies (Figure 1). Beginning with the earliest available set of measurements for each site, each subsequent measurement was examined with respect to relative changes in each variable (increase, decrease, or no change). For each comparison, the number of opposite-from-expected (OFE) changes was recorded.

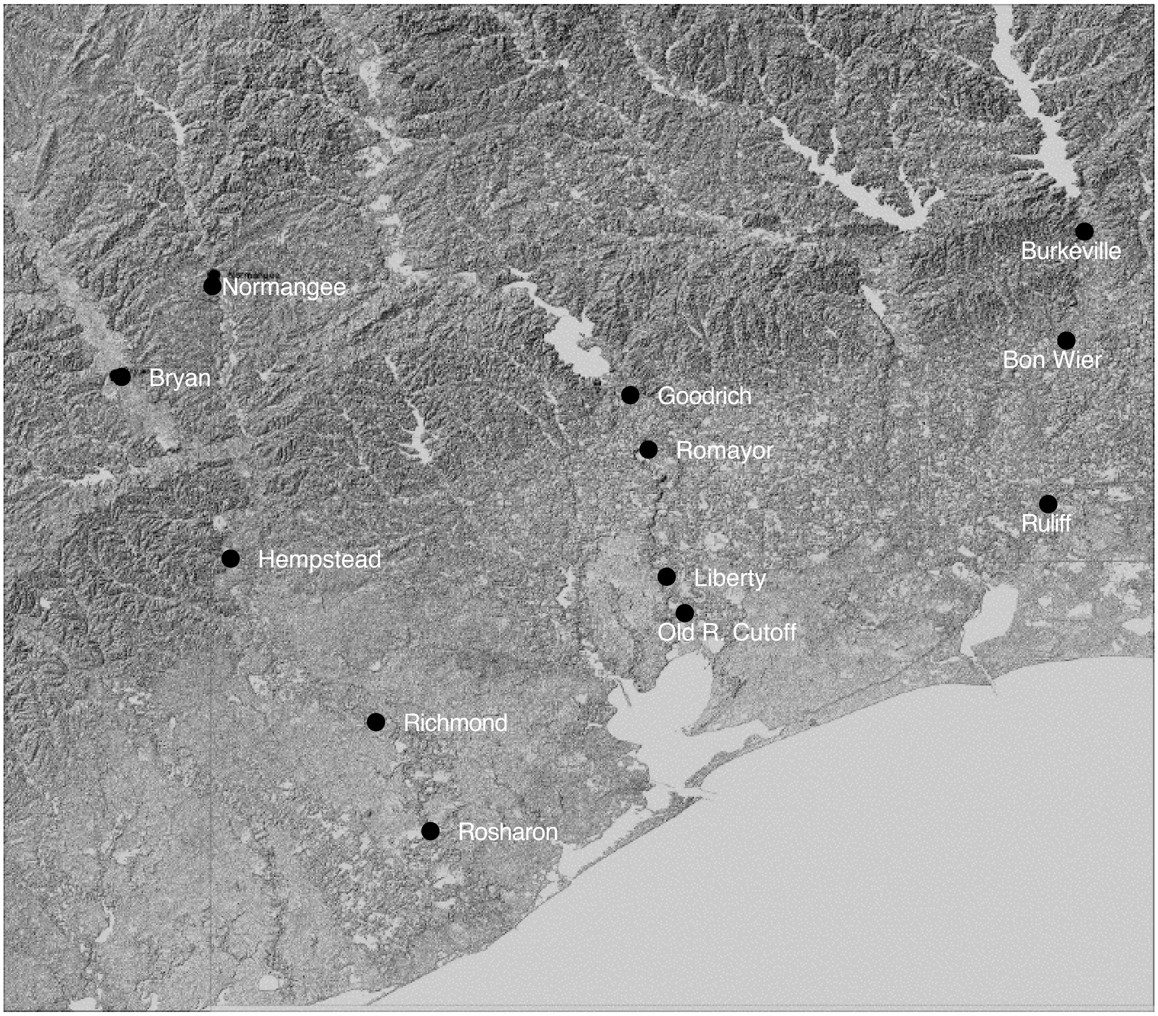


Figure 1. Location of gaging stations used in the analysis.

RESULTS

Results are shown in Table 1. At seven of the 11 stations more than half of the comparisons indicated OFE behavior in at least one parameter. The four other stations are all on the Brazos River. As discussed below, the Brazos stations may have generally more stable cross-sections than the others, which may account for the lower proportion of OFE behavior.

Table 1. Opposite-From-Expected behavior in surface water measurements at 11 southeast Texas gaging stations. The second column shows the number of comparisons where at least one parameter (w, d, A, v, F) changed in the opposite direction from discharge, along with the total number of comparisons.

Gaging station	*OFE/total*	*Percentage*
Brazos/Navasota		
Normangee	64/84	76.2
Bryan	15/90	16.7
Hempstead	74/233	31.8
Richmond	73/201	36.3
Rosharon	129/293	44.0
Trinity		
Goodrich	169/287	58.9
Romayor	92/163	56.4
Liberty	144/269	53.5
Sabine		
Burkeville	213/409	52.1
Bon Wier	429/494	86.8
Ruliff	380/475	80.0

To examine the potential implications of nonequilibrium hydraulic geometry, the same data set was used to explore relationships between velocity and depth. Because changes in depth or stage are the most commonly and easily-measured flow parameter, the ability to infer other parameters from depth would be extremely useful. This is in fact the basis of stage-discharge relationships. However, velocity may be more directly relevant for some sediment and pollutant transport problems, and for aquatic habitat assessment.

VELOCITY-DEPTH RELATIONSHIPS

Flow Resistance Equations

Flow resistance equations are generally of the form

$$V = k\, g\, R^{a} S^{b} f^{-c} \qquad (8)$$

Where g is the gravity constant, R is hydraulic radius, S is the energy grade slope, f is a roughness or friction factor, and k, a, b, and c are coefficients. Hydraulic radius is a function of cross-sectional area (A) and wetted perimeter (P); $R = A/P$. In the D'Arcy-Weisbach equation, for example, $k = 8$, and $a = b = c = 0.5$. In the empirically-derived Manning equation, $k = 1$, $a = 2/3$, $b = 0.5$, and $c = 1$.

Basic physics indicates that the velocity of water flowing due to gravity should vary as a function of $d^{0.5}$, where d is the depth. Chezy's equation for velocity in uniform, turbulent, kinematic flow is

$$V = C\,(RS)^{0.5} \tag{9}$$

where C is a roughness coefficient. The D'Arcy-Weisbach equation, originally designed for calculation of frictional head loss in pipe flow, when written for velocity is

$$V = (8g\,R\,S/f)^{0.5}, \tag{10}$$

Where f is a friction factor.

In channels where flow width (w) substantially exceeds depth ($w/d_{max} > 6$ as a rule of thumb), R is approximately equal to mean depth d.

Resistance in channels is due to grain roughness and boundary roughness. At a given reach or cross-section in the absence of major changes in boundary materials, variations in roughness within the channel will be due to the growth, destruction, or migration of bedforms, and the addition or removal of obstacles such as vegetation and woody debris. Temporal variations in roughness are typically a function of changes in depth, as roughness elements become drowned. Thus f ~ d, and assuming a power function form, $f \sim d^{-0.5}$. This implies

$$V \sim d^{0.5}\,d^{0.5} = d^{1} \tag{11}$$

Over multiple flow events, the general slope regime is controlled by channel slope,

$$S_c = (h_1 - h_2)/D_{12} \tag{12}$$

where h is the elevation of the channel bed at given upstream and downstream points (1,2), and D_{12} the distance between them. The downvalley elevation gradients are controlled by the regional topographic/geologic setting, and D_{12} by the local sinuousity (ratio of channel distance to valley distance). Thus, over time scales of decades or less, S_c should be relatively constant in the absence of changes in sinuousity. In the study area sinuousity changes are caused by the growth or cutoff of meanders.

If $R \approx d$, $S \approx S_c$ = constant, and f ~ d, then

$$V \approx k\,d, \tag{13}$$

where k is a constant reflecting S, roughness elements within the channel, and the gravity constant.

Methods

Surface water measurements collected by the U.S. Geological Survey (USGS) at 11 gaging stations on the Brazos-Navasota, Trinity, and Sabine Rivers were examined, as described above. All gaging stations were examined in the field, many on numerous occasions, over the 2001 – 2007 period. Aerial and satellite photographs of each gage site and the river channel in the vicinity were also examined. The field and image analyses were to ascertain evidence of significant changes in channel slope or major roughness elements.

Standard USGS data include instantaneous mean velocity (ft sec^{-1}), flow width (w; ft), and cross-sectional area of flow (A; ft^2), based on width times mean depth, with the latter based on multiple measurements across the section. No slope measurements are included. For each set of measurements, mean depth was determined from $d = A/w$. Velocity and depth were converted to SI units (m^3 sec^{-1} and m) and their relationship examined via scatterplots.

Simple regression relationships of the form $V = f(d)$ were explored. Linear, power, exponential, and logarithmic functions were applied to the data from each station. In 10 of 11 cases a linear relationship of the form $V = a + b\ d$ provided the best fit; in the other a power function was the best fit. The linear relationships were converted to the $V = kd^z$ form based on $z = 1$ and $k = (a + bd)/d$.

In addition, at a station at Old River Cutoff connecting the Trinity River near Moss Bluff, TX with the Old River anabranch distributary, the U.S. Army Corps of Engineers collects velocity as well as elevation (gage height) data. While the USGS surface water measurements are collected several times a year, the Old River Cutoff data represents a more or less continuous time series over a short period. For this analysis an arbitrarily-selected 31 day period (August 21 – September 21, 2007) was used, with measurements every 30 minutes over the period.

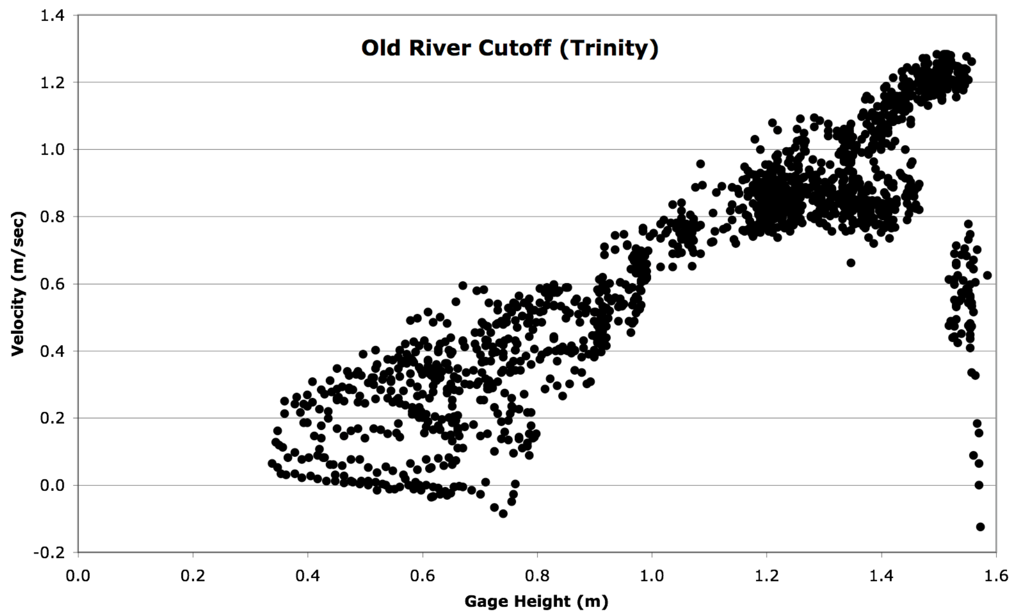
Results

The relationships are summarized in Table 2. Results show that, as expected, $V \sim d^1$ in most cases. However, in many cases the relationship is not strong (as indicated by low R^2) values in Table 2, and at five stations the relationship was not statistically significant at the 0.05 significance level.

Table 2. Relationships between mean velocity (V) and mean depth (d) at southeast Texas gaging stations. Columns k and b represent parameters in the relationship $V = k\, d^b$. R^2 is the coefficient of determination (percent variance explained), with asterisks (*) indicating relationships that are not statistically significant at the 0.05 level. N is the number of measurements, and year the calendar year in which the first measurements in the analyzed data were made.

Station	k	b	R^2	N	Year
Brazos River					
Bryan	0.122	1.37	0.90	98	1992
Hempstead	2.396	1.00	0.65	816	1938
Richmond	-1.065	1.00	0.70	249	1975
Rosharon	0.530	1.00	0.66	297	1967
Navasota River					
Normangee	0.708	1.00	0.33*	90	1996
Trinity River					
Goodrich	0.405	1.00	0.60	330	1965
Romayor	0.189	1.00	0.19*	204	1979
Liberty	0.389	1.00	0.23*	278	1931
Sabine River					
Burkeville	0.801	1.00	0.72	415	1955
Bon Wier	0.188	1.00	0.21*	687	1923
Ruliff (Deweyville)	0.070	1.00	0.06*	674	1924

The data for the 31-day Old River cutoff time series is shown in Figure 2. At gage heights of slightly over 1.5 m (5 feet) the relationship is strongly affected by the water control structure at this site. In the lower part of the figure the relationship with all these elevation values removed is shown.



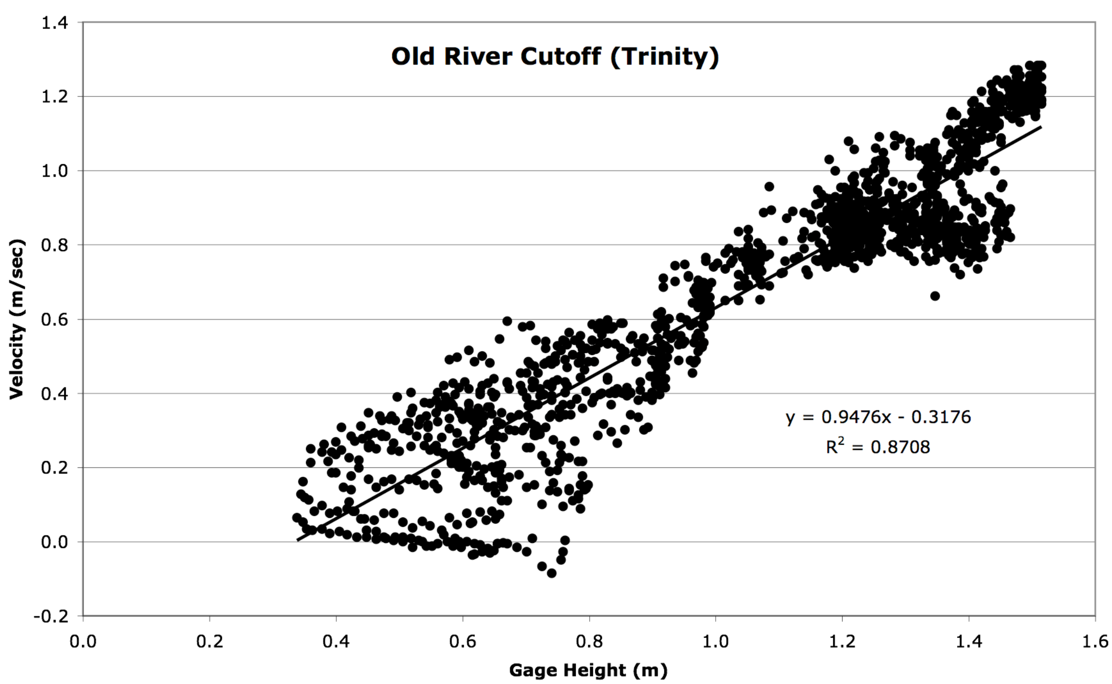


Figure 2. Velocity vs. gage height relationships at the Old River Cutoff control structure, based on data collected at 30 minute intervals August 21 – September 21, 2007. The regression trend line in the lower figure is based on removal of all elevation values >1.515 m.

DISCUSSION

Results from the Brazos River gaging stations, the Goodrich station on the Trinity River, and Burkeville station on the Sabine River, as well as from the Old River Cutoff, support the notion of V ~ d, as well as the fact that the exponent b ($V \sim d^b$) is 1.0 in every case except one, and near 1.0 in that instance (Bryan). However, five stations have low R^2 values (≤ 0.33) and relationships which are not significant at the 95 percent confidence level.

The idea that V ~ d is based on three key assumptions. The first, that $R \approx d$, is not likely problematic, as width-depth ratios are uniformly large at the study sites. The second is that energy grade slope is a function of channel slope, which at a given water level is constant over time ($S \sim S_c$ = constant). This is less likely to hold where recent channel change (aggradation, degradation, lateral migration) has occurred, or where backwater effects from downstream reduce the influence of channel gradient on water surface slopes and hydraulic gradients. The third assumption, that roughness or friction varies inversely with depth, could be violated or complicated over time if there is significant change in the roughness elements (particularly large bedforms and coarse woody debris).

Two of the stations with poor V vs. d relationships (Liberty and Ruliff) have channels cut to below sea level, and are influenced by coastal backwater effects. However, this is even more true of the Old River Cutoff station, which occasionally records negative velocities (i.e., net upstream flows). The datum of the Rosharon station is also approximately at sea level.

A more likely explanation is geomorphic changes in the channel in the vicinity of the gaging stations. Figures 3 and 4 show channel changes in the vicinity of the Trinity River Romayor and Liberty gaging stations, based on field geomorphic indicators. In both cases extensive change is evident. The same is true for the Bon Wier and Ruliff gaging stations on the Sabine River, as shown by Phillips (2003). However, the Burkeville station, which has a strong velocity-depth relationship, is also shown by Phillips (2003) to have experienced significant recent geomorphic change.

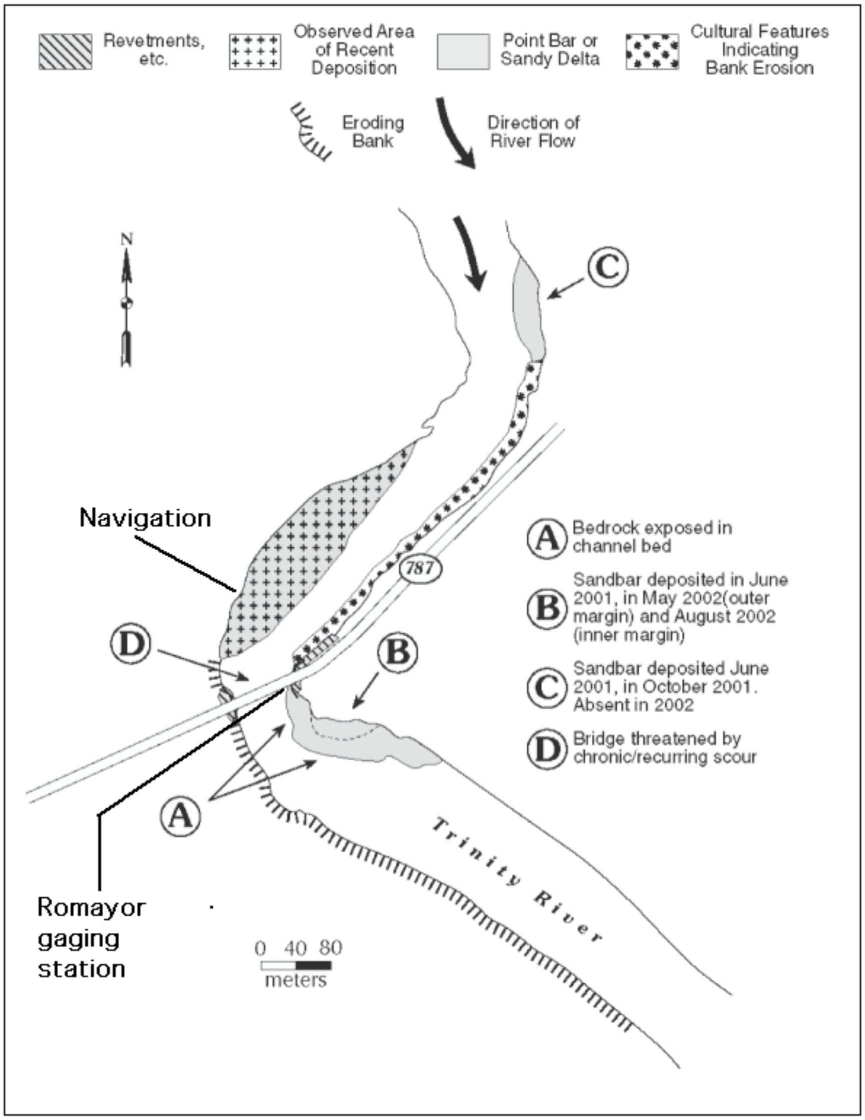


Figure 3. Geomorphic changes near the Romayor gaging station on the Trinity River. Modified from Phillips et al., (2005). "Navigation" marks the location of a navigational warning sign, originally affixed to a piling within the channel, discovered in 2005.

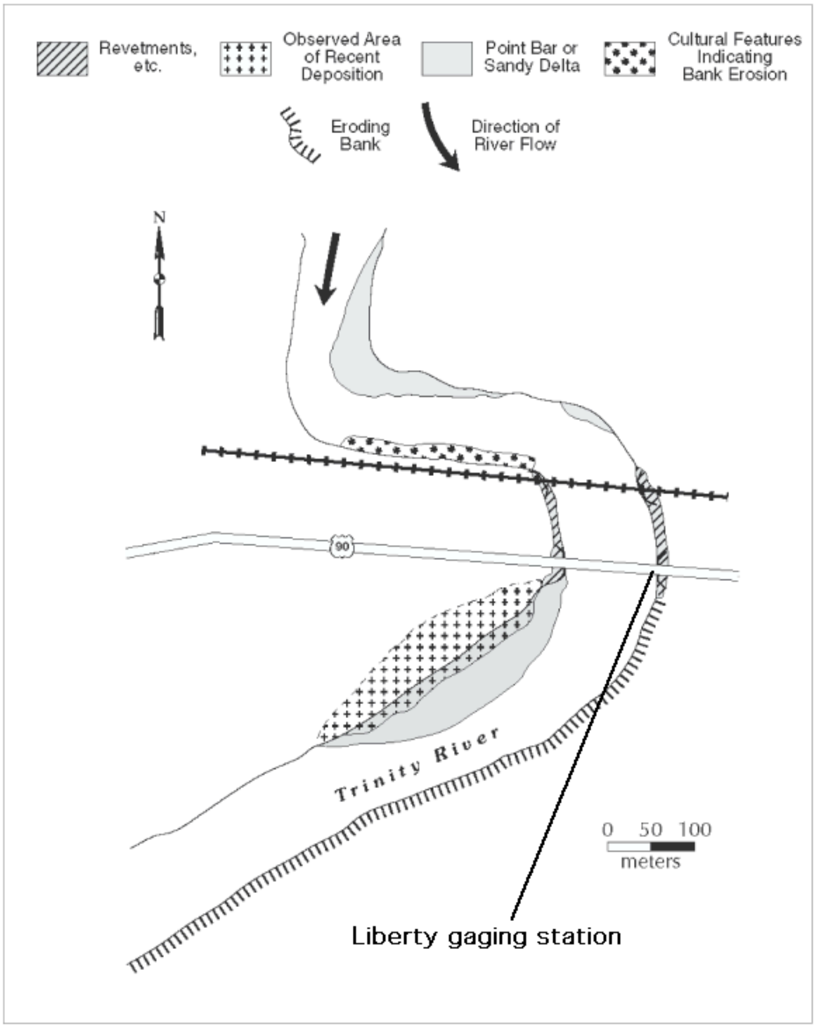


Figure 4. Geomorphic changes near the Liberty gaging station on the Trinity River. Modified from Phillips et al., (2005).

The Navasota station near Normangee is a special case, as this is an anabranching system, where most flow is in a single channel at low flows, but the other channels are activated at higher flows. Thus it is unlikely that a consistent V/d relationship would be detected based on data that includes both high and low flows.

Of the stations with relatively strong ($R^2 \geq 0.6$) statistically significant relationships, all except the Burkeville station appeared relatively stable when visited in the field at various times in the 2005-2007 period, in terms of geomorphic indicators of extensive recent change.

Velocity/depth/roughness relationships would also be expected to break down (or change dramatically) when flows go overbank. Table 3 shows the coefficient of determination for the velocity-depth relationship for each station, and the percentage of measurements analyzed which were overbank flows. A relatively high number of measurements during overbank flows could be related to poor relationships at Normangee and Liberty, but Ruliff, which had the worst relationship, had only 2.7 percent of the measurements taken at overbank flows. Note that the percentages in Table 3 refer strictly to the number of times field measurements were recorded at flows at or above flood stage, which is not necessarily related to flood frequency at the gaging sites.

Table 3. Coefficient of determination (R^2) for the velocity-depth relationship, and the number (percentage in parentheses) of measurements taken at flood stage or above.

Station	R^2	Overbank
Brazos River		
Bryan	0.90	0
Hempstead	0.65	1 (0.12)
Richmond	0.70	3 (1.20)
Rosharon	0.66	12 (4.04)
Navasota River		
Normangee	0.33*	7 (7.78)
Trinity River		
Goodrich	0.60	6 (1.82)
Romayor	0.19*	2 (0.98)
Liberty	0.23*	41 (14.75)
Sabine River		
Burkeville	0.72	3 (0.72)
Bon Wier	0.21*	9 (1.31)
Ruliff (Deweyville)	0.06*	18 (2.67)

Results provide some support for the notion that, due to the tendency of roughness or friction factor to vary inversely as a function of depth as roughness elements are drowned, mean velocity varies as a direct function of depth. However, poor relationships may be expected where the major assumptions of the model are violated—in this case, where channel slopes do not necessarily well represent energy grade slopes, or where roughness does not vary systematically with depth.

CONCLUSIONS

Theoretical analyses suggest that the relationship between fundamental hydraulic variables is dynamically unstable, with the instability manifested as multiple modes of adjustment and as opposite-from-expected (OFE) behavior. OFE responses occur when one or more hydraulic variables change in response to increases or decreases in discharge in the opposite direction from that expected from hydraulic theory.

At 11 gaging stations on the Brazos/Navasota, Trinity, and Sabine Rivers, 84 to 475 flow transitions were examined from USGS stream gaging data. All stations exhibited a significant proportion of OFE responses (16.7 to 80 percent) in that at least one of the variables of discharge, width, mean depth, cross-sectional area, mean velocity, and Froude number changed in the opposite direction from the others. At seven of the 1stations more than half of the comparisons indicated OFE behavior.

Multiple modes of adjustment and dynamical instability indicate that no characteristic form or steady-state is likely to characterize hydraulic geometry adjustments over time in a given reach, or along a channel. Nonequilibrium hydraulic geometry does not preclude some level of generalization, but does suggest caution in developing and applying generalizations. The same data set used for the OFE analysis was used to test the idea (based of fundamental flow resistance relationships) that velocity varies linearly with mean depth due to an hypothesized tendency for roughness to vary inversely with depth.

Results provide some support for the proposed relationship, but only as a relatively broad generalization. Further, , poor relationships may be expected where the major assumptions of the model are violated—in this case, where channel slopes do not necessarily well represent energy grade slopes, or where roughness does not vary systematically with depth. The instability of hydraulic geometry no doubt accounts for some cases where assumptions are violated, and for some of the scatter in the V-d relationship even where the assumptions hold.

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Section 3
Geomorphic Role of Avulsions in Southeast Texas Rivers

ABSTRACT

Avulsions—relatively sudden changes in course, or establishment of new anabranches—are an important process in alluvial rivers. Their key role in floodplain construction and alluvial architecture, and the general conditions favoring avulsions, are well known. However, avulsion processes and evolution, and their role in geomorphic adjustments of the fluvial system, are poorly understood. In the southeast Texas coastal plain, where avulsions are common features of the river valleys, avulsions were studied on the lower Brazos, Navasota, Trinity, Neches, and Sabine Rivers. Avulsions have important influences on the surface morphology and contemporary processes in all five. Features associated with avulsions are active and distinct throughout the study area, and all the rivers have experienced geologically (if not historically) recent avulsions, but no two of the study rivers have the same contemporary avulsion regime. Differences in avulsion style are controlled by the stage of valley filling, and within the three rivers characterized by an unfilled incised valley, antecedent morphology associated with late Quaternary and Holocene coastal, fluvial-deltaic, and neotectonic processes accounts for the major differences. In the Navasota (27 avulsions in 185 km) and Neches (21 in 340 km) subchannels associated with avulsions exist in all stages of development from active to infilled, and some are known to have occurred in recent decades. The other rivers have fewer avulsions, but both the Sabine and Trinity have experienced historic channel shifts. Only the Brazos has experienced no avulsions with the past ~300 years. The role of avulsions in these fluvial systems is as a mechanism for distributing sediment in deltas and infilling valleys, and as an unstable, contingent response to perturbations. Avulsions do not appear to be a mechanism for slope adjustments in a way comparable to meander growth/cutoff or channel aggradation/incision.

INTRODUCTION

Avulsions—relatively abrupt changes in course, or establishment of new anabranches—are a key but poorly understood process in alluvial rivers. Avulsions are an obvious concern for river users and managers, and play an important, sometimes dominant, role in the construction of floodplains and alluvial deposits.

In a comprehensive review, Slingerland and Smith (2004) found that the causes of river avulsions remain relatively unknown: "At present, we simply don't know the necessary and sufficient conditions causing a river avulsion" (258). Beyond the hydrologic, geomorphic, ecological, and engineering implications of avulsions, geomorphologists and sedimentologists increasingly see avulsions, rather than lateral migration and overbank deposition, as the major mechanism of floodplain construction in many river systems (Slingerland and Smith, 2004; Blum and Aslan, 2006).

Rivers of southeast Texas have historically been profoundly influenced by avulsions (Blum and Aslan, 2006). Much of the research on river avulsions in general, and in the Gulf Coast region in particular, has focused on the sedimentary record, due to the critical role of avulsions in floodplain construction and the profound influences on alluvial architecture. This study, by contrast, focuses on the effect of channel shifts on the contemporary river and valley morphology, and on their role in internal adjustments of the fluvial system, based on the lower reaches of five rivers in southeast Texas.

Avulsions and Anabranching

Slingerland and Smith's (2004) review indicates that avulsions are strongly associated with aggrading floodplains. While the review makes it clear that the causes are poorly known, this is not to say that avulsions are randomly distributed, or that both internal (autogenic) or external (allogenic) conditions or forcings promoting or inhibiting avulsions are unknown. In the Rhine-Meuse delta, for example, the most extensively-studied region of the world in this respect, Stouthamer and Berendson (2007) indicate that avulsion locations are nonrandom and can be related to allogenic factors of sea level rise, climate change, and human influences. Similar conclusions can be inferred from Taha and Anderson's (2007) work on the lower Brazos River, Texas. However, even in these cases the conclusion holds that the controls over the timing and specific location of avulsions are poorly understood.

Avulsions and anabranching are closely related, though avulsions are also common in single-channel systems. Anastamosing rivers most often form in relatively low-energy conditions near a local base level, and avulsions are the usual mechanism for creating anastamosing channel patterns (Makaske, 2001). This may be by forming bypasses, with the by-passed older channel segment persisting, or by bifurcation of the diverted avulsive flow, leading to scour of multiple channels in the floodplain. Both may be present in the same system, but the latter is generally only a stage in the avulsion process on a local part of the floodplain, whereas the former may be a long-lived phenomenon involving the entire floodplain (Makaske, 2001). Nanson and Knighton (1996) categorize mechanisms that produce multiple-channel, anabranching patterns as avulsion-based processes involving scouring of new channels into the floodplain, or reoccupation of old channels, and accretion-based processes. The latter includes channel extension into floodbasins that represents one of the avulsion styles recognized by other workers (Slingerland and Smith, 2004; Blum and Aslan, 2006).

Abrupt channel changes are best understood via a setup-and-trigger framework. The former represents necessary conditions (such as aggradation) that allow for the possibility of avulsion, while triggers are specific events that divert flow from the main channel (Nanson and Knighton, 1996; Jones and Schumm, 1999; Makaske, 2001; Slingerland and Smith, 2004). The overview of avulsion causes by Jones & Schumm (1999) describes triggers as events that abruptly modify channel capacities by changing bed geometry, discharge, or other factors. Trigger events are most commonly floods, but also include abrupt tectonic movements, ice or log jams, vegetation, debris, beaver dams, bank failures, and bar migrations which divert flows (Jones and Schumm, 1999).

The specific location and timing of avulsions is not predictable at present, and is highly contingent on localized conditions and histories, and the timing of flood and other hydrogeomorphic events (Jones and Schumm, 1999; Makaske, 2001; Slingerland and Smith, 2004). In general conditioning or setup factors making avulsions possible or likely include aggradation of channels and floodplains, low floodplain gradients, potential slope gradient advantages within the alluvial valley, and the presence of paleochannels and/or floodbasins which may be reoccupied (Aslan and Blum, 1999; Makaske, 2001; Slingerland and Smith, 2004; Aslan et al., 2005). While gradient advantages appear to be necessary for avulsions to occur, they are hardly sufficient. Aslan et al. (2005) found that though potential gradient advantages on the Mississippi River floodplain are common, avulsions are relatively rare. Based on this, Aslan et al. (2005) suggested that substrate composition and floodplain channel distributions are key controls of avulsions.
Locally, the outer portion of bends or meanders appear most favorable for avulsions, due to high velocity, local water superelevation, high incidence angles on banks, and narrower levees (Makaske, 2001; Slingerland and Smith, 2004).

Slingerland and Smith (2004) distinguish between full and partial avulsions, based on whether all flow is diverted, versus an anastamosing or distributary planform. They also identify three avulsion styles, characterized by annexation or existing active or abandoned channels, incision into the floodplain surface, or "spillover" (progradation of distributary networks, often by diversion into flood basins).

Texas Coastal Plain Avulsions

According to Aslan and Blum (1999), Texas Gulf coastal plain rivers undergo two distinct styles of avulsion—reoccupation of former channels, and diversion into flood basins. The Nueces and Trinity Rivers are believed to represent early stages of sedimentary infilling in response to Holocene sea level rise, and avulse by reoccupying late Pleistocene channels cut during falling and lower-stand sea levels. The Colorado River is characterized as representing a later stage of infilling where most of the accommodation space is filled. Avulsions here occur as repeated diversions into floodplain depressions.

Trinity (and Nueces) River channels may be short-lived due to the abundance of paleochannels and erodible channel deposits, which lead to frequent avulsions (Aslan and Blum, 1999). Reoccupation of paleochannels is discontinuous downstream, with Holocene channels typically occupying the paleochannels for only 5 to 10 km. Lateral migration which intersects paleochannels, or overflow into Pleistocene paleochannels during floods appear to be the chief mechanisms involved (Aslan and Blum, 1999).

Blum and Aslan (2006) linked floodplain formation and alluvial sedimentology in the region to avulsions. Transgressive to highstand facies-scale architecture reflects changes through time in the dominant styles of avulsion, and follows a predictable succession through different stages of valley filling. Complete valley filling promoted avulsion and the large-scale relocation of valley axes before the next sea-level fall, such that successive 100 kya valley fills show a distributary pattern. Deposits of individual avulsions are separated by massive to slickensided muds or buried weakly-developed soil horizons that represent periods of slow sediment accumulation or floodplain stability between episodes of avulsive deposition. As valley filling nears completion, avulsion by channel reoccupation again becomes the dominant process, and again results in amalgamated channelbelts. The Beaumont surface, a Pleistocene formation which comprises the valley walls in the lower coastal portions of the study rivers, consists of multiple cross-cutting meanderbelts with intervening flood basins, and interpreted alluvial plain surfaces to have been constructed by a series of autogenic meander-belt avulsions during sealevel highstand (Blum and Aslan, 2006).

Avulsions, and changes in avulsion styles through time, play a critical role in the architecture of the transgressive to highstand valley fill (Aslan and Blum, 1999). During the early stages of valley filling, avulsion occurs by reoccupation of abandoned falling stage and lowstand channels, with erosion and reworking of older channelbelt sands. This produces channel-in-channel stacking patterns, or multilateral and multistory channelbelts. As rates of valley filling increase, channelbelts aggrade rapidly and create raised alluvial ridges with significant cross-valley gradients, and avulsion occurs by repeated diversion into floodplain depressions. This creates ribbon-like channelbelts, ribbon-like crevasse channel sands, and thin (<5 m) multilateral and multistory crevasse–splay sheet sands that are encased in thick successions of massive to laminated floodbasin muds. When rates of aggradation are relatively low, avulsion by channel reoccupation again becomes the dominant process.

The Sabine/Neches and Trinity incised valleys are unfilled, in the early stages of filling as described above, and avulsion has so far taken place by reoccupation of Pleistocene falling stage to lowstand channelbelts. By contrast, the Brazos and Colorado valleys are filled, and has progressed through the entire sequence described above (Blum and Aslan, 2006).

Avulsions are still a regular occurrence in the region. Taha and Anderson (2007) date the channel shift of the Brazos River from the Oyster Creek to the current course at about 1.5 ka, and Waters and Nordt (1995) found evidence of Brazos avulsions as recently as 300 and 500 years BP. Radiocarbon dates from tree stumps in growth position indicate that the Colorado River avulsed 200 to 400 BP from the main post-Beaumont alluvial valley near Wharton, TX (Aslan and Blum, 1999). Evidence of avulsions within recent decades has been observed in the lower Navasota and Sabine Rivers (Phillips, 2007a; 2007b).

At least two studies in the region have focused on historical planform changes following river impoundment. Gillespie and Giardino (1997) found that lateral migration rates on the Brazos River decreased significantly following flow regulation, though post-regulation rates are still quite high. As other studies have indicated that effects of impoundments on flows in the lower Brazos are minimal (Hudson and Mossa, 1997; Dunn and Raines, 2001), the cause of the apparent changes are unclear. On the lower Trinity, Wellmeyer et al. (2005) also found lower (but still high) lateral migration rates in recent decades, but pointed out that in such relatively short-term studies based on aerial photography and other historical data, the presence or absence of meander cutoffs may disproportionately influence the lateral migration rates.

Other Channel Changes

Avulsions begin as crevasses or flow diversions, some of which do not persist. Those that do persist may result in channel relocations, or the development of anabranching or distributary patterns.

Diversions, crevasses, or other localized bank or levee breaches which persist do not necessarily constitute avulsions, however. Some of these are meander cutoffs, which may be further categorized as neck cutoffs (occurring at or near the base of the bend) or chute cutoffs (across a point bar). Meanders migrate laterally and downvalley, eroding their banks on the outside of bends and simultaneously depositing material on the inside. Growth of individual meanders may continue until cutoff occurs. Cutoffs are often the result of flow encountering more resistant material or shear stress reduction due to flattening of energy slope. Peakall et al. (2007) also report, based on laboratory experiments, that channel bars may initiate chute cutoffs.

CONCEPTUAL FRAMEWORK

Avulsion Occurrence

The literature indicates a consensus that avulsions are associated with floods or threshold discharges required to breach levees, and that slope advantages are a necessary condition. This is reflected in Mackey and Bridge's (1995) model of alluvial stratigraphy, in which the probability of an avulsion at a cross-valley transect is modeled as

$$P(a) = (Q_f/Q_a)^{eQ}\ (kS_{cv}/S_{dv})^{eS} \qquad (1)$$

Where Q_f is maximum flood discharge for a given time period, Q_a is the threshold discharge for an avulsion to occur, S_{cv} is cross-valley slope at the edge of the channel belt, and S_{dv} the local downvalley slope of the channel belt. Equation (1) is based on assumptions that for avulsions to occur a critical discharge threshold must be achieved (presumably associated with elevations necessary for levee breaches), and a cross-valley slope gradient advantage must exist. The slope proportionality constant k ranges from 0.1 to 0.5 in Mackey and Bridge's (1995) simulations, and is used to reduce the influence of large cross-valley slopes immediately adjacent to the channel belt relative to smaller S_{cv} values further from the alluvial ridge. If $S_{cv}/S_{cx} > 1$, their simulation model automatically sets $(kS_{cv}/S_{dv}) = 1$. The discharge and slope exponents eQ, eS are model coefficients used by Mackey and Bridge (1995) to tune the model to produce realistic avulsion frequencies.

The relative roles of autogenic and allogenic avulsion processes in the Rhine-Meuse delta were assessed by Stouthamer and Berendsen (2007) using the Mackey and Bridge (1995) model, acknowledging that the k, eQ, and eS terms in essence incorporate stochastically the local, contingent factors so critical in triggering avulsions.

The occurrence of an avulsion can be treated as a local perturbation to the fluvial system. The fate of such local perturbations depends in the dynamical stability of the system, which determines whether the effects of small disturbances are damped so that the pre-disturbance state is recovered (stable) or amplified so that a new system state is achieved (unstable). An intermediate condition (metastability) is possible where the effects of a perturbation persist without significant amplification, and a new stable state is created. Formally

$$\boldsymbol{x}(\mathrm{t}) = \boldsymbol{C}\, \boldsymbol{x}(\mathrm{o})\, e^{\lambda t} \qquad (2)$$

where $\mathbf{x}$ is a vector representing the set of variables or components comprising the dynamical (geomorphic) system, $\boldsymbol{x}(\mathrm{t})$, $\boldsymbol{x}(\mathrm{o})$ is the system state at time t and originally (at the time of perturbation), $\mathbf{C}$ is a vector constant, and $\boldsymbol{\lambda}$ are the Lyapunov exponents of the system. If all $\boldsymbol{\lambda} < 0$, then $\mathbf{x}(\mathrm{t}) \rightarrow \mathbf{x}(\mathrm{o})$ and the system is stable. Any positive λ indicates dynamical instability.

While specific locations of avulsions are opportunistic and geographically and historically contingent, and the mechanisms relatively unknown, stability analyses suggest that thresholds in the relative energy slope and Shields parameter of the bifurcating channel system are key factors (Slingerland and Smith, 1998). The model of Slingerland and Smith (1998) is focused on the question of whether a crevasse heals (infills and degrades), grows to an avulsion, or persists in a steady state. They found that this depends chiefly on the ratio of the slopes of the crevasse and main channel (S_c/S), the elevation of the crevasse bed above that of the main channel, and grain size. The theory underlying the model is that a flow split or bifurcation is stable if and only if sediment of original channel *a* is partitioned between *a, b* in proportion to their sediment conveying capacities. Otherwise, modifications continue until proportionality is achieved, and the avulsion becomes stabilized as an anastamosed or distributary system, or either the old or new channel closes (full avulsion or healed crevasse). The model results suggest that the stability of the bifurcation is a function of Shields parameters, friction coefficients, grain size, width/depth ratio of the main channel, slopes of *a, b* and the initial elevation difference (Slingerland and Smith 1998).

The Slingerland and Smith (1998) model combined with the more general dynamical stability relation in eq. (2) allows a straightforward test of the local stability of an avulsion. A "failed" avulsion where the main channel retains dominance suggests stable equilibrium, since adjustments following the perturbation restore the original state. A successful avulsion where the main channel is abandoned indicates dynamical instability, as a relatively small perturbation (a levee breach) results in disproportionately large changes in the system. A persistent anabranch or distributary bifurcation suggests metastability, in that a perturbation results in a new stable equilibrium state.

This discussion of stability focuses on local stability within a river reach influenced by a crevasse. Local instabilities in geomorphic systems may sometimes be directly related to broader-scale stability—that is, the unstable local responses in effect provide mechanisms or degrees of freedom to respond to changes at the broader scale (Trofimov and Phillips, 1992; Pahl-Wostl, 1995; Phillips, 1999; Hergarten, 2002). In this context (locally) unstable cutoffs and avulsions may be important mechanisms for broader-scale river adjustments of slope gradients, energy dissipation, and sediment distribution.

General Stability Model

The principles discussed above can be treated in a general qualitative stability model. While the specific quantitative relationships and process mechanical links among slope, aggradation, and avulsion may be quite variable, consensus exists with respect to qualitative relationships. Channel and valley aggradation promote avulsions, as avulsions are most common in aggrading systems, and aggradation thresholds are necessary (if not sufficient) setup factors. Aggradation also generally reduces downvalley and channel slopes. Downvalley slope has a negative relationship with both aggradation and avulsions. Other things (chiefly discharge) being equal, slope is directly related to stream power, and thus lower slope gradients promote deposition and aggradation, and vice versa. Lower downvalley slopes also tend to favor avulsions as they decrease relative to cross-valley slopes. Finally, avulsion has a direct, positive impact on slope because successful avulsions invariably exploit slope advantages.

These relationships are shown in Figure 1. The diagram also shows self-limiting links for slope and aggradation, and positive self-effects for avulsions. This reflects geomechanical upper limits on slope gradients and the need to maintain a minimal slope for downstream water movement, and the effects of accommodation space in promoting aggradation (or the filling thereof in limiting aggradation). The positive loop for avulsions represents the various factors other than slope and aggradation that may promote, inhibit, trigger, or prevent avulsions.

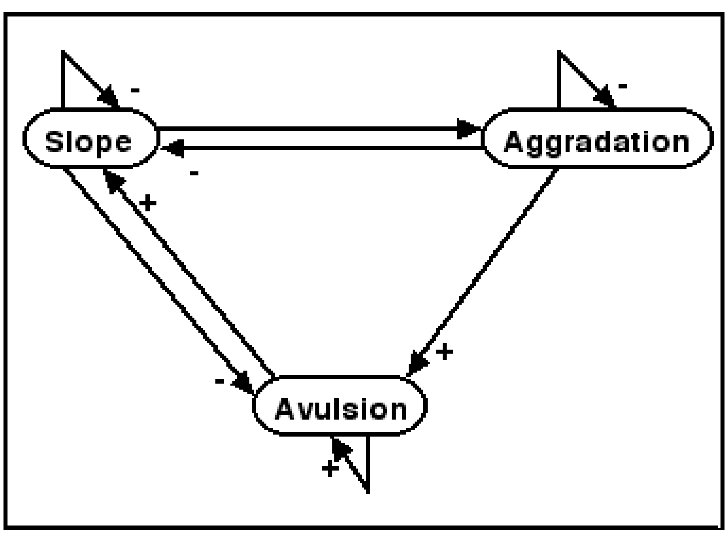

Figure 1. Relationships among (downvalley) slope, aggradation, and avulsions. See text for explanation.

Table 1. Interaction matrix for figure 1.

	Slope	Aggradation	Avulsion
Slope	$-a_{11}$	$-a_{12}$	$-a_{13}$
Aggradation	$-a_{21}$	$-a_{22}$	a_{23}
Avulsion	a_{31}	0	a_{33}

The relationships in Fig. 1 are shown in the form of an interaction matrix in Table 1, where each entry represents the positive, negative, or negligible influence of the column component on the row component. The stability of this system can be evaluated using the Routh-Hurwitz criteria, which are that all coefficients α of the characteristic equation are negative, and that successive Hurwitz determinants are positive. For a three-component system the latter is based on whether

$$\alpha_1 \alpha_2 + \alpha_3 > 0 \tag{3}$$

These are necessary and sufficient conditions for local stability.

The characteristic equation of Table 1 is

$$-\lambda^3 + [(-a_{11}) + (-a_{22}) + a_{33}]\,\lambda^2 + [(-a_{12})(-a_{21}) + (-a_{13})a_{31}]\,\lambda + [(-a_{12})a_{23}a_{31} - (-a_{12})a_{31}(-a_{ss})] = 0 \tag{4}$$

The real parts of the complex eigenvalues of the system (λ) are also the Lyapunov exponents of the system (eq. 2). The third coefficient (α_3) must always be negative. If the external factors promoting or preventing avulsions are strong compared to the self-effects of aggradation and slope, α_1 may be positive. Otherwise, the first coefficient is negative, and if the following holds, $\alpha_2 < 0$ and the system may be stable. Otherwise, the system is unstable.

$$(-a_{13})a_{31}) > (-a_{12})(-a_{21}) \tag{5}$$

This inequality will hold if the feedback relationships connecting slope and avulsions are stronger (operate at a faster rate) than those connecting slope and aggradation. This is likely to be the case where the river is not near the aggradation threshold. If $\alpha_1, \alpha_2, \alpha_3 < 0$, then eq. (3) is also likely to hold since the shorter loops generally operate more rapidly than the longer loops represented by α_3.

The model implies that in the absence of strong external (to the slope-aggradation-avulsion system) controls on avulsion, and where slope-avulsion feedbacks are stronger than slope-aggradation links, the system is dynamically stable. If limiting external controls are not dominant, and aggradation-slope feedbacks are strong, the system is dynamically unstable.

This result is consistent with the simulation models of Mackey and Bridge (1995) and Slingerland and Smith (1998), though the latter concerns the stability of a bifurcated channel, and with most empirical studies. Ignoring external controls which may obviously induce either stability or instability, a reach approaching the aggradation threshold, with strong aggradation-slope interrelationships, is unstable such that a small change—e.g. a levee breach enabled by local biological activity or local channel aggradation (c.f. Miller, 1991; McCarthy et al., 1992; Makaske et al., 2002)—is prone to grow into an avulsion. Far from this threshold, where slope-aggradation links are not as strong, or after an avulsion is established, where strong slope control exists, the system is stable and unlikely to avulse in the absence of strong triggers.

Role of Slope and Resistance

While a potential slope advantage seems necessary for an avulsion—particularly since the incipient channel is unlikely to have any roughness or channel capacity advantages—such advantages are apparently not sufficient. Aslan et al.'s (2005) work on the lower Mississippi River shows that while potential slope advantages relative to the main channel are common, avulsions are rare, and not necessarily associated with the greatest slope advantages.

The notion of a critical threshold slope ratio for avulsion was identified by Jones and Schumm (1999), and Slingerland and Smith (1998) estimated the value to be ~5. Tornqvist and and Bridge (2002) showed that avulsions have high probabilities of occurrence with ratios of 3 to 5. However, Aslan et al. (2005) found ratios of cross-valley to downvalley slope of 16 to 110, and typically >30. Thus Stouthamer and Berendson (2007: 312) conclude: "Although gradient advantages are considered necessary for an avulsion to occur, slope ratios apparently are not fully or in some cases possibly not at all responsible for the occurrence of avulsions."

In the Mississippi River, Aslan et al. (2005) conclude that substrate composition (particularly sandy crevasse deposits that are readily scoured) and floodplain channel distributions are more important than slope. This concurs with Hudson and Kesel (2000) who found that resistant clay plug channel fills inhibit lateral channel change.

Development of Avulsed Channels

The conceptual framework adopted here assumes that any channel change begins with a breaching of a levee. Some such breaches may result in spreading, decelerating flow and a crevasse splay or general floodplain inundation and thus no channel change. Otherwise, channelized flow may either incise into the floodplain surface, or occupy an old channel.

If such a channelized breach occurs in the upstream portion of meander bend, the result is a neck or chute cutoff. Otherwise, an avulsion occurs.

If the new channel does not persist, the avulsion may be transient. If the new channel does persist, and the old is not maintained a relocation avulsion results. If both channels persist, and eventually rejoin, the result is anastamosis. A distributary network is the usual outcome if both channels persist but remain separated. However, as the contemporary Brazos and Colorado Rivers show, such avulsions can result in watershed fragmentation if hydraulic connections are lost.

Even transient avulsions may have important impacts beyond their role in floodplain construction. Former avulsion channels may be occupied at high flows (flood or high-flow anabranches), or capture or become occupied by tributaries.

These channel changes and their outcomes can be presented graphically (figure 2) and in the form of a decision key (table 2).

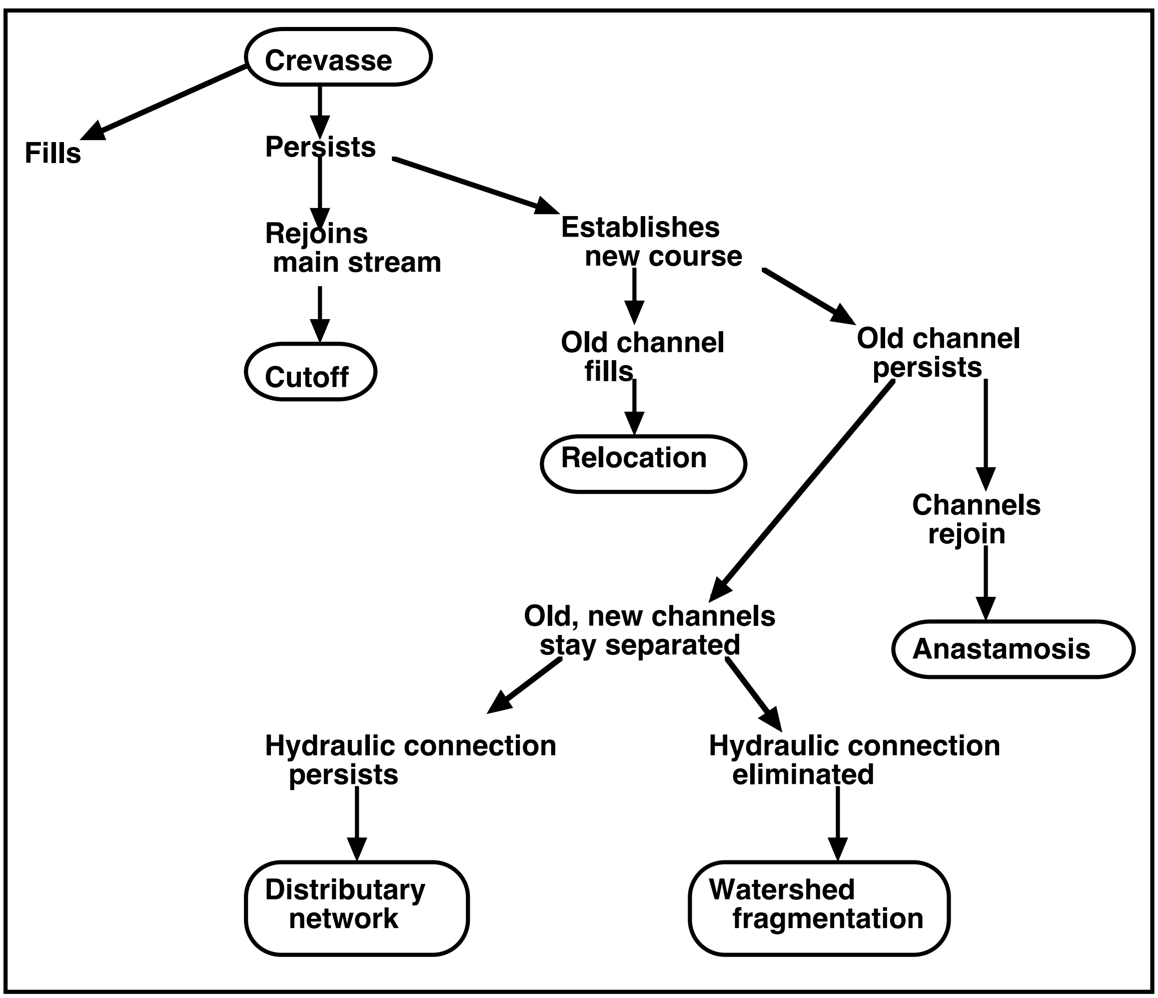

Figure 2. Possible outcomes of crevasses and avulsions.

Table 2. Decision key for evaluating channel changes and resulting geomorphic features.

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1. Does levee breach occur?
    - Yes: go to 2
    - No: no channel change

2. Breach results in spreading flow or ephemeral channel: Crevasse splay: no channel change
   Breach results in channelized flow
    - Cuts new channel: go to 3
    - Occupies old channel: *Reactivation*

3. Breach channel occurs on upstream side of meander bend.
    - Yes: Go to 4
    - No: Go to 5

4. Breach channel cuts across point bar: *Chute cutoff*
   Breach channel cuts across meander neck: *Neck Cutoff*
   Other: Go to 5

5. Do both channels persist?
    - Yes: Go to 7
    - No: Go to 6

6. Old (original) channel persists: *Transient Avulsion;* Go to 9
   New avulsion channel persists: *Relocation;* Go to 9

7. Channels rejoin: *Anastamosis*
   Channels remain separated: go to 8

8. Hydraulic connection eliminated at all common flows: *Watershed Fragmentation*
   Hydraulic connection persists:
    - At high flows only: *Partial Watershed Fragmentation*
    - At most flow levels: *Distributary*

9. Paleochannel reactivated at high flow: *Flood Anabranch*
   Paleochannel occupied by or captures tributary: *Paleochannel Tributary*
   Paleochannel infilled; does not convey flow: *Channel Plug*

Historical Contingency

The occurrence of an avulsion may reduce the short-term probability of a future avulsion in the same vicinity (Stouthamer and Berendson, 2007). Conversely, the presence of an abandoned but potentially re-occupiable channel may be potentially enhance the probability of avulsions in the longer term, when conditioning factors such as channel aggradation have had an opportunity to operate for a sufficiently long time. The importance of the latter may in turn be affected by the dominant avulsion style, related to the stage of valley filling (Aslan and Blum, 1999; Blum and Aslan, 2006). Infilled paleochannels may either promote or inhibit future avulsions, depending on whether the fill is easily erodible sand, or resistant clay plugs (Aslan et al., 2005; Hudson and Kesel, 2000).

In a deltaic setting avulsion sequences may occur as active channel belts aggrade to the avulsion threshold. When an avulsion occurs, the newly formed channel is less likely to avulse as it is still well below the avulsion threshold. Further upstream, however, where the channel belt is still near the aggradational threshold, avulsions are more likely. This continues until avulsions have shifted to the delta apex. Then the next avulsion occurs in the downstream part, as aggradation, growth of alluvial ridges, and cross-valley slopes have had time to increase, and the sequence begins again. This sequence was observed by Stouthamer and Berendson (2007).

Thus avulsions are historically contingent not only in terms of the setup and trigger factors, but also with respect to the avulsion history itself.

STUDY AREA (Note: this material is repeated, for convenience, from section 1)

The study area (Figure 3) includes the Brazos River from the bridge and gaging station on state highway (SH) 21 near Bryan to the Gulf of Mexico; the Navasota River from the Lake Limestone Dam to the Brazos River confluence; the Trinity River from (Lake) Livingston Dam to Trinity Bay; the Neches River from the SH 21 crossing to Beaumont; and the Sabine River from Toledo Bend Dam to the Sabine Lake estuary. The river distances are 469, 185, 175, 340, and 214 km, respectively.

The climate is humid subtropical, and the topography ranges from virtually flat in the coastal marshes to gently rolling. Soils—as might be expected in such a large area—are quite variable. The oldest and most strongly weathered soils are Paleudults and Kandiudults on Tertiary and older Quaternary uplands, but Vertisols, Alfisols, and Mollisols are common in smectitic parent materials and those with significant carbonate contents. A variety of recent, poorly developed Inceptisols and Entisols occur on floodplains, deltas, and coastal wetlands.

The Quaternary geologic framework is of most significance to this study, so it will be described in some detail.

Quaternary Geology

The uppermost portions of the studied Brazos, Navasota, and Neches reaches are in Tertiary coastal and marine formations, but otherwise the entire study area is in Quaternary material. Recent reviews and syntheses of the Quaternary geologic framework and sea level history of the region (and some of the controversies pertaining

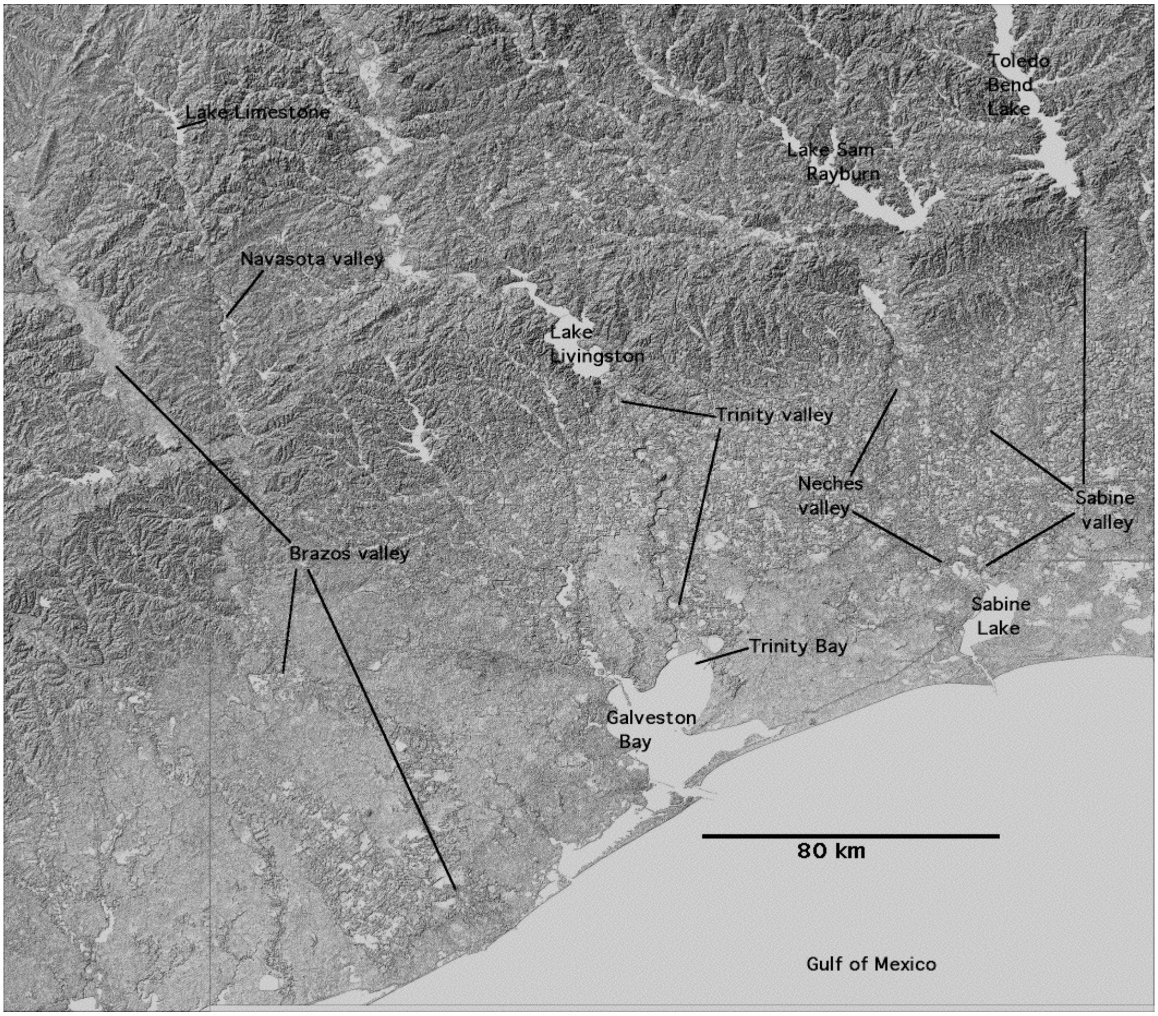

Figure 3. Study area, showing major river valleys, reservoirs, and estuaries.

thereto) are provided by Blum et al. (2002) and Otvos (2005). Recent research on the role of antecedent topography and recent geologic and sea level history on current forms, processes, and evolution are given for the Brazos River by Sylvia and Galloway (2006), Phillips (2007b), and Taha (2007; Taha and Anderson, 2007); for the Navasota by Phillips (2007b); for the Trinity by Rodriguez et al. (2005) and Phillips and Slattery (2007a); and for the Sabine by Phillips (2007a).

The study rivers are flanked by modern floodplains and flights of several Pleistocene Terraces. The oldest and highest are the Beaumont terrace (correlative with the Prairie surface in Louisiana). Dates for the Prairie-Beaumont formation in Louisiana and Texas reviewed by Otvos (2005) range from 33 to 195 Ka. Otvos' (2005) analysis places the deposition of the Beaumont terraces in Texas, which are 50 to 100 km wide from the coast, at 74 to 116 Ka--broadly consistent with Blum et al. (1995) and Thomas and Anderson (1994).

Below the Beaumont surface and often merging into the modern floodplain are a series of up to three alluvial terraces. These are typically referred to as Deweyville, though they are no longer interpreted as part of a single terrace system (Blum et al., 1995; Morton et al., 1996). In most locations "at least two" (Blum and Price, 1998), or three (Blum et al., 1995; Morton et al., 1996; Rodriguez et al., 2005) separate "Deweyville" surfaces are recognized, though not always exposed at the surface. Where exposed, the lowest of these terraces are only slightly higher than the modern floodplain (Alford and Holmes, 1985; Anderson et al., 2005; Blum et al., 1995). Aerial photographs show obvious palaeomeanders in the Trinity, Neches, and Sabine valleys, expressed as swampy depressions or meander scrolls. These occur on the Deweyville surfaces, with radii of curvature and amplitudes suggesting significantly larger palaeodischarges than at present (Alford and Holmes, 1985; Blum et al., 1995). Cuspate indentations in the valley wall of the Brazos, where most of the Deweyville terraces are buried, are also associated with these higher paleodischarges (Sylvia and Galloway, 2006).

In the Sabine River Alford and Holmes (1985) date the undifferentiated Deweyville surfaces at 4-9 ka. In the Colorado River, Texas, Blum and Price (1998) place the deposition of the Eagle Lake Alloformation, youngest of the group, from 20 to 14 Ka, followed by incision from 14-12 Ka, and then Holocene valley fill. The three Deweyville surfaces are designated (youngest to oldest) the Fredonia, Sandjack, and Merryville alloformations by the Louisiana Geological Survey (Heinrich et al., 2002).

Otvos' (2005: 102) chronology for the Sabine River indicates entrenchment from about 100 to 50 Ka, and aggradation, producing two terraces, from 40 to 20 Ka. Then followed entrenchment from 20 to 18 Ka and aggradation from 18 to 2 Ka (Otvos, 2005: 102). The Sabine and Trinity systems were connected during lower sea level stands on what is now the continental shelf, and the Neches, which now flows into Sabine Lake, was a Sabine River tributary. Thomas et al. (1994) reckon the oldest incision of the Trinity-Sabine system at about 110 Ka. Blum et al. (1995) associate the incision of the Beaumont surfaces with marine oxygen isotope stage 5 (115 to 75 Ka). Several stages of aggradation, degradation, and lateral migration, degradation, and aggradation occurred within those incised valleys during isotope stages 4, 3, and 2 glacials as channels flowed to shorelines further out on the current continental shelf (Blum et al., 1995; Morton et al., 1996). The variations in shelf slope and antecedent morphology associated with those Pleistocene events are directly related to along-strike variability in Holocene coastal retreat rates between Louisiana and Galveston Bay (Rodriguez et al., 2004)—and by extension, to fluvial responses.

Morton et al.'s (1996) analysis suggests Trinity River incision sometime after 13 Ka, followed by aggradation triggered by sea level rise and progressive onlap and burial of Deweyville surfaces sometime during isotope stage 1, from about 10 Ka. This is consistent with analyses of offshore and estuarine sediments, which indicate that Galveston Bay began forming initially by flooding of incised valleys about 8 Ka, with subsequent, apparently rapid inundation of valleys creating the approximate modern version of Galveston Bay about 4 Ka (Anderson et al., 1992). Rodriguez et al. (2005) identified flooding surfaces in Galveston Bay from decreases in sedimentation rates and changes from delta plain to central estuarine basin facies in cores. Formation of these surfaces dates to 8.2 and 7.7 Ka, at depths matching the elevations of relatively flat alluvial terraces.

According to Waters and Nordt (1995) the lower Brazos River was a competent meandering stream from 18 to 8.5 ka, leaving thick coarse lateral accretion deposits (such as those associated with Deweyville terraces) as it migrated across the floodplain. At about 9 to 9.4 ka a transition to an underfit stream incised into those deposits and dominated by vertical accretion occurred .

METHODS

Digital orthographic aerial photographs (digital ortho quarter quads or DOQQs), satellite imagery, digital elevation models and 1:24,000 topographic maps were used to identify potential avulsions on the lower Brazos, Navasota, Trinity, Neches, and Sabine Rivers. These were identified on the basis of former river channels visible on the alluvial valley floor. Apparent abandoned (or partially abandoned) channels or anabranches were considered candidates if their course was generally downvalley, the width of the trough, depression, or channel was consistent with the width of the modern river channel in the vicinity, and if the size and wavelength of any meanders was consistent with an abandoned river channel. Some of the features so identified are anabranches, distributaries or sloughs of the modern river, some are occupied by underfit tributaries, and some are wholly or partially infilled (figure 4).

Figure 4. Site of the Oyster Creek avulsion of the Brazos River near San Felipe, TX. Portions of the Brazos paleochannel in various stages of development are shown. A Number of cutoffs are also visible in this false-color DOQQ image.

For the Brazos, Trinity, and Sabine Rivers, at least one site (and sometimes several) along each potential paleochannel were examined in the field to determine via survey whether the channel dimensions and other features were consistent with former river channel positions. Nine field sites in the Navasota River valley were also examined. This resulted in the elimination of some apparent paleochannels. For example, one infilled channel on the lower Brazos was found to be a former barge canal that once connected plantations in the lower valley. In other cases disconnected channel segments were determined to be part of the same paleochannel. No field work was conducted in the Neches River, so any uncertain or equivocal potential former river channels detected from the image analysis were excluded.

The locations of paleochannel intersections with the modern river were recorded. The avulsions were categorized as local or nonlocal, depending on whether the channel change was confined to a single meander belt or created (or reoccupied) a different meander belt. The avulsions were also classified as anastamoses, relocations, or distributary. Anastamoses are anabranches, and were so identified not only in the case of persistent anbranches (whether active or flood channels only) but also if the paleochannel could be clearly identifed as rejoining the modern river course. Former river channels not rejoining the main channel, and not exending into the coastal or deltaic portion of the valley, were considered relocations. Distributaries were identified where the anabranches or former channels extend into the coastal or deltaic section. Finally, avulsions were classified as active (conveying flow in most conditions), semi-active (high-flow channels), sloughs (standing water with ≤ 1 connections with the modern river), infilled, or tributary-occupied (figure 5). Many abandoned channels varied substantially along their course in the stage of development; the dominant stage was recorded.

Figure 5. Examples of active (top) and semi-active subchannels on the Navasota River.

In the Brazos, Navasota, and Neches Rivers, meander cutoffs were also identified based on oxbow lakes or swamps or clearly identified infilled isolated meanders. These were classified as neck cutoffs where the cutoff occurred at the base of the bend and isolated an entire loop, and as chute cutoffs where the cutoff (apparently) occurred across a point bar and isolated only a portion of the meander.

Finally, in the lower Brazos sandy crevasse splays were enumerated and located based on splay deposits visible on aerial photographs. Unlike the other study rivers, much of the lower Brazos alluvial valley is in cropland and other non-forest use, facilitating the identification of the sandy splay deposits.

To further explore the potential role of slope advantages, two ~50 km reaches, one each on the lower Brazos and Sabine Rivers, were examined using DEM data. Once the general area to be examined was chosen (the general vicinity of Brazos Bend State Park on the Brazos River, and of Deweywille, TX on the Sabine), a specific starting point was randomly selected. Then five additional points 10 km downstream from the start were examined (six cross-sections for each river). The downstream slope was determined for a distance of at least 10 channel widths, or to the next downstream point of significant change in sinuousity; whichever was greater. The cross-valley slope was determined for each side of the cross-section by routing flow from the levee or alluvial ridge top. If this was more than one channel width away from the river edge, flow was determined to be back into the main channel.

Slope determinations were made using the "imposed gradients plus" flow grid method of Peckham (1998; 2003), a variation on the method developed by Garbrecht and Martz (1997). The algorithm centers flow within flat areas in routing from higher to lower DEM pixels, and is preferable in alluvial valleys where flats are an issue. Because flood basins and other depressions exist on the floodplains of both rivers, depressions in the DEM were not filled for this analysis.

RESULTS

Local (within a meander belt) channel changes, if not cutoffs, are anastamoses by definition. Of the non-local avulsions, anastamoses and relocations are approximately equally common, particularly if distributary avulsions are considered a form of relocation. However, the relative importance varies greatly among the rivers studied (tables 3, 4, 5). Relocations are dominant in the Brazos River, where eight of nine avulsions were relocations and none were anastamoses. The latter were prevalent in the Neches River, where 17 of the 21 avulsions resulted in anabranches. Anastamoses were also dominant in the Navasota, but a significant number of relocations (10 of 27 avulsions) were found. Three of the seven avulsions in the Sabine River resulted in distributaries, the most in both absolute and proportional terms. The Trinity was the only sample river with no relocations (five anastamoses and two distributaries).

Table 3. Summary of avulsions and cutoffs in the study rivers. Blank entries indicate parameters that were not measured for a specific river.

River	*Distance (km)*	*Avulsions*	*Cutoffs*		*Splays*
			Neck	*Chute*	
Brazos	469	9	14	3	46
Navasota	185	27	6	8	
Trinity	175	8			
Neches	340	21	117	23	
Sabine	214	7			

Table 4. Contingency tables for the entire study area showing relationships between types of avulsions, local vs. non-local avulsions, and the contemporary state of avulsed channels. NA = not applicable.

Overall	Anastamosis	Relocation	Distributary
Local	14	NA	NA
Non-local	28	23	6

Overall	Active	Semi-active	Slough	Infilled	Tributary
Local	3	5	2	3	1
Non-local	19	7	1	14	16

Overall	Active	Semi-active	Slough	Infilled	Tributary
Anastamosis	18	9	3	14	8
Relocation	NA	1	0	13	8
Distributary	4	1	0	0	2

While only 22 of 71 avulsions function as active anabranches or distributaries, a majority of avulsed channels are at least partially active (active, semi-active, sloughs, or tributary occupied). Only 38 percent of the identified abandoned channels overall were infilled. This varies by type of avulsion—relocations, as might be expected, generally infill unless occupied by a tributary. The endpoints in this respect are the Brazos, where six of nine avulsions are infilled, and the Navasota, where only six of 27 are infilled.

Table 5. Contingency tables for study rivers showing relationships between types of avulsions, local vs. non-local avulsions, and the contemporary state of avulsed channels. NA = not applicable.

Brazos	Anastamosis	Relocation	Distributary
Local	0	NA	NA
Non-local	0	8	1

Brazos	Active	Semi-active	Slough	Infilled	Tributary
Local	0	0	0	0	0
Non-local	0	0	0	6	3

Brazos	Active	Semi-active	Slough	Infilled	Tributary
Anastamosis	0	0	0	0	0
Relocation	NA	0	0	6	2
Distributary	0	0	0	0	1

Navasota	Anastamosis	Relocation	Distributary
Local	4	NA	NA
Non-local	13	10	0

Navasota	Active	Semi-active	Slough	Infilled	Tributary
Local	2	2	0	0	0
Non-local	11	2	0	6	4

Navasota	Active	Semi-active	Slough	Infilled	Tributary
Anastamosis	13	4	0	0	0
Relocation	NA	0	0	6	4
Distributary	0	0	0	0	0

Trinity	Anastamosis	Relocation	Distributary
Local	0	NA	NA
Non-local	5	0	2

Trinity	Active	Semi-active	Slough	Infilled	Tributary
Local	0	0	0	0	0
Non-local	1	0	1	1	4

Trinity	Active	Semi-active	Slough	Infilled	Tributary
Anastamosis	0	0	1	1	3
Relocation	NA	0	0	0	0
Distributary	1	0	0	0	2

(continued next page)

Table 5. Continued.

Neches	Anastamosis	Relocation	Distributary
Local	9	NA	NA
Non-local	8	3	1

Neches	Active	Semi-active	Slough	Infilled	Tributary
Local	1	2	2	3	1
Non-local	5	3	0	0	4

Neches	Active	Semi-active	Slough	Infilled	Tributary
Anastamosis	5	4	2	3	3
Relocation	NA	1	0	0	2
Distributary	1	0	0	0	0

Sabine	Anastamosis	Relocation	Distributary
Local	1	NA	NA
Non-local	2	1	3

Sabine	Active	Semi-active	Slough	Infilled	Tributary
Local	0	1	0	0	0
Non-local	2	2	0	1	2

Sabine	Active	Semi-active	Slough	Infilled	Tributary
Anastamosis	0	1	0	0	2
Relocation	NA	0	0	1	0
Distributary	2	1	0	0	0

Several trends are apparent. First, cutoffs are more numerous than avulsions in the Brazos and Neches Rivers, while avulsions are more common in the Navasota. While cutoffs were not recorded in the Trinity and Sabine, there are clearly more cutoffs in the study reaches than the seven to eight avulsions recognized. All rivers but the Navasota are dominantly single-thread meandering channels, with some strongly meandering and tortuous reaches. The Navasota, by contrast, is an anabranching system, with multiple channels (at least at high flows) over more than 90 percent of the study area length. As the Navasota has more cutoffs per unit length than the Brazos, the preponderance of avulsions rather than a lack of cutoffs in the Navasota is the striking feature. The greater proportion of chute rather than neck cutoffs in the Navasota is presumably attributable in part to generally lower sinuousity. While the lower Navasota has sinuousity values of 1.6 to 1.8, it lacks the high-sinuousity reaches (>2.0, and occasionally >4) present in the other rivers.

Second, the Brazos River avulsions are entirely relocations or distributaries, six of nine are infilled, and the rest occupied by tributaries. In the other rivers anastamoses are more common than relocations, and in the Navasota, Neches, and Sabine, at least some are active. This likely reflects the differing avulsion styles identified by Aslan and Blum (1999) of the Brazos (and Colorado) Rivers compared to the others.

Third, the Neches River experienced an extraordinarily high number of channel changes compared to the other rivers. The avulsions on the Neches were also in all stages of development, including active anabranches, semi-active high flow channels, sloughs, tributary-occupied channels, and infilled channels.

The Brazos is the only one of the study rivers to have a watershed fragmentation avulsion, where the tributary occupying the abandoned channel (Oyster Creek) is not hydraulically connected with the Brazos and maintains an independent path to the Gulf of Mexico. The Colorado River just to the west, however, has a similar feature. The Trinity River is characterized by at least two avulsion channels which function differently according to flow levels, as described by Phillips and Slattery (2007a). Mussel Shoals Creek flows into the Trinity River at normal Trinity flow levels, but at high (but sub-bankfull) flows is an anabranch, distributing a portion of the Trinity's flow via a floodbasin and Big Creek. Pickett's Bayou conveys local runoff into Old River at normal flow levels, but at high (but again sub-bankfull) flows diverts Trinity River water as a distributary (Phillips and Slattery, 2007a).

If the Brazos is representative, crevasses are more common than avulsions and cutoffs. The Brazos data most likely underestimate crevasses (even more so than avulsions or cutoffs), since many smaller crevasses leave little evidence detectable even in the field, much less from imagery. Even large splays are liable to be obscured by vegetation, overbank deposition from suspension, and cultivation.

Multiple nearby levee breaches will generally result in no more than one successful avulsion. At two field sites on the Navasota River, for instance, active levee breaches were observed during floods, but the water was flowing directly into high-flow channels associated with previous avulsions. At the confluence of Pickett's Bayou and the Trinity River, five separate channel mouths through the levee exist, all conveying flows into the bayou.

Slope Ratios

At the Brazos River test cross-sections, three of six sites had cross-valley slope advantages relative to downstream slopes. At one of these, the advantage was on only one side of the river, and the S_{cv}/S_{dv} ratio was only 2.54. In the other two cases, however, the cross-valley slope advantages were immense, with ratios >65. At both of these sites cross-valley flow paths led to floodplain depressions or flood basins. At the other three Brazos test sections, alluvial ridges were far from the channel edges, so flow was routed back into the river in the same general vicinity.

Results were similar for the Sabine. Four of six test sections had $S_{cv}/S_{dv} > 1$, but in one case the ratio was barely greater than unity. In another $S_{cv}/S_{dv} = 4.7$, and in the two others very large advantages existed ($S_{cv}/S_{dv} > 10$). Rather than flood basins, however, flow at the Sabine sites was routed into sloughs, tributaries, or distributaries.

While the DEM-based tests are coarse, they generally confirm Aslan et al.'s (2005) suggestion that cross-valley gradient advantages are more common than avulsions.

DISCUSSION AND INTERPRETATIONS

Regional Patterns of Avulsion

The five study rivers show five distinct patterns with respect to avulsions. The difference between the Brazos and the Trinity-Neches-Sabine can be accounted for by the contrasting styles of avulsion associated with extrabasinal rivers such as the Brazos and Colorado which have largely filled their incised valleys, and those of rivers such as the Trinity, Neches, and Sabine, which have not (Aslan and Blum, 1999; Blum and Aslan, 2006). The avulsion by progradation into flood basins associated with the former is more likely to lead to relocation and distributary avulsions (vs. anastamoses). It also seems likely that reoccupation of former channels, the dominant style in the eastern rivers of the study area, is more likely to result in maintenance of active or semiactive channels, vs. infilled channels.

The numerous avulsions in the Navasota River, and the active or semi-active nature of the multiple channels, is consistent with the anastamosing channel pattern, which in most cases are created and maintained by avulsions (Makaske, 2001; Nanson and Knighton, 1996). Unlike the other study rivers, and unlike other large tributaries of the Brazos, the Navasota channel is not strongly incised, and most of the lower Navasota valley is strongly aggrading. Direct evidence of recent aggradation in the Navasota valley includes (Phillips, 2007b):

•Buried soil profiles in floodplain alluvium, with minimal pedogenic development and preserved stratification in overlying deposits.

•Burial of tree root crowns and basal flares, other vegetation, and recent litter layers by alluvium.

•Human-made objects of contemporary or recent historical origin (e.g., glass, plastic) in alluvial deposits.

Indirect evidence includes the high frequency of overbank flow at two gaging stations within the study reach (> 4 times per year; Phillips, 2007b).

The reasons for the high rates of aggradation and sediment storage in the Navasota River compared to others in the region are beyond the scope of this study, but there are several possibilities. One is that erosion and slope-to-stream sediment delivery is higher in the Navasota watershed.

Repeat surveys of Lake Limestone, at the upper end of the Navasota study reach (Austin et al., 2003) show changes in lake storage capacities from 1979 (impoundment began in late 1978) to 1993, when the reservoir was surveyed, and 2002, when the lake was resurveyed. The documented loss in capacity is likely due to sediment accumulation, which has been documented in Lake Limestone via acoustic profiling and coring (Dunbar and Allen, 2003), though differences in lake survey methods may introduce some error (Austin et al., 2003). Assuming a density of lake sediments of 1 t m^{-3} (consistent with other studies; e.g. Smith et al. 2002.) for converting volumetric changes to mass, this implies a mean annual sediment yield of about 530 t km^{-2} yr^{-1} for the 1748 km^2 watershed upstream of Lake Limestone Dam. Dellapena et al. (2004) report evidence of steady-state accumulation in analysis of lake bottom cores, which is consistent with the lake surveys, which indicate a nearly constant yield (531 t km^{-2} yr^{-1} over the entire 1979-2002 period; with rates of 533 for 1979-93 and 527 for 1993-2002). This is a higher sediment yield than that reported in the region from suspended sediment sampling or lake resurvey data (SCS, 1959; Coonrod et al., 1998; Dunn and Raines, 2001; Phillips, 2003; Phillips et al., 2004; Phillips and Slattery, 2006; Slattery et al., 2007).

In a study of a Brazos River tributary upstream of the study area for this project, Nordt (2004) showed that the depositional and erosional phases of Cowhouse Creek are out of phase with trends in the Brazos. Thus it could be that the Navasota River is still in a pre-incisional phase. However, other lower Brazos tributaries are typically incised and do not exhibit the strongly aggradational, anabranching characteristics of the Navasota. Nordt (2004) identified an apparent increase in soil erosion on Cowhouse Creek in response to warmer Holocene climate conditions, which resulted in widespread valley filling. This may have also occurred in the Navasota system. However, in the latter case either this fill was not strongly incised, or any incision has subsequently been buried by historical and recent sediment. At this point the latter interpretation seems more likely, given the recent/historical nature of much of the Navasota valley alluvium. Further, longitudinal profiles of lower Navasota tributaries show evidence of a downcutting response, which would be expected if base levels on the Navasota had been lowered by incision.

Rather than, or in addition to, the possibility of higher erosion and sediment yield rates than the Brazos, the narrower, bedrock-controlled valley of the Navasota may limit sedimentary accommodation space such that even if per-unit-area erosion and sediment yield rates were similar, more aggradation would result in the Navasota system. This is still speculative, however, and further research is needed.

The intense channel change activity along the lower Neches River may be attributable to neotectonic activity. The tectonic map of Ewing et al. (1991) shows at least 12 mapped faults crossing the lower Neches valley, and White and Morton (1997) documented wetland losses related to reactivation of faults by hydrocarbon production along the southeast Texas coast, including the Port Neches oil field in the lower Neches valley. Recent or earlier movements could also be linked to channel changes. Taha and Anderson (2007), for example, argue that an avulsion node on the lower Brazos is associated with a previously unmapped listric fault. Schumm et al. (2000) documented tectonic influences further upstream on the Neches, including systematic differences that are likely to influence channel changes.

The Neches River has also experienced some reduction in peak and mean flows due to Sam Rayburn Reservoir. Mainstem reservoirs on the other study rivers are for water supply or hydroelectric power, and do not appear to have changed the general flow regime (Hudson and Mossa, 1997; Phillips, 2003; Wellmeyer et al., 2005). Sam Rayburn, however, is a flood control impoundment. It is not clear, however, whether or if this difference could account for the greater occurrence of channel change on the Neches, as flow regulation has been found in most cases to reduce lateral channel change (Wellmeyer et al., 2005).

Between Sabine Lake and western Galveston Bay, Rodriguez et al. (2004) documented variations in coastal retreat associated with variable inner-shelf gradients and antecedent morphology. According to their reconstruction, at about 7.7 ka a barrier shoreline was approximately 55 km offshore the current coastline. Near the west end of Galveston Island, the shoreline retreated 55 km by about 5.3 ka, to a position on the lagoon side of the island. Toward the Sabine, the shoreline retreated more gradually, and at 5.3 ka was seaward of Sabine Bank, offshore from Sabine Lake. Between 4.7 ka and 2.8 ka the shoreline at Sabine Bank retreated roughly 30 km, while Galveston Island prograded seaward, and Bolivar Peninsula began to accrete around 1.5 ka (Rodgriguez et al., 2004). These coastwise variations may explain the more extensive deltaic/distributary system currently found on the lower Sabine and Neches Rivers, compared to the Trinity, and the associated differences in avulsion patterns. Neotectonically-triggered stream capture from the Sabine toward the Houston-Calcasieu River system, Louisiana, may have also played a role in the development of the Sabine deltaic distributary system (figure 6; Phillips, 2007a).

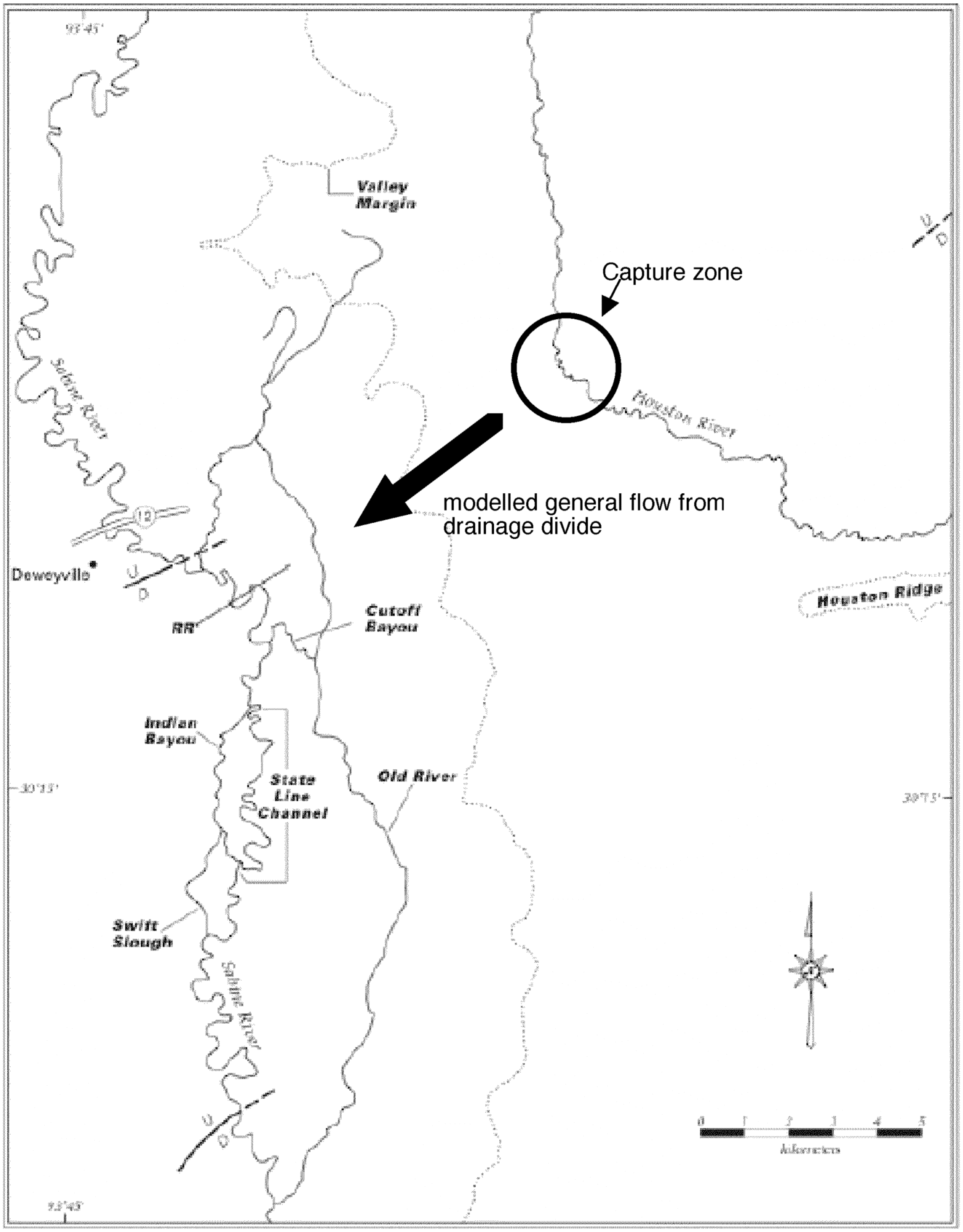

Figure 6. Lower Sabine River. The Houston River, a former Sabine tributary, was diverted by faulting east to the Calcasieu River, Louisiana. Sometime after this, the Sabine avulsed upstream into the current channel. When the Sabine River avulsed via Cutoff Bayou into Old River, the larger, deeper channel of the latter formed before the Houston River capture presented distinct slope advantages. About 70 percent of Sabine

River flow upstream of Cutoff Bayou is now diverted into the Old River channel. The "state line channel" is a former Sabine Channel marking the Texas/Louisiana border which has largely infilled since the 1930s. The two fault sections shown on the west side are shown as solid lines where mapped, and dotted where inferred by Phillips (2007a). The fault in the northeast section of the figure is inferred from a fault mapped by Heinrich et al. (2002) immediately to the east.

Figure 7 summarizes the major controls over the different patterns of avulsion. The valley filling regime distinguishes the Brazos, Navasota, and Trinity-Neches-Sabine Rivers. Within the latter, Holocene geomorphic history and antecedent topography determine the different avulsion styles. All have likely experienced delta backstepping, as indicated for the Trinity River, but in addition the Neches seems to be influenced by a denser network of faults, and the Sabine by an abandonment of a portion of its delta due to loss of a major tributary to stream capture, and subsequent reoccupation.

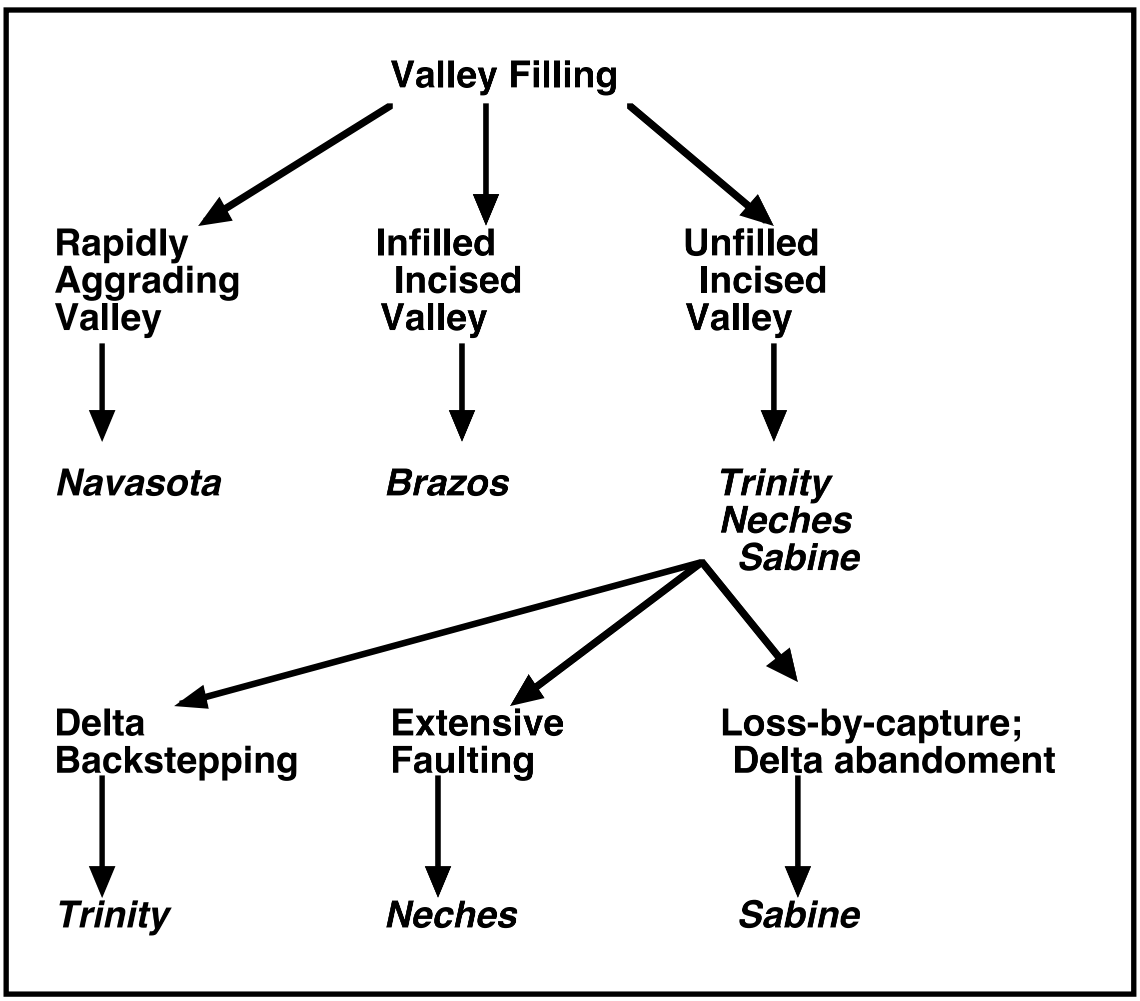

Figure 7. Summary of major factors hypothesized to control the major differences in avulsion regimes in the study area rivers.

Dynamical Stability

With respect to the outcome of a given avulsion, stability is indicated by a failed avulsion where the main channel regains dominance. There is no clear evidence this has occurred in the study area, but short of monitoring an observed bifurcation, such evidence may be hard to come by, as failed channels may be too short-lived to be recognized. Further, without detailed field investigations it cannot be determined whether a given crevasse splay is associated with a failed avulsion. Thus, despite the inability to unequivocally identify any failed avulsions, they have certainly occurred.

Dynamical instability is indicated by a successful relocation avulsion where the main channel is abandoned. This has occurred at least 21 times in the study area (table 4). The success of nearly all cutoffs—particularly neck cutoffs—also indicates instability. This is not surprising, however, since meanders are known to grow to a point of incipient instability. A persistent anabranch or distributary bifurcation suggests metastability. At least 22 anastomoses and distributaries are currently active in the study area.

No precise statements on the relative importance of stable, unstable, and metastable avulsions can be made, but clearly all occur.

The results generally support the broader-scale qualitative stability model based on slope-aggradation-avulsion feedbacks. The model indicates that in the absence of strong external controls on avulsion, and where slope-avulsion feedbacks are stronger than slope-aggradation links, the system is dynamically stable. If external controls are not dominant, and aggradation-slope feedbacks are strong, the system is dynamically unstable. The most active systems, where successful avulsions are most likely, are the Neches, with strong external controls, and the strongly-aggrading Navasota, where proximity to the aggradational threshold promotes instability throughout the system.

Frequency and Longevity

Avulsions are well-dated only on the Brazos River. An avulsion node near Brazoria is believed by Taha and Anderson (2007) to be associated with a previously unrecognized listric fault in the vicinity, and experienced an avulsion about 7 ka. Another avulsion from the Oyster Creek channel occurred about 4 ka near Rosharon. The avulsion causing the Brazos to divert from what is now the Bessie's Creek/Oyster Creek channel occurred about 1.5 ka (Taha and Anderson, 2007). Stratigraphic evidence from the Bryan-Navasota section of the Brazos shows that avulsions occurred at about 9 to 9.4 and 2.5 ka, and about 500 and 300 years BP (Waters and Nordt, 1995). The location of these shifts was not specified, but all occurred after the system began incising into valley fills deposited before 9.4 ka.

Historic channel shifts are known to have occurred on the Sabine and Navasota Rivers. In one case a deliberate attempt in the 1930s to divert flow toward the west (Texas) side of the Sabine deltaic system by sinking a barge at the Sabine/Indian Bayou confluence resulted in the abandonment of the former channel. By 2006 the latter persisted only as a semi-active high flow channel and slough. Historic maps and aerial photographs show other examples of shifting channels in the Sabine delta region.

In the Navasota River a U.S. Geological Survey gaging station (at the SH 21/US 190 crossing east of Bryan) was discontinued after an upstream avulsion resulted in the partial abandonment of the gaged channel. In another instance (Democrat Crossing), recollections of local residents who recalled (in 2007) a channel shift “12 or 15 years ago” are supported by morphological and vegetation evidence in the field.

On the lower Trinity River, topographic maps show clearly a relatively wide “blue” connection of Pickett’s Bayou with the Trinity, and 1994 DOQQs, taken during flood, show hydraulic connections at two points. In 2005, field surveys showed five separate subchannels across the levee into Pickett’s Bayou, all with channel slopes and flow indicators showing flow from, rather than to, the Trinity. The beds of these subchannels are well below the levee top, but 3.5 to 4 m above the bed of the river (figure 8). The evidence thus suggests a short-lived or failed avulsion in recent history. Pickett’s Bayou flows into a floodplain depression associated with a low or falling-stand “Deweyville” channel, and has a strong local slope advantage (fig. 9). However, further downvalley the Old River channel to which Pickett’s Bayou connects is at a higher elevation than the Trinity River in the same vicinity (fig. 10). Comparing this with the avulsion of the Sabine into Old River, Louisiana, the bed of which is at a lower elevation than the Sabine, suggests the possible importance of broader-scale as well as local slope advantages in determining avulsion longevity.

Figure 8. One of the channels through the Trinity River levee into Pickett’s Bayou. The view is looking toward the river.

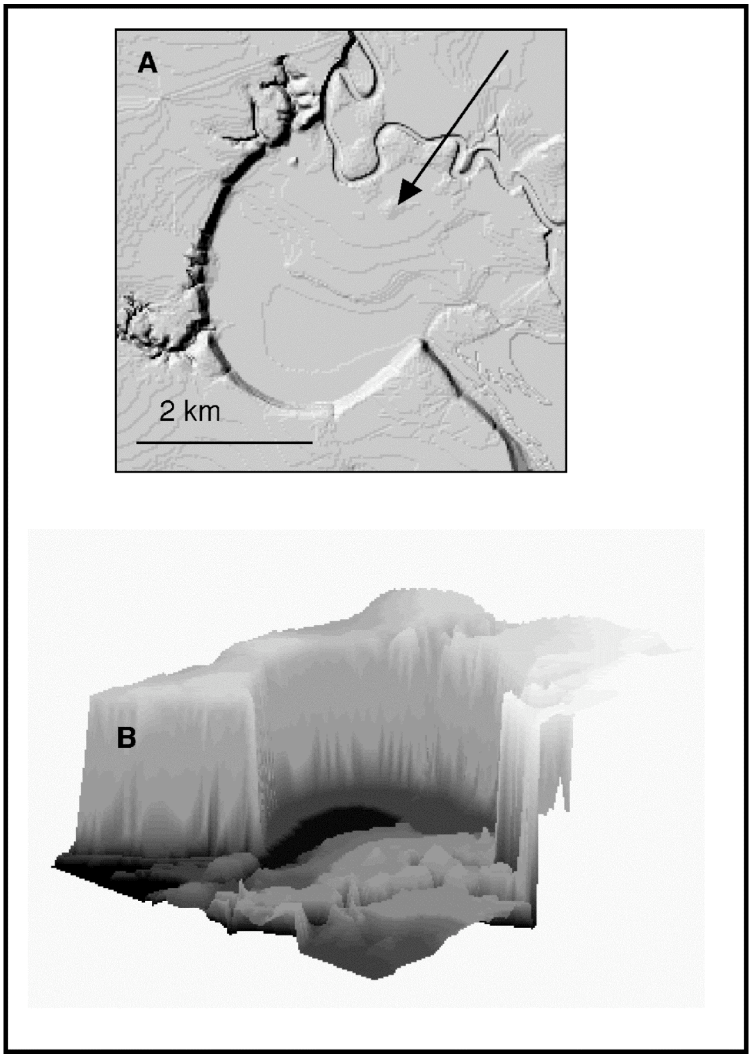

Figure 9. Trinity River valley near Moss Bluff, TX, showing the Pleistocene meander depression in the vicinity of Pickett's Bayou. The arrow on the relief map (A) shows both the general direction of flow into Pickett's Bayou and the vantage point for the surface plot (B). Vertical exaggeration 50X. After Phillips and Slattery (2007a).

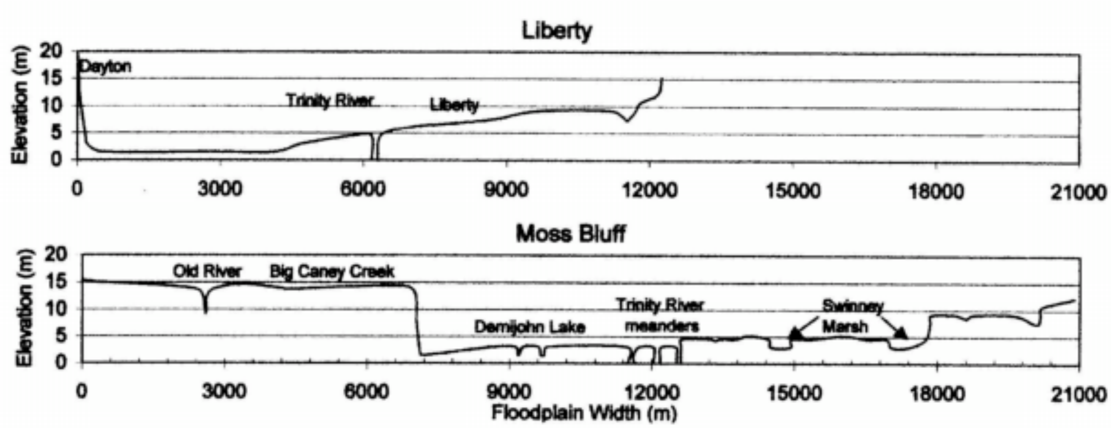

Figure 10. Cross-valley profiles (west to east) of the lower Trinity River showing variable slope and elevation relationships between the modern and abandoned Trinity River channels. The profile near Liberty shows the strong gradient toward the former channel near the western valley wall. The profile near Moss Bluff shows that the Old River channel is higher than the modern channel.

Makaske et al. (2002) indicate that avulsed channels in an anastamosing system go through a series or cycle of morphological changes or stages. To the extent this is true (in the Navasota, for example, it is clear that any such successional trends are sometimes interrupted by paleochannel reoccupation), the stage of development indicates relative age.

In the Brazos all the abandoned channels are infilled unless occupied by a tributary, and with the exception of the portion of the Brazos paleochannel occupied by the lowermost Navasota River and the tidal portion of Oyster Creek, the tributary-occupied paleochannels are not only underfit, but strongly infilled. While local aggradation, the availability of reoccupiable channels, and the presence of cross-valley flow during floods make future avulsions likely, there is no evidence of any shifts since the most recent (300 years BP) identified by Waters and Nordt (1995).

The Neches and Navasota Rivers, by contrast, have subchannels in all stages of activity or development, indicating recent and ongoing avulsions. In the Trinity and Sabine the most active or early-stage channels are in the deltaic areas, whereas abandoned channels further upstream are either infilled or occupied by tributaries in partially filled channels.

Geomorphic Role of Avulsions

Avulsions are a key mechanism in floodplain construction—the dominant mechanism in many situations—and the stratrigraphy and alluvial architecture in southeast Texas indicates their prevalence throughout (at least) the Quaternary (Waters and Nordt, 1995; Blum and Price, 1998; Aslan and Blum, 1999; Blum and Aslan, 2006; Taha and Anderson, 2007). However, avulsions and the flow networks and valley morphologies associated with them also have important implications for contemporary processes and water and sediment fluxes, as shown in recent studies of the Brazos (Sylvia and Galloway, 2006), Trinity (Phillips and Slattery, 2007a; 2007b), and Sabine (Phillips, 2007a) rivers.

River meanders are generally conceptualized as mechanisms for dissipating energy according to least-work principles, and/or as outcomes of local instabilities in flow-channel interactions (see reviews and syntheses by Rhoads and Welford, 1991; Seminara, 2006). Meander neck cutoffs occur as meander geometry and size reach unstable stages, and chute cutoffs as local channel aggradation related to meander growth redirects flows across the bend. In coastal plain rivers, the growth of meanders (increasing sinuousity) is a common response to rising sea level, as a mechanism for reducing slope gradients (Phillips et al., 2005 and Phillips and Slattery, 2007b discuss this in the specific context of the lower Trinity River). What (if any) broadly analogous roles do avulsions play in meandering rivers?

First, avulsions are mechanisms for distributing sediment within a depositional system. This is most apparent in the case of deltaic avulsions, where the occasional shifts of channels or channel dominance is obviously related to changing nodes of deposition. The link between dominant avulsion styles and the general state or stage of valley filling—outlined by Aslan and Blum (1999) in the region and confirmed by this study—also supports this role. The instability of the slope-aggradation-avulsion feedback system when slope-aggradation feedbacks are stronger than slope-avulsion links, thus making successful avulsions more likely, is also consistent with avulsions as a sediment-distribution mechanism.

Second, avulsions can also be viewed as locally unstable, historically and spatially contingent responses to local perturbations. While the conditions favoring avulsions are predictable, their specific locations and timing are highly dependent on very localized conditions—e.g., a log jam or an animal trail across the levee. Much as meanders or changes therein may propagate their effects downstream (e.g. Lane and Richards, 1997; see Wellmeyer et al., 2005 for Trinity River examples), the localized instabilities associated with avulsions in turn trigger or set the stage for further changes downstream.

Finally, while avulsions result in slope changes when they occur, their role as a mechanism in the fluvial system for slope adjustment is unclear. In the study area, as elsewhere, slope advantages are a perhaps necessary but by no means sufficient condition for avulsions, and local slope advantages do not guarantee avulsion success, as the Pickett's Bayou example shows. Slope variations are an important influence on avulsions, and slope changes an outcome thereof, but it does not appear that avulsions are a significant fluvial system mechanism for slope adjustment in the way that meander growth and cutoffs are.

CONCLUSIONS

Avulsions are a common feature of the rivers of the southeast Texas coastal plain. Beyond the well-known role in floodplain construction and alluvial stratigraphy, avulsions have important influences on the surface morphology and contemporary processes in the lower Brazos, Navasota, Trinity, Neches, and Sabine River valleys.

While features associated with avulsions are active and distinct features throughout the study area, and all the rivers have experienced geologically (if not historically) recent avulsions, no two of the study rivers have the same avulsion regime. Differences in avulsion style are controlled by the valley filling regime, and within the three rivers characterized by an unfilled incised valley, antecedent morphology associated with late Quaternary and Holocene coastal, fluvial-deltaic, and neotectonic processes accounts for the major differences.

In the Navasota (27 avulsions in 185 km) and Neches (21 in 340 km) subchannels associated with avulsions exist in all stages of development from active to infilled, and some are known to have occurred in recent decades. The other rivers have fewer avulsions, but both the Sabine and Trinity have experienced historic channel shifts. Only the Brazos has experienced no historic avulsions, though one apparently occurred as recently as 300 years ago.

The big-picture role of avulsions in these fluvial systems is as a mechanism for distributing sediment in deltas and infilling valleys, and as an unstable, contingent response to perturbations. Avulsions do not appear to be a mechanism for slope adjustments in a way comparable to meander growth/cutoff or channel aggradation/incision.

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Section 4
Nonequilibrium Longitudinal Profiles in Coastal Plain Rivers

ABSTRACT

Longitudinal stream profiles are fundamental properties of fluvial systems, both reflecting and determing slopes and energy gradients, and are a common indicator of landscape evolution, tectonic and base level influences, lithological resistance, and evnrionmental change. The profiles of 30 streams in the lower Brazos, Navasota, Trinity, Neches, and Sabine River systems were analyzed to determine the extent to which they exhibit smoothly concave profiles, and to relate profile convexities to environmental controls. Few stream profiles in southeast Texas conform to the ideal of the smoothly concave graded or steady-state equilibrium profile. Deviations are caused, in various cases, by inherited topography, geologic controls, recent and contemporary geomorphic processes, and anthropic effects. Both the legacy of Quaternary environmental change and ongoing changes in the region make it unlikely consistent boundary conditions for these fluvial systems will exist for long. Further, the exceptions within the study area—i.e., strongly and smoothly concave longitudinal profiles—suggest both that ample time has occurred for strongly concave profiles to develop, and that such profiles do not necessarily represent any mutual adjustments between slope, transport capacity, and sediment supply. I propose that the simplest and most likely explanation of any tendency toward concavity is related to basic constraints on channel steepness associated with geomechanical stability and minimum slopes necessary to convey flow.

INTRODUCTION

The longitudinal profile of rivers and streams is an elemental property in fluvial geomorphology and hydrology, reflecting—and determining—slope and energy gradients and elevation changes. The profile is also of fundamental importance in geology and geophysics in general, as it is often used as an indicator, diagnostic, or determinant of factors such as stages of landscape evolution, tectonic uplift or subsidence, variations in rock resistance, base level changes, and the effects of climate or other environmental changes on landscapes.

The longitudinal (or simply long) profile is a plot of channel elevation over streamwise distance from the drainage divide or other upstream reference point to the stream mouth. As the "least transient expression of fluvial processes," (Richards, 1982: 222) the profile is not only an important morphometric parameter in process studies, but a key topographic signature of a variety of lithologic, tectonic, and base level effects. Examples go back at least as far as Playfair (1802), and Goldrick and Bishop (2007) present a review of the uses of longitudinal stream profiles in interpretations of landscape history. A sample of recent work relating long profiles to various external forcings includes Tornqvist (1998) on stratal patterns of basin margin sedimentary sequences and van Heijst & Postma (2001) on sea-level change; Snyder et al. (2000), Duvall et al. (2004), and Whipple (2004) on tectonic and lithologic controls on bedrock channels; Sinha and Parker (1996), Morris and Williams (1997), and Stock et al. (2005) on the relative importance of geomorphic controls along river courses; and Smith et al. (2000) on the steady-state equilibrium or grade of a fluvial system. Within the study area, Phillips and Slattery (2006, 2007a) have shown the key influences of downstream changes in channel bed slope, associated with the long profile, on stream power in lower river reaches, and on sediment fluxes to the coastal zone,

The purpose of this study is to examine the longitudinal profiles of streams in southeast Texas in the context of grade or steady-state equilibrium in fluvial systems, and to relate variations in profiles to environmental controls and geomorphic evolution.

Steady-State, Grade, and Equilibrium

A more-or-less smooth, concave-up longitudinal profile has long been considered a characteristic form in fluvial systems, a normative or attractor state for channel evolution, and an indicator of steady-state or grade in fluvially-eroded terrain (e.g., Davis, 1902; Gilbert, 1877; Mackin, 1948; Hack, 1957; 1973; Richards, 1982; Leopold, 1994; Sinha and Parker, 1996; Morris and Williams, 1997; Smith et al., 2000; Snyder et al., 2000; Roe et al., 2002; Whipple, 2004; Goldrick and Bishop, 2007). Concave profiles are indeed widely observed, and the association with grade or steady-state (a state where a stream is just able to transport the sediment supplied to it, with no persistent net aggradation or degradation) is based on the notion that as discharge increases downstream, the slope gradient necessary to transport the available debris decreases. The earlier qualitative expressions of this idea (e.g. Davis, 1902; Gilbert 1877; Mackin, 1948) are readily linked to stream power theory, where sediment transport is a function of the product of discharge and energy grade slope (e.g, Smith et al. 2000; Snyder et al. 2000; Roe et al., 2002; Duvall et al. 2004; Goldrick and Bishop, 2007).

Despite the persistence of the notion of smooth concave-up long profiles as steady-state equilibrium forms, and explanations which appeal to both intuition and physical reasoning, the notion is problematic. Richards (1982), among others, notes that (especially in alluvial rivers) channel slope is only one of several factors that can be mutually adjusted in response to sediment supply or other factors. Thus, for instance, Xu's (1991) study of alluvial rivers in China relating profile concavity to energy expenditure distributions showed that with heavy sediment loads, channel gradients are not able to decline rapidly downstream, and thus to create concavity in the lower reaches. Concavity was also found to be related to channel planforms, indicating multiple adjustments to imposed sediment loads (Xu, 1991). Richards (1982) accepts that the decrease in slope with increased discharge explains the general tendency to develop broadly concave profiles, but notes that this is a *general* adjustment to *average* discharge (225, italics in original).

According to Knighton (1998: 244-5), "various explanations imply that convexities [in the long profile] are in some way abnormal, and that in line with Davis . . . a smooth concave-upward profile is diagnostic of the graded or equilibrium state. That view has variously been challenged and a more dynamic approach developed . . . ." Modelling studies, for instance (Snow and Slingerland, 1987; Sinha & Parker 1996), show evidence of equifinality—that is, different causes or processes can produce the same effect (a smoothly concave longitudinal profile). A model of profiles at grade using basic equations of open-channel flow and sediment transport, and standard empirical relations for downstream variation in discharge, sediment flux, sediment size, and channel width was developed by Snow and Slingerland (1987). Results showed that in some, but not all, cases the computed profiles could be fit exactly by the logarithmic, exponential, or power functions proposed for equilibrium profiles. More importantly with respect to attempts to use profiles as an indicator of grade or equilibrium, they found that in most cases *any* of the functions provides a good fit. Their modeling of river profile evolution as the system approaches grade also indicated that a disequilibrium profile (i.e., associated with non-steady-state sediment flux) approximates a graded shape (Snow and Slingerland, 1987). Sinha and Parker's (1996) model investigated four potential influences on river profiles (horizontal wave-like progradation, bed material abrasion, channel aggradation balancing subsidence, and tributary inputs). They found that the first three all create concave quasi-equilibrium profiles, and that the fourth can also do so under some circumstances.

Ohmori (1991) showed that some aggrading Japanese rivers are not at grade, but their profiles can nonetheless be described using one of the mathematical functions proposed for graded rivers. Longitudinal profiles can also respond simultaneously to both upstream (e.g., sediment supply) and downstream (e.g., sea-level) forcings (Tornqvist, 1998). In his review of bedrock streams in active orogens, Whipple (2004) notes that in some cases multiple models explicitly based on steady-state or non-steady-state can readily describe observed profiles.

As Goldrick and Bishop (2007) point out, a fundamental issue is that profile convexities are most commonly interpreted as "disequilibrium" features that will presumably be degraded as streams approach steady-state, but are also sometimes interpreted as "equilibrium" responses to lithological variations (e.g. Hack, 1957; 1973). This raises two separate issues—to what extent does a smoothly concave river profile represent grade or steady-state equilibrium, and to what extent is steady-state a normative or characteristic condition in fluvial systems?

As noted above, ungraded, non-steady-state fluvial systems may feature smoothly concave profiles well-fit by standard logarithmic, power function, or exponential models, complicating any relationship between profile shape and steady-state. Studies of sediment production, transport, and storage in drainage basins suggests that in many cases a steady-state relationship between sediment supply and transport is rare and transient (see review by de Vente et al., 2007). Even where fluvial outputs are relatively constant over Holocene or longer time periods, this is often due to alluvial buffering effects rather than steady-state (Metivier and Gaudemar, 1999; Phillips, 2003a; Phillips and Gomez, 2007). Additionally, more general considerations of steady-state in fluvial geomorphology and landscape evolution question the idea of steady-state equilibrium as a normative state or goal, as opposed to a possible condition not necessarily more common or likely than nonequilibrium states (e.g., Renwick, 1992; Harrison, 1999; Phillips, 1999; Thomas, 2001; Hooke, 2003; Sivakumar, 2004).

A longitudinal profile which significantly deviates from a smooth, concave form, and where such deviations are not systematically related to variations in lithological resistance indicates a profile which is not in grade or steady-state equilibrium in the sense of Davis (1902), Gilbert (1877), Hack (1957, 1973), or more recent workers (e.g. Snow and Slingerland, 1987; Sinha and Parker, 1996; Goldrick and Bishop, 2007). However, the presence of a smooth concave profile, without other supporting evidence, does not necessarily indicate grade or steady-state.

It should also be emphasized that the interpretation of longitudinal profiles is not contingent on the extent to which they may be related to steady-state or graded conditions. Brierly and Fryirs (2005), for instance, provide an overview of how long profiles may inform river management with no reference to grade or equilibrium as a normative or expected condition.

Finally, as with virtually all earth science phenomena, spatial and temporal scale issues are important in the interpretation of longitudinal profiles. Rice and Church (2001), for instance, successfully modeled longitudinal profiles for a British Columbia river using exponential or quadratic functions—but only for individual links with insignificant lateral inputs. The overall more irregular river form structured by these fundamental length-scale units is consistent with Whipple's (2004) observation for bedrock streams that knickpoints often separate reaches with distinct steepness and concavity.

A study of the long profile of the Mississippi River by Harmar and Clifford (2007) illustrates the importance of scale, the role of multiple processes and adjustments, and the problematic nature of attempting to apply concave profiles as indicators of grade to specific river systems. The Mississippi River profile is concave at the largest scale, but is characterized by discontinuities, shorter trends, and zonal variations. These in turn are a response to morphology and bed material changes relating to a range of physical (lithologic, tectonic, tributary input) and engineering controls. Despite an apparent correspondence to a graded condition, profile shape is actually a complex, scale-dependent property (Harmar and Clifford, 2007). The Mississippi profile is best considered as a complex product of multiple system dynamics operating over (at least?) three process-form domains at the regional, reach, and sub-reach (pool-crossing) scales. Thus classic reasoning based on "global" relationships between discharge, bed material, and channel slope are not appropriate. "At best, the concave river profile [is]. . . . a property emerging from several scales of process-form interaction, and at worst, it is no more than an artefact arising from the juxtaposition of multiple controls and interactions" (Harmar and Clifford, 2007: 239).

THEORY

Attempts to relate qualitative notions of graded profiles to geomorphic processes have generally been based on stream power theories or "erosion laws" relating sediment transport capacity to discharge and slope (Hack, 1973; Knighton, 1998; Smith et al. 2000; Snyder et al. 2000; Roe et al., 2002; Duvall et al. 2004; Stock et al., 2005).

Stream power at a cross section is given by

$$\Omega = g\, Q\, S \qquad (1)$$

where g is the specific weight of water, Q is discharge, and S the energy grade slope. The latter is typically approximated by channel slope over large spatial and temporal scales.

Erosion laws are typically of the form

$$E = KQ^{m}S^{n} \qquad (2)$$

with K a constant and the exponents m, n typically constrained by standard flow resistance and stream power relations. Q is often considered a function of contributing drainage area (A), such that

$$E = K'\ A^{m}\, S^{n} \qquad (3)$$

In a topographic steady state, rock uplift is balanced by erosion, so

$$S = (U/K')^{1/n}\ A^{-m/n} = k\ A^{-q}, \qquad (4)$$

with q = m/n is considered a concavity index whereby profile form is directly related to energetics.

A number of variations and elaborations have been produced; see Goldrick and Bishop (2007) for a discussion and novel derivation. As stream length is generally closely and directly related to A, S can also be depicted as a function of length.

Erosion-law-based models have been widely used to interpret longitudinal profiles, but Stock et al. (2005) suggest that in readily-erodible rocks and where coarse sediment undergoes breakdown during transit, channel slope is set not by bedrock strength or sediment supply, but primarily by threshold motion of some characteristic grain size. Further, Whipple (2004) indicates that several models may be consistent with the predictions of the power function erosion law, at or away from steady-state.

Various least-work principles have been applied to many aspects of fluvial geomorphology, including long profiles. Leopold (1994) considers the concave profile as a “most probable state” directly related to energy expenditures. According to Leopold (and numerous others, c.f. Rodriguez-Iturbe and Rinaldo, 1997) fluvial systems attempt to simultaneously satisfy two incompatible goals—minimum total work (a function of QS) and uniform power expenditure. Using the power function form on a log-log graph where $S \sim Q^{b} \sim A^{b}$, uniform power expenditure implies $b = 0$ and a linear profile, while minimum total work gives b = 1 and maximum concavity (Leopold, 1994: 274-6). The compromise between the two goals yields 0 < b < 1.

Profile Constraints

An alternative theory is presented below which does not depend on steady-state, erosion laws, or least-work principles. This theory was developed not necessarily as a critique of existing theories but to see if an alternative line of reasoning not requiring goal functions could potentially explain both the general tendency toward concave profiles and the numerous local exceptions to that tendency.

A river channel is fundamentally meant to move water from point A (the drainage divide) to point B (the river mouth or base level), recognizing that the locations and characteristics of both A and B (and the amount of water to be moved) are dynamic. As the movement is driven by gravity, one fundamental constraint is that $H_A > H_B$, where H represents height or elevation. The longitudinal profile is thus $\int_A^B (dH/dx)$, where x represents the flow distance from A to B.

Locally in space and time slope gradients (dH/dx) may be vertical or zero (or even overhanging or negative). In general, though, channel slope is constrained by the maximum steepness the material comprising the bed can maintain over distances equal to several channel widths, and the minimum gradient required to maintain net mean downstream flux. Denoting these as $S_{max,}$, S_{min}, then for any segment of the profile

$$S_{min} \leq dH/dx \leq S_{max} \qquad (5)$$

L is the stream length or distance from A to B, and in most cases

$$H_A - S_{min} L > H_B \qquad (6)$$

That is, the minimum slope, over the entire length of the stream, does not result in sufficient drop to get water from the source to base level. Similarly in most situations,

$$(H_A - H_B)/S_{max} < L \qquad (7)$$

indicating that the maximum slope does not enable the horizontal distance from A to B to be covered.

Any gradient from S_{min} to S_{max} could be encountered anywhere along a channel, and indeed many channel profiles are quite complex and irregular, and at some scales regular variations in S associated with riffle-pool or step-pool sequences may be present. Figure 1 shows the hypothetical profiles of maximum concavity or convexity.

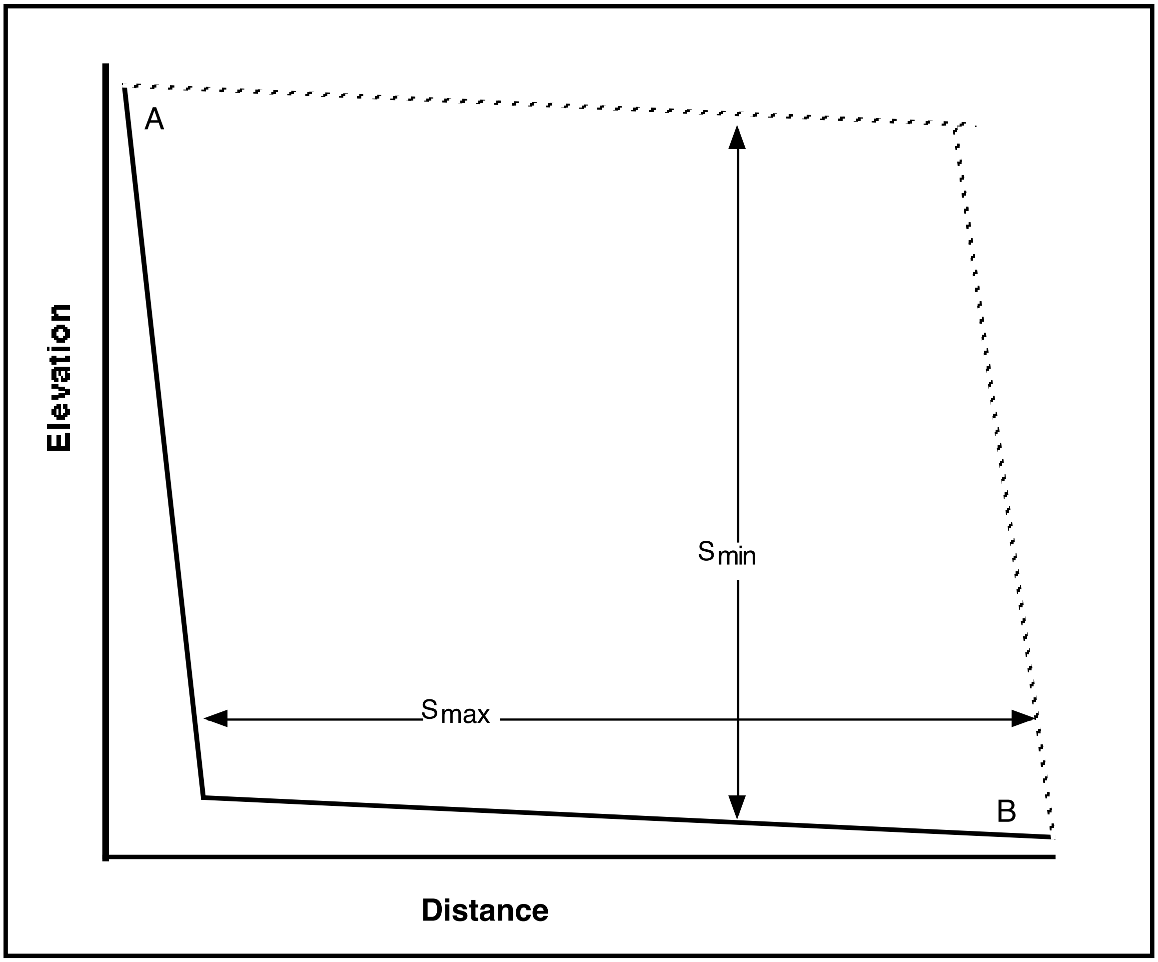


Figure 1. The profiles of maximum concavity (lower, solid line) and convexity (upper, broken line) for a given maximum and minimum channel slope. Actual profiles would fall between the extremes.

Gravity tends to drive water toward base level by the shortest, most efficient path possible. Thus, where flows are able to overcome resistance and height above base level is sufficient, $dH/dt \rightarrow S_{max}$. Meanwhile, as base level is approached slopes may tend toward S_{min}. Thus a general tendency towards S_{max} in the upper and S_{min} in the lower reaches would produce concavity in longitudinal profiles—in the limit, a profile of maximum concavity. This is consistent with the fact that channel incision driven by tectonics, climate or other factors tends to increase concavity (e.g. Zaprowski et al., 2005; Brierly and Fryirs, 2005: 64-68), and also with the observation that extremely convex profiles are associated with streams extending over exposed low-gradient coastal plains as sea level falls (Richards, 1982). The upstream migration of knickpoints in response to base level fall also increases concavity. Concavity may also be greater when streams flow from areas of greater to less substrate resistance as compared to more uniform substrates (Duvall, et al., 2004; Whipple, 2004). However, where streams lack sufficient power to incise their substrate there may be minimal slopes upstream and steep slopes near the mouth, as witnessed by hanging valleys in some systems (Wobus et al., 2006).

STUDY AREA

The study area and location of the studied streams is shown in figure 2. A complete description of the study area and its Quaternary geology is given in sections 1 and 3.

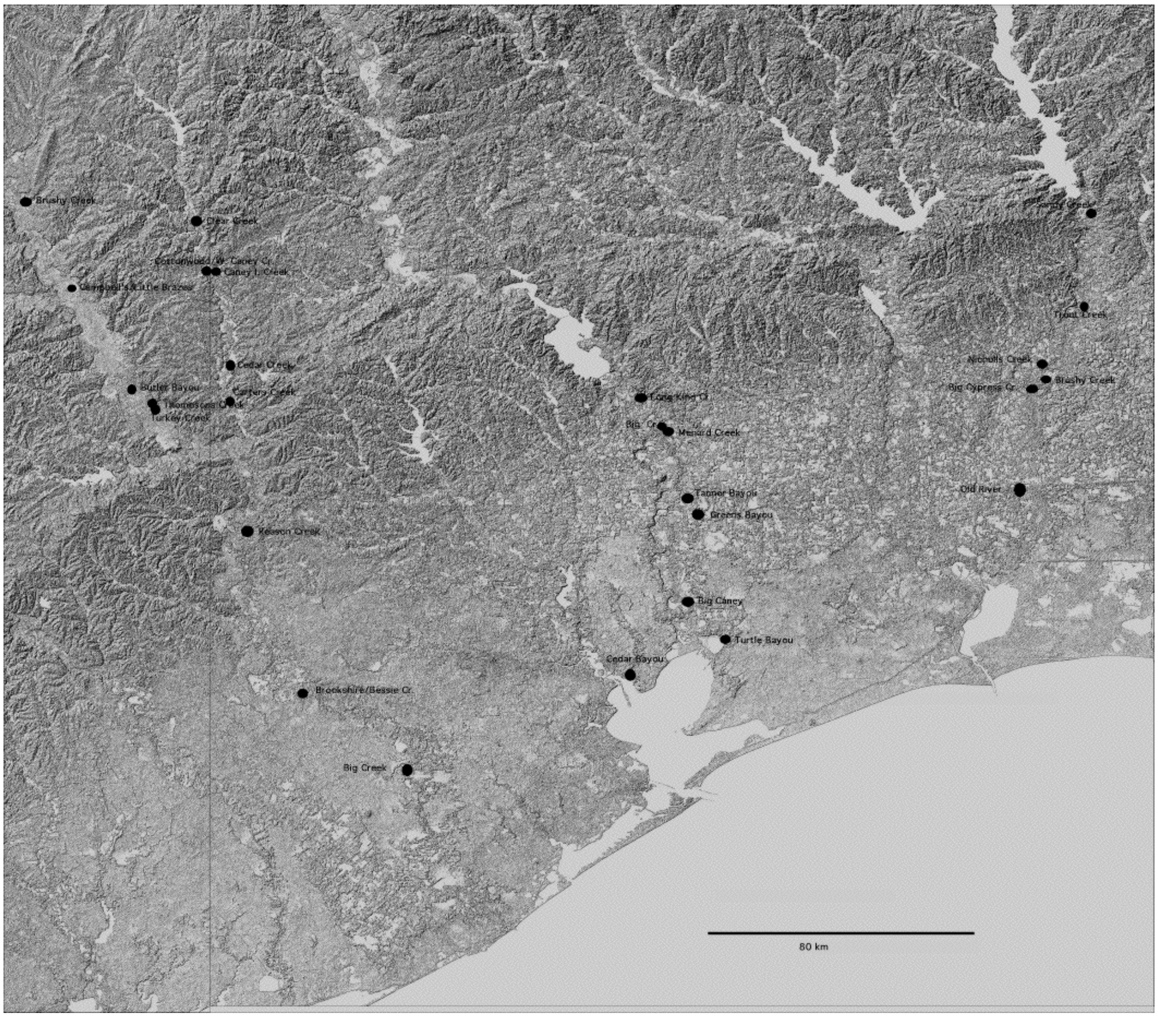


Figure 2. Southeast Texas coastal plain study area, showing approximate location of the studied streams at their confluences with (west to east) the Brazos, Navasota, Trinity, and Sabine Rivers.

METHODS

Longitudinal profiles were derived for 26 tributaries of the Brazos, Navasota, Trinity, and Sabine Rivers (figure 2), designed to represent the geomorphological variety of the study area. In addition, profiles were examined of the rivers themselves from a drainage divide of a tributary in the upstream reaches of the the studied river length, giving a total of 30 profiles. The profile data were extracted from digital elevation models (DEM). Extracting or estimating profiles from DEMs or topographic maps is both less accurate and precise than field surveys—particularly in the lowermost reaches of the main rivers, where DEM data do not reflect the fact that channel thalwegs are cut to below sea level. However, due to the time and expense of field surveys, DEM and map data allow for much greater spatial coverage. At broad scales of several km or more, map and DEM-derived profiles are generally considered sufficient for assessing profile characteristics.

A standard method for constructing longitudinal profiles from contour maps is to plot distance along the channel against elevation as measured from points at which contours cross the channel. This often results in few data points along long stretches of low-gradient channel, such as are common in the study area.

This project uses the RiverTools software (Rivix, Inc.) to extract profiles from 30 m DEM data, which contain an elevation value for each 30 X 30 m pixel. Stream lines are determined by routing flow from pixel-to-pixel along the line of steepest gradient, using the “imposed gradients plus” flow grid method of Peckham (1998; 2003), a variation on the method developed by Garbrecht and Martz (1997). The algorithm centers flow within flat areas in routing from higher to lower DEM pixels, and is preferable in alluvial valleys where flats are an issue. Because flood basins and other depressions exist on the floodplains of both rivers, depressions in the DEM were not filled for this analysis. Comparison of derived stream lines with aerial photographs showed excellent agreement on channel locations for larger streams, except in some floodplain areas which had experienced recent channel change.

The longitudinal profile is based on a distance vs. elevation plot along the streamlines, which produces a step-like appearance in many cases. To smooth out these profiles, best-fit trend lines were computed and plotted for each. Linear, power, exponential, logarithmic, quadratic, and third-order polynomial functions were fitted to each profile, and the function with the best fit according to the coefficient of determination (R^2) was applied. As in previous studies, in some cases several different functions provided excellent fits and $R^2 \geq 0.95$.

A concavity index was computed based on deviations from a straight line profile:

$$CI = \sum(H^*_i - H_i)/N \qquad (8)$$

Where H_i is the elevation at distance *i*, H^*_I the elevation along a straight line from the uppermost to lowermost point along the stream line, and N the total the total number of measurement points. Negative values indicate concavity, CI > 0 convexity.

For a given profile with $H_{max} = H_A - H_B$,

$$-H_{max}/2 < CI < H_{max}/2 \qquad (9)$$

The relative concavity for a profile with a given relief is

$$CI_{releative} = CI/(H_{max}/2) \tag{10}$$

For positive concavities, $CI_{relative}$ varies between 0 and 1.

Richards (1982) also suggests the index $2a/H_{max}$, where a is the (absolute value of the) maximum deviation from a straight-line. The general profile shapes, and significant convexities, were then assessed in the context of the environmental setting and geomorphic history of each river system as determined outlined in previous work.

RESULTS

Tables 1-4 show the results, organized by watershed. Several general phenomena are noteworthy. First, most of the profiles (19 of 30) have significant convexities, and only the Navasota watershed (Table 2) has a majority of samples without convexities. Second, the profiles are, on the whole, not strongly concave. Classic concave profiles would have $CI_{relative} > 0.5$, and $2a/H_{max} \geq 1$. Only five (13 percent) have this characteristic (figure 3).

Table 1. Characteristics of the longitudinal profiles of the lower Brazos River watershed. Brazos/Thompsons represents the profile from upper Thompson's Creek to the mouth of the Brazos. Column headings are as follows: Elev = elevation difference, highest vs. lowest point in meters; L = profile length, kilometers; CI = concavity index; CI rel = relative concavity; 2a/H = (2 * maximum deviation from straight line)/relief; BFE = best-fit equation, with R^2 value (Poly 3 = 3rd order polynomial; Exp = exponential); Convexity = presence of significant convexities in profile.

Brazos	*Elev*	*L*	*CI*	*CI rel*	*2a/H*	*BFE*	*Convexity*
Big Cr.	29	63	- 0.20	-0.016	0.316	Poly 3, 0.97	Y
Brazos/Thompsons	109	474	25.24	0.464	0.798	Poly 3, 0.97	Y
Brookshire/Bessie	50	30	3.44	0.226	0.550	Poly 3, 0.99	Y
Brushy	143	31	8.86	0.327	0.558	Poly 3, 0.99	N
Butler Bayou	74	13	-3.24	-0.387	0.027	Poly 3, 0.92	Y
Campbell's Cr.	128	32	14.32	0.438	0.748	Poly 3, 0.99	Y
Reason Cr.	55	32	6.40	0.877	1.624	Exp, 0.66	N
Thompson's Cr.	109	33	5.80	0.224	0.433	Poly 3, 0.99	Y
Turkey Cr.	103	12	6.40	0.276	0.575	Poly 3, 0.99	Y

Table 2. Characteristics of the longitudinal profiles of the lower Navasota River watershed. Navasota/Clear Cr. represents the profile from upper Clear Creek to the mouth of the Navasota. Column headings as in Table 1.

Navasota	*Elev*	*L*	*CI*	*CI rel*	*2a/H*	*BFE*	*Convexity*
Caney Island Cr.	117	19	7.12	0.339	0.608	Poly 3, 0.99	Y
Carter's Cr.	109	33	7.64	0.298	0.551	Poly 3, 0.99	N
Cedar Cr.	70	32	0.77	0.170	0.070	Poly 3, 0.95	Y
Clear Cr.	145	24	8.53	0.281	0.416	Poly 3, >0.99	N
Cottonwood Cr.	155	24	14.19	0.352	0.577	Poly 3, >0.99	N
Navasota/Clear Cr.	145	179	21.02	0.443	0.803	Poly 3, 0.98	N

Table 3. Characteristics of the longitudinal profiles of the lower Trinity River watershed. Trinity/Long King represents the profile from upper Long King Creek to the Trinity River at Liberty. Column headings as in Table 1.

Trinity	*Elev*	*L*	*CI*	*CI rel*	*2a/H*	*BFE*	*Convexity*
Big Caney Cr.	12	9	3.46	0.579	1.106	Poly 3, 0.98	Y
Big Creek	92	46	15.91	0.405	0.644	Poly 3, >0.99	N
Greens Bayou	19	22	1.76	0.243	0.728	Poly 3, 0.94	Y
Menard Cr.	85	62	5.90	0.174	0.351	Linear, 0.99	Y
Tanner Bayou	39	27	3.33	0.201	0.418	Exp, 0.99	Y
Trinity/Long King	105	173	37.23	0.713	1.223	Exp, 0.94	N
Turtle Bayou	11	24	0.65	0.132	0.576	Poly 3, 0.98	Y
Cedar Bayou*	26	67	2.97	0.232	0.594	Quadratic, 0.98	Y

*Tributary of Trinity Bay.

Table 4. Characteristics of the longitudinal profiles of the lower Sabine River watershed. Sabine/Sandy Cr. represents the profile from upper Sandy Creek to Sabine Lake. Column headings as in Table 1.

Sabine	*Elev*	*L*	*CI*	*CI rel*	*2a/H*	*BFE*	*Convexity*
Big Cypress Cr.	13	31	1.04	0.175	0.477	Poly 3, 0.99	Y
Brushy	41	24	5.33	0.346	0.670	Exp, 0.98	N
Nicholls	9	32	1.41	0.402	0.897	Poly 3, 0.95	Y
Old River	26	67	7.55	0.604	1.105	Poly 3, 0.96	Y
Sabine/Sandy Cr.	97	254	33.98	0.706	1.292	Poly 3, 0.94	N
Sandy Cr.	97	29	11.81	0.349	0.597	Poly 3, 0.99	N
Trout Cr.	61	25	1.64	0.076	0.183	Linear, >0.99	Y

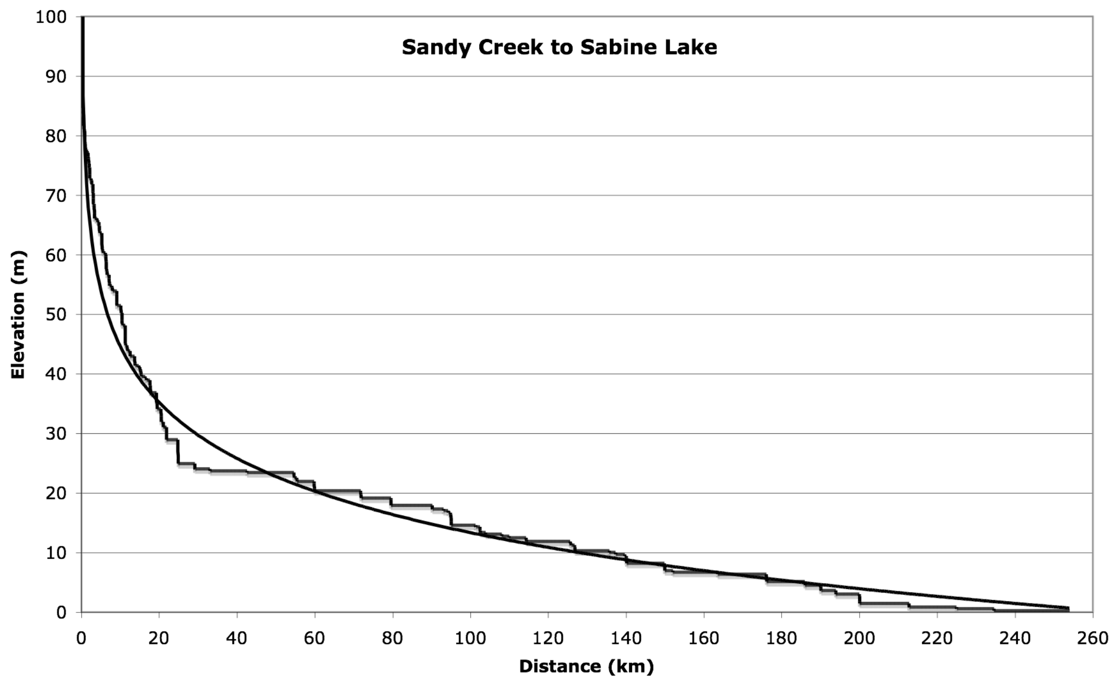
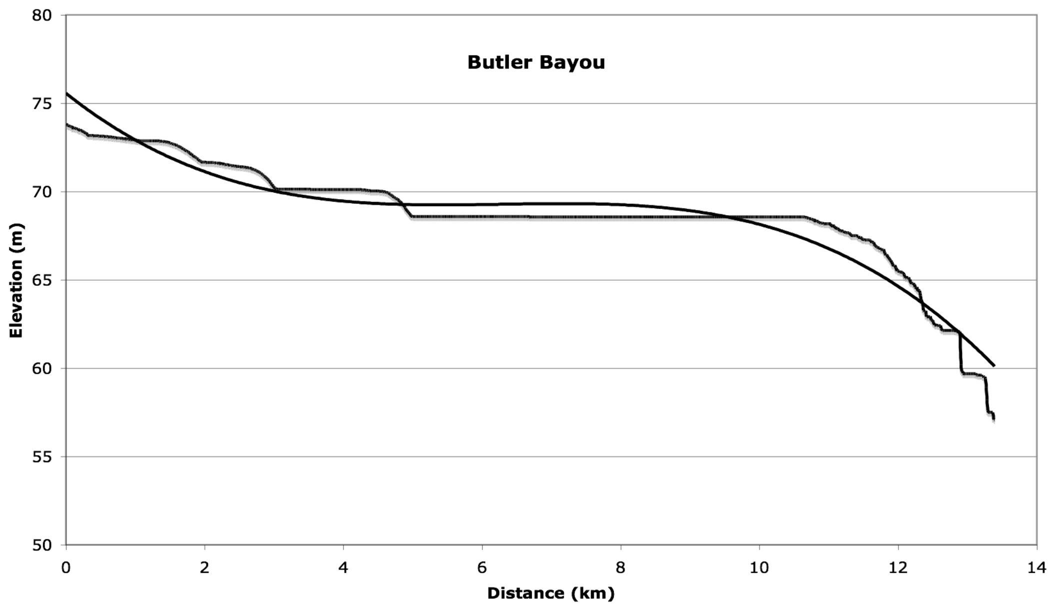


Figure 3. Example of classic concave up long profile, from upper Sandy Creek down the Sabine River. Best-fit trend line is shown along with DEM-derived profile.

Third, the most common (23 of 30; 77 percent) best-fit equation is a third-order polynomial of the form

$$y = a - b_1x^3 + b_2x^2 + b_3x \tag{11}$$

where y is elevation and x is distance, and *a* and the *b*'s are regression coefficients. In many cases the other nonlinear functions typically fit to long profiles, especially exponential but also quadratic, logarithmic, and power functions, showed fair to excellent fits as well. The third-order polynomial provides better fit for many profiles because in many cases there are steep sections in the lowermost portions of tributary profiles. These are interpreted to be due to tributary responses to incision of the trunk streams. The third-order polynomial thus provides a better fit to profiles that are concave in their upper and concave in their lower portions, or which are generally concave but have minor convexities in the lower reaches (figure 4).



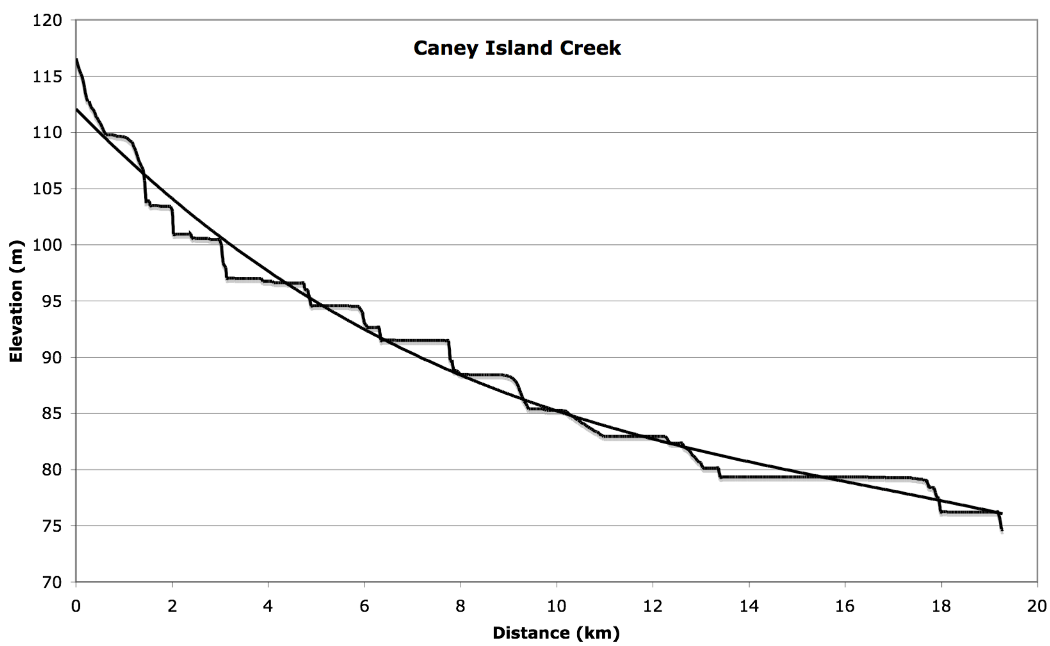


Figure 4. Two examples of profiles best fit by a third-order polynomial. Butler Bayou, a Brazos River tributary has a strong, steep convexity in the lower ~ 3 km, and Caney Island Creek, a Navasota River tributary, has a less pronounced convexity.

Two of the sample reaches had negative concavity indices (i.e., convex profiles)—Big Creek (Brazos River tributary in Fort Bend County), and Butler Bayou (see fig 4). Three--Menard (Trinity) and Trout (Sabine) Creeks, and Tanner Bayou (Trinity), had essentially linear profiles, though an exponential function provided a slightly better fit for the latter. Interpretations of these and the convexities in the otherwise concave profiles are given in the next section.

No systematic relationships were found between the concavity indices and relief. There were also no significant relationships found between CI or $2a/H_{max}$ and a relief index ($RI=H_{max}/length$). However, $CI_{relative}$ and the relief index do appear to have a relationship, in that (with the exception of the Butler Bayou outlier), lower RI is associated with a wide spread of concavity indices, with the spread apparently decreasing at higher RI (fig. 5). However, this could be an artifact of the number of low vs. high RI data points, and needs additional research.

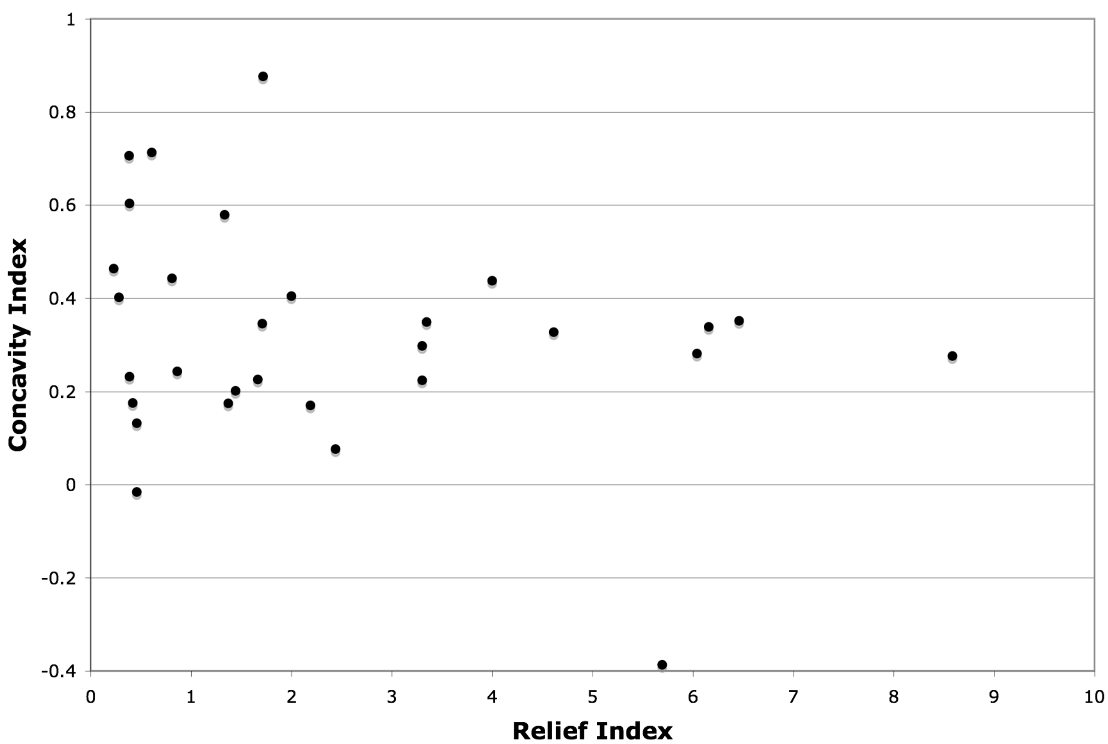


Figure 5. Relationship between the relative concavity index (CI_{rel}) and the relief index (RI).

INTERPRETATIONS

Overall results suggest that the river systems in the study area are not in a graded or steady-state equilibrium condition. Regional incision driven by falling and low sea levels early in the Quaternary probably accounts for the common steep sections in the lower reaches of many tributaries. However, an examination of the apparent causes of the convexities in the profiles reveals a variety of possibilities rather than a single regional explanation.

Two profiles have negative concavity indices. In the case of Big Creek (Fort Bend County, in contrast to another Big Creek which is tributary to the Brazos in Washington County), the convexity is due to a very steep slope in the lowermost reaches (figure 6). This is due primarily to rapid Brazos River bank retreat in the vicinity, which has truncated the lower reaches of the creek. The effect is essentially similar to that of a lowered base level (Musselman, 2006), and the steep convexity is in essence a knickpoint which might be expected to migrate upstream when the lateral migration of the Brazos which is truncating the creek is slowed or halted.

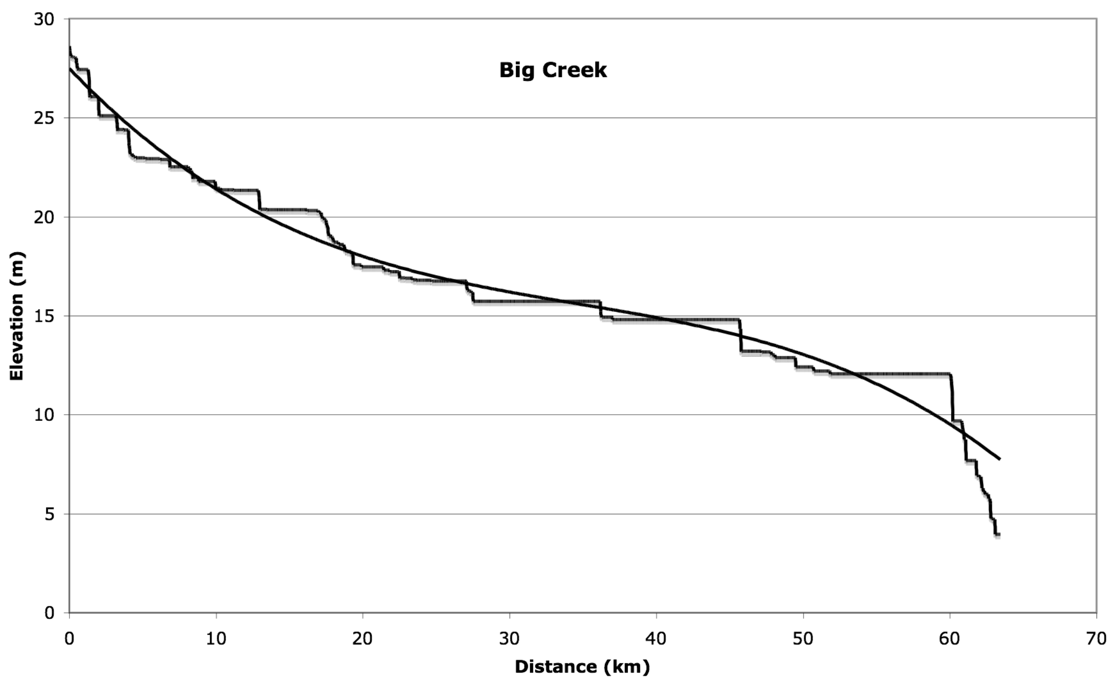


Figure 6. Longitudinal profile of Big Creek, a Brazos tributary in Fort Bend County.

The other convex profile, Butler Bayou (figure 4) occupies an abandoned Brazos River channel. Sometime after the river avulsed to its modern course, it began incising (see Waters and Nordt, 1995) and Big Creek occupied the paleochannel. When the Brazos incised, Butler Bayou began downcutting at its mouth in response, creating the pronounced convexity.

In three cases convex sections within overall concave (though sometimes weakly concave) profiles appear to be attributable to variations in resistance. Cedar Creek has a steep lower section that may be a response to earlier incision in the now-aggrading Navasota valley (Phillips, 2007b), but a convexity in the upper profile occurs where the stream leaves harder Eocene rocks and flows onto less-resistance Quaternary fill. The broad, gentle convexity in mid-profile in Caney Island Creek occurs where it flows down the face of a cuesta composed on resistant Eocene strata. In the lower Brazos, a broad gentle convexity (figure 7) is associated with a bedrock-confined valley reach upstream of an unconfined, wide alluvial valley. The major convexity in the profile of Campbell's Creek, which drains to the Brazos River via the Little Brazos River, is associated with a pronounced change from lower to higher sinuousity. This is in turn in the vicinity of a mapped fault, which appears to have produced changes similar to those documented in an analagous situation in the Neches River, Texas by Schumm et al. (2000).

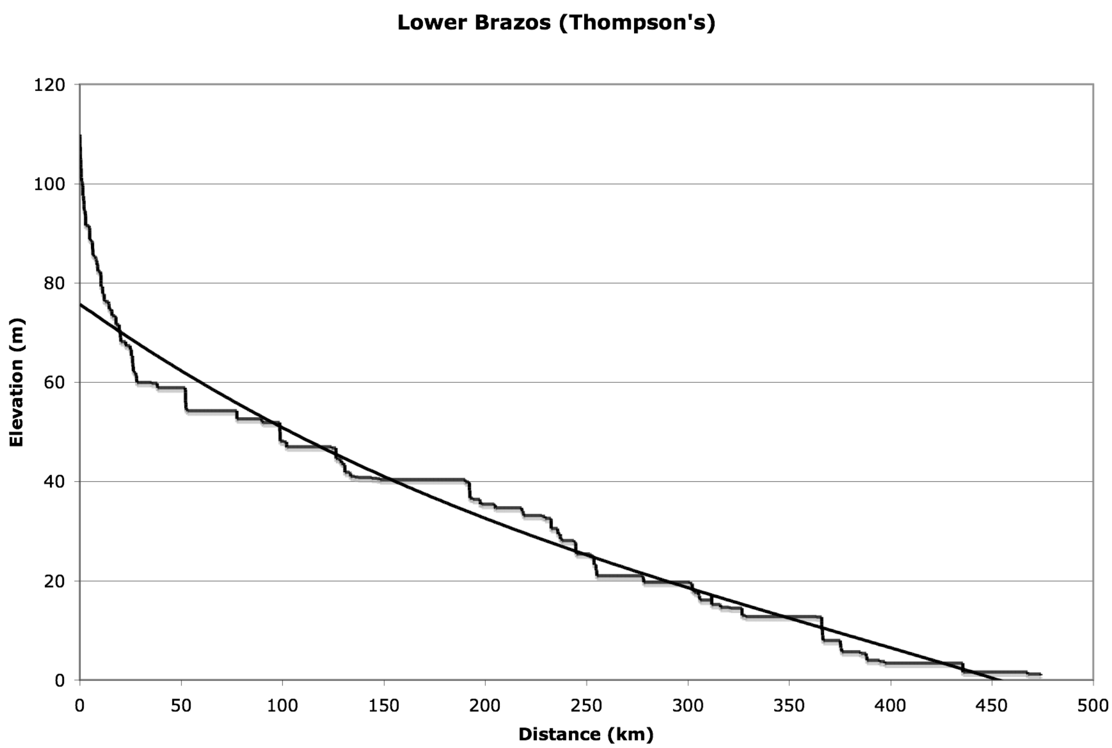


Figure 7. Longitudinal profile from headwaters of Thompson's Creek down to the mouth of the Brazos river. Note the broad convexity from about 125 to 250 km, and the local convexity at about 360 km.

Antecedent topography and inherited morphologies were directly associated with convexities in a number of cases, including Big Cypress, Big Caney, and Nicholls Creeks, Greens and Turtle Bayous, and Old River (LA). In several instances convexities or steps in the profile are associated with the sides of the incised valleys, where the streams leave the Beaumont or other upland surfaces and enter the late Pleistocene incised valleys. "Deweyville" flood basins, depressions, and paleomeander scars, and the occupation of river paleochannels also influence the long profiles. Greens Bayou, for instance, shows a step in the profile at about 7 km where the stream encounters the valley side (figure 8). A long nearly flat stretch is associated with a Deweyville flood basin, terminating in a steep reach as the bayou descends to the incised Trinity River. In the case of Old River (fig. 9), a convexity on the upper profile corresponds with the up-valley boundary of a geomorphic transition zone associated with a Pleistocene stream capture event (Phillips, 2007a).

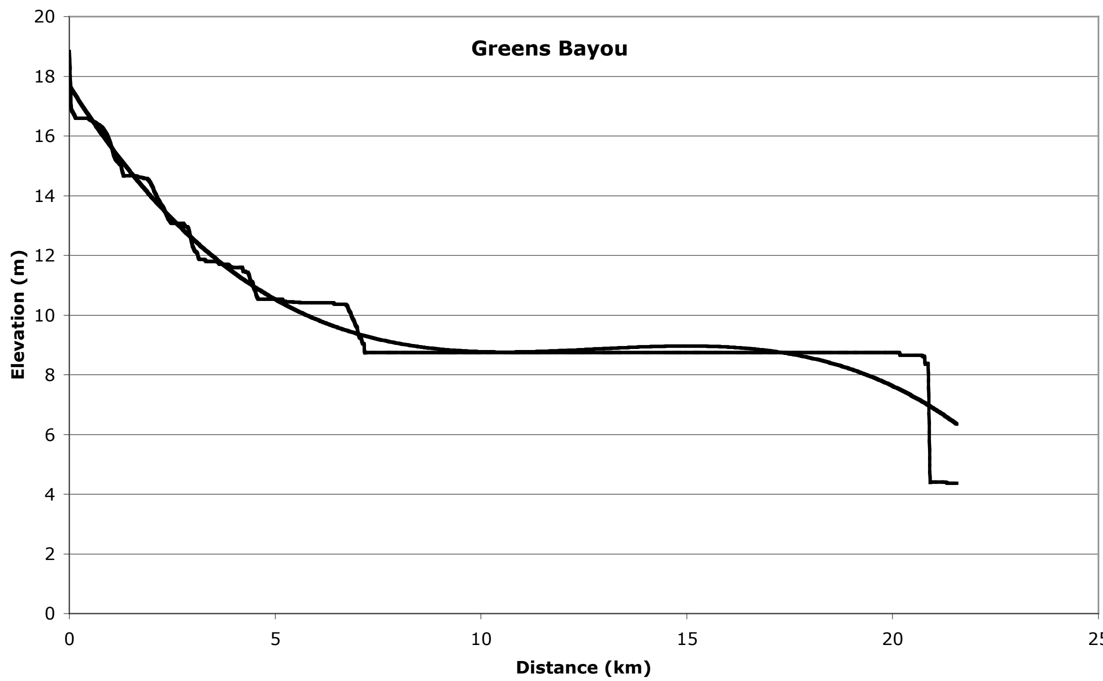


Figure 8. Longitudinal profile of Greens Bayou, a Trinity River tributary.

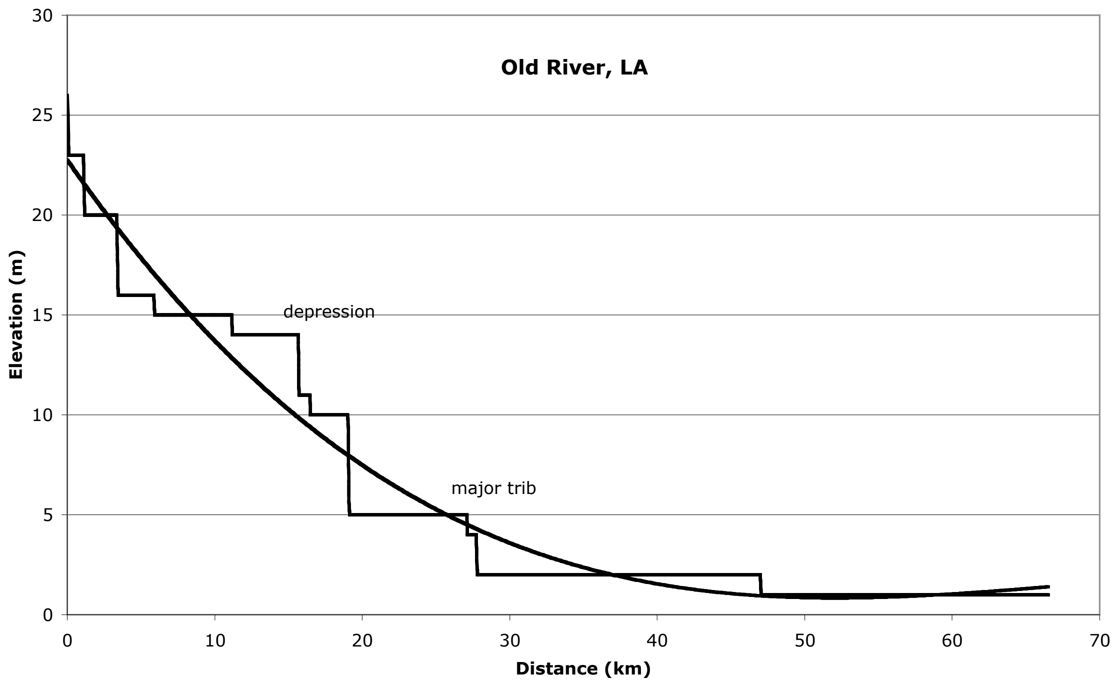


Figure 9. Longitudinal profile of Old River, an abandoned and reoccupied Sabine River channel which is now the dominant anabranch. A depression associated with Pleistocene morphological changes (see Phillips, 2007a) and the junction with a major tributary are associated with the two major convexities in the profie.

Anthropic changes may also play a role. Cedar Bayou exhibits an essentially stepped profile, apparently attributable to long reaches of channel which were straightened by artificial meander cutoffs. The long profile of Brookshire/Bessie Creek exhibits three convexities, one of which is related to the (apparently natural) cutoff of a large meander. The other two, however, are associated with artificially straightened reaches.

The profiles which exhibit or come closest to the classic concave profile are those of the major rivers (starting from tributary drainage divides), and Brazos tributary Reason Creek. The latter is one of the few tributaries in the study which is contained entirely within the Quaternary alluvial valley. The river profiles are also contained mainly within the alluvial valleys.

By contrast, the three profiles which are straight or nearly so (Menard and Trout Creeks and Tanner Bayou) differ from the others in having little or no crossing of the alluvial valley before joining the trunk river. The upland reaches of many of the profiles are also approximately straight.

DISCUSSION

The 30 sample longitudinal profiles contain more convex and straight forms (five) than strongly concave (three). Of the remainder, many are only weakly concave and/or feature significant deviations from a concave trend. Convexities are associated with at least six different causes—geological variations in resistance, tectonics, antecedent or inherited topography, downcutting in response to trunk stream incision, tributary truncation by lateral channel migration, and anthropic effects. Given that these are general categories that may include several different phenomena (e.g., antecedent topography), it seems clear that explanation of deviations from convexity requires examination of individual feature, even within a single region such as southeast Texas.

Clearly the streams of southeast Texas generally deviate from the classic graded profile, in a variety of ways and for a variety of reasons. However, it could be argued that the graded profile is still a useful reference condition, and that given sufficient time, at least some of the study streams would achieve something approximating a relatively smooth, concave profile.

While the latter is arguably useful as an abstraction, it may have little utility in describing, explaining, or modeling contemporary fluvial systems in the region, since the implicit assumption is relatively unchanged boundary conditions. The Quaternary has seen a succession of sea level and climate changes profoundly influencing the rivers of the study area, as well as neotectonic activity, and more recently, dams and other human influences (e.g., Alford and Holmes, 1985; Waters and Nordt, 1995; Blum and Price, 1998; Otvos, 2005; Rodriguez et al., 2005; Blum and Aslan, 2006; Sylvia and Galloway, 2006; Taha and Anderson, 2007). Beyond the direct influences associated with these environmental changes, antecedent and inherited morphology has important influences on modern forms and processes, as seen in the results of this study and a number of earlier ones (e.g., Blum et al., 1995; Blum and Aslan, 1999; Rodriguez et al., 2004; Phillips et al., 2005; Rodriguez et al., 2004; Sylvia and Galloway, 2006; Phillips, 2007a; Phillips and Slattery, 2007). Even without human agency and the possibility of accelerated climate and sea level change, there is no reason to expect consistent boundary conditions.

The deviations from the graded profile cannot be simply explained as a lack of sufficient time for profile development. Reason Creek, for example, is developed entirely on late Quaternary surfaces within the Brazos alluvial valley, showing there has been sufficient time for development of strongly concave profiles. The strongly concave lower Sabine and Trinity River profiles are also developed almost entirely in Quaternary sediments. In the latter cases, studies of sediment flux and storage show that the concavity is clearly *not* a reflection of a dynamic balance between sediment supply and transport capacity (Phillips, 2003a;b; Phillips et al., 2004; 2005).

The migration and smoothing of knickpoints, steps, and convexities that is likely to occur is consistent with progress toward an idealized graded profile. However, the notion of grade is neither necessary nor sufficient to explain the profile changes, which can be readily linked to relationships between slope and stream power and/or shear stress.

Further, a simpler explanation is available—that of a tendency for upper-basin incision to steepen toward the geomechanically limiting slope gradient (S_{max}), with the lower reaches constrained to S_{min}.

CONCLUSIONS

Few stream profiles in southeast Texas conform to the ideal of the smoothly concave graded or steady-state equilibrium profile. Deviations from this ideal are attributable to geologic and tectonic controls, inherited morphology, recent and contemporary geomorphic processes, and anthropic effects. Both the legacy of Quaternary environmental change and ongoing changes in the region make it unlikely that consistent boundary conditions for these fluvial systems will exist for long. Further, the exceptions within the study area—i.e., strongly and smoothly concave longitudinal profiles—suggest both that ample time has occurred for strongly concave profiles to develop, and that such profiles do not represent any mutual adjustments between slope, transport capacity, and sediment supply.

There is no evidence of any single characteristic form in the long profiles of the study area, though some may be diagnostic—for example, the concave-upper, convex-lower tributary profile is apparently related to the tributary reponse to trunk stream incision. Any broad, general tendency toward a smoothly strongly concave profile is not linked to any contemporary or Quaternary steady-state adjustments among slope, discharge, and sediment load. A simpler and more likely explanation is based on simple, fundamental constraints on channel slope.

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Section 5

Summary and Conclusions

INTRODUCTION

A review of the literature relevant to geomorphic responses of southeast Texas Rivers to factors such as sea level change, impoundments, and changes in flow was presented in Section 1. The results suggest that relaxation time equilibrium is probably common with respect to geomorphic phenomena such as along-valley patterns of aggradation or degradation, general sediment transport/storage regimes, and cross-sectional adjustments to flows. The stronger forms of equilibrium—characteristic forms and steady-state—are far less likely.

RTE implies only that fluvial response or adjustment to new boundary conditions or to a disturbance has been completed, and is useful primarily in assessments of river condition. A determination that a fluvial system (or, more accurately, some specific aspect thereof) is in RTE is often necessary to define the domain of applicability of particular models or assumptions, or for accurately defining reference levels such as bankfull flow elevation. The notion of RTE does not imply any particular normative, natural, or desired condition, as do the stronger forms of equilibrium (CFE, SSE).

The general consideration of geomorphic equilibrium in Section 1 was conducted in the context of responses to specific forcings. However, the rivers of Texas are subject to the simultaneous, interacting influences of changes in sea level, climate, tectonics, biota, hydrologic response, and anthropic effects. Thus three specific phenonmena were examined for rivers of the study area—hydraulic geometry (cross-sectional response to changes in flow), avulsions (channel changes), and longitudinal profiles.

Relaxation time equilibrium (RTE) has no particular theoretical implications, as it implies only that changes in response to a disturbance or to new boundary conditions have run their course, or at least slowed to negligible rates. In an applied perspective, notions of RTE are typically employed to define the domain of applicability of particular models, techniques, or assumptions.

HYDRAULIC GEOMETRY

Hydraulic geometry, relating the characteristics of channels, the flows they carry, and their mutual adjustments, is fundamental to any understanding of fluvial system response to changes and disturbances. Theory suggests that the relationship between fundamental hydraulic variables is dynamically unstable, with the instability manifested as multiple modes of adjustment and as opposite-from-expected (OFE) behavior. OFE responses occur when one or more hydraulic variables change in response to increases or decreases in discharge in the opposite direction from that expected from hydraulic theory.

At 11 gaging stations on the Brazos/Navasota, Trinity, and Sabine Rivers, 84 to 475 flow transitions were examined from USGS stream gaging data. All stations exhibited a significant proportion of OFE responses (16.7 to 80 percent) in that at least one of the variables of discharge, width, mean depth, cross-sectional area, mean velocity, and Froude number changed in the opposite direction from the others. At seven of the 1stations more than half of the comparisons indicated OFE behavior.

The results indicate that hydraulic geometry is not characterized by CFE and SSE. RTE may exist due to the very rapid adjustment possible in the hydraulic variables, but this is of limited relevance at time scales beyond those of individual flow events.

The suite of possible reach or cross-section responses is indeed constrained by general laws and principles. For example a decline in discharge will be accommodated by some change in channel capacity and/or conveyance efficiency, but even the qualitative combination of increases, decreases, or no change in hydraulic variables may be unpredictable—except, perhaps in the case of individual sites where detailed data is available, and with some difficulty even then.

One fundamental implication is that even qualitative results cannot necessarily be transferred from one river to another. For example, the response of Yegua Creek to major reductions in peak flow dominated by infilling (decrease in depth) cannot be assumed to apply even to similar streams in the region. Another is that even within a single river system or along a single reach one cannot necessarily expect a consistent response.

The implication for river management is that design, management, or prediction for a specific reach or section requires detailed analysis of that specific site—rules of thumb or generalities derived from other sites, however nearby and similar, cannot be confidently applied. For more general or broader-scale assessments, it is clear that no particular normal, stable, natural, or (quasi-)equilibrium condition can be assumed or specified. It would be more fruitful and appropriate to constrain the set of possible responses, with further constraints possible based on local conditions (for example, exposed bedrock in a channel makes an incision response to increased slope or discharge less likely).

Finally, where modifications to the channel or valley are made—for erosion and flood control, fish and wildlife habitat, water supply, transportation, or other purposes—it must be recognized a complex chain of changes can be triggered which (due to dynamical instability) may be quite large relative to the magnitude of the original change.

The nonequilibrium of hydraulic geometry does not necessarily preclude some level of generalization, but does suggest caution in developing and applying generalizations. The same data set used for the OFE analysis was used to test the idea (based of fundamental flow resistance relationships) that velocity varies linearly with mean depth due to an hypothesized tendency for roughness to vary inversely with depth.

Results provide some support for the proposed relationship, but only as a relatively broad generalization. Further, , poor relationships may be expected where the major assumptions of the model are violated—in this case, where channel slopes do not necessarily well represent energy grade slopes, or where roughness does not vary systematically with depth. The instability of hydraulic geometry no doubt accounts for some cases where assumptions are violated, and for some of the scatter in the V-d relationship even where the assumptions hold.

AVULSIONS

Avulsions are common, from a geomorphic perspective, in the rivers of the southeast Texas coastal plain, and have important influences on floodplain construction, alluvial stratigraphy, surface topography, and hydrologic and geomorphic processes in the lower Brazos, Navasota, Trinity, Neches, and Sabine River valleys.

Avulsion-related landforms are active and distinct features throughout the study area, and all the rivers have experienced geologically (if not historically) recent avulsions. However, no two of the study rivers have the same avulsion regime. Differences in avulsion style are controlled by the valley filling regime, and within the three rivers characterized by an unfilled incised valley, antecedent morphology associated with late Quaternary and Holocene coastal, fluvial-deltaic, and neotectonic processes accounts for the major differences.

All study rivers except the Brazos have experienced recent or historic avulsions, and even the Brazos experienced a major avulsion as recently as 300 years ago. The Navasota and Neches Rivers, in particular, have subchannels associated with avulsions exist in all stages of development from active to infilled. The big-picture role of avulsions in these fluvial systems is as a mechanism for distributing sediment in deltas and infilling valleys, and as an unstable, contingent response to perturbations. Avulsions do not appear to be a mechanism for slope adjustments in a way comparable to meander growth/cutoff or channel aggradation/incision.

Relaxation time equilibrium is difficult to evaluate other than on a case-by-case basis. Some avulsions have clearly reached RTE, as is the case with those on the Brazos River, for example. In other cases, particularly the Navasota, Neches, and deltaic portion of the Sabine River, while some individual subchannels have achieved RTE, avulsions and channel switching is common enough so that no general assumption of RTE is valid.

Clearly no single characteristic form is associated with channel shifts, which may result in crevasse splays, neck cutoffs, chute cutoffs, anastamoses, relocations, distributaries, or even watershed fragmentation. Abandoned, semi-abandoned, and bifurcated channels may exist in all states from infilled to active. Further, transitions among these states occur as new channel changes occur.

No sort of steady-state stable equilibrium framework can be usefully applied to the occurrence of individual channel shifts. While the conditions promoting avulsion, such as aggradation and/or possible flow deflecting features, allow assessment of avulsion probability, the specific location and timing is highly contingent on local factors.

With respect to the outcome of a given avulsion, stability is indicated by a failed avulsion where the main channel regains dominance. Direct evidence of this is inherently unlikely to be observed, but it has no doubt occurred. Dynamical instability is indicated by a successful relocation avulsion where the main channel is abandoned. This has occurred at least 21 times in the study area. The success of nearly all cutoffs—particularly neck cutoffs—also indicates instability. This is not surprising, however, since meanders are known to grow to a point of incipient instability. A persistent anabranch or distributary bifurcation suggests metastability. At least 22 anastomoses and distributaries are currently active in the study area. Thus no precise statements on the relative importance of stable, unstable, and metastable avulsions can be made, but clearly all occur.

The results generally support the broader-scale qualitative stability model based on slope-aggradation-avulsion feedbacks. The model indicates that in the absence of strong external controls on avulsion, and where slope-avulsion feedbacks are stronger than slope-aggradation links, the system is dynamically stable. If external controls are not dominant, and aggradation-slope feedbacks are strong, the system is dynamically unstable. The most active systems, where successful avulsions are most likely, are the Neches, with strong external controls, and the strongly-aggrading Navasota, where proximity to the aggradational threshold promotes instability throughout the system.

In a system such as the Brazos, Trinity, or Sabine upstream of the delta, occasional future avulsions are likely. If these are a management concern, assessment of factors promoting avulsions (chiefly slopes and aggradation) can allow identification of high- and low-probability sites or reaches. Given the role of avulsions in the fluvial system, they should be understood as a normal adjustment mechanism in a dynamical fluvial/alluvial system and accepted as such. However, if other considerations dictate an engineering response, then the principles in section 3 can be used to encourage the success of the preferred channel. In an aggrading, avulsion-prone system such as the Navasota, channel shifts are common and the river should be understood and managed as a dynamic multi-channel system.

LONGITUDINAL PROFILES

Few stream profiles in southeast Texas conform to the ideal of the smoothly concave graded or steady-state equilibrium profile. Several different factors lead to these deviations, including geologic and tectonic controls, inherited morphology, recent and contemporary geomorphic processes, and anthropic effects. Both the legacy of Quaternary environmental change and ongoing changes in the region make it unlikely that consistent boundary conditions for these fluvial systems will exist for long. This, along with the variety of common factors accounting for convexities in the profiles, suggests that a classic "graded" profile should not be an expectation. Further, the exceptions within the study area—i.e., strongly and smoothly concave longitudinal profiles—suggest both that ample time has occurred for strongly concave profiles to develop, and that such profiles do not necessarily represent any mutual adjustments between slope, transport capacity, and sediment supply.

It would be difficult to identify a characteristic form in the long profiles of the study area, though some of the variations in form may be diagnostic—for example, the concave-upper, convex-lower tributary profile is apparently related to the tributary reponse to trunk stream incision. Any broad, general tendency toward a smoothly strongly concave profile is not linked to any contemporary or Quaternary steady-state adjustments among slope, discharge, and sediment load. A simpler and more likely explanation is based on simple, fundamental constraints on channel slope.

No assumption of CFE or SSE is valid within the study area. RTE may be indicated by profiles where the relevant section—not necessarily the entire profile—is approaching a limiting slope. For example, RTE may be indicated where local slope adjustments are approaching constraints set by substrate erodibility or base level—or the endpoint of maximum concavity. The latter is clearly not the case in some of the study profiles, though in some RTE can be inferred.

CONCLUSIONS

Relaxation time equilibrium may be present in the rivers of southeast Texas, and the presence (or absence) of RTE is useful in assessing river conditions and in the application of analytical techniques and models. Characteristic form and steady-state equilibrium are far less common, and clearly cannot be assumed. In general, no inherent tendency toward any stronger form of equilibrium—characteristic forms, steady-states, grade, etc.—can be assumed, at least not in the form of any single characteristic or stable equilibrium state.

Equilibria are arguably useful as a reference condition, but should not be assumed to necessarily any more common, important, or "natural" than disequilibrium or nonequilibrium states. Managers cannot assume that there is any *single* normal, natural, or otherwise normative condition for the alluvial rivers of the study area, and should recognize the possibility—indeed, the likelhihood—of multiple modes of adjustment and potential responses to disturbance.

Appendix

SCOPE OF WORK PLAN

Geomorphic Equilibrium in Southeast Texas Rivers

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Overview

This work plan addresses a cooperative research study of the geomorphic equilibrium of the coastal plain portions of the Brazos, Trinity, and Sabine Rivers. River and stream management, assessment, engineering, and classification is often based on concepts of geomorphic equilbrium, and implicit or explicit assumptions that fluvial systems are in, or develop towards, some form of equilibrium.

However, the assumption of equilibrium (or tendencies toward it) is often invalid and increasingly criticized as a reasonable assumption for models and assessments. Further, equilibrium is variously, often poorly, and rarely rigorously defined.

This project will develop three rigorous and increasingly restrictive concepts and related definitions of geomorphic equilibrium, and apply them to the study rivers:

4. *Relaxation Time:* a fluvial system is in equilibrium if it has completed its response to a given disturbance or environmental change. This is the weakest concept of equilibrium, implying only that a response has had time to be completed.

5. *Characteristic Form:* this stronger concept implies relaxation time equilibrium, with the additional criterion that the system achieves (or at least moves toward) a form or state which is adjusted to its environmental constraints and contexts. This has traditionally been interpreted in terms of a more-or-less universal equilibrium form (for instance a concave-up longitudinal profile).

6. *Steady-State*: This, the strongest form of equilibrium, implies that the characteristic form is stable in response to all but very large perturbations, and self-maintaining.

The specific objectives are to:

(1) For a matrix of geomorphic processes and changes described in items 2 and 3 below, determine the general equilibrium conditions of the river study reaches as

a whole, and of critical transition zones and environmentally sensitive areas, according to the relaxation time, characteristic form, and steady-state criteria described above.

(2) Determine the equilibrium status of the study rivers with respect to three geomorphic processes or phenomena:

(a) Channel and valley aggradation/degradation;

(b) Upstream-downstream variation in dominant sediment transport and depositional regimes; and

(c) Channel cross-sectional changes (hydraulic geometry).

(3) Determine the equilibrium status of the study rivers with respect to three general types of change:

(a) Holocene sea level fluctuations;

(b) Downstream effects of dams and reservoirs; and

(c) Changes in flow regimes associated with climate change, land use, and water withdrawals or redistributions.

(4) Assess the viability of equilbrium assumptions with respect to water resource management in the study area.

Methods

The river segments included in the study are the Brazos River downstream of Bryan (SH 21), the Trinity downstream of Lake Livingston, and the Sabine below Toledo Bend Reservoir. This is feasible due to recent and ongoing work on geomorphic changes, landscape evolution, and geomorphic classifications in all three rivers.

Space does not permit a full discussion of the methods, techniques, data, and evidence used to establish and estimate the types, rates, and timing of geomorphic change in the study area. However, these methods, based on a combination of map, imagery, and GIS data; analysis of published data; and field interpretations of topography, morphology, stratigraphy, and pedologic and vegetation evidence, are described in a number of publications based on recent work by the PI and collaborators in southeast Texas (Phillips, 2001; 2003a;b; Phillips and Marion, 2001; Phillips and Musselman, 2003; Phillips and Slattery, 2006; Phillips, et al., 2004; 2005; Wellmeyer et al., 2005).

Relaxation time equilibrium may be assessed in two ways. For disturbances which are discrete in time (e.g., dam construction), the progress of adjustments can be directly assessed. For ongoing or long-lasting changes (e.g., sea level) the characteristic time scales or rates of changes and adjustments will be compared. Formally, relaxation time equilibrium will be assessed based on a determination of whether $(t - t_d)/T_r \geq 1$, where t is the time of interest, t_d is the time of disturbance, and T_r is relaxation time.

Characteristic form equilibrium (CFE) will be assessed for those elements where the relaxation time criterion is met. If the relaxation criterion is met, CFE requires that the response is typical (e.g., characteristic) within a given river, among the study rivers, and in general. For instance, if an increase in sinuousity in response to sea level rise, or a decrease in lateral channel migration in response to flow reduction, have reaction times rapid enough relative to the changes, then CFE would require that these responses consistently occur in reaches with similar environmental constraints.

Steady-state equilibrium (SSE) further requires that the fluvial (sub-)system in question is dynamically stable. This can be determined by identifying the key system components and the positive or negative feedback links between them, and applying the Routh-Hurwitz criteria to the resulting interaction matrix.

Personnel and Responsibilities

TWDB will oversee the activities and serve as contract manager. Dr. Jonathan Phillips of the University of Kentucky (but acting as an independent contractor) is responsible for all objectives and tasks in the scope of work, assisted as needed by research assistants arranged for and compensated by Dr. Phillips.