Geomorphic Responses to Changes in Flow Regimes in Texas Rivers

Project Report for the Texas Water Development Board and Texas Instream Flow Program, TWDB contract number 1104831147

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FINAL REPORT

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Introduction and Background

OVERVIEW

The purpose of this study is to develop a model to predict the geomorphic response of alluvial rivers in Texas to changes in flow regimes. The adjustments of alluvial river channels to changes in water and sediment inputs are related to changes in transport capacity, sediment availability, and modes of adjustment, but are characterized by complex responses, nonlinear dynamics, and path-dependent development. Potential modes of adjustment include various combinations of channel widening, narrowing, deepening, and shallowing at the cross-section scale, and changes in planform, slope, and roughness at the reach scale. The dominant mode of adjustment is dependent on the resistance or erodibility of the bed and banks relative to hydraulic forces, how the slope of the channel has been modified, and the relationship between sediment supply and transport capacity. The model is based on a combination of theoretical modeling and empirical data from observations of the effects of dams, water withdrawals-additions, and wet-dry climate cycles.

The specific objectives are to:

(1) Identify the modes of channel adjustment to changes in flow (fluvial system state) and the potential transitions among these states.

(2) Develop a state transition model (STM) linking transitions among fluvial system states with changes in flow and sediment supply.

(3) Test and refine the STM using existing data for the Trinity, Sabine, Brazos, Navasota, Guadalupe, and San Antonio Rivers related to geomorphic responses of dams, flow diversions, climate change, and wet-dry climate cycles.

(4) Develop a version of the model for managers in decision-tree or flow-chart form that, given a proposed or hypothesized modification of flow regimes, would guide the user through a series of questions and criteria to either predict channel responses or develop likely scenarios of channel response.

The approach is based on the concept of transport- vs. supply-limited fluvial systems, the relationship between sediment supply or availability and transport capacity as measured by stream power, and on critical thresholds for bed and bank erosion. Modes of adjustment (system states) represent various combinations of increases, decreases, and no change in channel slope, planform, roughness or resistance, width, and depth. The fluvial response STM is conceptually similar to the STMs frequently used in rangeland ecology and management to predict vegetation community responses to, e.g., grazing systems, fire, and brush management (c.f. Briske et al., 2005).

This study focuses on alluvial rivers in the broadest sense of the term—that is, streams that are not strongly controlled by bedrock along a majority of their length. In general, alluvial channels flow through or across alluvial deposits in valley bottoms. They are considered self-formed in the sense that flows are at least occasionally capable of eroding the bed and banks, and the size, shape, and path of the channel is not strongly constrained by geologic factors. The main reason for this distinction is that processes of mutual adjustments between flows and channels in bedrock streams are quite different from those of alluvial channels.

Management Context

This work is undertaken in the context of the Texas Instream Flow Program. Instream flow programs (IFP) are intended to balance human and non-human uses of water, the latter usually summarized in terms of ecosystem requirements. IFPs are typically instituted to assess surface water withdrawals and flow modifications with respect to flow regimes required to maintain aquatic and riparian ecosystems (and sometimes instream recreational and economic activities). As a National Academy of Sciences report put it, IFPs "are being developed to answer the often politically-charged question, 'how much water should be in the river?'" (NAS, 2005: vii).

The Texas IFP has its roots in legislation establishing a state water planning process to consider environmental values in water development and allocation. The Texas Water Development Board (TWDB), Parks and Wildlife Department (TPWD) and Commisson on Environmental Quality (TCEQ) were directed to jointly establish and maintain an instream flow data collection and evaluation program, and to determine flow conditions in Texas streams necessary to support, in the words of the enabling legislation, "a sound ecological environment." The IFP work plan and technical overview developed by the three agencies are available from http://www.twdb.state.tx.us/instreamflows/.

In addition to changes in flow regimes associated with human use and modifications of water, ongoing and future climate change has the potential to significantly alter hydrologic regimes in Texas (Norwine and Kuruvilla, 2007; Schmandt et al., 2011).

STUDY AREA

The study area includes the entire state of Texas (figure 1), in the sense that all available case studies in Texas were utilized, and that the results are intended to be applicable to alluvial rivers within the state. These occur throughout the state. However, the largest alluvial streams or stream segments occur in the coastal plain, a natural consequence of the entire state being within the Gulf of Mexico drainage. The chief exception to rivers draining directly to the Gulf is in northeast Texas, where rivers such as the Red and Sulphur reach the Gulf of Mexico via the Mississippi River system. Ephemeral streams occur in some dryland areas of west Texas, and bedrock controlled channels are relatively common in the Edwards Plateau region. Some east Texas tributary streams, and even some sections of larger rivers, are cut to or near bedrock. However, bedrock control is rare in the banks, and in many cases the bedrock is relatively weak, or is actually pre-

Quaternary sediments that are not rock *per se*. Thus these may be treated as alluvial channels for purposes of analyzing and predicting channel responses.

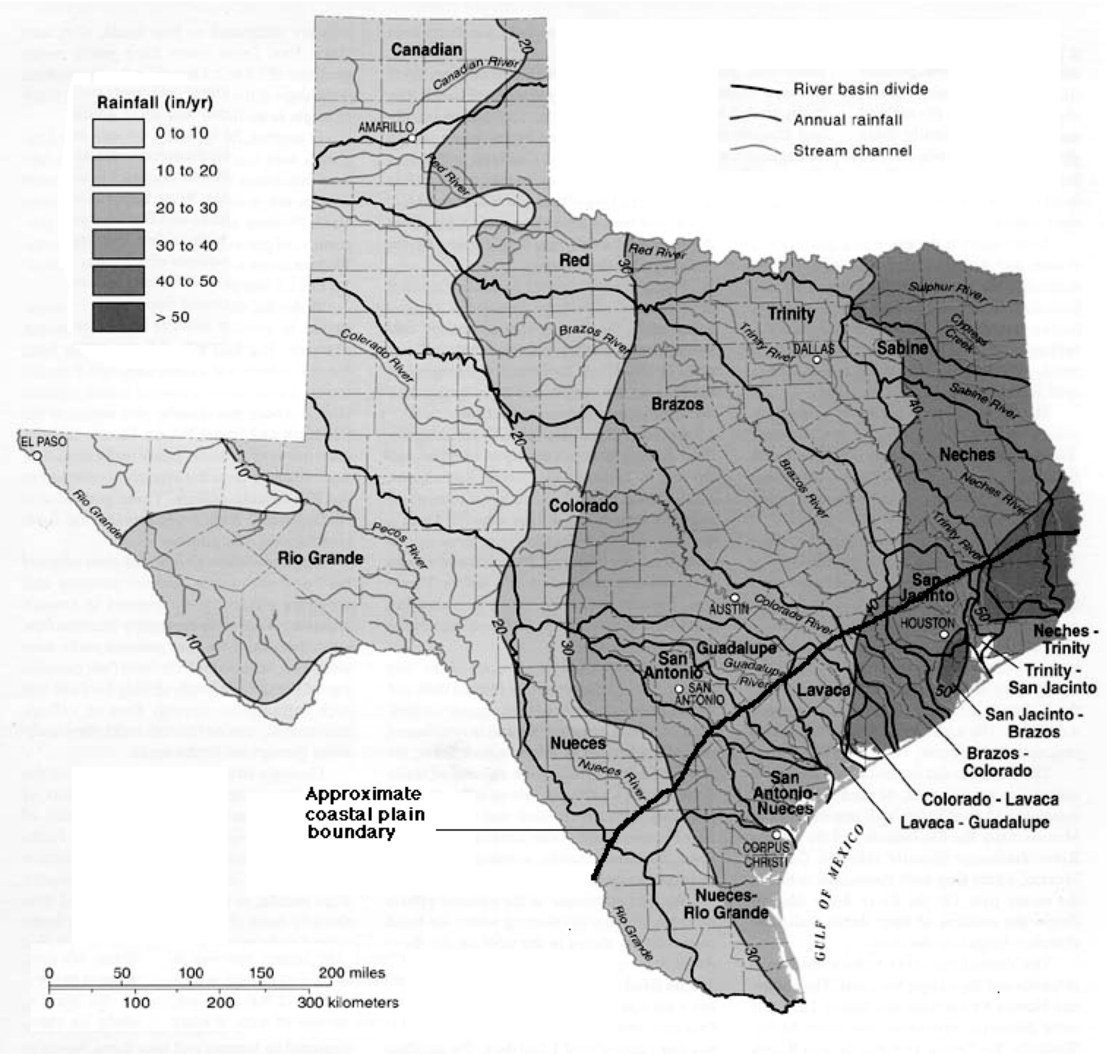

Figure 1. Major rivers and drainage basins of Texas. Modified from Texas Bureau of Economic Geology, 1996, River Basin Map of Texas.

A full overview of the physical geography and hydrology of Texas is beyond the scope of this study. A key point is that the vast area (696,242 km^2/268,581 mi^2) encompasses a wide variety of fluvial systems, from cypress bayous in the east to ephemeral desert streams in the west. There is a general east-west gradient of decreasing rainfall (see Fig. 1), with the 100th meridian providing a rough demarcation between the moister forested areas to the east, and the drier western grasslands, shrublands, and savannas. Texas also encompasses more than 10 degrees of latitude, from near-tropical (25° 50’ N) to 36° 30’ N.

Geological controls also create important geographical differences between and within fluvial systems. For example, the Guadalupe River basin can be divided into six broad landscape units based on physiography and underlying geology (Figure 2). Within each of these, however, more detailed geological variations sometimes create significant differences in both hydrology and morphology. Even in coastal plain alluvial rivers, geological controls can exert significant influence on fluvial forms and processes (for Texas examples, see Blum et al., 1995; Morton et al., 1996; Blum and Aslan, 2006; Taha and Anderson, 2008; Phillips and Slattery, 2007b; 2008).

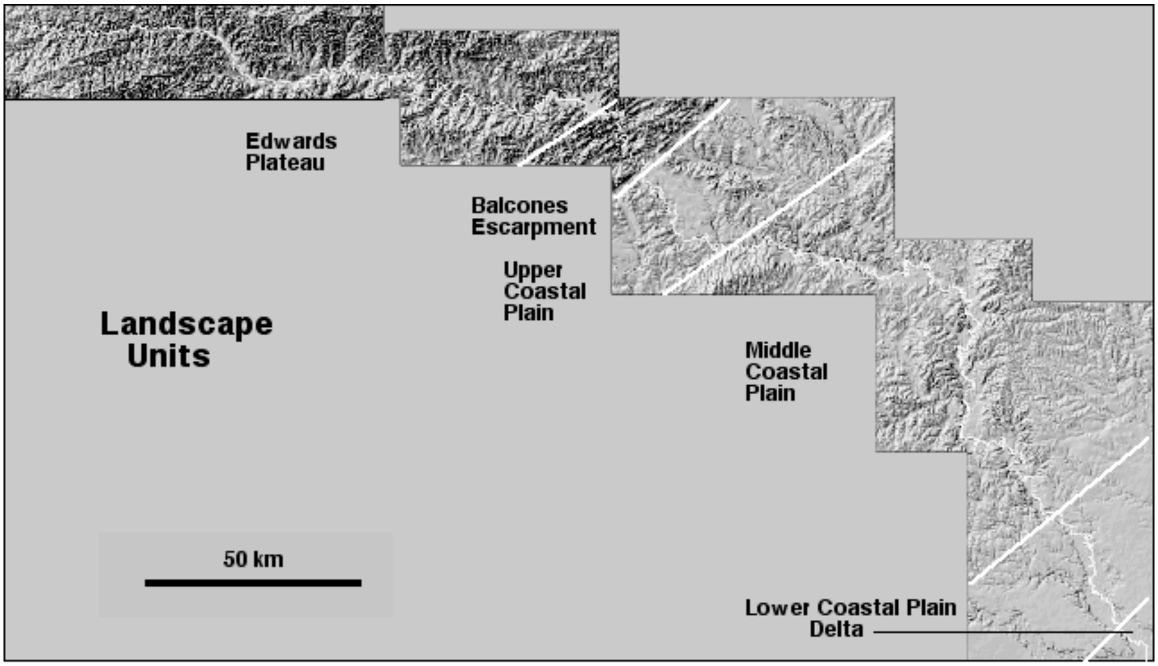

Figure 2. Landscape units of the Guadalupe River valley (Phillips, 2011a).

Chapter 2
Channel Response to Changing Flow Regimes

INTRODUCTION

The primary concern driving this study is changes in water flow or discharge. However, changes in flow may be quite varied and complex, and factors or changes resulting in changes in water flow may also result in changes in other factors, particularly the supply of sediment, and the energy grade slope.

The flow regime of a river encompasses the total flow over a given time period (typically annual or seasonal), modal or characteristic flows such as mean or median discharges, high and low flow extremes, flow variability, and timing or seasonality.

Using dams and reservoirs as an example, the impacts on flow can be quite variable depending on their size relative to the fluvial system, the environmental setting, and dam purpose and operation. The degree of influence decreases downstream from the dam at varying rates, but influences immediately downstream may range from minor to overwhelming.

The Guadalupe River, for instance, has a number of low-head run-of-river dams originally constructed primarily for hydropower generation. These dams have minimal impacts on discharge quantities, but do have substantial local impacts on flow velocities and energy grade slopes (and thus sediment transport capacity). However, Canyon Lake, a large flood control reservoir on the same river, has much more profound influences on flow. Hydrology of the reach downstream of the dam is dominated by dam releases, and even in the lower river hundreds of miles downstream about a fifth of the flow is derived from dam releases.

In general, flood control reservoirs such as Sam Rayburn Lake on the Neches River or Lake Somerville on Yegua Creek have the most significant influences on downstream flow, reducing the frequency and magnitude of peak discharges. Water supply and hydropower impoundments may have less severe impacts on flow regimes if the lake has no flood control function. Lake Livingston on the Trinity River (water supply) and Toledo Bend Reservoir on the Sabine River (hydropower), for instance, have had minimal impacts on high and medium-range flows. Many impoundments, regardless of function, have the effect of increasing low flows (that is, elevating discharges during dry periods), as dam releases usually provide a minimum flow.

Dams and reservoirs may also be very efficient sediment traps, sometimes approaching 100 percent. The trap efficiency of a reservoir is generally a function of the capacity/inflow ratio, with the latter defined as the mean annual inflow. The nearly sediment-free water released from many dams is referred to as “hungry water,” because the sediment transport capacity of the flow greatly exceeds the supply of transportable sediment. Thus, some channel scour downstream of dams is a common feature.

In addition to dams, direct human impacts on flow (as opposed to indirect impacts by changing hydrological responses due to land use and management) include surface water withdrawals directly from channels as well as reservoirs, and ground water use. Humans may also locally increase flows due to, e.g., discharges of treated wastewater and artificial drainage features. Interbasin water transfers may decrease flow in one watershed, while increasing it in another.

Below a number of conceptual frameworks used to assess or predict channel responses to changes in flow, sediment supply, and slope are reviewed.

HYDRAULIC GEOMETRY

Hydraulic geometry concerns the relationships between channels and the flows they convey. The basis of hydraulic geometry is that channel width, depth, and velocity (and to some extent slope, though this is considered to be partly imposed by geology) are determined by the discharge regime, the latter typically conceived as a dominant or formative discharge (often associated with bankfull flow). At-a-station hydraulic geometry deals with how flows are accommodated at a given cross-section. Downstream hydraulic geometry (DHG) is concerned with spatial changes in channel characteristics along a stream channel associated with changes in discharge. In humid-region perennial streams this involves a downstream increase in discharge.

Though basic ideas of hydraulic geometry (and the closely related notion of regime theory) go back further, the typical approach to hydraulic geometry derives mainly from Leopold and Maddock (1953), who developed a well-known set of empirical power functions relating width (w), mean depth (d), mean velocity (v), and other variables to power functions of discharge (Q). The three most important are

$$w = aQ^b \qquad (1)$$

$$d = cQ^f \qquad (2)$$

$$v = kQ^m \qquad (3)$$

a, c, k, b, f, and m are coefficients. The continuity relation $Q = w\ d\ v$ dictates $a\ c\ k = 1$ and $b + f + m = 1$. Physically based theoretical justifications for the power function form are given by Griffiths (2003) and Savenjie (2003).

At-a-station hydraulic geometry has shown to be dynamically unstable with respect to the interactions among the fundamental hydraulic variables of width, depth, velocity, roughness, and energy grade slope (Phillips, 1990; 1991; Fonstad, 2003; Fonstad and Marcus, 2010; Dodov and Foufoula-Georgiou, 2004). It is not unreasonable to expect similarly complex mutual adjustments in the spatial domain.

Despite nearly 60 years of research since Leopold and Maddock, efforts to derive theoretical, physically based explanations for observed global regularities in DHG relationships continue to the present (e.g., Griffiths, 2003; Savenjie, 2003; Singh et al., 2003a; Dodov and Foufoula-Georgiou, 2004; Eaton et al., 2004; 2007; DeRose et al., 2008; Alfzalimehr et al., 2010; Nanson et al., 2010). Recent publications also show active research in improvements, modifications, and applications of DHG to hydraulic engineering and channel design (e.g., Lee and Julien, 2006; Afzalimehr et al., 2010; Riahi-Madvar et al., 2011); aquatic ecology and instream flow management (e.g., Lamouroux and Jowett, 2005; Rosenfeld et al., 2007); and paleohydrologic reconstructions (e.g., Sylvia and Galloway, 2006; Davidson and North, 2009).

However, correlations between channel characteristics and discharge often contain considerable scatter, and numerous examples exist of channels that are much too large or too small relative to their supposed dominant flows and the expectations of hydraulic geometry and regime theory. Further, even in channels without strong geologic constraints and not recently incised or aggraded, numerous deviations may exist to the expected downstream trends of covariation among channel discharge, width, and depth. Increasingly detailed data sets becoming available in some rivers, in fact, call for a rethinking of river continua ideas in general, including DHG (Carbonneau et al., 2011).

Correlations between discharge and the dependent variables are reasonably high in most data sets, and remarkable consistency (given the observed variety in fluvial systems) exists in the values of the exponents in equations (1) – (3). Yet, even within self-formed alluvial channels of humid perennial streams, a number of exceptions to expected trends (e.g., a general increase in width and depth downstream) are typically found, as well as considerable scatter around the general trends (Park, 1977; Phillips and Harlin, 1984; Ferguson, 1986). Thus, expressions more complex, complicated, and flexible than the simple power-function equations are typically needed to reliably estimate DHG (Rhoads, 1991; Kolberg and Howard, 1995; Alfzalimehr et al., 2010; Navratil and Albert, 2010; Riahi-Madvar et al., 2011). These can be effective where detailed local measurements are available for implementation, but are impractical for general, broad-scale implementation.

LANE RELATIONSHIP AND BRANDT MODEL

The response of rivers to changes in imposed water and/or sediment discharge was conceptualized by Lane (1955) as

$$Q_{sed} D \propto Q\, S \qquad (4)$$

which indicates that sediment discharge (Q_{sed}) and particle size (D) vary in proportion to water discharge (Q) and slope (S). This is often interpreted as an equilibrium relationship, in part because the $\propto$ is often replaced with ~ or ≈ signs, implying adjustments to balance sediment size and quantity with transport capacity. A broader and more accurate interpretation, however, is simply that sediment quantity and size adjust to discharge and slope, without necessarily equalizing them.

Various elaborations of the Lane relationship have been used to predict channel responses to variations in flow and sediment loading, with mixed success, and are generally tied to an assumption that a steady-state equilibrium is attained between the left and right sides of the relation—a defensible reference condition, but not a viable assumption about the way fluvial systems actually work (c.f. Phillips, 2007b; 2010b).

The Lane relationship is useful for making qualitative predictions, however, independently of equilibrium assumptions. No steady-state equilibrium is evident in channel responses of the Trinity River, Texas, downstream of Livingston Dam, for instance, but the Lane relationship accurately predicts the qualitative changes in D and S in response to reductions in Q_{sed} (Phillips et al., 2005).

Brandt (2000) devised a qualitative conceptual model based on principles of the Lane relationship to examine channel changes downstream of dams. The model considers cases of increases, decreases, or no change in discharge, and whether post dam sediment loads are greater, less than, or equal to sediment transport capacity. The Brandt model is shown in Table 1.

Table 1. Conceptual model of Brandt (2000a) showing possible cross-section changes in response to changes in discharge (Q), and sediment load ("load") relative to transport capacity (TC). *A* indicates cross-sectional area.

	Load < TC	Load ≈ TC	Load > TC
Decreased Q	1A. Incision; reduced A^1 1B. Widening; reduced A^1 1C. Incision & widening; reduced A^1	2. No change in depth or width; reduced proportion of *A* occupied	3A. Narrowing; reduced *A* 3B: Aggradation; reduced *A* 3C. Narrowing & aggradation; reduced *A*
No change in Q	4A. Incision; increased *A* 4B. Widening; increased *A* 4C. Incision & widening; increased *A*	5. No change	6A. Narrowing; reduced *A* 6B: Aggradation; reduced *A* 6C. Narrowing & aggradation; reduced *A*
Increased Q	7A. Incision; increased *A* 7B. Widening; increased *A* 7C. Incision & widening; increased *A*	8. Increased *A*	9A. Narrowing; reduced *A* 9B: Aggradation; reduced *A* 9C. Narrowing & aggradation; reduced *A*
Relative amount of change	case 7 > case 4	case 2 > case 8 > case 5	case 3 > case 6 > case 9

[1] Degradation may not occur if reduced discharges insufficient to erode channel boundary.

GRADE

The concept of grade (an approximate balance between sediment supply and transport capacity) underlies or relates to several of the approaches described here, including the section above. Here a particular recent quantitative/analytical approach is described.

Eaton and Church (2011) recently used dimensionless stream power to develop a sediment transport scaling relationship based on the concept of grade. Their model provides a useful tool for predicting channel responses to flow changes, as long as one recognizes the graded condition as a reference state rather than a normative condition for channels.

They derived

$$Q_b/QS \propto [(d\,S)/(D_b\,\Theta_c)]^{-1.5x} \qquad (5)$$

The term on the left is bedload transport (Q_b) relative to stream power and D_b is the characteristic grain size. The exponent x is variable, ranging from >10 when the ratio of dimensionless stream power to the critical value for motion is very low, and approaching zero as the stream power ratio increases toward maximum transport. Equation (5) is applicable at the reach scale; for application at the cross-section scale a roughness term must be added to the right side (Eaton and Church, 2011).

The model indicates that as the ratio of bed shear stress ($\propto dS$) to $D_b\,\Theta_c$ increases, the transport efficiency decreases as a power function, with the magnitude of decrease dependent on x. Eaton and Church (2011) interpret D_b as representing the potential for the degree of surface armoring to adjust, while Θ_c is a bed state parameter indicating the potential for surface structure development to modify the entrainment threshold. If the latter are considered given properties of a reach, then equation (5) shows that sediment transport efficiency (as opposed to total transport magnitude) declines as flow depth and slope increase.

BED MOBILITY

One key issue in assessing channel responses to increases or decreases in flows is the transport of material comprising the channel bed. Decreased bed mobility may result in the disruption of bedforms and their movement, and thus of related aquatic habitat. Bed aggradation, or accumulation of finer materials within or over a coarser matrix, may also result. Increased bed mobility can result in channel incision or downcutting, rearrangement or removal of bedforms and other hydraulic/habitat units, and increased downstream sediment transport.

A variety of bed stability and bed load sediment transport relations have been developed; here the framework of Gao (2011) is used.

$$i_b/\omega = (1 - \theta_\chi/\theta)^\alpha \qquad (6)$$

Variables are defined as:

i_b = bed load transport rate at capacity (i.e., sufficient sediment is available to saturate transport capacity; kg m^{-1} s^{-1}).

ω = stream power per unit bed area (kg m^{-1} s^{-1}) = τV

θ = dimensionless shear stress; θ_c = critical value for initiation of motion.

τ = mean bed shear stress (kg m^{-2}) = $\rho g d S$

The exponent α is determined empirically, but is greater than 1, and ρ (water density ≈ 1000 kg m^{-3}) and g (gravitational acceleration, 9.8 m s^{-2}) are treated as constants.

Equation (6) is dimensionless, and the left side indicates sediment transport relative to the available stream power. If dimensionless shear stress is less than the critical value, eq. (6) yields negative values that have no direct physical interpretation, but could imply deposition (negative transport) in some cases. As shear stress exceeds the critical value, relative bed load transport increases exponentially.

Mean bed shear stress is rendered dimensionless by

$$\Theta = \rho\, d\, S\, (\rho_s - \rho)\, D_{50} \qquad (7)$$

where ρ_s is sediment density, and D_{50} is median particle diameter (mm). Critical shear stress for initiation of motion of a given particle diameter D is determined by

$$\tau_c = \Theta_{cr}\, (\rho_s - \rho)\, D \qquad (8)$$

Θ_{cr} is typically around 0.06 for hydraulically rough beds, but can vary according to stream type.

If no major changes in bed material or channel boundary conditions occur, then D_{50} and Θ_{cr} before and after a change in flow regime are identical. With densities constant, the ratio of mean dimensionless shear stress at times t and $t+1$ reduces to

$$\Theta_t / \Theta_{t+1} = (d_t S_t)/(d_{t+1} S_{t+1}). \qquad (9)$$

Thus, according to this interpretation of Gao's (2011) model, changes in bed mobility attributable to changes in flow are due to changes in depth and/or energy grade slope.

SCHUMM MODEL

Schumm (1977) developed a conceptual model of channel responses to hydrological changes, which can be represented as (analogous to the Lane relationship)

$$P^{-1},\ w/d \propto Q,\ Q_{sed} \tag{10}$$

Sinuosity (P) varies inversely and width/depth ratio (w/d) directly with water and sediment discharge. Xu (2001) considered that Schumm's model was applicable if the channel boundary material was unchanged, or if it changed proportionally with that of other factors. For other situations, Xu (2001) developed an additional relationship, indicating

$$(w/d)^{-1},\ P \propto Mp,\ \tau_{cw}/\tau_{cb} \tag{11}$$

Mp is the silt-clay percentage in point bars, and (τ_{cw}/τ_{cb}) is the ratio of critical shear stresses for bank and bed materials. As bank resistance relative to that of the bed, and proportion of fines increase, sinuosity increases and w/d decreases (and vice-versa).

Schumm (1977) treated these changes as tendencies rather than laws, recognizing the effects of a variety of local, contingent factors in conditioning channel responses to imposed flows. Later, he developed a more comprehensive framework linking specific responses in alluvial river channels to increases or decreases in discharge, sediment load, and base level. Base level changes influence channels via slope, so Schumm's later model (Schumm et al., 1984; 2005) is expressed in Table 2 in terms of slope, which may be influenced by human modifications such as channelization and artificial cutoffs, or low-head dams, as well as via base level change.

Table 2. Channel responses to imposed changes, adapted from Schumm, 2005, table 3.1. By columns, the table shows what responses could occur due to increases (+) or decreases (-) in discharge, sediment input, and slope. A zero entry indicates no direct effect, and a +, - that either increases or decreases could result in the associated response. By rows, the table shows what changes might trigger a particular response.

Channel Response	**Discharge**	**Sediment load**	**Slope**
Incision (degradation)	+	-	+
Nickpoint formation & migration	+	-	+
Bank erosion*	+	+, -	+, -
Aggradation	-	+	-
Backfilling; downfilling	-	+	-
Marginal infilling	-	+	0
Meander growth & migration*	+	0	0
Island, bar formation & shift*	+	+	0
Meander cutoffs*	+	+	+, -
Avulsions*	+	+	-
Planform transitions:			
Straight to meandering	+	-	+
Straight to braided	-	+	+, -
Braided to meandering	+	-	+
Braided to straight	-	-	+
Meandering to straight	+	+	+, -
Meandering to braided	-	+	-

*Given sufficient time, these may occur independently of any changes in discharge, sediment load, or slope.

TRANSPORT CAPACITY

Geomorphologists recognize a fundamental distinction between supply- and transport-limited fluvial systems. In the former, the supply of transportable sediment to the channel is less than the sediment transport capacity, and thus the supply limits sediment yield. Transport-limited systems receive more sediment than they are capable of transporting; thus transport capacity is the limiting factor. This is the starting point for the stream power based model outlined by Brandt (2000b) for assessing downstream affects of dams.

Given a particular change in water and sediment inputs, the model starts by determining whether the system is supply or transport-limited (or in steady state) based on comparing sediment load to transport capacity (based on stream power). For supply-limited systems, a key distinction is whether velocities exceed the key threshold for initiation of particle motion. If this is not the case, the channel is stable. Otherwise, and for transport-limited cases, a number of pathways are possible, depending on effects on channel bed elevation, width, depth, and characteristic grain size, with knock-on effects on a variety of hydraulic and morphological factors resulting in new values of stream power and channel geometry (Brandt, 2000b).

Brandt's model (figure 1 in Brandt, 2000b, and distinct from the qualitative model of Brandt 2000a and table 1) shows nine different parameters that may be directly modified following a change in the sediment supply vs. transport capacity relationship, and an additional seven variables that may be modified via knock-on effects, resulting in potential new values of specific stream power (power per unit bed width), unit stream power, slope, width, depth, and grain size. For the various steps and stages in the model, Brandt (2000b) reviews a number of calculation and estimation techniques. While this approach provides a framework for detailed analyses of specific cases, it is far too complex for general applicability. However, it does illustrate the complexity, numerous degrees of freedom, and large number of feedback relationships inherent in the problem of determining channel responses to changes in water and sediment inputs.

Brandt (2000b) also considers effects on, and of, tributaries, which have been rarely considered in studies of channel response to flow changes (see Musselman, 2011 for a recent Texas-based exception).

RIVER EVOLUTION DIAGRAM

The river evolution perspective developed by Brierley and Fryirs (2005) is based on two levels of fluvial change: adjustment and metamorphosis. Adjustment, characterized by the "natural capacity for adjustment," relates to changes that do not result in a new set of process-form relationships or metamorphosis into a new river style. Metamorphosis refers to a broader scale of changes constrained by boundary conditions that define an outer band of variability. Thus, for instance, adjustments within an unconfined reach of a meandering alluvial river might include meander development, migration and cutoffs, associated bar development and migration, changes in sinuosity, lateral migration, and local scour, infill, or widening. However, transformation into an anabranching planform would constitute metamorphosis and development of a new river style.

The framework is summarized in the river evolution diagram (Figure 3). Brierley and Fryirs (2005) use stream power as the primary determinant of adjustments, and to define thresholds or flux boundary conditions (Figure 3). Besides total cross-sectional stream power (Ω), they also make use of stream power per unit area (specific stream power; ω):

$$\Omega = \gamma Q S = \gamma w d V S \qquad (12)$$

$$\omega = \Omega / w = \gamma w d V S \qquad (13)$$

Brierley and Fryirs (2005) use the term unit stream power as synonymous with specific stream power, but the former term is more typically used to indicate power per unit weight of water:

$$\psi = (\rho g Q S)/(r g A_{cx}) = V S \qquad (14)$$

where A_{cx} is cross-sectional area.

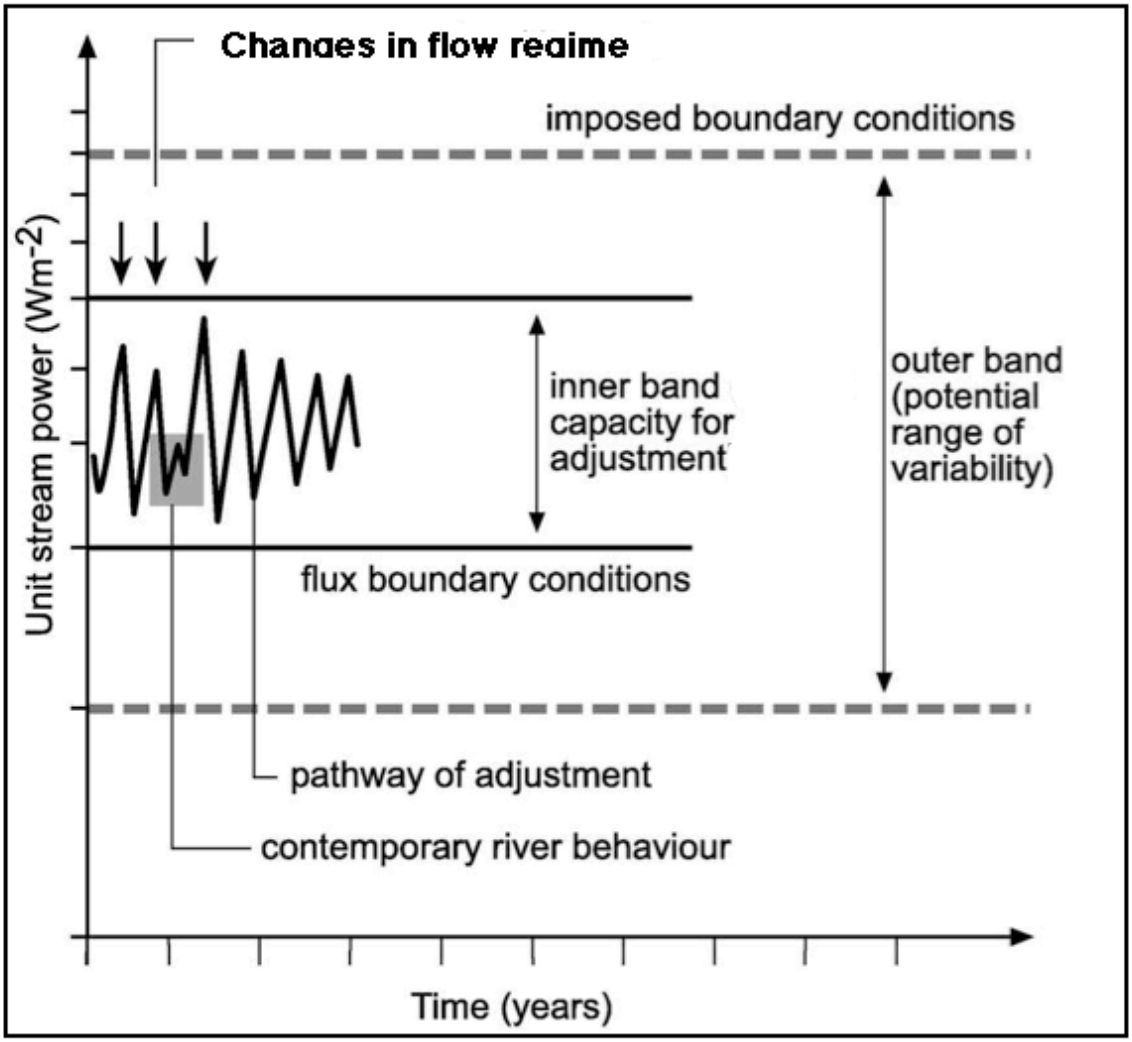

Figure 3. River evolution diagram. Modified slightly from Brierley and Fryirs, 2005 (figure 5.2).

The river evolution approach can be quite effective, but requires extensive analysis of the fluvial system, and considerable geomorphological expertise to implement. Among other things, unit stream power thresholds must generally be determined on a case-by-case basis, from field and historical evidence.

CHANNEL EVOLUTION MODELS

A channel evolution model (CEM) is a sequence of stages of channel development in response to a specific type of disturbance. CEMs are also relatively specific with respect to type of channel. For example, the most widely used CEMs describe the response of sandy alluvial channels to incision (Schumm et al., 1984). These typically involve an initial phase of incision, dominated by downcutting but including some widening to create a greatly enlarged channel. The second phase involves trenching of the bottom of the new channel, followed by a phase of channel widening and associated bank steepening. In phase four, bank failure and channel aggradation begin infilling the incised channel, and in the final phase vegetation becomes established and a new channel resembling the pre-incision channel is formed in the alluvium within the incised channel (Figure 4).

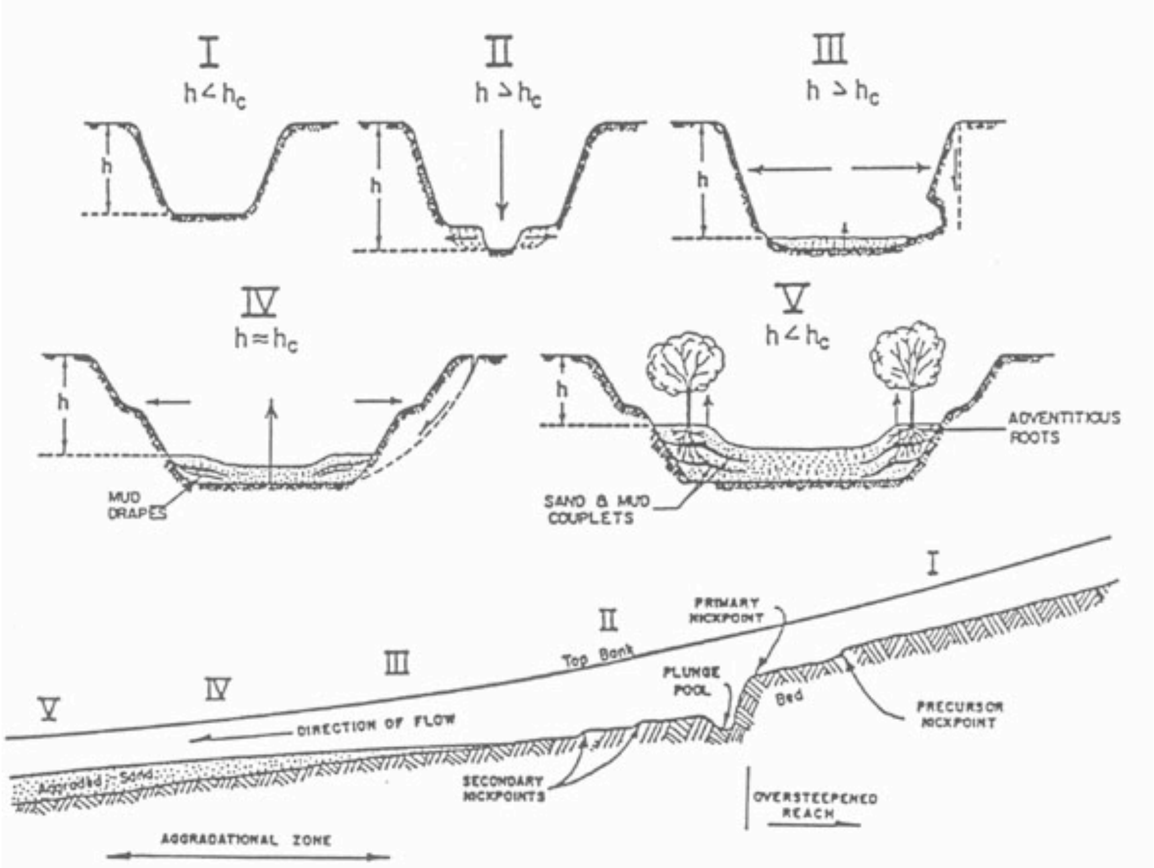

Figure 4. Channel evolution model for sand-bed incised channels with cohesive banks, after Schumm and Harvey, 1984, in both temporal and spatial domains. A critical variable is whether bank height (*h*) is greater than the critical height for stability (h_c).

Watson et al. (2002) outlined the use of incised channel CEMs to evaluate rehabilitation alternatives, and Bledsoe et al. (2002) developed a method for quantifying CEM stages. CEMs have also been applied to channelized streams in west Tennessee (Simon, 1989), as well as a number of other incised channels. Doyle and Shields (2000) incorporated bed texture into the CEM model, with limited predictive success, but indicated that CEMs may need to be developed or adapted for specific situations. Several examples exist, including Doyle et al.'s (2002) development of a CEM for channel responses following dam removal. Beechie et al. (2008) examined channel incision and recovery in the northwestern U.S., and found that two CEM's were needed—one similar to the classic model for larger streams, but an alternative for smaller streams. In streams of the Blue Ridge Mountains, Leigh (2010) identified a typical channel evolution sequence where channel enlargement in early phases following major deforestation and land use change is due to floodplain accretion rather than channel scour, followed by reduced sediment inputs and lateral channel migration.

The discussion above suggests that existing CEMs cannot be uncritically applied to new situations, and use of this approach may require development of a model specifically for the problem(s) at hand. Second, the models described above are analogous to vegetation succession models in that they usually indicate a single developmental pathway, and assume that the original change or disturbance has run its course. These assumptions have proven to be problematic for vegetation change, and are both suspect and untested for fluvial channels.

There are a few examples of CEMs that describe and allow for more complex behavior than monotonic progression along a fixed successional path. The development of large arroyos in the southwestern U.S. was described using a single-path CEM by Elliott, et al. (1999). Smaller arroyos, however, were modeled using a CEM that, following an initial sequence of incision, widening, and floodplain development, might follow several different pathways. Similarly, Makaske et al.'s (2002) study of an anastamosing channel in Canada outlined two different pathways in their evolution model, depending on the supply of bed load. The richest variety of pathways and outcomes in a published CEM results from Leyland and Darby's (2008) study of gully evolution on the Isle of Wight (U.K.). Both incising and infilling/recovering sequences are possible, with switches between them and multiple possibilities at several stages in each (Figure 5).

In plant ecology, state-and-transition models (STM) were developed as an alternative to monotonic successional trends, with a classic successional sequence a special case of an STM. The emergence of multiple-pathway CEMs suggests that an analogous succession-to-STM approach may be appropriate in fluvial geomorphology.

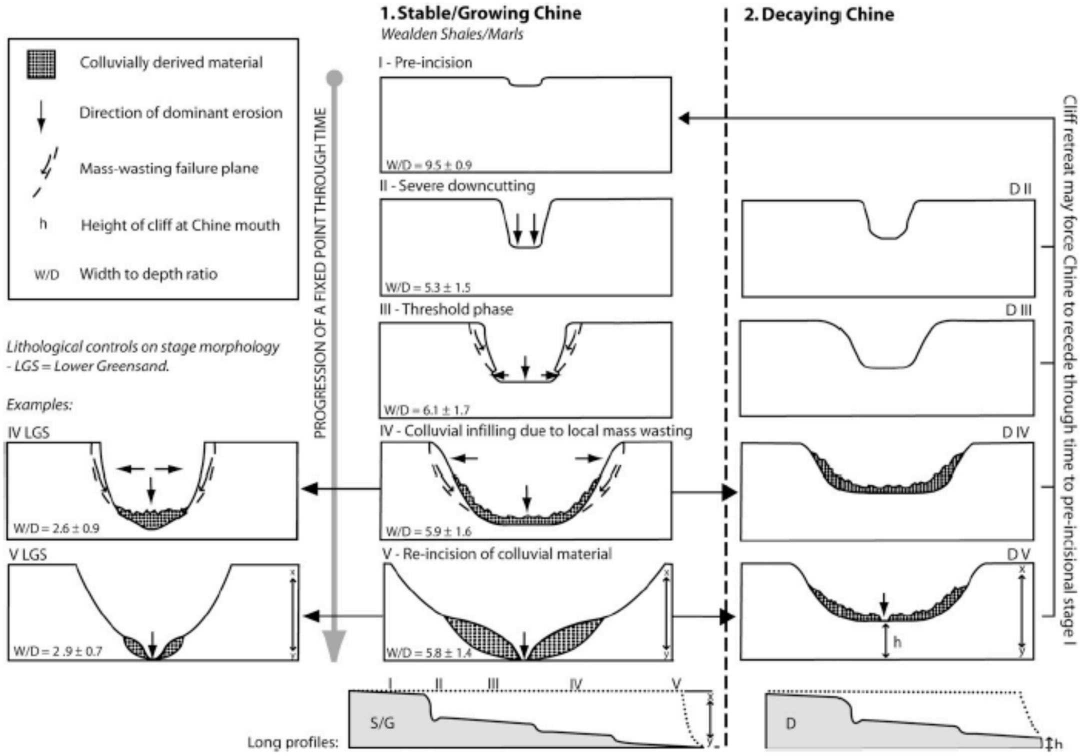

Fig. 5. CEM for incised coastal channels on the Isle of Wight.

Figure 5. CEM for incised coastal channels on the Isle of Wight (from Leyland and Darby, 2008: figure 5). “Chines” are a local name for the incised gullies.

SYNTHESIS

Key points of the approaches described above are summarized in table 3 with respect to the key variables or factors considered, and the underlying conceptual or theoretical basis. Synthesis of some key ideas from these approaches led to development of the flow-channel fitness model, described below.

Table 3. Summary of models or conceptual frameworks described.

Model type	*Key parameters*	*Theoretical/conceptual basis*
Hydraulic geometry; Regime theory	Q (typically bankfull or other "channel forming" flow)	Channel w, d, S adjust to imposed discharges
Lane relationship	Q, Q_{sed}, D, S	Mutual adjustments between sediment transport capacity (=f[Q,S]) & supply (Q_{sed}, D)
Qualitative Brandt model	Q, Q_{sed} relative to transport capacity	Channel w, d adjust to imposed Q & sediment supply-transport capacity relationship
Grade[1]	d, S, D	Mutual adjustments between sediment transport capacity & supply, based on dimensionless stream power
Bed mobility	d, S, D	Threshold of bed material motion; channel mobility a function of D and shear stress (=f[dS])
Schumm model	Sinuosity, w/d, Q, Q_{sed}	Channel cross section & planform a function of Q, Q_{sed}
Stream power model[2]	Q, S, Q_{sed}, V	Mutual adjustments between sediment transport capacity (=f[Q,S]) & supply (Q_{sed}, D); threshold velocities of motion for boundary materials
River evolution	d, V, S	"Natural capacity for adjustment" within boundary constraints; thresholds of specific stream power
Channel evolution models	Time since change or disturbance	Successional sequence(s) of adjustment following change or disturbance
Flow-channel fitness[3]	Q, S, d, A_{cx}	Q relative to channel capacity; thresholds of shear stress (=f[dS]) & transport capacity (=f[QS])

[1]Specifics based on Eaton and Church (2011) model.
[2]Specifics based on Brandt (2000b).
[3]Described below.

FLOW-CHANNEL FITNESS

Fitness, in this context, refers to the extent to the "fit" between a given discharge and channel capacity. The terminology derives from the traditional geomorphic concept of underfit streams, referring to valleys that are much too large to have been created by the streams currently occupying them. Fitness need not imply a precise geometric fit. Rather, a particular design or reference flow, or range of flows, is considered to be in a state of fitness if:

(1) Flows are contained within the channel banks, or if overbank flows do not occur more often than similar undisturbed or seminatural reference channels.

(2) Stages and discharges are sufficient to maintain continuous downstream flow and inundation of the channel bed and aquatic habitats, and to prevent significant prolonged or chronic vegetation encroachment on the channel bed and lower banks.

These criteria are applicable to humid perennial channels, but analogous concepts of channels too large or small relative to flows could be derived for seasonal, ephemeral, and dryland fluvial systems. Fitness does not necessarily imply channel stasis, or even stability. “Fit” channels might experience lateral migration, bedform change and movement, scour and fill, and a variety of local changes consistent with the inherent, natural dynamism and variability of fluvial systems. Likewise, overfit or (especially) underfit channels may experience relatively little change in some cases.

The flow-channel fitness concept is consistent with the hydraulic geometry and regime theory, and the qualitative Brandt model, with respect to notions of channel adjustment to imposed flows. The model is also consistent with the Lane relationship, grade, bed mobility, stream power, and river evolution approaches in that it considers key thresholds of stream power and bed/bank mobility. However, it makes no assumptions of steady-state or equilibrium tendencies. Finally, in the sense of predicting qualitative system states, the flow-channel fitness model is similar to the Schumm and channel evolution models. In some senses then, the fitness concept synthesizes portions of the approaches described above.

Applying the concept to assess potential changes in response to changes in imposed flow involves three stages, and results in a determination of one of seven fitness states, described below.

(1) *Persisting fitness.* This state represents an ongoing condition of fitness between the flows and channel. Many sections of the lower Sabine, Neches, Trinity, and Guadalupe Rivers, for instance, fall into this category. While active lateral migration and other changes are common, there is no persistent change in cross-sectional area relative to the flow regime (Phillips and Slattery, 2007; Phillips, 2008; Phillips, 2011c).

(2) *Increasing underfitness* is where the channel is underfit, and becomes increasingly large relative to imposed flow. This was the case in rivers such as the Colorado and Brazos during periods of incision earlier in the Holocene. The downcutting was associated primarily with sea-level effects, so during the incision the channels increased in size without concomitant increases in flow (e.g., Blum et al., 1995; Morton et al., 1996). The scour zones downstream of dams such as Toledo

Bend (Sabine River), Livingston (Trinity River), and Loco (Loco Bayou) also fell into this category in years immediately following dam construction (Phillips and Marion, 2001; Phillips, 2003; 2008; Phillips et al., 2005).

(3) *Persisting underfitness* occurs where the channel is underfit, and there is no significant trend toward channel enlargement or contraction (Figure 6). The scour zones downstream of the dams mentioned above fit this definition at present. Incision has cut to or near bedrock, and widening has ceased in many cross-sections. However, due to sediment sequestration in the reservoirs, sediment supply is less than transport capacity, and channel infilling is minimal.

Figure 6. An example of an underfit stream, the incised Turkey Creek (Brazos County).

(4) *Underfit adjusting toward fitness* (channel is infilling and becoming less underfit). Yegua Creek below Lake Somerville is an example. The channel became underfit due to decreased flow, but channel infilling is adjusting the system toward fitness (Chin et al., 2002). This may also be observed in the lowermost San Antonio River, where the channel is infilling in response to reduced flow due to an avulsion (Phillips, 2011b).

5. *Increasing overfitness* (channel continues infilling despite overfitness; Figure 7). A good example is the Navasota River from Lake Limestone to near the town of Navasota (see Phillips, 2007a; 2009).

Figure 7. Buried trees along the bank of the Navasota River in Grimes County. This is an increasingly overfit stream, with frequent overbank flow leading to deposition such as that pictured above, as well as frequent avulsions.

6. *Persisting overfitness* is where the channel is overfit, and there is no significant trend toward channel enlargement or contraction. The lower Sabine River near Deweyville is in this condition (Phillips and Slattery, 2007).

7. *Overfit adjusting toward fitness* (channel is enlarging and becoming less overfit). Many sections of the San Antonio River downstream of Bexar County are in this state (Cawthon, 2007).

The first stage of analysis is determining fitness based on the criteria above, or more specific criteria associated with project goals (for example, bankfull channel capacity relative to the discharge with a one-year recurrence interval). Then the shear stress associated with the reference flow is compared to the threshold required for mobilization or erosion of the channel boundary. Finally, the sediment transport capacity (a function of cross-sectional stream power, Ω) is compared to the critical power required to transport the available load. Based on these assessments, the channel fitness can be determined based on Figure 8 or table 4.

However, even if the key thresholds are not known quantitatively, the assessment of fitness can be based on indicators of channel behavior and trend, such as widening, narrrowing, incising, or shallowing. These indicators are discussed later in this report, and summarized in Tables 10-12 in Chapter 4.

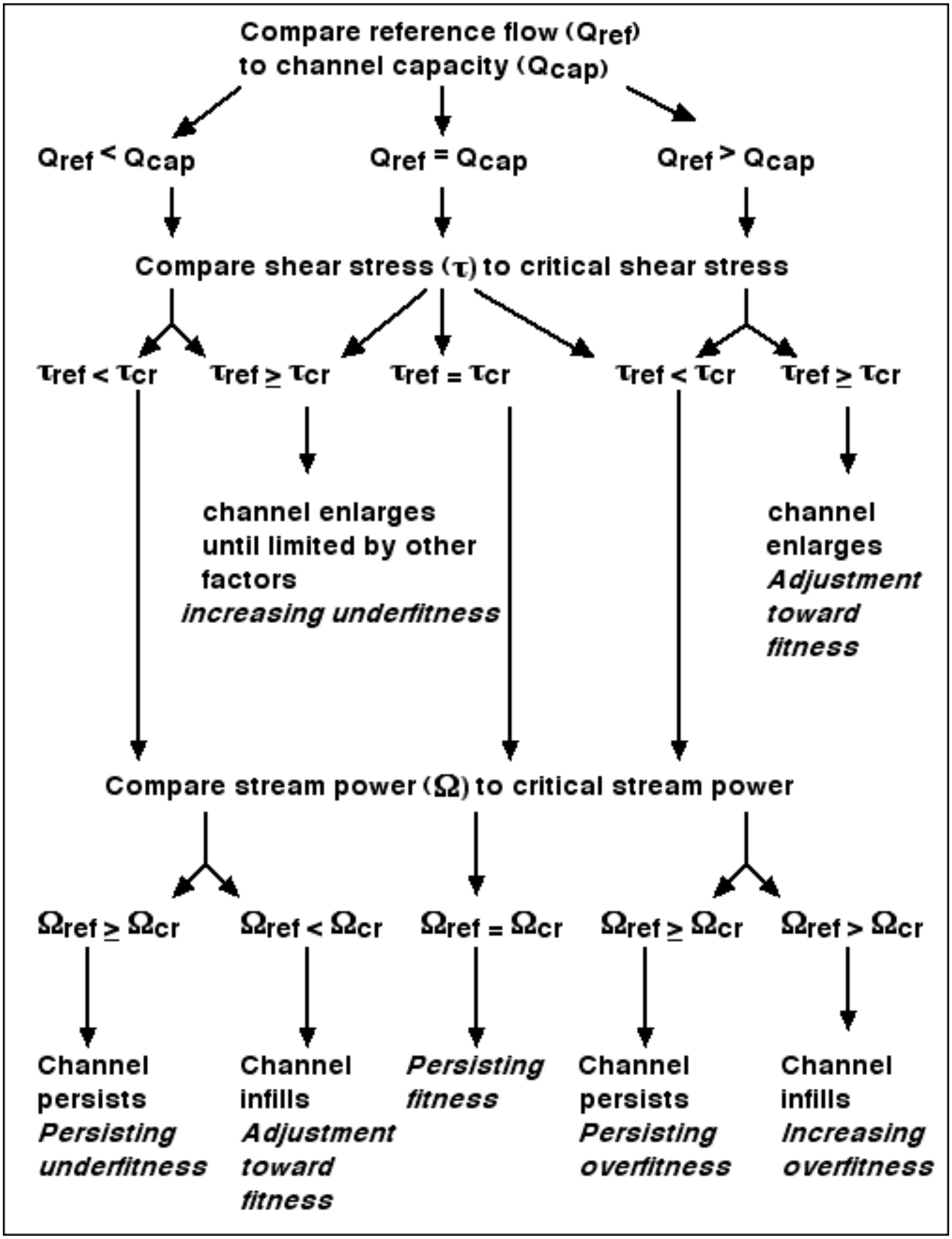

Figure 8. Flow-channel fitness evaluation flow chart.

Table 4. Decision key for flow-channel fitness evaluation.

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1. Compare reference flow to channel capacity
    - A. Underfit: go to 2
    - B. Fit: go to 4
    - C. Overfit: go to 6

2. Compare shear stress to critical shear stress.
    - A. Less than: go to 3.
    - B. Greater than or equal to: channel enlarges until limited by other factors; *increasing underfitness*

3. Compare stream power to critical stream power.
    - A. Greater than or equal to: *persisting underfitness or fitness*
    - B. Less than: channel infills; *Underfit adjusing toward fitness*.

4. Compare shear stress to critical shear stress.
    - A. Less than or equal to: go to 5.
    - B. Greater than: channel enlarges until limited by other factors; *increasing underfitness*

5. Compare stream power to critical stream power.
    - A. Greater than or equal to: *persisting fitness*
    - B. Less than: channel infills; *increasing overfitness*

6. Compare shear stress to critical shear stress.
    - A. Less than: go to 7.
    - B. Greater than or equal to: channel enlarges; *overfit adjusting toward fitness*

7. Compare stream power to critical stream power.
    - A. Greater than or equal to: *persisting overfitness*
    - B. Less than: channel infills; *increasing overfitness*

RESISTANCE

The flow-channel fitness approach, and several others in table 3, requires some assessment of boundary resistance. Local (at a point or cross-section) issues of resistance relative to force can be approached based on measurements of boundary shear strength (using, e.g., penetrometers, shear vanes, etc.) or particle sizes, vs. measured or reference boundary shear stresses. Likewise, critical threshold conditions for transporting particles of a given size can be determined based on particle size (median diameter).

The most common criterion for determining the general mobility of a channel is the Shields number:

$$\tau^* = (\rho\, g\, d\, S)/g(\rho_s - \rho)D \qquad (15)$$

Using typical values of the constants g, ρ, and ρ_s, this reduces to

$$\tau^* = (d\, S)/(1.65\, D) \qquad (16)$$

Critical entrainment values generally range from $\tau^* \approx 0.03$ to 0.06, with 0.045 a typical value for mixtures of sediment sizes when $D = D_{50}$ (the median grain size).

The critical threshold necessary to entrain a particle of diameter D can be estimated by the Shields entrainment function,

$$\tau_{cr} = \tau^*_{cr}\, g(\rho_s - \rho)D \qquad (17)$$

Table 5 is an elementary classification of stream channels developed by Church (2006) from earlier, similar classifications, and linked to characteristic Shields numbers. The relationships in the table suggest that changes in depth, slope, and/or particle size sufficient to substantially change the typical Shields number can potentially alter the sediment transport regime, morphology, and stability of the channel.

Assuming no changes in sediment density, a quick assessment of relative change in Shields number can thus be based on

$$\tau^*_a / \tau^*_b = (d_a/d_b)\,(S_a/S_b)(D_b/D_a), \qquad (18)$$

where the subscripts b, a indicate conditions before and after the change in flow regime.

Table 5. Elementary stream channel classification based on Shields numbers (adapted from Church, 2006).

Sediment type	*Type/characteristic Shields number*	*Sediment transport regime*	*Channel morphology*	*Channel stability*
Silt to sand bed; silty to clayey banks	Labile ≥ 10	Suspension dominated; minor bedform development; minor bed load	Single thread (sinuosity > 1.5) or anastamosing; prominent levees; very low gradient; w/d < 15 in individual channels	Slow or no lateral movement; extensive wetlands and floodplain lakes; vertical accretion on floodplain
Sand bed; fine sand to silt banks	Labile > 1	Suspension dominated; sandy bedforms; possibly significant bed load	Single thread meandering (sinuosity > 1.5) w/ point bar development; significant levees; low gradient; w/d < 20; serpentine meanders w/ cutoffs	Meander extension, progression, & cutoffs; anastamosis possible; vertical accretion of floodplain; vertical incision of channel
Sand to fine gravel	Transitional 0.5 – 1.0	Mixed suspended & bed load; full mobility w/ sandy bedforms	Mainly single-thread, irregularly sinuous to meandering (sinuosity < 2); lateral/point bar development ; levees present; moderate gradient; w/d < 40	Single thread: irregular lateral migration or meander progression; braided channels laterally unstable; degrading channels experience scour & widening
Sandy-gravel to cobble-gravel	Threshold ≤ 0.15	Bed load dominated but suspended load may be significant; partial transport to full mobility; bed load 1-10% of total load	Single thread to braided, low sinuosity; complex bar development by lateral accretion; moderately steep; w/d > 40	Subject to avulsion & channel shifts; braided may be highly unstable; single-thread subject to chute cutoffs & deep scour at sharp bends

Continued	*from preceding*	*page*		
Sediment type	*Type/characteristic Shields number*	*Sediment transport regime*	*Channel morphology*	*Channel stability*
Cobble-gravel	Threshold ≥ 0.04	Bed load dominated; low total transport in partial transport regime; bed load may be <10% of total	Single thread or wandering; low sinuosity, relatively steep; w/d > 20	Stable for extended periods, but major floods may cause lateral instability & avulsion; may exhibit serially reoccupied secondary channels
Cobble- or boulder-gravel	Jammed ≥ 0.04	Bed load dominated; low total transport, but subject to debris flow	Single thread low sinuosity; step pools or boulder cascades; steep gradient (>3°)	Stable for long periods with throughput of sediment finer than structure-forming clasts; possible catastrophic destabilization in debris flows

Where site-specific measurements are not practical, guidelines for critical shear stresses and velocities have been developed by the U.S. Army Corps of Engineers in the context of stream restoration (Fischenich, 2001). These may be used as general guidelines for rough estimates of key thresholds (table 6). Note that sediments of mixed sizes behave differently than more uniform distributions. Particles larger than the median will generally be entrained as shear stresses less than those shown in table 6, while particles smaller than the median may require shear stresses greater than those shown to initiate motion. table 7 was developed for assistance in choosing appropriate channel lining materials, but may also be used as a general guideline for estimating critical shear stresses and velocities.

Table 6. Critical shear stresses and shear velocities for various size classes of material (from Fischenich, 2001). Note that shear velocity is not the same as mean channel velocity, which is about 8X shear velocity.

Size Class	*Diameter (upper limit, mm)*	*Diameter (inches)*	*Shear Stress ($N\ m^{-2}$)*	*Shear Velocity (ft sec^{-1})*	*Shear Velocity (m sec^{-1})*
Boulders					
very large	2032.0000	80	1791.3335	4.36	1.32886
large	1016.0000	40	895.6667	3.08	0.93874
medium	508.0000	20	445.4387	2.2	0.67053
small	254.0000	10	225.1134	1.54	0.46937
Cobbles					
large	127.0000	5	110.1624	1.08	0.32917
small	63.5000	2.5	52.6866	0.75	0.22859
Gravel					
very coarse	33.0200	1.3	25.8641	0.52	0.15849
coarse	15.2400	0.67	11.9741	0.36	0.10972
medium	7.6200	0.3	5.7477	0.24	0.07315
fine	4.0640	0.16	2.8733	0.17	0.05181
very fine	2.0320	0.08	1.4372	0.12	0.03657
Sand					
very coarse	1.0160	0.04	0.4787	0.07	0.02133
coarse	0.5080	0.02	0.2874	0.055	0.01676
medium	0.2540	0.01	0.1913	0.045	0.01372
fine	0.1270	0.005	0.1432	0.04	0.01219
very fine	0.0762	0.003	0.0961	0.035	0.01067
Silts					
coarse	0.0508	0.002	0.0481	0.03	0.00914
medium	0.0254	0.001	0.0481	0.025	0.00762

Table 7. Permissible shear stress and mean velocity for various boundary materials for maintenance of stable channels (after Fischenich, 2001).

Boundary category	***Boundary type***	***Permissible shear stress (N m^{-2})***	***Permissible shear stress (lbs ft^{-2})***	***Permissible Velocity (m sec^{-1})***	***Permissible Velocity (ft sec^{-1})***
Soils	Fine colloidal sand	1.00 - 1.49	0.02-0.03	0.46	1.50
	Sandy loam (noncolloidal)	1.50 - 2.19	0.03-0.04	0.53	1.75
	Alluvial silt (noncolloidal)	2.20 - 2.40	0.045-0.05	0.61	2.00
	Silty loam (noncolloidal)	2.20 - 2.40	0.045-0.05	0.53 - 0.69	1.75-2.25
	Firm loam	3.69	0.075	0.76	2.50
	Fine gravels	3.69	0.075	0.76	2.50
	Stiff clay	12.68	0.26	0.91 - 1.37	3.00-4.50
	Alluvial silt (colloidal)	12.68	0.26	1.14	3.75
	Graded loam to cobbles	18.56	0.38	1.14	3.75
	Graded silt to cobbles	20.96	0.43	1.22	4.00
	Shales to hardpan	32.64	0.67	1.83	6.00
Gravel/Cobble	1 in./25.4 mm (median diameter)	16.07	0.33	0.76 - 1.52	2.50-5.00
	2 in/50.8 mm (median diameter)	32.64	0.67	0.91 - 1.83	3.00-6.00
	6 in/152.5 mm (median diameter)	97.41	2.0	1.22 - 2.29	4.00-7.50
	12 in/304.8 mm (median diameter)	194.92	4.0	1.68 - 3.66	5.50-12.00

Chapter 3

Case Studies of Channel Response

INTRODUCTION

A number of case studies of fluvial channel responses to changes in flow regime were examined to determine the extent to which trends or generalities exist. Direct comparisons between studies are difficult due to different goals, methods, and time frames. Some studies examined were directly concerned with channel responses to imposed flow changes; in other cases channel responses were not the primary goal of the research.

TEXAS STUDIES—DIRECT HUMAN IMPACTS

Pecos River

Salinization is the major concern of Hoagstrom (2009), but morphological responses were also addressed. The Pecos River saw a large decrease in flow, due mainly to a series of dams and water withdrawals. Before extensive dam development, flows were sufficient for navigation along the Pecos. During exploration and settlement of the area (1535-1880), there were swift currents, deep channels, and a shifting-sand substrate. Around Girvin, TX, surveyors in the 19th century recorded water depths between 5 and 25 ft (1.5 and 7.6 m). Since the early 20th century various dams have been constructed along the lower Pecos, and increasing levels of groundwater extracted. Estimates show that around the time development began along the river, stream flows at Girvin averaged 650 cfs (18.5 m^3sec^{-1}); contemporary means are < 35 cfs. Before 1950, groundwater irrigation in the Texas portion of the Permian Basin was minimal, and springs contributed to stream flow; but groundwater overdraft and significantly diminished spring inflows reduced discharge. In some reaches flow direction was actually reversed, which led to conveyance losses as water seeped into the aquifer. The river is now characterized as sluggish, unnavigable, and during summer is intermittently dry (Hoagstrom, 2009).

Rio Grande River

Mack and Leeder (1998) studied channel shifting in a 50 mi (80 km) reach of the Rio Grande River in New Mexico and west Texas prior to dam impacts. They examined the 1844-1916 period, before construction of Elephant Butte Dam. Major responses occurred following floods, typically in the spring, while the channel remained stable for the remainder of the year in most cases. From 1844-1916, channel width averaged 656 ft (200 m) in this reach, although it widened up to 4265 ft (1,300 m) during severe flood events, and narrowed to 328 ft (100 m) at other times. The maximum channel depth was usually a few meters, but could increase up to 26 ft (8 m). Similarly, channel sinuosity varied over time, with a maximum value of 1.9 from 1844-52, and a minimum of 1.2 measured in 1893. Meander cutoffs, lateral erosion, and avulsions were the primary mechanisms of channel shifting. The most dramatic changes came in response to lateral erosion and avulsion events. Between 1852-1889, for instance, the position of the Rio Grande in the Hueco basin shifted ~ 0.6 mi (1 km) southward. An avulsion in 1865 in the Mesilla Valley repositioned the river significantly; it migrated from a starting point of a few hundred meters east of Mesilla to a position along the western edge of the floodplain, up to 4 km in some places. This avulsion was the outcome of an especially intense flooding season in 1865. Another significant avulsion occurred around 1905 in the southern portion of the Mesilla Valley, along a reach where the river was narrow and sinuous, and flowed along the western edge of the floodplain. This avulsion caused the Rio Grande to relocate to the opposite side of the floodplain, and 12 mi (20 km) downstream from the avulsion node the post-avulsion channel re-occupied the pre-avulsion channel. Mack and Leeder (1998) suggest the historical Rio Grande exhibited wide variations in channel widths and sinuosity. However, they argue there is no evidence of broad climatic controls being the overarching factor. This indicates that effects of individual flow events or episodes were the critical factors in channel change, rather than longer-lived shifts in discharge regimes.

The flow of the Rio Grande declined substantially after 1916, and Everitt (1993) examined channel changes in response to this decline due to Elephant Butte Dam in the Ft. Quitman-Presidio reach. Annual discharge declined by 52% compared to pre-dam levels for the 1916-40 interval; temporarily rebounding in 1941-42 because of large floods. Annual discharge dropped precipitously again afterward, with occasional small increases in wet years. Everitt (1993) identified a first-order set of responses involving reduced width, depth, and cross-sectional area. More delayed responses include meander cutting, tributary adjustments, and slope adjustments in the main channel. Everitt (1993) also documented a shift from a bed load dominated to a suspended load dominated sediment transport regime, increased vegetation in the channel, and a phase of hydrographic discontinuity.

Historical channel changes in the Big Bend National Park area (downstream of the Rio Grande/Rio Honcho confluence) were examined by Dean and Schmidt (2011). There was a general decrease in flow during the 20th century. At the gage below Rio Conchos (BCR), mean annual flow was 1400 cfs (39.3 m^3/s) from 1901-2008. Between 1901-1944, mean annual flow was 2260 cfs (64.0 m^3/s), and declined to 1020 cfs (28.8 m^3/s) for the 1945-2008 period; flows were elevated from 1986-1992 (2200 cfs/62.8 m^3/s) before dropping significantly during the 1993-2008 interval (615 cfs/17.4 m^3/s). The frequency and intensity of flood events have diminished also. The authors found a similar pattern at the Johnson Ranch gage as well, which is downstream of BCR in the park. The decrease is attributed to dams, and also increased water use by phreatophytes such as tamarisk. In some places (Hot Springs Canyon) the lower Rio Grande is 50% narrower than it was in 1901. Based on photographic evidence, the authors estimated the fluctuations in channel width for the Catolon, Johnson Ranch and Boquillas Reaches. The active channel of the Catolon reach narrowed from 335 ft (102 m) in 1941 to 144 ft (44 m) in 2004 – a 56.8% decline; at Johnson Ranch, the active channel shrank from 290 to 140 ft (88 to 43 m) over the same period (51.1%); the Boquillas Reach experienced slightly lower losses (33%). Vegetation establishment accelerated channel narrowing rates along the Rio Grande. Giant cane established on sandy levees and the channel banks while thick groves of tamarisk were positioned above the channel banks. Vegetation expansion aided the conversion of active channel surfaces to floodplains. It also encouraged sediment deposition and vertical floodplain accretion. Dean and Schmidt (2011) also found evidence of increased gravel accumulation in channels, and of faster recovery times following floods.

Further upstream, near Albuquerque, N.M., historical channel narrowing of the Rio Grande was documented by Swanson et al. (2010) in response to a reduction in peak flows due in part to a variety of human modifications, including levees, dams, dredging, jetties, and bank stabilization. Peak flows declined by 44 to 54 percent, with pronounced narrowing in response between 1918 and 1962. After a period of widening from 1967-73, the channel became more stable, with minor narrowing rates. Swanson et al. (2010) also found decreased sediment transport and lateral mobility. Slightly further upstream, Richard et al. (2005) also found channel narrowing (and incision) associated with Cochiti Dam, which reduced the mean annual flood by almost 40 percent. The incision is likely due to a >18-fold decrease in suspended sediment concentrations. Richard et al. (2005) also observed a pronounced decrease in lateral migration.

Major flood events have occurred on the Rio Grande in recent years not covered by the studies above. In particular, flooding in August, 2008 resulted in extensive erosional removal of woody channel vegetation and channel widening, particularly in the general area of Brewster and Presidio Counties, Big Bend National Park, and neighboring areas of Mexico. Hydrological and meteorological assessments of this flood, and damage assessment photos, are available via the National Weather Service (http://www.srh.noaa.gov/maf/?n=hydrology_rio_grande_flood_2008). Geomorphic studies of these changes are in progress as of this writing.

Nueces River

Sediment transport from the lower Nueces River downstream of Lake Corpus Christi into Corpus Christi Bay was studied by Ockerman and Heitmuller (2010). Sediment sampling data shows a significant decrease in sediment loads after completion of the Wesley E. Seale dam. They also found that about 32 percent of the sediment load is accounted for by releases from the lake. They did not directly address channel morphology, but their estimate of 18 percent of the total suspended sediment load derived from bed and bank erosion indicates net channel degradation and enlargement. This is supported by limited cross-section data analyzed by Ockerman and Heitmuller (2010).

San Antonio River

20th century hydrological changes in the San Antonio River system were documented by Sahoo and Smith (2009) based on measurements of 27 hydroclimatic variables at gaging stations. Stations in the upper half of the watershed tended to show a decreasing trend in flow and runoff. Above a station along the southeast border of Bexar County (which includes the city of San Antonio), all statistically significant trends in stream flow showed a decline. A comparison of stream flows for periods with comparable precipitation in the 1960s and 1990s shows that stream flows decreased for most seasons and precipitation levels. Additionally, baseflow contributed less to total stream flow in this very urbanized area. However, in the lower half of the watershed, all statistically significant trends were positive. Baseflow appears to contribute more to overall stream flow. Stream flows have also increased from the 1950s to the 1990s. Increased runoff from impervious surfaces in the San Antonio urban area is thought to be the primary cause of the increased flow in the lower river, and ground water use the major driver of decreases in the upper river.

Cawthon (2007) examined channel changes downstream of the San Antonio metropolitan area for the 1948-2003 period, which represents an interval during which there has been a general increase in stream flows. Chanel widening occurred throughout much of the river system, particularly in the lower study reaches in Goliad County. Some incision may also have occurred, but evidence is limited. Lateral migration was minimal in the upper portions of the study area, but grew more pronounced further downstream. Cawthon's (2007) analysis of historical aerial photographs also indicates an increase in sediment deposition in channel bars and at tributary mouths—again, more pronounced downstream. Though not focused on channel responses to changes in flow, both Engel (2007) and Curran (2010) indicate similar channel widening trends for the same time period.

Guadalupe River

Canyon Lake, with a normal capacity of 382,000 acre-feet (0.47 km^3), dominates the hydrology of the middle and lower Guadalupe River, with dam releases accounting for about 20 percent of river flow into Guadalupe Bay. However, because the dam site for the lake corresponds with a major geologic and topographic transition at the Balcones Escarpment, any channel changes attributable to the dam are difficult to distinguish from changes associated with other geomorphic controls (Phillips, 2011c). Canyon Lake and Dam, along with a number of smaller impoundments along the Guadalupe, are significant factors in distinguishing among the 13 geomorphic zones delineated along the river by Phillips (2011c), but their effects are not readily distinguished from those of other factors such as geology, inherited valley morphology, sources of streamflow, and climate.

Brazos River

While they did not quantify changes in flow or sediment regimes, Gillespie and Giardino (1996; 1997) examined lateral migration of the Brazos in the general area of Waco to Hempstead using a migratory activity index (MAI) over time spans related to upstream dam construction. The highest values measured on the MAI occurred across the 1941-51 period, which preceded construction of four dams situated within 100 miles of the study reach during the 1960s; more dams were added thereafter. The migratory activity index decreased in all subsequent periods, which Gillespie and Giardino (1997) attribute to dam effects. Reduced lateral migration downstream of dams has been frequently observed, and is often attributed to modulation of flow extremes (c.f. Shields et al., 2000; Richard et al., 2005). Other studies in Texas, however, attribute reduced lateral migration to cross-sectional changes such as channel deepening (Chin, 2002; Wellmeyer et al., 2005).

Giardino and Lee (2011) recently completed a more extensive study of Brazos River channel migration between Waco and Brazos County, finding that pre-reservoir channel migration rates and amounts are significantly greater than post-dam. They also found that channel width post-reservoir was generally smaller and less variable than before dam construction. Despite sediment trapping in reservoirs upstream of the study reach, they found net sediment storage along the channel.

Changes in sand transport in the lower Brazos River were investigated by Dunn and Raines (2001), based primarily on the gaging station at Richmond. Dams and reservoirs on the upper Brazos and some tributaries resulted in more consistent low flows, but decreases in higher flows (>90th percentile) and annual peaks. Channel width increased over the 1960-95 study period, but cross sectional area did not change, indicating a decrease in depth. Sand transport at Richmond decreased during the study period, but Dunn and Raines (2001) were unable to pin down a specific cause. Sediment trapping in upstream reservoirs has not influenced sediment transport downstream at Richmond, as the inputs from tributaries and other sources compensates for the reservoir storage. Osting et al. (2004a) focused their hydrologic analyses on the Richmond gaging station, comparing the pre-dam 1903-1940 period with the post-dam 1970-2004 period (in between numerous dams were constructed on the upper and middle Brazos River and its tributaries). The comparison indicated a small increase in median discharge, and a significant reduction in high flows. Osting et al. (2004a) did not independently address geomorphic changes, however, relying on the work of Dunn and Raines (2001).

Heitmuller and Greene (2009) used records of field measurements, changes in rating curves, and aerial photographs to examine historical changes at gaging stations on the Brazos and several other Texas streams. At a station near Waco, they found insignificant changes in discharge, but reduced sediment supply due to upstream dams resulted in channel erosion (bed lowering and widening). Downstream at the Highbank station, however, a reduced sediment supply without significant changes in discharge was associated with reduced bank erosion, bank stabilization, and slight incision. Rapid meander migration in the vicinity was also observed. Reduced channel width and increased depth was documented near Bryan, where a 15 percent reduction in median discharge was recorded. Further downstream insignificant discharge changes were evident, but all three stations experienced some geomorphic change: some incision and channel bench development at Hempstead; deepening, narrowing, and bank steepening and stabilization at Richmond; and deepening and narrowing at Rosharon (Heitmuller and Greene, 2009). Indeed, incision is common throughout the lower Brazos River, and is both a legacy of Holocene trends, and in some cases an apparently ongoing phenomenon that cannot be unambiguously linked to any human impacts on flow regimes (Phillips, 2007).

The Heitmuller and Greene (2009) study also included several stations on Brazos River tributaries. On the Little River near Cameron general degradation was noted, though some aggradation at low flows, along with vegetation establishment on the floodplain. A 21 percent increase in median discharge was observed. One of three locations on the lower Navasota River, near Groesbeck, had little change. Near Easterly, a 20% increase in median discharge was associated with channel degradation, and a 28% increase near Bryan accompanied channel degradation and floodplain accretion (Heitmuller and

Greene, 2009). Despite sediment trapping in Lake Limestone, the Navasota River downstream of the lake (except for the usual scour zone) is a generally aggrading system, characterized by an anastamosing channel pattern (Phillips, 2007a; 2009).

Chin et al. (2002) examined adjustments of channel capacity in Yegua Creek, a Brazos River tributary, following closure of Somerville Dam. The stream experienced a small decrease in monthly mean flows, and an increase in minimum flows, but large decreases in both monthly maximum discharges and annual peak flows. Small changes in channel width occurred downstream of the dam, but significant decreases in depth (61%), with a 65% reduction in overall channel capacity. Chin et al. (2002) also noted increases in riparian vegetation, which has contributed to lateral stability of the channel, and no significant lateral migration.

Trinity River

Several studies have examined downstream geomorphic impacts of Lake Livingston and Livingston Dam on the lower Trinity River. The lake is a water supply reservoir that is essentially flow-through. Therefore effects on discharge, other than a decrease in the frequency of very low flows, are minimal (Wellmeyer, et al., 2005). Several studies have suggested that sediment trapping in the lake—which is indeed extensive—has reduced sediment delivery to the coastal zone. However, these conclusions are based on records at the Romayor gaging station 32 mi (52 km) downstream of the dam. Sediment records from the station further downstream at Liberty show no indication of any post-dam decline (Phillips and Musselman, 2003; Phillips et al., 2004).

Phillips et al. (2005) found that various combinations of downcutting, channel widening, slope decreases, and sediment coarsening have occurred downstream of the dam, but the extent of these responses is only about 37 mi (60 km) from the dam (which includes the Romayor station). However, a number of qualitatively different combinations of responses of width, depth, slope, and sediment size were observed at individual cross-sections within this zone. Further downstream, there is no evidence of morphological change related to the dam, or sediment starvation effects (Phillips et al., 2004; 2005). Wellmeyer et al.'s (2005) study of planform change also did not identify any effects directly attributable to Livingston Dam.

The downstream limit of observed dam effects apparently has less to do with diminution of those effects than with increasing dominance of the system by other factors, including antecedent landforms (Phillips et al., 2005; Phillips and Slattery, 2008). This critical zone marks an important transition in river channel and valley forms, dominant processes and resulting geomorphological, hydrological and ecological characteristics. Its location is not a transient result of upstream or downstream propagation of effects. Rather, the zone marks the contemporary upstream extent of the effects of Holocene sea-level rise, which in turn coincides with the point at which the Pleistocene upper Deweyville alluvial terrace surface is encountered (Phillips and Slattery, 2008).

A key point is that the lowermost Trinity River is a bottleneck for sediment due to low slopes and stream power, and to extensive accommodation space for sediments. Thus, sediment delivery to Trinity Bay was very low before Livingston Dam, and would be even in its absence (Phillips et al., 2004; Slattery et al., 2010). The capacious alluvial storage in the lower Trinity not only limits flux to the bay, but the large amount of remobilizable alluvium also allows the system to adjust to localized sediment shortages. Internal adjustments within the lower Trinity River valley thus buffer the bay from changes in sediment supply upstream (Phillips et al., 2004; Phillips and Slattery, 2008).

In a broader study of the Trinity River from the Dallas area to Trinity Bay, Phillips (2010a) examined the relative importance of intrinsic (adjustments within the fluvial system), extrinsic, and human factors on the geomorphic zonation of the river. Based on a statistical analysis, the relative contributions to variation in river morphology due to lithology, tectonics, sea-level, avulsions, lateral migration, Quaternary terraces, paleomeanders, Lake Livingston, and water withdrawals were assessed. Each accounted for about 4 to 15% of the variation, with the lake and withdrawals accounting for 12 and 10 percent, respectively. Lake Livingston effects were manifested (beyond the lake itself) in the 37 mi (60 km) scour zone downstream, and in an upstream zone of backwater effects. Water withdrawals downstream of the lake, though averaging about 10 percent of mean flow, do not correspond with any evident changes in river or valley morphology. Overall, human factors accounted for about 30 percent of the variability of geomorphic zones (Phillips, 2010a).

Neches-Angelina River

A major flood control reservoir (Sam Rayburn Lake) exists on the Angelina River just above its confluence with the Neches River, connected to the latter by a flow-through impoundment (B.A. Steinhagen Lake). The Neches River has experienced a reduction in peak and mean discharges, but no geomorphic studies of the lower Neches or Angelina Rivers have been published. Phillips (2009) speculated that the effects of the flow regulation may partly account for the different avulsion regime compared to the nearby Trinity and Sabine Rivers, but evidence is too limited to draw conclusions.

Lake Nacogdoches on Loco Bayou (a tributary of the Angelina River) is a water supply reservoir with a rare permit that allowed them to release no water from the dam. The effect of this impoundment on sedimentation downstream was investigated by Phillips (2001). At a site less than 10 mi (16 km) downstream of the dam, which controls 86% of the 265 km^2 drainage basin, turbidity levels were as high or higher than those upstream of the lake. Floodplain sedimentation rates in the post-dam period were high enough to suggest the dam has had no effect on sediment supplies at the site. Evidence of post-dam channel incision and channel narrowing is evident immediately downstream of the dam, however (Phillips and Marion, 2001). Various indicators of sediment sources and alluvial residence times are consistent with sediment contributions from source areas in the lower watershed, downstream of the dam, which apparently make up for any deficit due to trapping by the dam (Phillips and Marion, 2001; Yeager et al., 2002).

Sulphur River

Osting et al. (2004b) examined the effects of Cooper Dam and Jim Chapman Lake on hydrology, hydraulics, and fish habitat. Despite channel response not being the focus of the study, their results do shed some light on geomorphic adjustments. The dam, completed in 1991, reduced median flows by about half, and high flows by an even greater proportion. Minimum flows were increased. Channel narrowing and decreased sinuosity has occurred, but this is at least partly due to channelization. Despite presumed sediment trapping behind the dam, sediment transport and deposition increased post-dam in the channelized sections (Osting et al., 2004b).

Sabine River

The lower Sabine River is influenced by Toledo Bend Dam and Reservoir, operated primarily for hydropower. The dam has had minimal effects on the flow regime of the lower Sabine, with peak and mean flows minimally influenced. However, dam releases do clearly influence flows on hourly and daily time scales, and may dominate flows immediately downstream of the dam (Phillips and Slattery, 2007). Downcutting and channel widening are evident for about 15.5 mi (25 km) downstream, but further downstream Phillips (2003) found no evidence of geomorphic change attributable to dam effects. While geomorphic changes are evident and ongoing, they are not discernibly different from pre-dam conditions, or from those of larger undammed tributaries (Phillips, 2003).

Analysis of historical field measurements and rating curves for the three gaging stations downstream of Toledo Bend revealed generally similar trends (Heitmuller and Greene, 2009). At the Burkeville station closest to the dam a twofold increase in median discharge was recorded, along with a reduced sediment supply. In response, general channel degradation, thalweg incision, and increased cross-sectional areas occurred. However, at the Bon Weir station downstream a 43 percent increase in median discharge produced no systematic change, and at the Ruliff station the observed changes were not apparently related to the 32 percent increase in median discharge (Heitmuller and Greene, 2009).

TEXAS STUDIES—CLIMATE AND SEA-LEVEL CHANGE

Texas has experienced a number of climate and sea-level changes in the recent geologic past. These induced changes in runoff, sediment supply, and slope gradients in Texas Rivers. Boulter et al. (2010) developed a chronology of environmental change in semi-arid central Texas from pollen stratigraphy. They inferred a cool, moist climate at the end of the last glacial maximum (18.7 - 14.8 ka; ka = thousand years), with temperatures 8° C lower than present conditions. From 14.8 - 13.6 ka conditions grew increasingly mesic, and temperature increased. Continued slight warming was inferred for 13.6 - 11.7 ka, along with drier conditions. Species assemblages indicate brief fluctuations in climate between cool, moist conditions and a warmer, drier state around from 11.7 – 10.9 ka. A warmer, more xeric climate prevailed from 10.9 – 5.4 ka, but with conditions cooler and wetter than the present climate. Continued warming and drying occurred from 5.4 to 1.2

ka. Interpretations of the past 1200 years are complicated by disturbance of the study site, but pollen suggests warm, dry conditions up to about 200 years before present (BP), with moister conditions afterward.

Interpretation of geomorphic responses to the climate changes identified by Boulter et al. (2010) is complicated by effects of sediment supply. Sediment availability, rather than direct effects of climate, serves as the main control (Boulter et al., 2010). Small-scale climatic events, or processes such as bioturbation, can influence sediment availability, but the connection between climate and geomorphic dynamics was weaker than expected. Spatial and temporal scale may be a factor, depending on the event examined – for instance, vegetation changes occur in response to long-term change in climate, while erosion and sediment re-deposition may react to short-term, or single-event, climatic changes (which do not show up in the pollen record).

Hall (1990) investigated channel trenching and climate changes in river systems of the U.S. Great Plains, including the Colorado, Brazos, and Trinity Rivers, Texas, focusing on the period from 2 ka – 0.8 ka. Beginning 2 ka, sedimentation rates slowed dramatically, from 1/3 to 1/10 of the rate typical of the previous 3,000 years. This decline in sedimentation lasted from 2 to 1 ka, which could indicate a decline in stream flows; Hall (1990) characterizes the moist climate as producing a permanent stream flow and slow sedimentation. Beginning 1 ka, a period of channel deepening occurred, suggesting an increase in stream flows. Starting about 800 years BP fluvial deposition recommenced, pointing towards higher flow levels. The roughly 200-year period of trenching corresponds with a change from a wetter to a drier precipitation regime.

Patton and Dibble (1982) used archaehological, pollen, and geomorphic evidence to reconstruct the paleohydrology of high-magnitude flows of the Pecos River near its confluence with the Rio Grande. Evidence from this site suggests a climate cooler and more humid than present before 10 ka, and generally increasingly drier and warmer thereafter. However, this trend was punctuated by excursions to more mesic climates 9-7 ka and 3-2 ka. The mesic periods are associated with alluvial stratigraphy indicating frequent, moderate flooding events. Drier periods are associated with evidence of infrequent but higher-magnitude floods. Patton and Dibble (1982) suggested that the most extensive geomorphic changes occur during arid episodes, when the combination of larger floods and sparse vegetation cover that provides minimum stabilization allows for extensive reworking.

A 17 ka chronology of Cowhouse Creek, a Brazos River tributary in central Texas, shows apparently climate-driven episodes of incision and aggradation (Nordt, 2004). However, like Hall (1990) and other studies based on paleoenvironmental constructions, changes in fluvial channels are often used as evidence of changes in precipitation, runoff, and sediment supply, making it difficult to infer fluvial changes in response to climate without circular reasoning. In Cowhouse Creek, extensive incision into bedrock occurred around 15.3 ka, during a time when paleovegetation evidence from carbon isotopes suggests higher precipitation than at present and stable vegetation cover. A period dominated by channel and floodplain deposition between 11 and 8 ka was associated with a wetter, cooler climate as indicated by C isotopes. It is unclear the extent to which other degradation, aggradation, and channel stability episodes were linked to climate/runoff changes, sediment supply, or interactions within the slope and fluvial system (Nordt, 2004). Similarly, Waters and Nordt (1995) unravelled the late Quaternary floodplain history of the Brazos River between Hearne and Navasota. They identified several episodes of channel, planform, and floodplain change, attributable to a combination of direct hydrologic effects of climate change, upland vegetation and sediment supply changes, and internal geomorphic adjustments.

As a broad generalization, three general responses to direct and indirect effects of climate change, and to sea-level change, are widespread in Texas' alluvial rivers, particularly in the coastal plan. The details and degree of expression of these phenomena vary, but their occurrence is widespread. The first is episodes of downcutting and entrenchment, generally associated with lower sea-levels and thus lower base levels and steeper channel slopes. These episodes are also generally associated with cooler glacial climates at higher latitudes. Second, aggradation occurred during stable or rising sea-levels during warmer global climates. Evidence of these episodes of incision and aggradation is preserved in a series of three late Quaternary alluvial terraces, widely known as "Deweyville" terraces (see, e.g., Blum and Price, 1994; 1998; Blum et al., 1995; Morton et al., 1996; Blum and Aslan, 2006). These terrace surfaces lie between the modern floodplain and older Quaternary surfaces of the Beaumont formation.

The third, related phenomenon is meander scars and paleochannels associated with the Deweyville surfaces. These features are less evident in the Rio Grande, Colorado and Brazos Rivers due to the greater degree of valley filling, but even there scallop-shaped indentations of the valley walls provide evidence of the paleochannels. The amplitude of the meanders and width of the paleochannels are both greatly and obviously larger than those of the modern rivers. It is widely, if not universally, agreed that these reflect significantly higher paleodischarges. However, there is uncertainty and disagreement as to whether this applies to mean or median flows, to high flows only, or both (c.f. Alford and Holmes, 1985; Blum et al., 1995; Sylvia and Galloway, 2006; Blum and Aslan, 2006).

Note that the details of sea-level history and relative importance of climate, sea-level, and other factors in evolution of rivers and estuaries of the Texas and Gulf of Mexico coastal plain are quite controversial (see, e.g., Anderson and Rodriguez, 2008). However, the aggradation-incision responses to sea-level changes, and the association of the Deweyville paleomeanders with larger discharges are agreed upon.

DAM REMOVAL

Dam removal is a relatively recent hydrologic change that is not yet widespread in Texas. Removal of low-head dams on two Wisconsin rivers resulted in local erosion and increased sediment transport (Doyle et al., 2003). On the Koshkong River a major increase in shear stress initiated a headcut knickpoint and led to local channel widening near the former dam site. On the Baraboo River, depth increased within and upstream of the former pool, except during passage of a large slug of passing sediment evacuated after dam removal.

Burroughs et al. (2009) examined geomorphic effects of dam removal on the Pine River, Michigan. The main hydraulic effects were an increase in water surface slope in the vicinity of the former impoundment, and increased and more variable velocities. Width and width/depth ratios did not change upstream or downstream, but decreased in the former impoundment area. Sediment transport increased downstream, and coarsening was observed.

The breaching of eight old mill dams on the South River, VA was concurrent with an increase in bank erosion (Pizzuto and O'Neal, 2009). They found that the breaching of mill dams explained the erosion trends at nine of 14 monitoring sites along their 19 mi (30 km) study reach.

SUMMARY AND SYNTHESIS

Table 8 provides a summary of the Texas-based case studies of channel responses to changes in flow regime due to human activity, or at least in recent history. Some key lessons are:

- Channel responses downstream of dams are often limited in their downstream extent.

- It is often difficult to attribute observed channel changes to changes in flow regime, partly because of confounding factors, and partly because alluvial streams are prone to change, with or without anthropic modifications.

- Specific modes of response to a given flow change may vary both between and within fluvial systems.

Table 8. Summary of Texas studies of channel responses to changes in flow regimes.

River	*Change in discharge*	*Channel responses*	*Reference*
Rio Grande	Floods	Lateral migration, avulsions, cutoffs; channel widening & deepening after major floods with subsequent recovery	Mack & Leeder, 1998
Rio Grande	Decline	Channel narrowing & shallowing; transition from bed to suspended dominated sediment load; increased vegetation	Everitt, 1993
Rio Grande	Decline	Narrowing, incision, increased vegetation, decreased lateral migration and sediment transport; increased sediment size, multi- to single-thread planform	Dean & Schmidt, 2011
Pecos	Decline	Decrease in depth & cross-sectional area	Hoagland, 2009
Lower Nueces	Upstream dam construction	Channel erosion	Ockerman & Heitmuller, 2010
San Antonio	Increase (below city of San Antonio)	Channel widening; increased lateral migration	Sahoo & Smith, 2008; Cawthon 2007
Yegua Creek	Small decline in mean flows; increase in low flows; large decrease in high flows	Minor channel narrowing; large decreases in depth & cross-sectional area	Chin et al., 2002
Lower Brazos River	Increase in low flows; small decrease in high flows	Channel widening & depth increase with no change in cross-sectional area; reduced sand transport—however, effects could not be clearly lined to flow changes	Dunn & Raines, 2001; Osting et al., 2004a
Middle-lower Brazos River	Upstream dam construction	Decreased lateral migration & meander translation	Gillespie & Giardino, 1996; 1997
Continued	*on next page*		

River	*Change in discharge*	*Channel responses*	*Reference*
Middle-lower Brazos River	Upstream dam construction	Decreased lateral migration & meander translation; decreased channel width; continued net sediment storage	Giardino & Lee, 2011
Middle-lower Brazos River	Slight decline in median Q; reduced sediment supply	Incision & widening at Waco; reduced bank erosion or infill & slight incision at Highbank & Bryan	Heitmuller & Greene, 2009
Little River	21% increase in median Q	Channel degradation; some aggradation at low flows	Heitmuller & Greene, 2009
Lower Navasota River	20 to 28% increase in median Q	Minor change or channel degradation; floodplain accretion at one site	Heitmuller & Greene, 2009
Lower Trinity River	Withdrawals of about 10% of mean Q	No obvious changes in river or valley morphology	Phillips, 2010
Lower Trinity River	Slight increase in low Q; reduced sediment supply	General increases in channel width & depth; decrease in slope; coarsening of sediment. Specific responses highly variable, however, & limited to a 60 km zone downstream of dam.	Phillips et al., 2005
Lower Sabine River	Increased median Q; reduced sediment supply	Degradation, channel enlargement, increased velocity at Burkeville; no obvious change downstream	Heitmuller & Greene, 2009
Lower Sabine River	Minimal change in Q; reduced sediment supply	Degradation, channel enlargement for about 25 km downstream; no obvious effects further down	Phillips, 2003
Loco Bayou	Reduced Q at all flows; reduced sediment supply	Channel enlargement immediately downstream; no effects further downstream	Phillips, 2001; Phillips & Marion, 2002
Sulphur River	Reduced high & median Q; increased low Q; reduced sediment supply	Channel narrowing & deepening; increased sediment transport & deposition; but flow effects not separable from channelization	Osting, 2004b

It should also be noted that changes in the seasonal pattern of high and low flows may not result in significant geomorphic changes (e.g., Phillips, 2003; Alibert et al., 2011), but such changes may be highly significant from a hydrological or ecological perspective.

Downstream effects are not always consistent. In the lower Trinity River, Phillips et al. (2005) documented several qualitatively different responses downstream of Livingston Dam. Even where a particular mode of adjustment is dominant, it is not necessarily universal. Hupp et al.'s (2009) study of bank erosion downstream of a series of reservoirs on the lower Roanoke River, N.C. found that while widening occurred at 90 transects, another 12 showed narrowing. Meanwhile, even though sediment starvation effects are evident immediately downstream of the dams, Hupp et al. (2009) found an increase in floodplain sedimentation downstream. While they attribute this to sediment supplied from bank erosion, studies on other N.C. coastal plain rivers indicate that sediment sources within the coastal plain account for observed floodplain accretion (Phillips, 1992a; 1992b; Benedetti et al., 2006).

The type of complex, geographically and historically contingent responses downstream of dams noted for Texas Rivers (Phillips, 2003; Phillips et al., 2005; Wellmeyer et al., 2005) is not uncommon, as revealed in Friedman et al.'s (1998) synthesis of studies on rivers of the U.S. Great Plains. The theme of complex downstream responses has perhaps been pursued most diligently by Xu in his studies of Chinese rivers (e.g., Xu, 1990; 1996; 2001).

It is commonly assumed or asserted that sediment trapping in Texas reservoirs is a key issue with respect to sediment (especially sand) delivery to the coastal zone, and a cause of shoreline retreat. However, this is not necessarily the case. Despite the high sediment trap efficiency of many reservoirs, there typically exists a relatively short scour zone downstream of the dam, with little or no evidence of sediment starvation further downstream (Phillips, 2001; 2003; 2007; Chin et al., 2002; Dunne and Raines, 2001; Phillips and Musselman, 2003; Phillips et al., 2004). Rivers crossing coastal plains are often inefficient conveyors of sediment due to low slopes and stream power, so that changes in upstream sediment dynamics may not be evident at the river mouth. Large accommodation spaces and low stream power result in extensive sediment storage upstream of estuaries (independent of dams). However, most gaging stations with sediment records are upstream of these lower coastal plain sediment bottlenecks, and thus overestimate sediment delivery to the coast. Phillips and Slattery (2006; Slattery and Phillips, 2011) illustrate these phenomena with several examples from Texas. Reservoirs on the Brazos, Trinity, and Sabine Rivers and on Loco Bayou apparently have limited influence on sediment supply in the lower reaches of those streams (Dunne and Raines, 2001; Phillips, 2001; 2003; Phillips and Marion, 2001; Phillips et al., 2004; Slattery et al., 2010). However, in cases such as the Nueces and Lavaca rivers, where impoundments are much closer to the river mouth and estuary, this may not be the case.

Chapter 4
Channel Response Model

The models and conceptual frameworks outlined in Chapter 2 have a number of common elements and overlaps, but some distinct characteristics as well. These will be discussed here in the context of channel responses to changes in flow, though some of the models have other applications in addition to this. Several of the frameworks are intended primarily to predict or assess changes in channel size and geometry. These include hydraulic geometry and regime theory approaches, and the qualitative Brandt (2000a) model. By contrast, the Lane relationship and grade-based models, along with bed mobility, are primarily concerned with the relationship between sediment transport capacity or erosive force versus sediment supply or boundary resistance (note that the Brandt 2000a model is a means for applying principles of the Lane relationship to predict changes in channel size). The Schumm model, channel evolution models, river evolution diagram, transport capacity model of Brandt (2000b)**,** and flow-channel fitness models are best described as efforts to predict the state of the channel system, based on multiple criteria.

DECLINING DISCHARGE

If flow decreases and slope is unchanged or also decreases, then cross-sectional stream power and transport capacity also decline. The key question then becomes whether sediment supply (Q_{sed}) changes proportionally. Using the subscript *b* to indicate pre-flow-change conditions,

$$\Phi = Q_{sed}/(Q_{sed})_b \qquad (19)$$

If $\Omega/\Omega_o < \Phi$, transport capacity has decreased by a greater proportion than sediment supply, and aggradation is expected. The smaller the ratio $\Omega/\Omega_\beta/\Phi$, the greater the expected aggradation. $\Omega/\Omega_\beta > \Phi$ indicates that sediment supply has decreased by a greater proportion than stream power. Aggradation due to excess sediment will not occur. The channel may remain relatively unchanged, or experience degradation, depending on the relationship between shear stress and boundary resistance. If shear stress is sufficient to erode the channel bed or banks, degradation is possible.

INCREASING DISCHARGE

For the case of increasing flows, an important distinction is whether there is also likely to be a significant increase in sediment inputs as well. Local discharge augmentation due to effluent discharges, return flows, dam releases, interbasin water transfers for municipal or industrial uses, or urban runoff generally does not include significant volumes of sediment (though other pollutants and constituents may be of concern). Increasing discharges due to increased runoff from land disturbance or land use change (mining, logging, agriculture, construction, overgrazing) often do involve significant increases in sediment. These cases will be treated separately.

Increased Discharge with Minimal Change in Sediment Load

In this case the key consideration is whether the shear stress associated with the higher flow is sufficient to erode the channel boundaries. Shear stress is a function of hydraulic radius (approximated by mean depth in most cases) and energy grade slope ($\tau = \gamma\, d\, S$). Unless the change in discharge is associated with activities that also increase channel width, mean depth should remain constant or (more likely) increase. Unless slope is decreased by a greater or equal proportion than the increase in depth, this results in an increase in shear stress. Denoting τ_{cr} as the critical value necessary to erode the channel, if $\tau/\tau_{cr} \geq 1$, degradation is expected. If $\tau < \tau_{cr}$, no change in channel dimensions would be expected, though a possible increase in flood frequency and duration may occur due to larger flows confined in a constant channel size. The extent to which this occurs depends on the state of channel fitness at the outset, and the extent to which discharge increases may be incorporated by increases in velocity. Standard flow resistance equations show V to be a function of hyraulic radius, enery grade slope, and flow resistance or channel roughness. The D'Arcy-Weisbach equation, for instance, is

$$V = (8\, g\, R\, S/f)^{1/2} \qquad (20)$$

where f is a friction factor. If relative changes in R or d, S, and f are known, velocity change can be predicted. If $V/V_o \geq Q/Q_b$, then the flow can be accomodated without an increase in out-of-channel flow. Roughness or friction factor is partly a function of instantaneous hydraulic conditions, but general changes in the channel roughness regime, if any, will be tied to changes in channel irregularity, bedforms, and woody or other debris obstructions.

Increased Discharge and Sediment Load

Where water flow and sediment inputs both increase, the relative increase in sediment supply and transport capacity is the critical factor. An increase or no change in slope (or a decrease proportionally less than the increase in Q) will result in an increase in stream power and transport capacity. If $\Omega/\Omega_o < \Phi$, transport capacity has increased less than sediment supply, and aggradation is expected. $\Omega/\Omega_o > \Phi$ indicates that transport capacity has increased by a greater proportion than sediment inputs. In this case degradation is expected if shear stress is sufficient to overcome boundary resistance. If shear stress is not sufficient to erode the channel bed or banks, aggradation is possible. Otherwise, no change in channel size is likely, with the posibility of overfitness and increased flooding, under the same conditions as described above.

CHANNEL RESPONSE MODEL

This section is a step-by-step outline for predicting channel responses to changes in flow regime.

Step 1. Determine current or pre-change channel state.

There are seven possible channel states, as shown in table 9. The relationship between these states and the fitness conditions depends on the starting point. For example, a degrading channel could be adjusting toward fitness if starting from an overfit condition, or becoming underfit or increasingly underfit if starting from a state of fitness or underfitness, respectively. Steady-state is marked by stable banks, or by lateral migration with no net change in channel width, and by an absence of persistent or chronic aggradation or degradation. Indicators of under or overfitness (table 10) should generally be absent. Aggradation may be dominated by decreasing width (narrowing) or depth (shallowing), and is reflected by the indicators shown in table 11. Aggrading channels may be underfit, but adjusting toward fitness, or becoming increasingly overfit. Degradation states may also be dominated by adjustments of width (widening) or depth (incision and deepening). Degrading channels may be overfit but adjusting toward fitness, or becoming increasingly underfit. The latter two states are associated with over or underfit conditions, but with little or no channel change (evidence of aggradation or degradation).

Table 9. Possible channel states, linked to fitness conditions described earlier. The increasing, decreasing, or no change trends (+, -, 0) for cross-sectional area *(A_{cx})* and width-depth ratio *(w/d)* are shown.

Channel state	*A_{cx}*	*w/d*	*Fitness*
Steady-state	0	0	Persisting fitness
Aggradation Narrowing dominated	-	-	Underfit adjusting toward fitness, or increasing overfitness
Aggradation Shallowing dominated	-	+	Underfit adjusting toward fitness or increasing overfitness
Degradation Widening dominated	+	+	Overfit adjusting toward fitness, or increasing underfitness
Degradation Deepening dominated	+	-	Overfit adjusting toward fitness, or increasing underfitness
No channel change Underfit	0	0	Persisting underfitness
No channel change Overfit	0	0	Persisting overfitness

Table 10. Indicators of channel over- or underfitness in alluvial rivers (absence indicates channel fitness). Asterik* indicates sufficient indicator. Others, not marked with asterik, require presence of at least one other indicator for confident determination.

Indicators of Underfitness

Infrequent occurrence of flows near banktop stage
Overbank flood recurrence interval > 2 years
Overbank flood recurrence interval > 10 years*
Inset floodplains within morphological bank tops*
Tops of point bar surfaces well below bank top elevation*
Slow or non-removal of bank slope failure features
Establishment of obligate upland vegetation below bank top elevation
Absence of wetland vegetation above bank top elevation

Indicators of Overfitness

Frequent occurrence of flows at or near banktop stage
Overbank flood recurrence interval < 0.5 years
Overbank flood recurrence interval < 0.3 years*
Evidence of active aggradation of both channel and floodplain
Frequent crevasses and/or avulsions
Anabranching or anastamosing channel patterns (normal or high flow)
Very high channel-floodplain connectiviity
Occurrence of valley-filling floods

Table 11. Field indicators of channel incision and aggradation. Some of the following are not caused exclusively by general channel incision or aggradation; two or more indicators should be present for confident interpretations. Potential alternate causes for the indicators are given in [brackets].

Indicators of Channel Incision

Exposure or undercutting of cultural features such as bridge pilings, boat ramps, docks, pilings, etc. [localized flow or slope increases or flow deflections]
Exposure of bedrock or pre-Quaternary material in bed [lithological variations]
Knickpoints [lithological or structural variations; antecedent morphology; local sediment inputs]
Channel ledges or paleobanks [lateral infilling]
Obligate hydrophytes well above normal water levels [perched ground water]
Riparian trees back-tilted away from river [wind throw]
Evidence of reduced overbank flow, e.g., reduced sedimentation, soil formation, soil redox features, vegetation changes [vertical floodplain accretion]
Channel narrowing without evidence of significant changes in discharge, stream power, or sediment supply. [local slope failures]
Channel ledge
Tributary downcutting; indicators above observed in tributaries

Indicators of Channel Aggradation

Burial or partial burial of channel and lower-bank vegetation
Burial of large woody debris
Island formation; relatively young islands as indicated by vegetation and soil characteristics
Sand sheets
Cypress buttressed-banks (other than in deltaic or fluvial/estuarine transition zones)
Crevasses and avulsions [local levee damage or flow diversions]
Evidence of increased frequency of overbank flow, e.g., increased floodplain sedimentation, soil redox features, vegetation changes, floodplain flow and hydrologic indicators [erosional floodplain stripping; increased discharge]
Tributary aggradation; indicators above observed in tributaries
Increased tributary backflooding; indicators of floodplain or channel aggradation along lower tributary reaches; organic deposits near tributary mouths

Table 12. Indicators of bank erosion and accretion.

Indicators of Bank Erosion

Concave bank profile or lower profile
Absence of vegetation cover
Scarps and failure surfaces
Exposed roots
Toppled trees (toward channel)
Encroachment on or toppling of cultural features (buildings, boat ramps, docks, utility poles, etc.)
Isolation in channel of formerly bank-attached features (bulkheads, docks, signs, etc.)

Indicators of Bank Accretion or Infilling

Inset floodplains
Channel benches
Burial or partial burial of bank vegetation
Burial of organic litter layers
Vegetation encroachment/establishment on lower banks, channel margins, and marginal bars
Fresh sediment deposits
Burial of cultural features (stairs, boat ramps, docks, rip-rap, etc.)
Isolation away from channel of formerly bank-attached or in-channel features (bulkheads, docks, signs, bridge pilings and abutments, etc.)

Step 2. Determine Changes in Discharge and Slope

This will be based on known, proposed, or hypothesized changes in flow. Meaningful analyses should be based on one or more design or reference flows, as some changes may not result in uniform increases or decreases across a range of flows. If specific quantitative changes are unknown, proportional changes (percentage increase or decrease) may suffice. Changes in hydraulic radius or mean depth should also be determined or estimated.

Water surface slope is generally the best available surrogate for energy grade slope, and changes may be estimated based on any structural effects on water surface elevations, local base level changes, or backwater effects.

Step 3. Determine Changes in Shear Stress

Changes in hydraulic radius or mean depth and slope allow the determination of changes in shear stress. Where quantitative values are available, these can be compared to measurements of bank and bed shear strength, or critical values from Tables 6 and 7 to determine whether the key threshold of $\tau = \tau_{cr}$ will be crossed.

Otherwise, educated guesses can be made based on judgements of the proximity of the pre-flow-modification channel to the threshold. Channels well below the threshold will exhibit no bed or bank erosion, while those well above will show evidence of frequent bed and/or bank erosion. In these cases large increases or decreases in relative shear stress will be required to exceed the thresholds. Channels close to the threshold will be stable (steady-state or persisting under or overfit conditions), or show mixed evidence of erosion, such as limited evidence of erosion, or erosive features undergoing recovery. In those cases smaller changes in shear stress could initiate channel change.

Step 4: Determine Changes in Sediment Supply

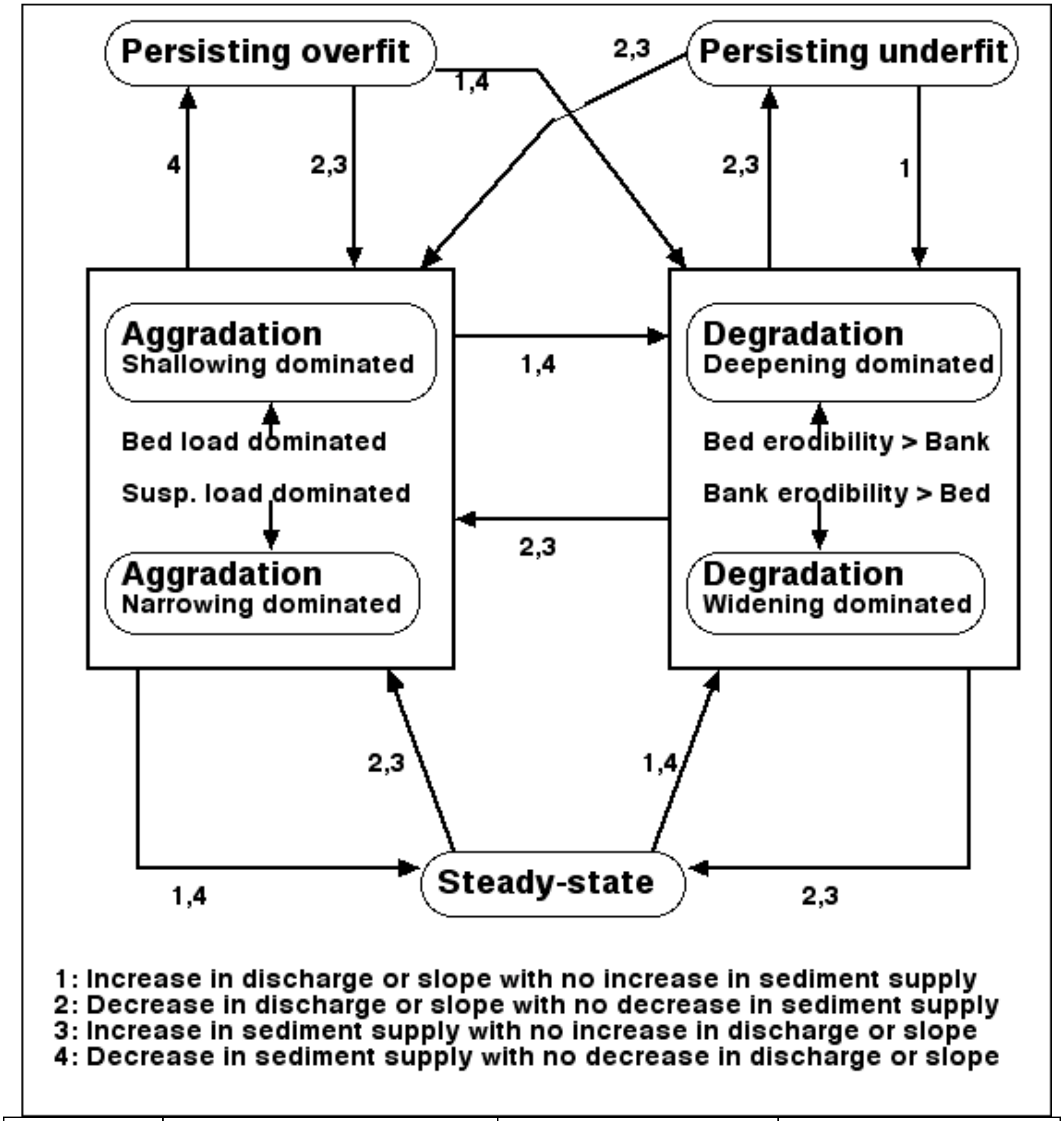
In the absence of extensive pre-modification data and post-modification modeling, this may be a qualitative estimate (increase, decrease, no change), or a proportional estimate (percentage increase or decrease). The key factor is the relative change in sediment supply compared to that of sediment transport capacity.

Step 5: Use the State-and-Transition Model to Determine Potential State Changes

The state-and-transition model (Figure 9) links the seven channel states with changes in discharge, slope, and sediment supply that may cause state transitions. Once the starting point has been identified, the possible state transitions, given the potential changes in flow, slope, and sediment supply, can be determined. As indicated earlier in Table 9, aggrading and degrading states may correspond with different channel fitness adjustments.

Step 6: Use the Fitness Assessment to Predict State Change

The fitness assessment procedure outlined in table 13 below and Figure 8 (Chapter 2) includes the key thresholds, so that from a given fitness starting point the channel response can be determined.



	Fit	*Overfit*	*Underfit*
Steady-state	Persisting fitness	Persisting overfitness	Persisting underfitness
Aggradation	Adjustment toward overfitness	Increasing overfitness	Adjustment toward fitness
Degradation	Adjustment toward underfitness	Adjustment toward fitness	Increasing underfitness

Figure 9. State-and-transition model for alluvial channels in response to changes in discharge, slope, and/or sediment supply. Degradation can correspond with adjustment toward fitness or increasing underfitness, and aggradation can correspond with adjustment toward fitness or increasing overfitness, depending in each case on the

starting point. The matrix below links the fitness starting point (column headings) with steady-state, aggradation, or degradation (row headings):

Table 13. Decision key for flow-channel fitness evaluation (similar to table 4, Chapter 2; with fitness adjustments linked to aggradation or degradation).

---

1. Compare reference flow to channel capacity
    - A. Underfit: go to 2
    - B. Fit: go to 4
    - C. Overfit: go to 6

2. Compare shear stress to critical shear stress.
    - A. Less than: go to 3.
    - B. Greater than or equal to: channel enlarges until limited by other factors; degradation leading to *increasing underfitness*

3. Compare stream power to critical stream power.
    - A. Greater than or equal to: *persisting underfitness or fitness*
    - B. Less than: channel infills; aggradation, *underfit adjusing toward fitness*.

4. Compare shear stress to critical shear stress.
    - A. Less than or equal to: go to 5.
    - B. Greater than: channel enlarges until limited by other factors; degradation leading to *increasing underfitness*

5. Compare stream power to critical stream power.
    - A. Greater than or equal to: *persisting fitness*
    - B. Less than: channel infills; aggradation leading to *increasing overfitness*

6. Compare shear stress to critical shear stress.
    - A. Less than: go to 7.
    - B. Greater than or equal to: channel enlarges; degradation leading to *overfit adjusting toward fitness*

7. Compare stream power to critical stream power.
    - A. Greater than or equal to: *persisting overfitness*
    - B. Less than: channel infills; aggradation leading to *increasing overfitness*

The STM of Figure 9 can also be presented as an interaction matrix, as shown in table 14. This shows the circumstances in which the existing state (vertical axis) is likely to persist (shaded cells) or transition to states on the horizontal axis.

Table 14. Interaction matrix for the alluvial channel change state-and-transition model.

	Persisting overfit	*Persisting underfit*	*Aggradation*	*Degradation*	*Steady-state*
Persisting overfit	Any change in transport capacity vs. supply relationship may trigger shift	No direct transition	Transport capacity falls below sediment supply; boundary not erodible	Transport capacity exceeds sediment supply; boundary erodible	No direct transition
Persisting underfit	No direct transition	Any change in transport capacity vs. supply relationship may trigger shift	Transport capacity falls below sediment supply	Transport capacity exceeds sediment supply; boundary erodible	No direct transition
Aggradation	Sediment supply declines to less than or equal to transport capacity; overfit	No direct transition	Shift only when transport capacity exceeds sediment supply	Transport capacity exceeds sediment supply; boundary erodible	Transport capacity exceeds sediment supply; boundary not erodible
Degradation	No direct transition	Shear stress falls below critical value; transport capacity still exceeds sediment supply; overfit	Transport capacity falls below sediment supply	Shift only when transport capacity falls below sediment supply	Shear stress falls below critical value; transport capacity still exceeds sediment supply; fit or adjusting toward fitness
Steady-state	No direct transition	No direct transition	Transport capacity falls below sediment supply	Transport capacity exceeds sediment supply; boundary erodible	Any change in transport capacity vs. supply relationship may trigger shift

IDENTIFICATION OF CRITICAL THRESHOLDS

Shear Stress and Boundary Erosion

According to Fischenich (2001), critical boundary shear stresses for the unconsolidated material typical of alluvial streams in the Texas coastal plain ranges from about 1 to 4 N m^{-2}. Reach-scale slope gradients on coastal plain reaches of Texas rivers range from about 0.000001 to 0.003, with gradients up to about 0.02 on the Edwards Plateau (Cawthon, 2007; Phillips, 2007a; 2008; 2011; Phillips and Slattery, 2007), though local slopes may be greater or less during some flow conditions. Figure 10 shows the boundary shear stress for slope gradients in this range, for depths up to 10 m (33 ft). This shows that the critical boundary shear stresses are unlikely to be exceeded for any slope gradient less than 0.00001, and only during very high flows (mean depths $\geq$ 4 m or 13 ft) for slopes up to 0.00005. Slopes of 0.0001 or greater, by contrast, are likely to exceed critical shear stresses at flow depths of about a meter or more. Figure 10 can also be used as a rough guide for estimating threshold energy grades slopes for a given depth. For a depth of 2 m (6.4 ft), for instance, the threshold slope would be about 0.0001.

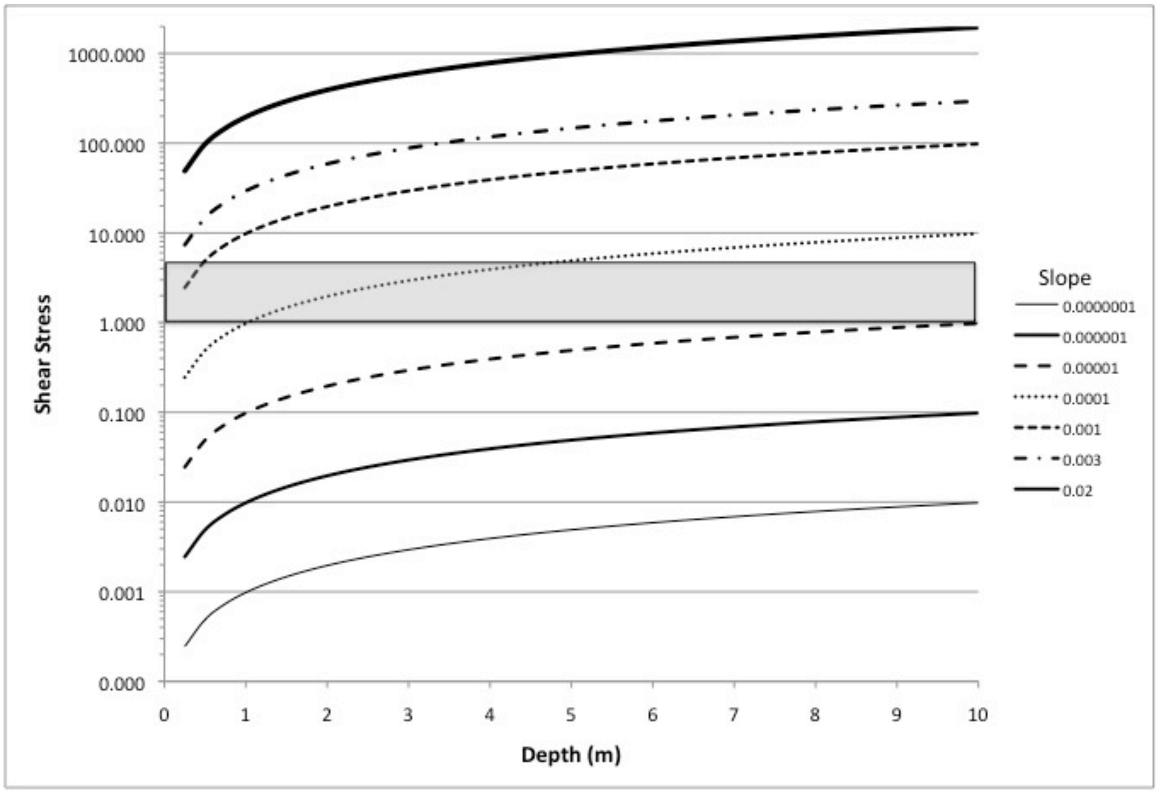


Figure 10. Mean boundary shear stress (N m^{-2}) vs. mean depth relationships for the range of slope gradients of Texas Rivers. The critical shear stress for materials typical of alluvial coastal plain rivers is shown by the shaded area.

Threshold Condition for Transport Capacity = Sediment Supply

The threshold condition for a suspended-load dominated stream occurs when sediment transport capacity is equal to sediment supply or available sediment. Transport capacity is proportional to cross-sectional stream power:

$$\Omega = \rho\, g\, Q\, S \qquad (21)$$

Ω has units of N m^{-1} = kg m s^{-3}, s = seconds.
ρ is water density, ≈ 1000 kg m^{-3}
g = gravity constant (9.81 m sec^{-2})
Q = discharge, $m^3\ s^{-1}$
S = energy grade slope (≈ water surface slope; dimensionless)

Sediment supply is represented by the input of suspended sediment. Suspended sediment concentration (SSC) is measured in mg l^{-1}, which can be divided by 1000 to produce units of kg m^{-3}. Total input is concentration times discharge, multiplied by the gravity constant to produce units of work (kg m s^{-3}, same as cross-sectional stream power): sediment supply = $SSC/1000\ Q\, g$.

The threshold condition is therefore

$$\rho\, g\, Q\, S = SSC/1000\ Q\, g, \qquad (22)$$

which reduces to

$$\rho\, S = SSC/1000. \qquad (23)$$

Plugging in the constant value for ρ, then

$$S = SSC/10^6 \qquad (24)$$

This implies that, for a given SSC, slopes less than the threshold value will result in aggradation; while $S \geq SSC/10^6$ will not. For a given slope, the implication is that $SSC/10^6 > S$ results in aggradation.

If sediment sources other than suspended sediment are important, sediment input in $m^3\ sec^{-1}$ is denoted by ζ . Multiplying by sediment density (ρ_s) and g to produce work units, the threshold condition is

$$\rho\, g\, Q\, S = \zeta\, \rho_s\, g \quad \text{or} \quad Q\, S = \zeta\, \rho_s/\rho. \qquad (25)$$

For typical sediment densities (about 2650 kg m^{-3}), ρ_s/ρ ≈ 2.65. This implies a threshold condition of

$$S = 2.65\ \zeta/Q. \qquad (26)$$

As ζ/Q is an indication of sediment input volume relative to water input volume, and is analogous to a sediment concentration.

Because SSC is more easily and commonly measured than ζ, an expedient form of the threshold criterion for suspended load streams is

$S = SSC/10^6 + k,$

where k represents sediment inputs other than suspended sediment (in the same units), or

$S \geq SSC/10^6$

In studies on the lower Trinity River and two of its tributaries, Slattery and Phillips (2007) found that bed load was about 10 percent (mean 9.7 percent). This implies that for a given discharge, in the absence of local mass wasting or spoil inputs, $k \propto 0.1\ SSC$.

Table 15 shows the suspended sediment concentrations for several Texas coastal plain stations from the U.S. Geological Survey suspended sediment database (http://co.water.usgs.gov/sediment/).

Table 15. Suspended sediment concentrations at gaging stations in the Texas coastal plain.

Site	*Suspended Sediment Concentrations (mg l^{-1})* *Mean*	*Median*	*Maximum*
Rio Grande River at Brownsville	172	69	6,000
Colorado River at Columbus	193	79	5,650
Brazos River at Richmond	572	220	13,500
Navasota River near Bryan	80	65	748
Bedias Creek near Madisonville	52	30	915
Trinity River at Romayor	99	47	1,370

Threshold of significant change in response to a change in discharge

Assuming that all sediment (from whatever source) is transported by the flow, the criterion is that the transport capacity per unit weight of water remains unchanged. The latter is given by unit stream power:

$$\phi = (\rho\, g\, Q\, S)/(\rho\, g\, A) = VS \qquad (27)$$

where A is cross-sectional area and $Q = AV$.

The criterion is then

$$\phi_a/\phi_b = 1, \text{ or } (V_a S_a) \approx (V_b S_b), \tag{28}$$

where subscripts b, a indicate before and after the flow change. If $\phi_a/\phi_b > 1$, channel degradation and enlargement is likely, at least if critical thresholds for erosion or entrainment of boundary materials are exceeded. If $\phi_a/\phi_b < 1$, aggradation and infilling is expected, unless the system is supply-limited.

Standard flow resistance equations relate velocity to slope (S), hydraulic radius (R = A/wetted perimeter), and roughness or friction factor f. Using the D'Arcy-Weisbach equation and substituting for V,

$$(8g\, R_a\, S_a/f_a)^{0.5}\ S_a = (8g\, R_b\, S_b/f_b)^{0.5}\ S_b \tag{29}$$

which reduces to

$$R_a^{0.5}\, S_a^{1.5}\, f_a^{-0.5} = R_b^{0.5}\, S_b^{1.5}\, f_b^{-0.5} \tag{30}$$

This enables threshold criteria to be established for R, S, or f:

$$R_a/R_b = (S_b/S_a)^3\ (f_a/f_b) \tag{31}$$

$$S_a/S_b = (R_b/R_a)^{1/3}\ (f_a/f_b)^{1/3} \tag{32}$$

$$f_a/f_b = (R_a/R_b)\ (S_a/S_b)^3 \tag{33}$$

EXAMPLES

Lower Trinity River

Lake Livingston on the lower Trinity River is a flow-through water supply reservoir. Though the dam increased low flows above pre-dam levels, medium and high flows were not discernibly affected. The lake did result in a drastic reduction in sediment supply downstream. The details of the geomorphic response of the lower Trinity river to effects of the impoundment are discussed by Phillips et al., (2004; 2005). Here the method described above will be applied to a reconstructed pre-dam situation.

Based on analysis of undammed tributaries to the lower Trinity River, and the Trinity upstream of Lake Livingston and downstream of the dam effects, the pre-dam state was likely narrowing-dominated aggradation. This is based on active alluvial sedimentation, an apparently transport-limited regime, and active cutoffs and avulsions. Given the incision history of the Trinity, this is interpreted as an underfit channel adjusting toward fitness. In Step 2, no change in discharge or direct change in slope would be identified, given the flow-through nature of the reservoir. Because “hungry water” incision is common downstream of dams (and in fact has occurred in the lower Trinity; Figure 11), the possibility of increased depth and hydraulic radius could have been inferred before dam construction (Step 3). The size, and large capacity-inflow ratio, of Lake Livingston would also have predicted a large decline in sediment supply downstream (step 4).

Figure 11. Scour zone below Livingston Dam on the Trinity River. Exposed tree roots indicate downcutting and bank retreat. The gray stains on the tree trunk (box) are due to scour of the clayey bed material beneath the thin alluvial layer.

The STM (step 5) shows that an aggrading state will persist unless there is a decrease in sediment supply relative to transport capacity, indicating a transition to steady-state, degradation, or persisting underfitness.

In step 6, the underfit starting point was chosen, despite the aggradational state, due to the legacy of incision in the Trinity, the result of which is a channel which rarely experiences overbank flooding in the reach downstream of Livingston Dam. This leads to a comparison of shear stress with critical shear stress. Given the low resistance of the dominantly sandy banks and sandy alluvium on the channel bed, it can be assumed that the shear stress will, at least at higher flows, be sufficient to erode the channel margins. Further, a likely increase in depth and no decrease in slope suggests that shear stress will increase. This predicts (see table 13) that the channel will enlarge until limited by other factors (increasing underfitness). With respect to the STM, that indicates degradation.

This is also consistent with the critical shear stress relationships shown in Figure 10, given the slope gradients involved (Phillips and Slattery, 2007). A pre-dam analysis would likely have predicted deepening-dominated degradation, based on comparable material properties of bed and banks, with greater shear stress and thus greater erodibility on the bed.

In retrospect, the prediction that would have been generated from this procedure was correct, at least for the initial response. However, channel incision eventually encountered more resistant pre-Holocene clays and bedrock, resulting in a shift from deepening to widening-dominated degradation. This continued until critical bank heights were reached sometime before the early to mid 2000s (Phillips et al., 2005). The channel is now in a state of persisting underfitness.

Several caveats are in order. First, though the general change in channel state was apparently consistent downstream, the local, cross-section scale responses varied considerably in detail (Phillips et al., 2005). Second, the effects of the dam extend for a finite distance downstream, as would be expected (in this case about 34 mi or 55 km). However, this distance is a function not only of distance decay effects, but also of the increasing and sometimes overwhelming effects of other geomorphic controls further downstream (Phillips et al., 2005; Phillips and Slattery, 2008). Third, while no direct change in slope occurred due to the dam, channel slope decreased as a result of the channel incision resulting from the reduced sediment supply, a result predicted by several of the models discussed in Chapter 2.

Lower Sabine River

Toledo Bend Reservoir on the lower Sabine River on the Texas-Louisiana border was completed in 1969, about 125 mi (200 km) upstream of the Sabine Lake estuary. The impoundment provides hydropower, with no flood control function. Dam operation profoundly affects the timing of flows and flow pulses, particularly in the 19 mi (30 km) or so of channel immediately downstream of the dam, but has had minimal impact on mean, median, or peak flows. The reservoir does trap most of the incoming sediment, however, so that dam releases have unfilled sediment transport capacity. These hydrologic changes, and geomorphic responses downstream, are described by Phillips (2003) and Heitmuller and Greene (2008).

Based on analysis of historical changes and of large unregulated tributaries of the lower Sabine (Phillips, 2003; 2008), it can be inferred that, though the valley as a whole was (and continues to be) characterized by net floodplain aggradation, the channel itself was in approximate fitness. The dam effects amount to no significant change in discharge, an increase in slope in the immediate vicinity of the dam spillways and turbines with no slope change further downstream, and a sharp decline in sediment supply.

Banks and bed material are dominantly unconsolidated sandy material with low shear strength, such that shear stress of the dam release flows exceed shear strength. Under these conditions the fitness assessment and STM predict channel enlargement, and incision-dominated degradation, since little suspended sediment is available downstream of Toledo Bend dam. The observed response of the channel, for about 15.5 mi (25 km) downstream, is exactly as predicted (Phillips, 2003; Heitmuller and Greene, 2008). The channel incision is not evident further downstream, however, illustrating the distance decay effects of channel responses downstream of the flow changes.

San Antonio River Delta

Since the 1950s an avulsion has been ongoing in the lower San Antonio River delta area, near Tivoli, Texas. The Elm Bayou channel is increasingly capturing the flow of the river (about 70 percent as of 2011). The channel shift has thus resulted in an increase in flow to the Elm Bayou pathway, and a decrease downstream of the split to the San Antonio River channel. The geomorphic context, avulsion history, and causes and consequences of the avulsion are discussed in detail by Phillips (2011b).

There is no evidence of slope change in either pathway, and as the lower San Antonio is a mud-dominated system, it is reasonable to assume in the absence of other factors influencing sediment supply that the sediment load at the split is directly proportional to the discharge (since flow is competent to transport available sediment at all flows). The lowermost San Antonio, like most deltas, is a strongly aggrading system, and the frequent avulsions (see Phillips, 2011b) are a direct result of the overfitness of the channels. Both channels could therefore be assumed to be overfit prior to the avulsion, as essentially all channels except tributary-occupied river paleochannels are in this state (Phillips, 2011b).

For the San Antonio (reduced flow) channel, the response model suggests an acceleration of narrowing-dominated aggradation in response to the reduced discharge. This is indeed the case, as channel insets and depositional benches are common, and channel width (26 to 39 ft; 8 to 12 m) is much lower than for the river upstream of the flow split (> 100 fit or 30 m).

For Elm Bayou, the model indicates initial widening (due to relatively low shear strength of the unconsolidated fine-grained deltaic sediments). While this was not observed directly, and pre-avulsion data for the bayou is not available, the contemporary widths greater than that of the San Antonio channel downstream of the split suggest that this widening probably occurred. Because of the high sediment loads, the channel is currently in an overfit state of narrowing-dominated aggradation along most of its length.

An additional perturbation near this site is the formation of a large log jam beginning in the mid 1990s. The jam has been wholly or partly removed on several occasions, but has reformed, and was about 3 km long in 2011. The large volume of channel occupied by the woody debris has locally elevated water levels—during field observations in 2010 and 2011, water levels were near the bank tops in the vicinity of the log jam when flows elsewhere in the lower San Antonio River were well below bank top level. This local water surface elevation creates a local increase in slope gradient, and thus an increase in shear stress. The response model predicts channel widening in this case, and pronounced widening indeed occurs in the San Antonio River and Elm Bayou in association with the log jam (Phillips, 2011b).

Guadalupe River

The lower, alluvial Guadalupe River has several low-head run-of-river dams that do not influence the quantity of flow, but do locally influence water surface slopes and sediment supply. Upstream of the dam, velocity and slope are decreased, depth is increased, and discharge and sediment supply are unchanged. Changes in shear stress depend on the relative change in depth and slope, which is unknown. However, in this case, if any basal scour due to increased shear stress occurs, the sediment would be mainly retained behind the dam, with minimal morphological impacts. Sediment transport capacity must be reduced (constant Q and decrease in S). Assuming critical shear stress less than or equal to the critical value, the response model predicts channel infilling, no matter what the initial pre-dam fitness state was.

Downstream, an increase of slope and a reduction in sediment supply occurs, with no change in discharge. This points to channel enlargement, whatever the pre-dam condition, since the unconsolidated coastal plain channel material is likely to have its shear strength exceeded by some flows. At low-head dams on the alluvial portion of the Guadalupe River in Seguin and Gonzales, TX, channel enlargement is observed. However, at the Seguin site the response was apparently predominantly incision (based on field indicators), while at Gonzales pronounced but highly localized (about 660 ft or 200 m downstream of the dam) widening occurs (Figure 12).

Figure 12. Widening below a run-of-river dam on the Guadalupe River at Gonzales. The channel upstream of the dam (top of photo) is 66 to 90 ft (20 to 27 m) wide, while the widened area downstream is up to 312 ft (95 m) wide.

Chapter 5
Synthesis and Summary

MODELS OF CHANNEL CHANGE

Ten different types of models of alluvial channel response to changes in discharge were reviewed in chapter 2. These actually represent a far greater number of specific models, as some, such as hydraulic geometry or regime theory approaches, have dozens of individual models, techniques, or algorithms for implementation in various contexts. An additional approach was developed in this study, involving two more models: flow-channel fitness and a state-and-transition model. Table 16 summarizes the predictions of these classes of model for increases and decreases in discharge.

Two types of model can be broadly categorized as successional—the channel evolution and Schumm models. Analogous to concepts of vegetation succession, they anticipate (particularly in the case of CEMs) a specific progression of change. These are based on extensive empirical observations, and are intended to represent tendencies rather than rules or laws.

The hydraulic geometry (and regime theory), Lane relationship, and grade-based models are based on steady-state equilibrium concepts--that is, the notion that fluvial systems react to change so as to seek or maintain an approximate balance between, e.g., sediment supply and transport capacity, or channel size and bankfull flows. Steady-state is a useful reference condition, and models based on these concepts can be successfully used to predict channel responses in some circumstances. However, both Texas rivers and alluvial rivers in general are not often characterized by steady-state equilibrium, even without human modifications (Phillips, 2007b; 2010).

The Brandt, transport capacity, river evolution diagram, and bed mobility type models are based on thresholds. That is, the magnitude of change (or indeed, whether qualitative changes in channel state occur at all) depends on transgression of critical thresholds of sediment supply vs. sediment transport capacity, and of boundary force or stress vs. resistance. This type of model is most appropriate for predicting channel responses to changes in flow, and the fitness and STM models are therefore threshold-based.

In comparing the model predictions in table 16, none of the approaches are contradictory. In some cases, of course, the methods deal with different variables or types of outcome and are thus not directly comparable. However, in no case are the predictions inconsistent with each other, and where any two models overlap in terms of their predicted responses to discharge change, they give the same qualitative outcome. Thus, while threshold-based models are preferable in the first instance, all the described approaches remain potentially useful items in the toolbox for predicting fluvial responses.

Table 16. General predictions of various models of responses to changes in discharge (Q).

Model type	*Increased Q*	*Decreased Q*
Hydraulic geometry; regime theory	Increased w, d, S	Decreased w, d, S
Lane relationship	Potential increase in sediment transport & size, but depends on changes in sediment supply & slope	Potential decrease in sediment transport & size, but depends on changes in sediment supply & slope
Brandt model	Depends on sediment transport capacity vs. supply	Depends on sediment transport capacity vs. supply
Grade (general)	Decreased slope &/or increased sediment load	Increased slope &/or decreased sediment load
Grade (Eaton-Church model)	Sediment transport efficiency declines as d, S increase, but also depends on changes in D	Sediment transport efficiency increases as d, S decrease, but also depends on changes in D
Bed mobility	Bed mobility increases as d, S increases, but also depends on changes in D	Bed mobility decreases as d, S decrease, but also depends on changes in D
Schumm model	Possible incision, nickpoint formation, bank erosion, meander growth, migration & cutoffs, island/bar formation, avulsions, planform transitions, but also depends on changes in sediment load and S	Possible aggradation, channel infill, planform transitions, but also depends on changes in sediment load and S
Transport capacity	Depends on stream power & velocity relative to sediment supply & boundary resistance	Depends on stream power & velocity relative to sediment supply & boundary resistance
River evolution diagram (RED)	Depends on unit stream power (=VS) & (non)exceedence of flux boundary conditions; if VS increases then upward movement on RED	Depends on unit stream power (=VS) & (non)exceedence of flux boundary conditions; if VS decreases then downward movement on RED
Channel evolution models	Varies, but usually involves initial stages of channel enlargement followed by later infilling	Varies, but usually channel infilling
Flow-channel fitness	Depends on Q relative to channel capacity, shear stress ($\propto dS$) relative to boundary resistance, and stream power ($\propto QS$) relative to sediment supply	Depends on Q relative to channel capacity, shear stress ($\propto dS$) relative to boundary resistance, and stream power ($\propto QS$) relative to sediment supply
Continued	*on following page*	

Model type	*Increased Q*	*Decreased Q*
State-and-Transition Model	Depends on initial state, and relative change in Q, S, and sediment supply	Depends on initial state, and relative change in Q, S, and sediment supply

CONCLUDING REMARKS

Rivers in general, and alluvial rivers in particular, are dynamic. They are variable and subject to change over essentially all time scales, and cannot be expected to remain static, or even to fluctuate around any specific state or condition indefinitely. Also, there are no channel morphological responses to human changes in flow regimes that cannot and do not occur due to natural or nonhuman forcings.

In addition to direct (whether deliberate or inadvertent) human modifications to stream flows, discharges are modified by weather and climate changes (both natural and human-influenced), and by the development and evolution of vegetation and other biota, landforms and topography, and soils. Such changes and fluctuations might amplify or filter channel reactions to flow changes due to human activity. A drought, for example, might exacerbate the effects of human water withdrawals from a river system, or offset the impacts of increased water inputs.

It should be clear from this report that at least three other factors need to be considered in addition to changes in flow or discharge. Slope gradients must be considered because energy grade slope, in conjunction with discharge, velocity, or depth, determines cross-sectional and unit stream power, and shear stress. Second, potential changes in sediment supply or availability must be considered due to the importance of sediment transport capacity/supply thresholds. Finally, the resistance of channel boundaries relative to the shear stress of flows must be considered.

The STM approach developed here is highly generalized, but should be adaptable to more specific concerns or channel states for particular river systems. Just as STMs for rangeland vegetation communities have been developed for specific soil and ecological types, fluvial STMs geared to specific rivers, ecoregions, or river management issues can be developed by first identifying the potential channel states of interest, and then the key thresholds separating them and triggering potential transitions.

ACKNOWLEDGEMENTS

Former TWDB hydrologist Greg Malstaff was instrumental in conceptualizing and initiating this project. Chris Van Dyke and James Jahnz of the University of Kentucky provided valuable assistance in literature review, analysis, and development and testing of key ideas. Mark Wentzel and TWDB staff made insightful comments and corrections on an earlier draft.

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Appendix A: Scope of Work

EXHIBIT A
SCOPE OF WORK

This research study will provide a conceptual model to predict the semi-quantitative geomorphic response of alluvial rivers in Texas to changes due to disturbances in and changes to the water and sediment flow regimes of the rivers. The conceptual model developed for this project will be based on a combination of theoretical concepts and empirical data from observations of the effects of floods, water withdrawals-additions, and wet-dry climate cycles. Observations from the San Antonio, Brazos, Sabine, and other Texas rivers will be used to ensure the conceptual model is representative of conditions of interest to the TIFP.

The approach will be based on the concept of transport- vs. supply-limited fluvial systems, the relationship between sediment supply or availability and transport capacity as measured by stream power, and on critical thresholds for bed and bank erosion. Modes of adjustment (system states) will be based initially on various combinations of increases, decreases, and no change in channel slope, planform, roughness/resistance, width, and depth. Additional modes may be identified during the study. Transitions will be identified based on empirical observations, published literature, and geomorphic theory, analogous as a first approximation to the qualitative model developed by Brandt (2000a; 2000b), and modified for use on the lower Trinity River by Phillips et al. (2005). The fluvial response State Transition Model (STM) will be conceptually similar to the STMs frequently used in rangeland ecology and management to predict vegetation community responses to, e.g., grazing systems, fire, and brush management (c.f. Briske et al., 2005). The STM will be applied to case studies on alluvial rivers in Texas as described in objective (3). From these, several sites will be selected as baseline sites. Specific quantitative data on responses at these sites will be used to develop formulae for semi- quantitative predictions at other sites via the method of relative response (see, e.g., Phillips, 1987; 2004).

Task 1 Literature Review
Task 2 Analysis of case study data
Task 3 Development of geomorphic response (state transition) model
Task 4 Refinement and testing of geomorphic response model
Task 5 Production and Delivery of the Decision Model
Task 6 Produce and delivery Final Report

Appendix B: Staff Comments on Draft Final Report and Responses

Geomorphic Responses to Changes in Flow Regimes in Texas Rivers
Draft-final report to the Texas Water Development Board

Contract number 1104831147

REQUIRED CHANGES

General Draft Final Report Comments:

1. Please correct the following typos (correction in bold font):
    a. Page 6, 3rd paragraph, "Council on Environmental Quality" should be "**Commission** on Environmental Quality."
    b. Page 10, 4th paragraph, "functions of discharge" should be "functions of discharge **(Q)**."
    c. Page 11, 3rd paragraph, "Correlations between Q" should be "Correlations between **discharge**."
    d. Page 11, 3rd paragraph, "complicated, and flexible that" should be "complicated, and flexible **than**."
    e. Page 11, 5th paragraph, "discharge (Q) and slope" should be "discharge (Q) and slope **(S)**."
    f. Page 14, 3rd paragraph, "bed load transport increase exponentially" should be "bed load transport **increases** exponentially."
    g. Page 16, 2nd paragraph, "If this is not case" should be "If this is not **the** case."
    h. Page 34, 3rd paragraph, "Catolon, Johnson Reach and Boquillas Reaches" should be "Catolon, Johnson **Ranch** and Boquillas Reaches."
    i. Page 34, 3rd paragraph, "at Johnson Reach, the active channel shrank" should be "at Johnson **Ranch**, the active channel shrank."
    j. Page 34, 3rd paragraph, "positioned above of the channel banks" should be "positioned above the channel banks."
    k. Page 35, 1st paragraph, "also found evidence increased" should be "also found evidence **of** increased."
    l. Page 35, 2nd paragraph, "the man annual flood" should be "the **mean** annual flood."
    m. Page 35, 5th paragraph, "historical aerial photographics" should be "historical aerial **photographs**."
    n. Page 36, 4th paragraph, "consistent low flows, but increases in higher flows" should be "consistent low flows, but **decreases** in higher flows."
    o. Page 37, 3rd paragraph, "median Q" should be "median **discharge.**" Note, there are two occurrences of this typo in this paragraph (both should be corrected).
    p. Page 40, 4th paragraph, "processes such bioturbation" should be "processes such **as** bioturbation."

q. Page 41, 1st paragraph, “corresponds with a wetter-to-drier precipitation regime” should be “corresponds with **a change from** a wetter-to-drier precipitation regime.”

r. Page 47, 2nd paragraph, “equations show V to be a function of hyraulic radius” should be “equations show **velocity** to be a function of **hydraulic** radius.”

s. Page 47, Equation 20, “$V =(8\ g\ R\ S/f)^{05}$” should be “$V =(8\ g\ R\ S/f)^{1/2}$."

t. Page 47, 4th paragraph, “no change is channel size” should be “no change **in** channel size.”

u. Page 48, 1st paragraph, “overfit but adjustement toward fitness” should be “overfit but **adjusting** toward fitness.”

v. Page 58, 1st paragraph, “water input volume, is analogous” should be “water input volume **and** is analogous.”

w. Page 59, 3rd paragraph, “Standard flow resistance equations relate velocity to S, hydraulic radius ($R = A/$wetted perimeter), and roughness or friction factor f” should be “Standard flow resistance equations relate velocity to **slope (S)**, hydraulic radius (R), and roughness or friction factor **(f)**.”

x. Page 59, Equation 29, “$(8g\ R_a\ S_a/f_a)^{0.5}\ \ S_a = (8g\ R_b\ S_b/f_b)^{0.5}\ \ S_b$,” should be “$(8g\ R_a\ S_a/f_a)^{0.5}\ \ S_a = (8g\ R_b\ S_b/f_b)^{0.5}\ \ S_b$” (Comma after equation is inconsistent with format in rest of document).

y. Page 63, 1st paragraph, “Upstream of the dam velocity” should be “Upstream of the dam**,** velocity.”

z. Page 63, 2nd paragraph, “the reponse was apparently” should be “the **response** was apparently.”

2. Please adopt a consistent format to refer to figures, tables and chapters throughout the document. In some portions of the text, these references are not capitalized (for example, “figure 1” on page 6, 5th paragraph; “table 4” on page 25, 6th paragraph; “chapter 2” on page 65, 1st paragraph). In other portions, they are capitalized (for example, “Figure 2” on page 7, 1st paragraph; “Table 1” on page 12, 3rd paragraph; “Chapter 4” on page 26, 1st paragraph).
3. For clarity, please insure consistency between the terms used to designate the fitness states described on pages 23 through 25 and those used in Figure 8 on page 26, Table 4 on page 27, and Table 13 on page 54. The following changes to Figure 8 are suggested:
   a. “_Increasing underfit_” should be changed to “_Increasing underfit_***ness***.”
   b. “_Adjustment toward fitness_” should be “***Overfit*** _adjust_***ing*** _toward fitness_.”
   c. “_Persisting underfit_” should be “_Persisting underfit_***ness***.”
   d. “_Adjustment toward fitness_” should be “***Underfit*** _adjust_***ing*** _toward fitness_.”
   e. “_Persisting overfit_” should be “_Persisting overfit_***ness***.”
   f. “_Increasing overfit_” should be “_Increasing overfit_***ness***.”

   The following changes to Tables 4 and 13 are suggested:

   g. On line 3.B, “_adjustment toward fitness_” should be “***underfit*** _adjust_***ing*** _toward fitness_.”

   h. On line 6.B, "*decreasing overfitness-increasing underfitness*" should be "***overfit adjusting toward fitness***."

4. In order to accommodate the widest audience for the report, please provide values in English as well as SI units. In Table 6 on page 31, please provide values of sediment diameter in units of inches. In Table 7 on page 32, please provide values for shear stress and velocity in units of pounds per square foot and feet per second, respectively. English units for values in these tables are available from Fischenich (2001). Throughout the document, please provide observations in both English and SI units. For example, on page 33, second paragraph, "water depths between 1.5 and 7.6 m" should be "water depths between 5 and 25 feet (1.5 and 7.6 meters)" and "flows at Girvin averaged 18.5 m^3sec^{-1}" should be "flows at Girvin averaged 650 cubic feet per second (18.5 cubic meters per second)."
5. The meaning of the last sentence of the 3rd paragraph on page 42 is not clear. Please reword to clarify. Perhaps the following would be suitable (additions in bold): "On the Baraboo River, depth increased within and upstream of the former pool, except during passage of a large slug of passing **sediment** evacuated after **dam** removal."
6. On page 46, 3rd paragraph, the following statement is made: "Aggradation due to excess sediment will not occur." Later in this paragraph, the following statement is made: "Otherwise, aggradation is possible." These comments seem contradictory. Please reword to clarify the intended meaning.
7. To the maximum extent possible, please make the terminology used in Figure 9 (page 53) and Table 14 (page 55) consistent with the terminology used in Figure 8 (page 26) and Table 4 (page 27). Within Figure 9 and Table 14, or in the text related to Step 5 on page 52, please clarify explicitly how the seven channel states described on pages 23 through 25 correspond to Figure 9 and Table 14. The following changes to Figure 9 and Table 14 are suggested:
   a. "Persisting overfit" should be "Persisting overfit**ness**."
   b. "Persisting underfit" should be "Persisting underfit**ness**."
   c. "Steady-state" should be "**Persisting fitness**."

   It would seem that the channel states "overfit adjusting toward fitness" and "increasing overfitness" could each correspond to either of the conditions "Aggradation/Shallowing dominated" or "Aggradation/Narrowing dominated." Similarly, "underfit adjusting toward fitness" and "increasing underfitness" could each correspond to either of the conditions "Degradation/Deeping dominated" or "Degradation/Widening dominated." Please confirm or correct these inferences in the text.

8. On page 59, in the last paragraph, the pre-dam state of the Trinity River upstream of Lake Livingston is described as likely being "narrowing-dominated aggradation." It is unclear how this relates to the seven states described on pages 23 through 25. Would this be the equivalent of "underfit adjusting toward fitness" or some other channel state? Please revise the text to clarify.

SUGGESTED CHANGES

9. In order to make the document easier to read for a more general audience, please consider adding a list of acronyms and symbols. Entries such as "DHG – downstream hydraulic geometry" and "Ω - stream power" would be very helpful.
10. The content of the 3rd paragraph on page 17 is a bit confusing. To clarify the nomenclature of the two levels of fluvial change, please consider rewording. Something like the following may suffice (changes shown with strikethrough and bold font): "The river evolution perspective developed by Brierley and Fryirs (2005) is based on two levels of fluvial change**: adjustment and metamorphosis**. Adjustment, characterized by the 'natural capacity for adjustment,' relates to changes that do not result in a new set of process-form relationships or metamorphosis into a new river style. **Metamorphosis relates to a** ~~The latter,~~ broader scale of changes ~~is~~ constrained by boundary conditions that define an outer band of variability."
11. For ease of reading, when tables require more than one page (for example, Table 5 on pages 29 and 30), please consider repeating column headings on the following page or pages. Also, there are two different fonts (Times and Cambria) used in Table 6 on page 31. Consider using only the Times font in this table.
12. For the benefit of the general reader, please consider providing definitions of the acronyms "cal. ka," "ka," and "BP" used in the section of the report entitled "Texas Studies – Climate and Sea-level Change" (pages 40-42).
13. For purposes of clarity, it would be preferable to adopt one method to indicate conditions before and after a flow change. On page 46, the subscript *o* is used to indicate pre-flow-change conditions and (by inference) post-flow-change conditions are implied when no subscript is used (for example Ω_o and Ω). On page 59, the subscript *b* is used to indicate before change conditions while the subscript *a* is used to indicate after change conditions (for example R_b and R_a). Either of these methods is acceptable, but to avoid confusion, please consider using only one of these methods throughout the document.
14. Giardino and Lee (2011) have recently completed a study of rates of channel migration on the Brazos River, including analysis of pre- and post-reservoir characteristics. Please consider adding a description of their work to Chapter 3, Case Studies of Channel Response. An electronic version of Giardino and Lee (2011) can be downloaded from the following link: http://www.twdb.state.tx.us/RWPG/rpgm_rpts/0904830898_Brazos.pdf.
15. Ockerman and Heitmuller (2010) studied suspended sediment concentrations in the lower Nueces River. Please consider adding a description of their work to Chapter 3, Case Studies of Channel Response. An electronic version of Ockerman and Heitmuller (2010) can be downloaded from the following link: http://pubs.usgs.gov/sir/2010/5194/.

AUTHOR RESPONSES

•All required changes have been made (items 1-8 above) by editorial changes and corrections.

•The table of variables and acroynms (suggested change 9) was not added, but in editorial revisions care was taken to make sure that all variables and acroynms are consistently and fully defined, and that standard usages, symbols, and terminology are employed.

•Suggested changes 10-13 were made as suggested.

•The additional references (items 14-15) have been added to chapter 3.