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GEOMORPHIC RESPONSES TO CHANGES IN INSTREAM FLOWS: THE FLOW-CHANNEL FITNESS MODEL

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ABSTRACT

The flow-channel fitness model is a conceptual and practical model for predicting the qualitative response of alluvial channels to modifications of flow regimes. 'Fitness' refers to the size of channels compared with the flows they convey, with the terminology derived from traditional geomorphic concepts of overfit and underfit streams. The qualitative predictions refer to whether channels experience aggradation, degradation or relative stability, and whether aggradation or degradation is dominated by width or depth. The model is based on transitions among seven possible fitness states, triggered by key thresholds of sediment supply versus transport capacity and shear stress versus shear strength, and requires that potential changes in sediment supply and water surface or energy-grade slope also be accounted for. The fitness approach can be used where only relative values and changes are known, as is illustrated in three example applications from Texas. The flow-channel fitness model synthesizes key elements from several existing approaches to predicting geomorphic responses to changes in flow and is intended to augment rather than replace quantitative approaches, providing a predictive tool where the data requirements and assumptions for quantitative models cannot be fully met. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: flow-channel fitness; alluvial channels; geomorphic response; channel change; instream flows

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INTRODUCTION

Several geomorphic and engineering models and methods exist, which allow predictions of various aspects of channel responses to changes in flow regimes. Quantitative, deterministic prediction requires numerous locally detailed measurements (or a commensurate number of estimates and assumptions) that are problematic for general application at broad spatial scales. Further, as the results are inevitably (and appropriately) specific to details of a given reach or cross section, generalization is difficult. Thus, there is a need for approaches in assessing geomorphic responses to changes in flow regimes that are more broadly applicable. This article will synthesize several quantitative, qualitative/conceptual and hybrid models for channel responses and propose a new approach—intended to be both heuristic and practical—based on the concept of channel fitness. Fitness refers to the relationship between the size of channels and the flows they convey: underfit channels are 'too big', and overfit channels are 'too small'. This will be more explicitly defined in the next section.

The study focus is on alluvial rivers in the broadest sense of the term—that is, streams that are not strongly controlled by bedrock along most 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 are 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.

This work was undertaken in the context of the Texas Instream Flow Program (for a full project report, see Phillips, 2012a). Instream flow programs are intended to balance human and nonhuman uses of water, the latter usually summarized in terms of ecosystem requirements. Instream flow programs are typically instituted to assess surface water withdrawals and flow modifications with respect to flow regimes required to maintain aquatic habitats. The Texas Instream Flow Program has its roots in legislation, establishing a state water planning process to consider environmental values in water development and allocation (a work plan and technical overview developed by the agencies involved 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).

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The project report (Phillips, 2012a) includes a discussion of the fluvial context of Texas,and several case studies of geomorphic responses to changes in flow regimes within the state. This article will focus on the methodological aspects of the study, which are not Texas specific and are potentially applicable to any alluvial stream.

CHANNEL RESPONSE TO CHANGING FLOW REGIMES

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

Using dams and reservoirs as an example, the effects on flow can be quite variable depending on their size relative to the fluvial system, the environmental setting, and the purpose and operation of the dam. The degree of influence decreases downstream from the dam at varying rates, but influences immediately downstream may range from minor to overwhelming. In general, flood control reservoirs 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 effects on flow regimes if the lake has no flood control function. Many impoundments, regardless of function, have the effect of increasing low flows (i.e. elevating discharges during dry periods), as dam releases often provide a minimum flow.

Dams and reservoirs may also be very efficient sediment traps, sometimes approaching 100%. 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 called *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 effects on flow (as opposed to indirect effects by changing hydrological responses due to land use and management) include surface water withdrawals and ground water use. Humans may also locally increase flows due to, for example, discharges of treated wastewater and artificial drainage features. Interbasin water transfers may decrease flow in one watershed while increasing it in another.

Several conceptual frameworks used to assess or predict channel responses to changes in flow, sediment supply and slope are reviewed in the following sections.

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, although 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.

Although 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). Griffiths (2003) and Savenjie (2003) give physically based theoretical justifications for the power function form.

At-a-station hydraulic geometry has been 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; Dodov and Foufoula-Georgiou, 2004; Fonstad and Marcus, 2010). It is therefore not surprising that similarly complex mutual adjustments occur in the spatial domain.

Despite approximately 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; 2003b; Dodov and Foufoula-Georgiou, 2004; Eaton *et al*., 2004; Eaton and Church, 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; Alfzalimehr *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).

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Correlations between discharge and dependent variables are reasonably high in most data sets, and remarkable consistency exists, given the observed variety in fluvial systems. Yet, even within self-formed alluvial channels of humid perennial streams, several 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

$$Q_{\text{sed}} D \propto Q \; S \tag{1}$$

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 $\approx$, 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 the right sides of the relation—a defensible reference condition, but not a viable assumption about the way fluvial systems actually work (cf. 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 (2000a) devised a qualitative conceptual model based on the 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. It does not assume steady-state equilibrium, only that adjustments occur between transport capacity on one hand and sediment supply on the other. The Brandt model is shown in Table 1; a more complex but conceptually similar model by the same author (Brandt, 2000b) is discussed in the Transport Capacity section.

Grade

The concept of grade (an approximate balance between sediment supply and transport capacity) underlies or relates to several of the approaches described here. Here, a specific quantitative/analytical approach is described. Eaton and Church (2011) used dimensionless stream power to develop a sediment transport scaling relationship based on the concept of grade. Their model provides a useful tool for

Table I. Conceptual model of Brandt (2000a) showing possible cross-sectional changes in response to changes in discharge (Q) and sediment load (‘load’) relative to transport capacity (TC)

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

A, cross-sectional area.
[a]Degradation may not occur if reduced discharges insufficient to erode channel boundary.

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predicting channel responses to flow changes, as long as the graded condition is recognized as a reference state rather than a normative condition for channels.

They derived

$$Q_b/QS \propto [(d\ \ S)/(D_b\ \ \theta_c)]^{-1.5x} \quad (2)$$

The term on the left is bed load transport (Q_b) relative to stream power (a function of the product of discharge Q and slope S), D_b is the characteristic grain size and θ_c is the critical Shields Number, typically 0.047 for mixed sediment sizes. 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 (2) is applicable at the reach scale; for application at the cross-sectional scale, a roughness term is 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) interpreted D_b as representing the potential for the degree of surface armoring to adjust, whereas θ_c reflects surface structure effects on entrainment. If the latter are considered given properties of a reach, then Equation (2) shows that sediment transport efficiency (as opposed to total transport magnitude) declines as flow depth and slope increase.

Bed mobility

A key issue in assessing channel responses to increases or decreases in flows is the transport of material comprising the channel bed. Many bed stability and bed load sediment transport relations have been developed, and a familiar approach based on the Shields number is described later. Here, the framework of Gao (2011) is used:

$$i_b/\omega = (1 - \theta_c/\theta)^{\alpha} \quad (3)$$

The variables are as follows: 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 ($kg\,m^{-1}\,s^{-1}$) = $\tau\ V$; θ = dimensionless shear stress; θ_c = critical value for initiation of motion; and τ = mean bed shear stress ($kg\,m^{-2}$) = $\rho\ g\ d\ S$. The exponent α is determined empirically but is >1, and ρ (water density $1000\,kg\,m^{-3}$) and g (gravitational acceleration, $9.8\,m\,s^{-2}$) are treated as constants.

Equation (3) 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, Equation (3) 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

$$\theta = \rho\ \ d\ \ S(\rho_s - \rho)D_{50} \quad (4)$$

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

$$\tau_c = \theta_{cr}(\rho_s - \rho)D \quad (5)$$

where θ_{cr} is typically around 0.03 to 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

$$\theta_t/\theta_{t+1} = (d_t\ \ S_t)/(d_{t+1}\ \ S_{t+1}) \quad (6)$$

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)

$$P^{-1},\ w/d \propto Q,\ Q_{sed} \quad (7)$$

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

$$(w/d)^{-1},\ P \propto Mp,\ \tau_{cw}/\tau_{cb} \quad (8)$$

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 the 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

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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; Schumm, 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.

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, several 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 after a change in the sediment supply versus 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. Brandt (2000b) reviewed several calculation and estimation techniques for the various steps and stages in the model. This model illustrates the complexity, the numerous degrees of freedom and the large number of feedback relationships inherent in the problem of determining channel responses to changes in water and sediment inputs.

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

Table II. Channel responses to imposed changes, adapted from Schumm, 2005, Table 3.1

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

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

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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 1). Brierley and Fryirs (2005) used stream power as the primary determinant of adjustments and to define thresholds or flux boundary conditions. Besides total cross-sectional stream power (Ω), they also make use of stream power per unit area (specific stream power; ω):

$$\Omega = \gamma \ Q \ S = \gamma w \ d \ V \ S \quad (9)$$

$$\omega = \Omega / w = \gamma w \ d \ V \ S \quad (10)$$

Brierley and Fryirs (2005) used 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:

$$\psi = (\rho \ g \ Q \ S)/(r \ g \ A_{cx}) = V \ S \quad (11)$$

where A_{cx} is the cross-sectional area.

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.

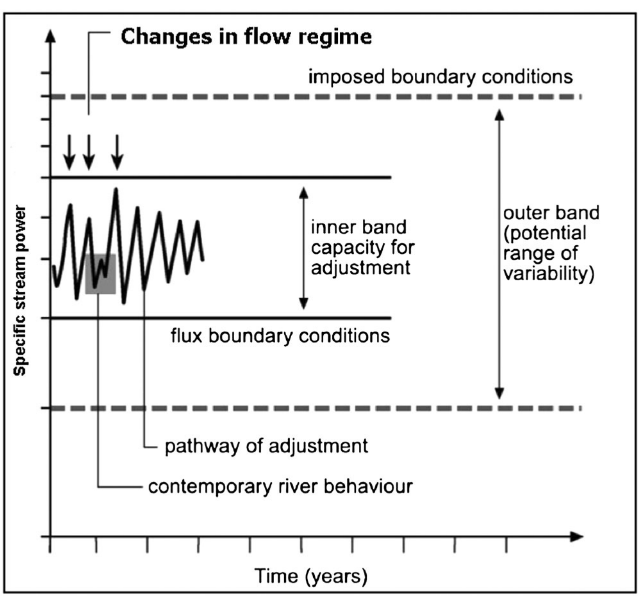

Figure 1. River evolution diagram. Adjustment occurs within the inner band; metamorphosis within the outer bands. Modified slightly from Brierley and Fryirs (2005, Figure 5.2)

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 4, bank failure and channel aggradation begin infilling the incised channel, and in the final phase vegetation becomes established, and a new channel resembling the preincision channel is formed in the alluvium within the incised channel.

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 several 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 the development of a CEM by Doyle *et al*. (2002) for channel responses after dam removal. Beechie *et al*. (2008) examined channel incision and recovery in the northwestern United States and found that two CEMs 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 after 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 previous discussion suggests that existing CEMs cannot be uncritically applied to new situations, and the use of this approach may require development of a model specifically for the problem(s) at hand. Although many CEMs are based on a single successional sequence, examples do exist of CEMs that describe and allow for more complex behavior. The development of large arroyos in the southwestern United States was described using a single-path CEM by Elliott *et al*. (1999). Smaller arroyos, however, were modeled using a CEM that, after an initial sequence of incision, widening and floodplain development, might follow several different pathways. Similarly, the study of Makaske *et al*. (2002) 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

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outcomes in a published CEM results from Leyland and Darby's (2008) study of gully evolution. Both incising and infilling/recovering sequences are possible, with switches between them and multiple possibilities at several stages in each (Figure 2).

SYNTHESIS

The key points of the approaches described earlier are summarized in Table 3, with respect to the key variables or factors considered and the underlying conceptual or theoretical basis.

All of the conceptual models reviewed here have a sound basis in fluvial geomorphology principles and proven utility for certain applications. Why, then, is there any need for a new framework? In the aggregate, these models provide adequate tools and theory for a river scientist with appropriate expertise and access to necessary data to deal with issues of predicting or interpreting channel responses to changes in imposed flow. However, none of the approaches by itself meet the criteria of broad applicability, potential implementation with minimal data and freedom from restrictive assumptions.

The grade and bed mobility approaches are applicable to the specific aspects of channel response but do not directly address the potential changes in channel dimensions often of interest to river managers and stakeholders and are not broadly applicable in that sense. CEMs may be tied to specific types of disturbance rather than general changes in flow regime and, as argued earlier, may not be applicable outside the domain of observations from which they were developed. The Schumm model is broadly appropriate in the sense of geographical and situational applicability but is not intended for anything other than description and interpretation of general tendencies.

In terms of data requirements, the river evolution model is tied to an assessment approach that requires a great deal of location-specific information and geomorphic expertise. The grade, bed mobility and stream power models require a large number of specific, local measurements and are

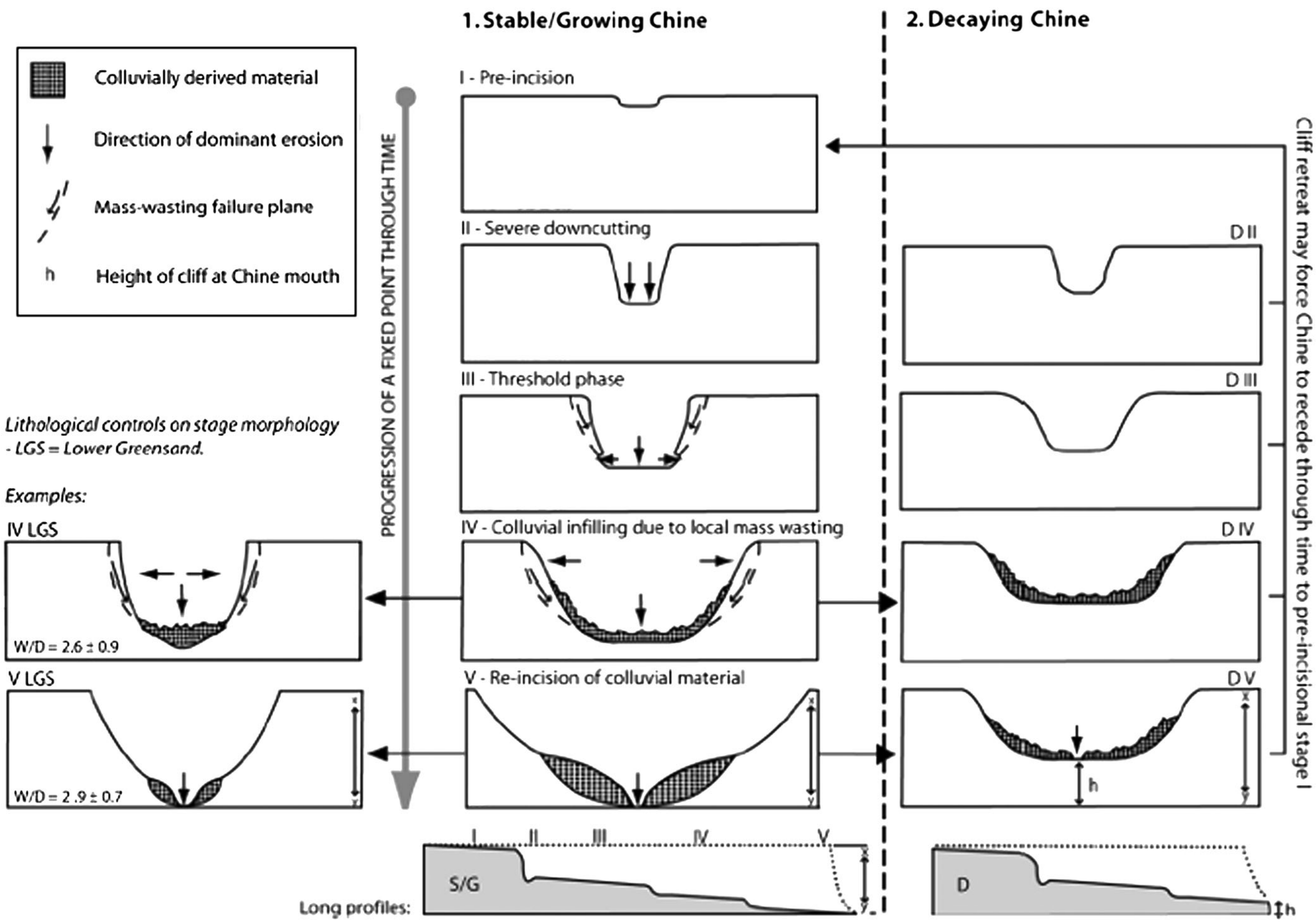

Figure 2. CEM for incised coastal channels on the Isle of Wight (modified slightly from Leyland and Darby, 2008, Figure 5). 'Chines' are a local name for the incised gullies

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Table III. 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 and S adjust to imposed discharges
Lane relationship	Q, Q_{sed}, D and S	Mutual adjustments between sediment transport capacity ($=f[Q,S]$) and supply (Q_{sed}, D)
Qualitative Brandt model	Q, Q_{sed} relative to transport capacity	Channel w and d adjust to imposed Q and sediment supply–transport capacity relationship
Grade[a]	d, S, D	Mutual adjustments between sediment transport capacity and 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 and Q_{sed}	Channel cross section and planform a function of Q, Q_{sed}
Stream power model[b]	Q, S, Q_{sed} and V	Mutual adjustments between sediment transport capacity ($=f[Q,S]$) and 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 after change or disturbance

[a]Specifics based on the Eaton and Church (2011) model.
[b]Specifics based on Brandt (2000b).

thus difficult to apply at a large number of sites or with limited data resources. If a proven CEM is not already available for a given area and situation, the observations necessary to construct one may be difficult (and time consuming) to come by. The hydraulic geometry/regime theory and the Lane relationship approaches can be applied at a general, qualitative level with minimal data, but quantitative site-specific predictions that obviate some of the conceptual shortcomings discussed earlier have extensive data requirements.

There is nothing inherent in the hydraulic geometry, Lane relationship, grade or CEM approaches that require an assumption of steady-state equilibrium as a normative condition. However, many applications of these approaches are implicitly or explicitly based on such assumptions. The first three are also implicitly based on continuum assumptions that often do not hold. Conceptual models of alluvial channels are also often based on an implicit or explicit assumption that channels are fully adjustable; that is, both width and depth may be modified in response to externally imposed changes. Because of the limitations of base level, resistant layers or materials, erosion thresholds and bank stability considerations, this is often not the case. Thus, theadjustments predicted by hydraulic geometry/regime theory or the Brandt model may not be possible in some systems.

The flow-channel fitness (FCF) model described in the next section can make use of extensive, detailed data; although where this is available, the FCF should perhaps be combined or supplemented with one of the existing approaches. However, it can be also implemented with minimal data, in a way broadly applicable to alluvial channels, and without restrictive assumptions of steady-state or full channel adjustment. FCF is in some senses a simplification and generalization of the stream power model described earlier, which is an expansion of the simple Brandt model itself, with some differences in detail (such as use of shear stress in the FCF rather than stream power to assess boundary erodibility). FCF is also compatible with the CEM approach in the sense that it can be used to develop problem-specific CEMs, but without the assumption of a monotonic successional trend (e.g. see Phillips, 2012a).

FLOW-CHANNEL FITNESS

Hydraulic geometry and regime theory and the qualitative Brandt model are at their core based on the notions of channel adjustment to imposed flows. The Lane relationship, grade, bed mobility, stream power and river evolution approaches all consider key thresholds of stream power and bed/bank mobility. The Schumm and CEMs predict qualitative system states. The FCF model combines these elements but makes no assumptions of steady-state or equilibrium tendencies.

Fitness refers to the extent of the 'fit' between a given discharge and channel capacity. The terminology derives from traditional geomorphic concepts. The idea of underfit streams, referring to valleys that are much too large to have been created by the streams currently occupying them, goes back at least to the study of Davis (1913) and is perhaps most closely linked to the work of Dury (1964, 1976).

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Overfit streams have channels or valleys that are insufficient to contain many normal flows and were also discussed by Davis (1913) and Dury (1964) and other fluvial geomorphologists (e.g. Smith, *et al*., 1997; Twidale, 2004). 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) most flows are contained within the channel banks and overbank flows do not occur significantly more often than similar undisturbed or semi-natural reference channels;
(2) stages and discharges are sufficient to maintain continuous downstream flow and inundation of the channel bed and aquatic habitats, to prevent significant prolonged or chronic vegetation encroachment on the channel bed and lower banks and to at least occasionally inundate the floodplain.

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.

Applying the concept to assess potential changes in response to changes in imposed flows results in a determination of one of seven fitness states, described as follows. Phillips (2012a) gives specific examples of Texas streams in each category.

(1) *Persisting fitness* represents an ongoing condition of fitness between the flows and the channel. Although active lateral migration and other changes may be common, there is no persistent change in cross-sectional area relative to the flow regime.
(2) *Increasing underfitness* is where the channel is underfit and becomes increasingly large relative to imposed flow. This was the case in some rivers draining to the Gulf of Mexico during periods of incision earlier in the Holocene, for example. 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).
(3) *Persisting underfitness* occurs where the channel is underfit, and there is no significant trend toward channel enlargement or contraction (Figure 3). The scour zones downstream of dams often fit this definition, where incision has cut to or near bedrock, and widening has ceased. However, because of sediment sequestration in the reservoirs, sediment supply is less than transport capacity, and channel infilling is minimal.

Figure 3. An example of an underfit stream, the incised Turkey Creek (Brazos County, Texas)

(4) *Underfit adjusting toward fitness* (channel is infilling and becoming less underfit).
(5) *Increasing overfitness* (channel continues infilling despite overfitness; Figure 4). A good example is the Navasota River, Texas (see Phillips, 2007a, 2009).
(6) *Persisting overfitness* is where the channel is overfit, and there is no significant trend toward channel enlargement or contraction.
(7) *Overfit adjusting toward fitness* (channel is enlarging and becoming less overfit).

The first stage of analysis is determining fitness based on the previously mentioned criteria, or more specific criteria associated with project goals (e.g. bankfull channel capacity

Figure 4. 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 as shown as well as frequent avulsions

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relative to the discharge with a 1-year recurrence interval). Then, the shear stress associated with the reference flow is compared with 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 with the critical power required to transport the available load. On the basis of these assessments, the channel fitness can be determined based on Figure 5 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, narrowing, incising or shallowing. These indicators are discussed later.

Resistance

The FCF approach requires some assessment of boundary resistance. Local (at a point or cross section) resistance relative to force can be approached based on measurements of boundary shear strength (e.g. using penetrometers, shear vanes, etc.) or particle sizes versus 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).

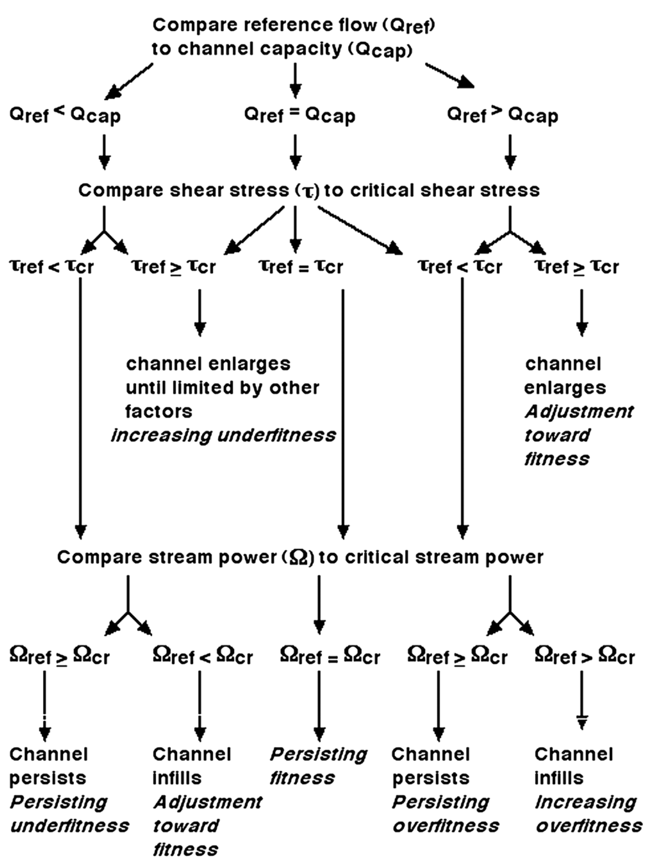

Figure 5. FCF evaluation flow chart

Table IV. Decision key for FCF evaluation

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 adjusting 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*

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

$$\tau* = (\rho \ g \ d \ S)/g(\rho_s - \rho)D \tag{12}$$

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

$$\tau* = (d \ S)/(1.65 \ D) \tag{13}$$

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,

$$\tau_{cr} = \tau*_{cr} g(\rho_s - \rho)D \tag{14}$$

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

$$\tau*_a/\tau*_b = (d_a/d_b)(S_a/S_b)(D_b/D_a) \tag{15}$$

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

Where site-specific measurements are not practical, guidelines for critical shear stresses and velocities have been developed by the US Army Corps of Engineers in the context of stream restoration (Fischenich, 2001). These

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may be used as general guidelines for rough estimates of key thresholds (Table 5). Note that sediments of mixed sizes behave differently than more uniform distributions. Particles larger than the median will generally be entrained at shear stresses less than those shown in Table 5, whereas particles smaller than the median may require shear stresses greater than those shown to initiate motion. Table 6 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 V. Critical shear stresses and shear velocities for various size classes of material (from Fischenich, 2001)

Size class	Diameter (upper limit, mm)	Diameter (in.)	Shear stress (N m^{-2})	Shear velocity (ft s^{-1})	Shear velocity (m s^{-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

Note that shear velocity is not the same as mean channel velocity, which is approximately 8× shear velocity.

Table VI. 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 (lb ft^{-2})	Permissible velocity (m s^{-1})	Permissible velocity (ft s^{-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

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RESPONSE TO CHANGES IN DISCHARGE

Decreasing discharge

If flow decreases and slope is unchanged or also decreases, then the 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 preflow-change conditions,

$$\Phi = Q_{sed}/(Q_{sed})_b \tag{16}$$

If $\Omega/\Omega_b < \Phi$, transport capacity has decreased by a greater proportion than sediment supply, and aggradation is expected. The smaller the ratio $(\Omega/\Omega_b)/\Phi$, the greater the expected aggradation. $\Omega/\Omega_b > \Phi$ 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 and overgrazing) often do involve significant increases in sediment. These cases will be treated separately.

Increased discharge with minimal change or decrease 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, although 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 hydraulic radius, energy-grade slope and flow resistance or channel roughness. The D'Arcy–Weisbach equation, for instance, is

$$V = (8\ g\ R\ S/f)^{1/2} \tag{17}$$

where f is a friction factor. If relative changes in R or d, S and f are known, velocity change can be predicted. If $V/V_b \geq Q/Q_b$, then the flow can be accommodated 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

If 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 $(\Omega/\Omega_b) < \Phi$, transport capacity has increased less than sediment supply, and aggradation is expected. $\Omega/\Omega_b > \Phi$ 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 possibility of overfitness and increased flooding under the same conditions as described previously (Table 7).

FITNESS MODEL APPLICATION

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

Step 1: determine current or prechange channel state

The seven possible channel states and their relationship to aggradation and degradation are shown in Table 7, which has nine entries because increasing underfitness or overfitness can occur either from the other state or from a state of fitness. 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,

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Table VII. Possible channel states, linked to fitness conditions described earlier.

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

The increasing, decreasing or no change trends (+, −, 0) for cross-sectional area (A_{cx}) and width–depth ratio (w/d) are shown.

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

	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

respectively (Table 8). 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 underfitness or overfitness (Table 9) should generally be absent. Aggradation may be dominated by decreasing width (narrowing) and/or depth (shallowing) and is reflected by the indicators shown in Tables 10 and 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 overfit or underfit conditions, but with little or no channel change (evidence of aggradation or degradation).

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.

Table IX. Indicators of channel overfitness or underfitness in alluvial rivers (absence indicates channel fitness)

Indicators of underfitness
Infrequent occurrence of flows near bank top stage[a]
Overbank flood recurrence interval >2 years[a]
Overbank flood recurrence interval >10 years[b]
Inset floodplains within incised channel[b]
Tops of point bar surfaces well below bank top elevation[b]
Slow or nonremoval of bank slope failure features[a]
Establishment of obligate upland vegetation below bank top elevation[a]
Absence of wetland vegetation above bank top elevation[a]
Indicators of overfitness
Frequent occurrence of flows at or near banktop stage[a]
Overbank flood recurrence interval <0.5 years[a]
Overbank flood recurrence interval <0.3 years[b]
Evidence of active aggradation of both channel and floodplain[a]
Frequent crevasses and/or avulsions[a]
Anabranching or anastamosing channel patterns (normal or high flow)[a]
Very high channel–floodplain connectivity[a]
Occurrence of valley-filling floods[a]

[a]Requires the presence of at least one other indicator for confident determination.
[b]Sufficient indicator.

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Table X. Field indicators of channel incision and aggradation

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 material known to be from a previous regime 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, for example, reduced sedimentation, soil formation, soil redox features and 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, for example, 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

Some 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.

Table XI. 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, riprap, etc.)
Isolation away from channel of formerly bank-attached or in-channel features (bulkheads, docks, signs, bridge pilings and abutments, etc.)

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 with measurements of bank and bed shear strength or critical values from Tables 5 and 6 to determine whether the key threshold of $\tau = \tau_{cr}$ will be crossed. Equation (15) may also be useful.

Otherwise, educated guesses can be made based on judgments of the proximity of the preflow modification channel to the threshold. Channels well below the threshold will exhibit no bed or bank erosion, whereas 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 underfit 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 premodification data and postmodification modeling, this may be a qualitative estimate (increase, decrease and no change) or a proportional estimate (percentage increase or decrease). The key factor is the relative change in sediment supply compared with that of sediment transport capacity.

Step 5: use the fitness assessment to predict state change

Once the starting point has been identified, the possible transitions, given the potential changes in flow, slope and sediment supply, can be determined. The fitness assessment procedure outlined in Table 4 and Figure 5 includes the key thresholds, so that from a given fitness starting point, the channel response can be determined (Table 12).

EXAMPLES

Lower Trinity River

Lake Livingston on the lower Trinity River is a flow-through water supply reservoir. Although the dam increased low flows above pre-dam levels, medium and high flows were not discernibly affected (Wellmeyer *et al*., 2005). The lake

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Table XII. Interaction matrix for alluvial channel change

	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

Entries represent phenomena that could result in a transition from the row state to the column state.

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 earlier will be applied to a reconstructed pre-dam situation.

On the basis of the 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), 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).

In step 5, 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 that 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 indicate that shear stress will increase. This predicts that the channel will enlarge until limited by other factors (increasing underfitness). 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, although the general change in channel state was apparently consistent downstream, the local, cross-sectional 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 (~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

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geomorphic controls further downstream (Phillips *et al.*, 2005; Phillips and Slattery, 2008). Third, although no direct change in slope occurred due to the dam, channel slope decreased because of the channel incision resulting from the reduced sediment supply, a result predicted by the Lane relationship.

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 (~70% 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 (2012b).

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 (because 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, 2012b) are a direct result of the overfitness of the channels. Both channels could therefore be assumed to be overfit before the avulsion.

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 (8–12 m) is much lower than for the river upstream of the flow split (>30 m).

For Elm Bayou, the model indicates initial widening (due to relatively low shear strength of the unconsolidated fine-grained deltaic sediments). Although this was not observed directly, and preavulsion data for the bayou are 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 logjam beginning in the mid-1990s. The jam has been wholly or partly removed on several occasions but has reformed and was approximately 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 near 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 (Figure 6; Phillips, 2012b).

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 effects. 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 occur, with no change in discharge. This points to channel enlargement, whatever the pre-dam condition, because 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, Texas, channel enlargement is observed. However, at the Seguin site, the response was apparently predominantly incision (based on field indicators), whereas at the Gonzales site, pronounced but highly localized (distance of approximately 200 m) widening occurs (Figure 7).

Figure 6. Channel widening associated with slope changes due to a logjam on the lower San Antonio River, Texas

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Figure 7. Widening below a run-of-river dam on the Guadalupe River at Gonzales. The channel upstream of the dam (top of photo) is 20 to 27 m wide, whereas the widened area downstream is up to 95 m wide

SUMMARY AND CONCLUSIONS

Ten different types of models of alluvial channel response to changes in discharge were reviewed. However, these actually represent a greater number of specific models, as some, such as hydraulic geometry or regime theory, have dozens of individual models, techniques or algorithms for implementation in various contexts. Table 13 summarizes the predictions of these classes of model and of the fitness model developed here for increases and decreases in discharge.

Two types of model are essentially successional—the channel evolution and the 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, for example, 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, 2010a).

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 the transgression of critical thresholds of sediment supply versus sediment transport capacity and of boundary force or stress versus resistance. This type of model is well suited for predicting channel responses to changes in flow, and the fitness model is therefore threshold based.

In comparing the model predictions in Table 13, 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, although threshold-based models are preferable in the first instance, all the described approaches remain potentially useful items in the toolbox for predicting fluvial responses.

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 types of channel morphological responses to human changes in flow regimes that cannot also occur due to natural or nonhuman forcing.

In addition to human modifications to streamflows, 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 effects of increased water inputs.

At least three other factors need to be considered in addition to changes in flow: (1) slope gradients because energy-grade slope, in conjunction with discharge, velocity or depth, determines cross-sectional and unit stream power and shear stress; (2) potential changes in sediment supply or availability due to the importance of sediment transport capacity/supply thresholds; and (3) resistance of channel boundaries relative to the shear stress of flows.

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Table XIII. 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 and S	Decreased w, d and S
Lane relationship	Potential increase in sediment transport and size but depends on changes in sediment supply and slope	Potential decrease in sediment transport and size but depends on changes in sediment supply and slope
Brandt model	Depends on sediment transport capacity vs. supply	Depends on sediment transport capacity vs. supply
Grade (general)	Decreased slope and/or increased sediment load	Increased slope and/or decreased sediment load
Grade (Eaton–Church model)	Sediment transport efficiency declines as d and S increase, but also depends on changes in D	Sediment transport efficiency increases as d and S decrease, but also depends on changes in D
Bed mobility	Bed mobility increases as d and S increase, but also depends on changes in D	Bed mobility decreases as d and S decrease, but also depends on changes in D
Schumm model	Possible incision, nickpoint formation, bank erosion, meander growth, migration and cutoffs, island/bar formation, avulsions and planform transitions, but also depends on changes in sediment load and S	Possible aggradation, channel infill and planform transitions, but also depends on changes in sediment load and S
Transport capacity	Depends on stream power and velocity relative to sediment supply and boundary resistance	Depends on stream power and velocity relative to sediment supply and boundary resistance
River evolution diagram (RED)	Depends on unit stream power (=VS) and (non) exceedance of flux boundary conditions; if VS increases then upward movement on RED	Depends on unit stream power (=VS) and (non) exceedance 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
FCF	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
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

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