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CHANNEL EVOLUTION MODEL OF SEMIARID STREAM RESPONSE TO URBAN-INDUCED HYDROMODIFICATION[1]

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ABSTRACT: We present a novel channel evolution model (CEM) that qualitatively describes morphologic responses of semiarid channels to altered hydrologic and sediment regimes associated with urbanization (hydromodification). The CEM is based on southern California data from 83 detailed channel surveys, hundreds of synoptic surveys, and historical analyses of aerial photographs along 14 reaches. Channel evolution sometimes follows the well-known sequence described by Schumm *et al.* (*Incised Channels: Morphology, Dynamics, and Control*, Water Resources Publications, Littleton, Colorado, 1984) for incising, single-thread channels; however, departures from this sequence are common and include transitions of single thread to braided evolutionary endpoints, as opposed to a return to quasi-equilibrium single-thread planform. Thresholds and risk factors associated with observed channel response are also presented. In particular, distance to grade control and network position emerged as key controls on channel response trajectory. The CEM and quantitative extensions provide managers with a framework for understanding channel responses and rehabilitation alternatives, and may be transferable to other semiarid settings. It also offers insights regarding channel susceptibility to hydromodification, highlights key boundary conditions for high-risk channels, and underscores critical knowledge gaps in predicting the complex, discontinuous response trajectories that are highly prevalent in urbanized watersheds.

(KEY TERMS: braiding; fluvial processes; geomorphology; hydromodification; land-use change, urbanization.)

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INTRODUCTION

Streams in urbanizing semiarid watersheds can exhibit radical morphologic responses that degrade aquatic and riparian habitat, threaten infrastructure, and remove substantial areas of valuable land (Trimble, 1997; Jordan *et al.*, 2010). Semiarid climates are generally associated with flashy flow regimes and predominantly ephemeral channels (Wolman and Gerson, 1978). Flow regimes and resultant morphology of these channels are easily modified by urbanization (Hawley, 2009; Hawley and Bledsoe, 2011). Receiving channels with sporadic sediment movements (Graf,

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1981), extended aggradation/degradation phases, lagged recovery times (Wolman and Gerson, 1978), and infrequent periods of equilibrium (Bull, 1997) have little resilience against unmitigated urban flow regimes. Consequently, amplified flows and durations can result in large sediment imbalances, accelerated changes in channel form, and extensive propagation of impacts (Trimble, 1997; Chin and Gregory, 2001; Hawley, 2009).

In southern California, stream channels respond in discontinuous, complex ways to alterations in flow and sediment regimes that accompany urbanization (i.e., "hydromodification"). Channel responses to urbanization in this region also appear to be disproportionately larger and more rapid than in most other regions of the United States (U.S.), with up to 1,000% channel enlargement in <10 years (Coleman *et al.*, 2005; Hawley, 2009). Morphologic responses range from incision trajectories that follow well-known channel evolution models (CEMs) (Harvey and Watson, 1986; Schumm *et al.*, 1984; Simon, 1989; Watson *et al.*, 1988) to pattern shifts from single thread to braided planforms with far-reaching effects on adjacent land and throughout drainage networks.

The inherently dynamic channels common to southern California result from a geomorphic setting that combines high relief, fine-grained bed materials, little vegetative reinforcement, extremely flashy flow regimes, and relatively high sediment yields exacerbated by an active fire regime (LACFCD, 1959; Florsheim *et al.*, 1991). The widely varied lithologies generally produce copious yields of sand but only limited amounts of coarse material; for example, <7% gravel or larger ($d > 2$ mm) by volume in regional debris dams (Taylor, 1981). Although some headwater reaches in areas of resistant lithology are well confined and relatively stable with coarse step-pool/cascade forms, downstream reaches in wide, unconfined valleys range from single-thread to braided across both sand and gravel substrates with extended periods of aggradation and degradation and infrequent states of equilibrium (Cooke and Reeves, 1976; Wolman and Gerson, 1978; Graf, 1981, 1988; Bull, 1997).

Compounding the inherently dynamic geomorphic setting, are southern California's approximately 20 million residents and associated infrastructure. Dams tend to be regarded as our most substantial fluvial impact and affect most of California's major rivers, resulting in large disruptions to water and sediment continuity (e.g., Kondolf and Swanson, 1993). Urbanization is often a primary driver of disequilibrium on smaller watersheds in the region (e.g., <250 km^2) (Hawley, 2009). Analysis of 43 U.S. Geological Survey (USGS) streamflow gages from the study area shows that urbanization is statistically significant in exponentially increasing discharge peaks and durations in southern California, making flashy systems even more variable (Hawley and Bledsoe, 2011). With little flow control evident at the subdivision scale, field investigations indicate that it often takes only 5 to 10 years following the development for channel responses to become so severe and widespread that instabilities must be addressed with instream measures to protect imperiled infrastructure (Hawley, 2009). This typically entails concrete/riprap lining of trapezoidal flood conveyance channels with little conservation of ecological and geomorphic functions (Florsheim *et al.*, 2008; Segura and Booth, 2010).

Most recent stormwater permits issued in southern California, under Section 402 of the Clean Water Act, mandate that local municipalities require future development or redevelopment to address potential changes in channel morphology and attempt to reverse past adverse effects. To accomplish these goals, managers, planners, and regulators need a better understanding of channel susceptibility to hydromodification, likely response trajectories and mechanisms, and potential dynamic equilibrium states.

Regional CEMs can address these needs by providing a valuable framework for interpreting past and present response trajectories, identifying the relative severity of response sequences and potential evolutionary endpoints, applying appropriate models in estimating future channel changes, and developing strategies for mitigating the impacts of processes likely to dominate channel response in the future (Simon, 1995). In addition to CEMs of channel incision processes, previous research has developed several conceptual models in which disturbed channels follow alternative sequences of morphologic adjustment when perturbed from equilibrium (Brice, 1981; Brookes, 1988; Simon, 1989; Rosgen, 1994; Downs, 1995). However, these existing CEMs do not adequately represent the diverse stream responses and alternate channel states often observed in urbanized semiarid regions such as southern California (Haltiner and Beeman, 2003). This study addresses these limitations by:

1. developing a detailed CEM of diverse stream responses to hydromodification in the semiarid climate of southern California;
2. identifying thresholds and risk factors for incision and braiding responses; and
3. developing a transferable framework to represent dimensionless departures from equilibrium as a quantitative extension to the qualitative CEM.

In the following sections, we provide a brief review of previous CEMs that are relevant to the present study, and subsequently describe the development of a novel CEM that provides a framework for hydromodification management in urbanizing watersheds of southern California.

Channel Evolution Models

Channel responses to land-use changes are often context-specific (Knighton, 1998; Jacobson *et al.*, 2001) and can depend on the type of disturbance (e.g., channelization, deforestation, fire, and urbanization), the regional/channel setting (i.e., climate, lithology, planform, boundary materials, and vegetative influences), and the spatial and temporal scale of the perturbation (i.e., local *vs.* watershed wide, and temporary *vs.* permanent). Despite this complexity, a diverse body of previous research has focused on the concept that channels often follow predictable sequences of response and morphologic adjustment (channel evolution) when perturbed from equilibrium.

Many previous CEMs focus exclusively on incising channels in which the initial bank-failure mechanism is primarily geotechnical and not driven by fluvial detachment (e.g., Schumm *et al.*, 1984; Simon, 1989). However, channel responses may involve initial lateral adjustments through both fluvial detachment and mass wasting that lead to planform changes and extensive width adjustments without incision. For example, Brice (1981) categorized channel responses into degrading, aggrading, widening, and shifting, and provided a detailed classification of planform patterns spanning equiwidth single-thread channels to braided channels, with intermediate forms exhibiting varying degrees of chute and central bar formation. Brookes (1988) focused on channelized streams and outlined a scheme that included degradation, armoring, bar development, bank erosion, and altered sinuosity. These classifications and others (e.g., Downs, 1995) collectively encompass many styles of morphologic adjustment, including depositional, migration, enlargement, undercutting, recovering, and compound phases; however, they do not provide the level of detail on specific sequences and thresholds of channel evolution that is needed in a hydromodification management context.

An archetypal CEM that provides detailed, process-based descriptions of a fundamental channel adjustment sequence was developed by Schumm *et al.* (1984) to provide a unifying framework for understanding the complex response of channelized streams in northern Mississippi, U.S. The Schumm *et al.* (1984) CEM has been subsequently verified in a variety of studies of incising channels (ASCE, 1998). In summary, the five stages of incised channel evolution in this CEM (Schumm *et al.*, 1984) are:

1. CEM Type I – stable;
2. CEM Type II – incising (degradation);
3. CEM Type III – incision depth exceeds critical height for bank failure and widening occurs (bank failure primarily due to geotechnically unstable banks, i.e., mass wasting);
4. CEM Type IV – aggrading to the point that bank failures begin to cease but channel has not rebuilt a floodplain; and
5. CEM Type V – quasi-equilibrium single-thread channel connected to stable floodplain formed within abandoned floodplain trench.

Key concepts noted by Schumm *et al.* (1984) that are particularly relevant in urbanizing semiarid watersheds include: (1) a downstream to upstream response progression via headcutting; and (2) complex, discontinuous response sequences that can be interrupted by additional headcutting and alterations in flow and/or sediment regimes that can "reset" response sequences (Harvey *et al.*, 1983). The general trajectory of incising, widening, aggrading, and a return to quasi-equilibrium was informed by observations across many settings including experimental drainage networks (Schumm and Parker, 1973), gullies/arroyos in Colorado and Nebraska (Begin and Schumm, 1979), and gully erosion in the South Carolina Piedmont (Ireland *et al.*, 1939). An extensive study of dredged/channelized rivers in a 250-km^2 area of western Tennessee independently corroborated the response sequence (Simon, 1989), which has since been observed throughout the entire loess area of the midwestern U.S. (Simon and Rinaldi, 2000). Studies that have quantified channel characteristics at various CEM stages indicate that slope, sediment load, and specific stream power consistently decrease as channels adjust morphologically to accommodate excess erosive energy (e.g., Bledsoe *et al.*, 2002).

In general, qualitative CEMs can be useful in assessing the channel stability, particularly at the reconnaissance level (Simon and Downs, 1995) and when used in combination with other measures (e.g., Simon *et al.*, 1989). However, CEMs have been criticized (Simon *et al.*, 2007), especially when used as a primary criterion in channel restoration design. As a preliminary step toward detailed design, Watson *et al.* (2002) extended the CEM concept with a quantitative diagram that informs channel-rehabilitation strategies. They segregated evolution stages by combining two nondimensional measures of stability into a four-quadrant sequence in two dimensions: (1) N_g (bank stability) and (2) N_h (hydraulic stability). N_g is the ratio of bank height (h) to critical bank height (h_c) for geotechnical failure at the given angle. N_h is a measure of the existing slope divided by the slope required to transport the given sediment supply. As depicted in Figure 1, incision begins (CEM Type II) when sediment-transport capacity exceeds sediment supply ($N_h > 1$). A channel that incises beyond critical height for the respective bank angle ($N_g > 1$) initiates mass wasting and proceeds to widen (CEM Type III). Aggradation (CEM Type IV) begins when the channel has sufficiently widened and reduced its slope to diminish sediment-transport capacity relative to the supply ($N_h < 1$). The return to equilibrium (CEM Type V) generally occurs once banks become geotechnically stable ($N_g < 1$) via aggradational toe protection and sediment-transport capacity matches the supply ($N_h = 1$).

The Watson *et al.* (2002) concept underscores the importance of arresting channel instability before incision has reached critical bank height because banks that are geotechnically unstable become disproportionately more difficult and expensive to rehabilitate. Moreover, the resulting channel erosion and habitat degradation that occurs as a channel adjusts to reattain equilibrium (Figure 1) can be detrimental to infrastructure (Gregory and Chin, 2002) and potentially devastating to native biota (Walsh *et al.*, 2005).

In this study, we develop a novel CEM on the foundation provided by the Schumm *et al.*'s (1984) CEM based on four primary motivations. First, the Schumm *et al.*'s (1984) CEM describes a well-defined sequence of multidimensional responses, key driving processes for vertical and lateral stability, and requirements for a return to quasi-equilibrium. Second, we observed that despite some important departures, many channel evolution sequences in our study region directly follow the Schumm *et al.*'s (1984) stages, particularly the downstream to upstream headcutting and mass-wasting processes. Third, the incision CEM is linked to a quantitative extension that informs management and rehabilitation (Watson *et al.*, 2002). Finally, the approach describes several complex processes in a simple and straightforward framework that is transferable to many geomorphic contexts and regions.

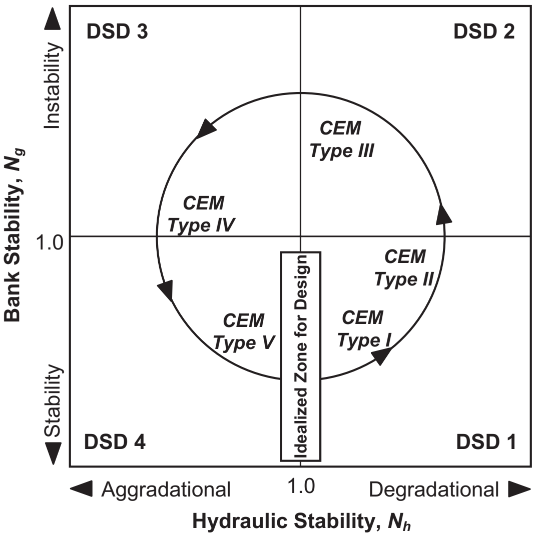


FIGURE 1. Dimensionless Stability Diagram (DSD) for the CEM in Incised Sand-Bed Streams (adapted from Watson *et al.*, 2002).

METHODS

Study Domain and Site Selection

Based on publicly available geospatial data (i.e., USGS Seamless Data Warehouse), we define southern California as the ca. 30,000 km^2 area that is geologically bound by mountain ranges to the north (Transverse Ranges) and east (Peninsular Ranges), with a total relief of up to 3,500 m and short travel distances to the ocean on the order of 100 km. The climate is predominately Mediterranean; however, precipitation and vegetation density increase with elevation from 200 to 1,000 mm/year and from sparse grasses/chaparral to dense coniferous stands, respectively (Natural Resources Conservation Service [NRCS] and Cal-Atlas data). Although low in frequency, regional precipitation can have high intensity; the two year 24-h rainfall ranges from 50 to 160 mm across the domain (National Oceanic and Atmospheric Administration [NOAA], Atlas 2 and 14 data).

In selecting sites for field reconnaissance, we targeted undeveloped, developing, and highly developed watersheds to capture a gradient of urbanization relative to rural settings. Sites included channel evolution stages of quasi-equilibrium single-thread, braided, incising, widening, and recovered. From synoptic surveys of hundreds of channels and field reconnaissance at more than 50 candidate streams, 33 reaches were selected for data collection. We define reach as a stream segment over lengths of at least 20 bankfull widths or up to ca. 1 to 2 km, and defined channel stability after Biedenharn *et al.* (1997). We focused on smaller watersheds because most larger streams were artificially reinforced and/or their flows were regulated by large reservoirs. Other selection criteria included spanning representative ranges across regionally important gradients such as slope, bed material, channel type, evolution stage, valley setting, drainage-basin size, geopolitical setting, and extent of urbanization. Ranges and means of selected variables are presented in Table 1. Locations of reaches used in the analysis are denoted in Figure 2.

TABLE 1. Select Metrics* of 33 Stream Reaches Used in CEM Development.

Reach/ County		Total Sites	CEM (Schumm *et al.*, 1984) Type					Southern California Bifurcations Phase				Braided CEM Phase					Drainage Area (km^2)	Impervious Area (%)	Average Precipitation (mm)	Drainage Density (km/ km^2)	Surface Slope (%)	Channel Slope (%)	d_{50} (mm)	Properties at Q_{10}[†] Q (m^3/s)	W (m)	W:D	Sinuosity	Approximate Length (km)
			I	II	III	IV	V	1Veg	2B	4B	5C	B1	B2	B3	B4	B5												
Acton	LA	7	2	2	2				1								1.6	11	11	0.3	19	4.8	7.3	1.9	8.0	22	1.1	1.0
Agua Hedionda	SD	3		2	1												27	26	13	1.2	13	0.3	5.0	29	11	4.2	1.1	0.4
Borrego	OR	5		1	1	1				1	1						6.5	14	15	1.5	24	2.2	19	10	19	39	1.0	1.4
Challenger	VT	3	2	1													7.3	2.0	19	1.7	36	1.3	41	12	23	14	1.2	0.6
Dry	VT	3			3												3.1	2.3	17	1.8	27	2.2	0.8	4.8	11	26	1.2	0.4
Dulzura	SD	2					2										70	0.3	16	1.5	24	0.6	41	87	32	13	1.1	0.6
Escondido	SD	2	1									1					157	14	14	0.9	17	2.5	80	162	42	14	1.1	0.4
Hasley 1	LA	2		1	1												4.0	4.0	17	1.2	22	3.1	8.1	5.8	5.5	6.4	1.1	0.2
Hasley 1 Trib	LA	1									1						0.4	14	17	0.2	18	2.6	3.2	0.8	7.9	24	1.1	0.1
Hasley 2	LA	2		1					1								9.1	5.0	17	1.7	22	1.7	2.1	12	31	54	1.0	1.0
Hasley 2 Trib	LA	1							1								5.1	2.9	17	2.1	21	3.5	1.5	7.5	22	66	1.1	0.5
Hicks	OR	9		5	3						1						3.7	1.6	15	1.5	27	1.9	1.4	6.1	13	12	1.4	0.8
Hovnanian	LA	2	2														3.7	1.5	20	1.1	40	3.1	26	7.6	8.2	7.6	1.4	0.4
Little Cedar	SD	2		1								1					7.2	0.1	15	2.0	36	2.3	24	11	19	26	1.0	0.3
McGonigle[‡]	SD	1						1									5.1	25	13	1.4	19	1.0	23	6.7	38	54	1.2	0.2
Oak Glenn	SB	1									1						1.8	0.5	30	1.4	52	7.3	23	4.9	4.7	7.4	1.0	0.2
Perris 1	RS	3	1	2													0.4	2.2	13	1.0	8	0.9	0.8	0.8	3.8	7.6	1.4	0.5
Perris 2	RS	2	2														0.1	1.6	13	1.0	5	3.0	0.7	0.3	2.5	12	1.3	0.5
Perris 3	RS	2										2					1.4	0.4	13	1.0	9	1.6	0.9	2.3	22	54	1.2	0.4
Perris Alt	RS	3	2									1					1.4	0.0	13	0.9	10	0.7	0.9	2.2	22	81	1.0	0.4
Pigeon Pass[‡]	RS	3		1									1	1			5.5	3.3	15	1.3	19	1.5	1.2	7.4	21	21	1.0	1.0
Proctor	SD	2										2					8.5	2.1	15	1.5	16	1.3	6.1	11	21	24	1.1	0.6
Proctor Trib	SD	1	1														3.5	0.0	15	1.6	20	2.1	6.1	5.0	15	21	1.0	0.3
San Antonio	VT	2										1	1				31	0.2	23	1.8	44	1.9	40	57	47	37	1.0	0.4
San Juan	OR	2	1									1					105	0.1	16	1.2	33	1.3	48	132	50	24	1.1	0.7
San Timetao	SB	3			3												1.4	11	15	0.4	12	5.8	0.9	2.4	6.7	23	1.1	0.6
Santiago	OR	2									1	1					34	0.2	21	1.2	46	1.6	28	55	34	20	1.0	1.0
Santiago BD	OR	2		1	1												18	0.0	22	1.3	48	1.9	11	31	20	17	1.0	0.4
Santiago NL	OR	2	1	1													17	0.0	22	1.4	48	2.8	17	30	12	8.4	1.1	0.4
Silverado	OR	2	2														22	0.0	20	1.2	50	4.2	133	41	12	5.8	1.0	0.4
Stewart	VT	1	1														4.7	0.1	21	1.7	46	10	152	11	9.3	7.7	1.0	0.3
Topanga	LA	3	2									1					50	1.4	25	1.7	31	4.8	230	71	24	12	1.0	0.6
Yucaipa	SB	2			1					1							14	1.9	24	1.4	28	3.7	4.2	24	176	30	1.0	0.4
Totals:		83	20	19	16	1	2	1	3	2	5	11	2	1	0	0												

Note: LA, Los Angeles; SD, San Diego; OR, Orange; VT, Ventura; SB, San Bernardino; RS, Riverside.

*Properties are average values from all sites within the reach.

[†] Hydrologic and hydraulic properties after Hawley and Bledsoe (2011) and Manning equation assuming normal depth, respectively.

[‡] Prior to the present states of 1Veg (McGonigle), B2 and B3 (Pigeon Pass), historic aerial photographs indicate that both reaches were single thread and that they transitioned to braided planform concurrent with watershed urbanization (i.e., Phase 2B).

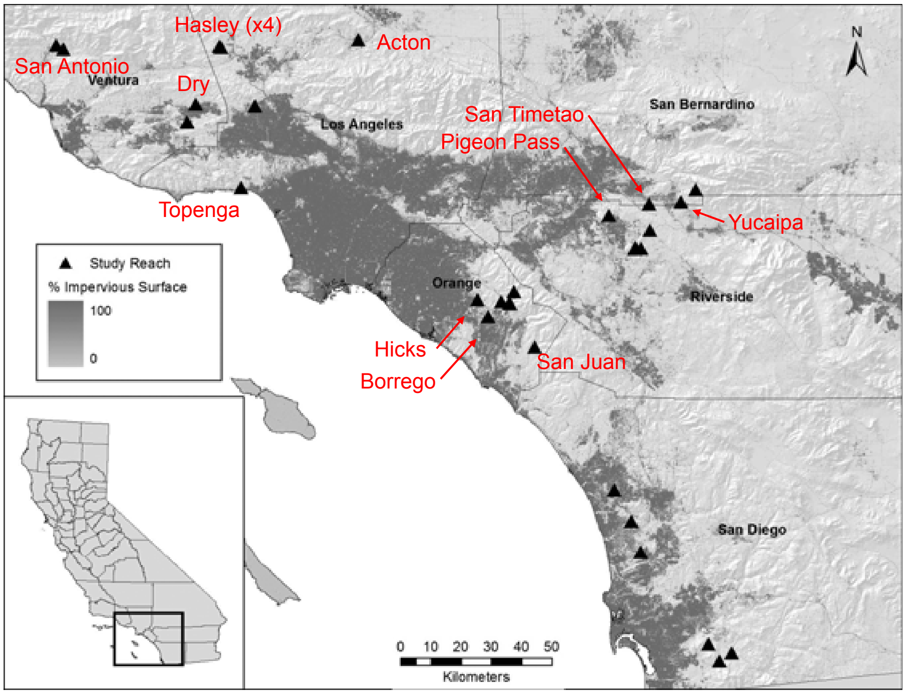


FIGURE 2. Overview and Locations of 33 Project Stream Reaches Used in Analysis with 14 Historic Aerial Photograph Reaches Indicated by Name.

Across 33 reaches, detailed surveys were conducted at 83 geomorphically distinct subreaches or project "sites" and used in our statistical analyses in support of this research. For example, a 2-km reach may have several "sites" due to significant differences in form (incised *vs.* widening), flow (additional tributaries), or valley setting (confined *vs.* alluvial valley). Where appropriate, reaches that encompassed multiple response stages enabled us to substitute space for time as one method of projecting channel change. Such space-for-time estimates were coupled with audits of historical aerial photography (Field and Geographical Information System Methods section) and tempered with the understanding that average rates of change tend to decrease as time spans increase (Schumm, 1991), especially evident in disturbance-recovery CEMs (e.g., Simon, 1989).

Field and Geographical Information System Methods

Channel-evolution sequences and planform data were compiled based on field observations during a combined six weeks of reconnaissance and data collection from Spring 2007 through Winter 2007/2008. Channel planform was classified based on single- or multithreaded flow paths. Due to low sinuosities (<1.3), single-thread channels were typically "straight" rather than meandering. Multithreaded systems at low-to-moderate flows were consistent with a braided classification, given their noncohesive floodplains and dynamic unvegetated bars (Nanson and Croke, 1992). Contemporary channel change and dominant processes in vertical (degradation/aggradation) and lateral (bank stability and failure mechanism) dimensions were qualified in the field based on geomorphic assessments over ca. 1- to 2-km reaches. Relative changes in sediment supply were qualified across channel and watershed sources based on reach-scale assessments of channel stability, recent land-use conversion, fires, and the fragmentation of channel networks that could create sediment constrictions. The qualitative estimates were subsequently corroborated (i.e., 100% agreement) via independent estimates of sediment yield using a geomorphic landscape unit model developed by Booth *et al.* (2010). Field-based inferences were cross-checked with publicly available historic aerial photographs and maps, primarily from the Seamless Data Warehouse of the USGS. Other geospatial data sources included Cal-Atlas (road coverages), Google Earth (present-day aerial photographs), NOAA (Atlas 2 and 14 precipitation data), and NRCS (soil and precipitation data).

A broad array of hydrogeomorphic variables was populated for each site across watershed, valley, and reach scales (see Hawley, 2009). Field data such as longitudinal profiles and cross-sectional geometries were collected in the field after Harrelson *et al.* (1994). Systematic pebble counts were performed according to Bunte and Abt (2001a,b). Sites with ca.

20% volumetric sand or greater were accompanied by sieve analyses; the mass and volumetric distributions were merged via a smoothing procedure developed by Kristin Bunte and David Dust (2008, personal communication, rigid and flexible procedures for combining volumetric pebble counts with sieve gradations by mass, Colorado State University). Valley and watershed metrics were populated using publically available geospatial data in a Geographical Information System (GIS).

We tested the CEM by comparing it with observable changes in channel morphology using historic aerial photographs. Low-resolution public domain aerial photographs were acquired for all 33 study reaches to make qualitative observations of channel dynamics and watershed development. High-resolution aerial photographs were purchased for 14 of the most dynamic study reaches (Figure 2) to make more quantitative estimates of channel change. The time series began with one or more photographs from the late 1940s or early 1950s, and included two to three photographs from the 1960s-1970s, and three to five photographs from the 1980s. The pre-1990 photographs were supplemented by high-resolution public domain photographs from the 1990s and 2000s to evaluate contemporary measures of development and channel evolution. High-resolution aerials were georectified via second-order polynomial transformations using a combination of root mean square error (RMSE) and independent test points after Hughes *et al.* (2006). We estimated the change in channel width via two methods: (1) by measuring active channel width at the same cross-section location and (2) by tracing the perimeter of the active channel in plan view over the length of the study reach and dividing the active channel area by half the plan view perimeter to estimate the average channel width over the reach.

Nondimensional Measures of Disequilibrium

From our large dataset of present-day stream geometries (Hawley, 2009), we used regionally representative quasi-equilibrium channel forms to develop indices to quantify the relative departure from reference conditions. Following Watson *et al.* (2002), one measure of disequilibrium is the ratio of bank height to critical bank height for mass-wasting failure at the same angle (N_g). Rather than attempting to measure individual stress parameters in the field (*sensu* Simon *et al.*, 2000), Hawley (2009) used geometric bank data to calibrate a regional threshold for mass wasting via multivariate logistic regression analysis of the height and angle of stable *vs.* unstable banks in support of a screening tool for hydromodification (Bledsoe *et al.*, 2010). Back-solving the logistic regression function for the 0.50 probability of being unstable returned regionally appropriate operational values for critical bank height at each angle, from which N_g was computed. This provided a simple way to represent the relative departure from critical bank height (and by consequence the relative extent of incision) based on measured channel geometries.

The Watson *et al.*'s (2002) index for hydraulic stability is dependent on an accurate estimate of sediment supply, which can be both variable in southern California (Graf, 1981) and difficult to estimate. As an alternative, we developed an index to represent the departure from lateral reference conditions, modeled after downstream hydraulic-geometry relations in which width tends to scale with discharge to a coefficient typically near 0.5 (Leopold and Maddock, 1953; Knighton, 1998). Recognizing that many factors affect channel size including bank material (Simons and Albertson, 1963; Schumm, 1971), bank vegetation (Andrews, 1984), bed material, and flow regime (Wolman and Gerson, 1978; Osterkamp and Hedman, 1982), regional data were used to calibrate a relationship.

We estimated flow using a regionally calibrated equation based on data from 43 USGS gages (Hawley and Bledsoe, 2011). The 10-year flow ($Q = e^{(2.90)} \times A^{0.868} \times P^{0.767}$, where Q is in ft^3/s, A is drainage area in mi^2, and P is mean annual precipitation of the watershed in inches) was used in this study because it better coincides with the channel-filling flow across the region as opposed to the more commonly used 1- to 2.5-year flow in other regions (Leopold and Wolman, 1957; Dury, 1973; Hey, 1975; Leopold, 1994; Biedenharn *et al.*, 2001). The corresponding top width for the given flow was estimated using the Manning equation and individually calibrated hydraulic geometry functions after Buhman *et al.* (2002).

After calibrating a regional reference width function from the nine single-thread equilibrium sites in unconfined settings, the relative departure from the single-thread reference width for a given flow provided an additional quantifiable measure of lateral disequilibrium in unconfined valleys. Similar to N_g, N_w is defined as the ratio of current width to reference width for the given flow:

$$N_w = \frac{W_{10}}{W_{ref}} \tag{1}$$

where N_w is the relative departure (dimensionless) from regional reference width at Q_{10}, W_{10} is the top width at 10-year flow, and W_{ref} is the regional reference width (single-thread equilibrium) for Q_{10}.

The relative measures of departure from regional reference forms, N_g and N_w, were used in combination to develop a dimensionless stability diagram (*sensu* Watson *et al.*, 2002). We used multivariate regression analysis of our detailed site data ($n = 83$) to test the statistical significance of an array of 65 standard hydrogeomorphic variables (Hawley, 2009) in predicting lateral (N_w) and vertical (N_g) response magnitudes. For these and all of our statistical analyses, we used the SAS 9.1 software package (SAS Institute, 2008, Companion for Windows; SAS Institute, Cary, North Carolina). Several transformations were tested on many of the nonnormally distributed variables (e.g., drainage area, downstream distance to hardpoint, etc.) to adhere to the assumptions of homoscedasticity, linearity, and independent, normally distributed residuals. We performed forward, backward, and best-subset selection to determine the most consistently significant, noncollinear variables, and used a standard p-value of 0.05 for statistical significance of individual variables unless otherwise noted.

RESULTS AND DISCUSSION

We present a novel CEM for the semiarid channels of southern California in response to urbanization (Figure 3). The modified CEM generalizes channel responses that were routinely observed across the urbanizing landscapes, including significant departures from the Schumm *et al.* (1984) CEM. One of the most prevalent departures was the transition from

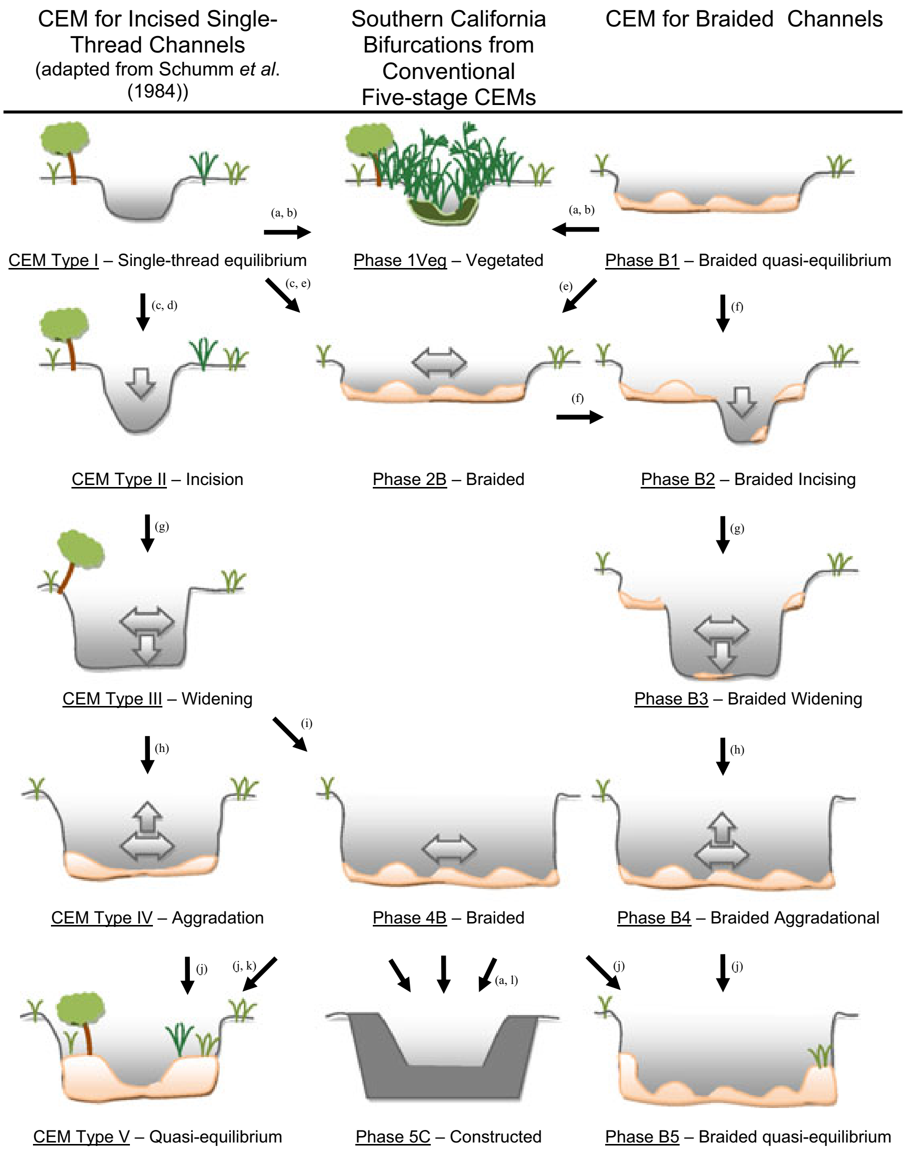


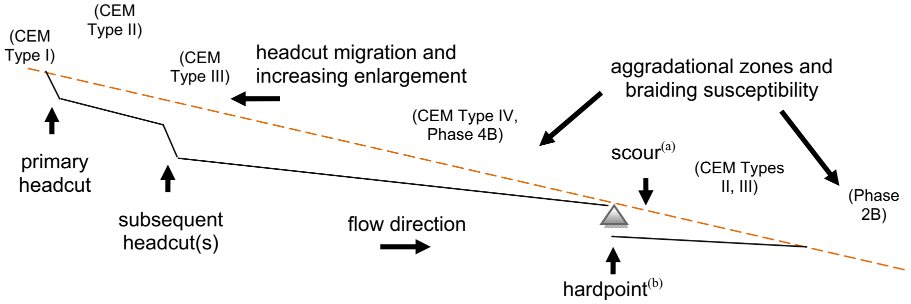
FIGURE 3. CEM of Semiarid Stream Response to Urban-Induced Hydromodification.

single-thread to braided planform, a response not commonly observed in urbanizing watersheds (but see Arnold *et al.*, 1982). The modified CEM for southern California also underscores the significance of grade control in affecting channel responses to hydromodification, including increasing channel incision moving upstream from hardpoints.

In the following sections, we: (1) present and describe the modified CEM; (2) offer preliminary verification via detailed case studies in support of the single-thread to braided trajectory and a quantitative energy-resistance analysis at all sites; (3) present a dimensionless stability scheme as a quantitative extension to the CEM, representing the relative departure from regional reference form; and (4) present risk factors for vertical and lateral response trajectories.

A Channel Evolution Model for Southern California

Channels in southern California were observed to respond in ways that were at the same time analogous to and departed from the CEM of Schumm *et al.* (1984) (Figures 3 and 4, Table 2). Qualitative drivers of responses (e.g., Q^{+}) were supported by field observations and were consistent with quantitative models. Trajectories that followed the Schumm *et al.*'s (1984) CEM were primarily driven by increases in flow (Q^{+}), and to a lesser extent, long-term decrease in basin-sediment supply ($Q_{\mathrm{s}}{}^{-}{}_{\mathrm{basin}}$), and/or base-level drop/channelization (S^{+}) – all of which were directly attributable to anthropogenic effects, primarily urbanization. The relative contribution of these drivers varies across sites; however, it can be generalized that the decrease in basin-sediment supply ($Q_{\mathrm{s}}{}^{-}{}_{\mathrm{basin}}$)



Notes:
CEM stages in parentheses
(a) the discontinuous effects of urban infrastructure such as scour downstream of grade control and increasing width-to-depth ratio moving downstream has also been observed in ephemeral Arizona streams in response to urbanization (Chin and Gregory, 2001)
(b) natural (e.g., bedrock) or artificial (e.g., riprap/concrete) grade control

FIGURE 4. Profile View of One Common Evolution Sequence in Southern California Channels in Response to Hydromodification.

TABLE 2. Footnotes to Channel Responses Depicted in Figure 3.

(a)	Can be preceded by any CEM stage
(b)	Induced by urban base flow such as lawn irrigation or wastewater treatment plant (WWTP) effluent
(c)	Relative erodibility of bed and bank material, available valley width, and downstream distance to hardpoint are key boundary conditions
(d)	Possible drivers include: S^{+}, Q^{+}, and/or $Q_{\mathrm{s}}{}^{-}{}_{\mathrm{basin}}$
(e)	Possible drivers include: $Q_{\mathrm{s}}{}^{+}{}_{\mathrm{basin}}$, and/or Q^{+} with $Q_{\mathrm{s}}{}^{+}{}_{\mathrm{channel}}$
(f)	Possible drivers include: S^{+}, Q^{+}, $Q_{\mathrm{s}}{}^{-}{}_{\mathrm{basin}}$, and/or $Q_{\mathrm{s}}{}^{-}{}_{\mathrm{channel}}$
(g)	Incision depth exceeds critical bank height for given angle (i.e., failure via mass wasting)
(h)	$\mathrm{Q_s}{}^{+}{}_{\mathrm{channel}}$ exceeds transport capacity leading to toe protection of banks via aggradation
(i)	$\mathrm{Q_s}{}^{++}{}_{\mathrm{channel}}$ leads to excessive/irregular aggradation, flow deflection, and continued bank failure (bank strength and general cohesiveness of floodplain are key boundary conditions)
(j)	In most unstable southern California systems, a proximate downstream hardpoint (natural or artificial) is critical as a fulcrum for complex response sequences and the eventual return to quasi-equilibrium
(k)	Conceivable from any prior braided state; however, increasing braiding extent (i.e., degree of departure from reference channel width) would seem to decrease the probability of a return to single-thread quasi-equilibrium
(l)	Predominant terminal condition in urban/suburban channels of southern California

would have greater influence on channel dynamics of finer grain live-bed systems than on coarser-grained threshold behavior systems (Howard, 1980; Hey and Thorne, 1986; Bledsoe, 2002). Hawley (2009) showed that independent of potential changes in sediment supply, urban-induced increases in the magnitude and duration of erosive flows (Q^+) resulted in substantial imbalances in cumulative sediment transport capacity, which were positively correlated to channel enlargement.

The similarity between response sequences induced by urbanization with those caused by channelization is consistent with the early observation that channelized streams and response sequences could serve as an analog for urbanization (Harvey *et al.*, 1983). Indeed, two reaches that were likely impacted by the historical channelization of adjacent reaches showed clear indications of the Schumm *et al.*'s (1984) single-thread evolution in historic aerial photographs. The stable present-day two-stage/terrace geometry at Dulzura (CEM Type V) in the exclusively rural watershed (0.3% impervious area) is indicative of the potential for self-stabilization without a proximate grade control structure, given sufficient space and time to recover relative to the scale and lack of temporal variability of the disturbance. By contrast, Borrego was impacted by watershed urbanization just as aerial photographs seemed to indicate a recovery trajectory several decades after historic channelization (further discussed in the Case Studies section below).

The importance of grade control in promoting the eventual return to quasi-equilibrium stages such as CEM Type IV or Type V is underscored in Column 1 of Figure 3. Incision-driven responses almost exclusively revolved around a hardpoint fulcrum as depicted in Figure 4 (see A Quantitative Extension of the Channel Evolution Model via Dimensionless Stability Numbers section for additional analysis). Self-stabilized reaches without a proximate grade control structure were rare both during field reconnaissance and in our dataset (2 of 33 reaches, 3 of 83 sites).

A similar trajectory was observed in a subset of braided systems, which in some cases follow a sequence analogous to the Schumm *et al.*'s (1984) CEM for incising single-thread channels. This was especially true for the initial stages of incision (Phase B2), widening (Phase B3), and aggrading (Phase B4), which were primarily triggered by a base-level drop (S^+) and the resulting headcutting. This was also caused by artificial increases in and/or concentration of flow (Q^+) from new stormwater outfalls or at road crossings via culverts that concentrate the hydraulic energy but reduce sediment through flow ($Q_s{}^-{}_{\text{channel}}$), consistent with Chin and Gregory's (2001) observations in urbanizing ephemeral streams of Arizona. Indeed, this response sequence was routinely observed in predominantly rural watersheds (i.e., < 1% imperviousness) where it seemed almost exclusively attributable to sediment discontinuities induced by channel fragmentation from infrequent human infrastructure, consistent with the widely documented response of channel incision downstream of dams (e.g., Kondolf, 1997).

Braided channels in the region can also widen through fluvial erosion associated with urbanization. This was primarily attributable to channel instability in upstream reaches induced by increases in flow (Q^+). The resulting increase in sediment supply from the channel ($Q_s{}^+{}_{\text{channel}}$) increased braiding extent, consistent with Germanoski and Schumm's (1993) experimental work on braided channel response to changes in sediment supply.

Although braided channels are widely considered less stable than single-thread channels (Schumm, 1977, 1981, 1985; Hoey and Sutherland, 1991; Nanson and Croke, 1992; Ferguson, 1993) with many classic examples of frequent and large shifts in channel position (Chien, 1961; Gole and Chitale, 1996), audits of historical aerial photography at several sites suggest that braided systems can also attain quasi-equilibrium for ca. 50 years. This is consistent with recognition by other researchers that braiding can be an equilibrium channel state, given the necessary boundary conditions that result in no net change in the vertical or lateral dimensions over time (Leopold and Wolman, 1957; Parker, 1976; Chang, 1979; You, 1987; Klaassen and Vermeer, 1988).

The most common geomorphic setting for equilibrium (Phase B1) braided channels in our dataset was at major valley expansions in otherwise confined, high-energy stream networks. Stream reaches downstream of such shifts, from supply limited to capacity-limited valley transitions, tended to have evolved their active channel bandwidth to accommodate natural fluctuations in sediment supply without major changes in channel planform. The equilibrium-braided condition could be maintained for relatively long stream reaches given the available valley width; however, fragmentation by urban infrastructure introduced clear discontinuities in sediment transport.

Beyond the trajectories that were relatively consistent with the Schumm *et al.*'s (1984) CEM discussed above, we observed several novel deviations (Figures 3 to 5, and Table 2) that are described in detail below:

Phase 1Veg (1 of 33 reaches, 1 of 83 sites, dozens of synoptic survey reaches) – vegetated, encroached low-flow channel from continuous urban base flow (e.g., irrigation or treatment plant effluent).

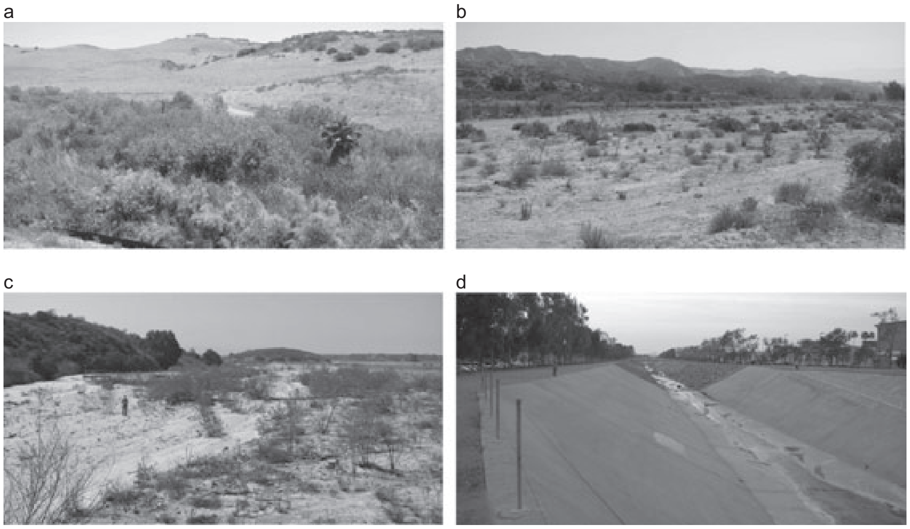


FIGURE 5. Southern California CEM Bifurcations. (a) Phase 1Veg: vegetated, encroached low-flow channel at Lusardi Creek (San Diego County). (b) Phase 2B: braided planform in formerly (1979) single-thread Hasley Canyon (Los Angeles County) following little initial incision (70-m wide, 1-m banks). (c) Phase 4B: braided planform in formerly (1967) single-thread Borrego Canyon (Orange County) following a significant incision phase (105-m wide, 2-m banks). (d) Phase 5C: constructed channel at San Diego Creek (Orange County) (photographs by David Dust).

It is possible for this form to occur following other less stable stages within the CEM, such as CEM Type II or even from previously braided states. This stage was more common in San Diego County, which tended to have greater valley confinement in lower relief valleys relative to other areas. San Diego County's noticeably different development (hilltop rather than valley floor) and irrigation (reclaimed *vs.* potable) practices may have also played a role (City of San Diego, 2008). Although channel vegetation may seem inherently temporary, among regional ecologists the ongoing debate between restoring to the native condition and managing to a new channel state (e.g., White and Greer, 2006) suggests that Phase 1Veg may be both widespread and semipermanent, similar to the persistence of exotic *Tamarix* spp. and the corresponding effects on channel banks throughout the semiarid southwest, particularly on rivers with reduced and stabilized base flows downstream of dams (e.g., Stevens *et al.*, 1995).

Phase 2B (3 of 33 reaches, 3 of 83 sites, with three additional sites historically undergoing Phase 2B prior to subsequent phases such as B2 and B3) – widening/braided planform with little initial incision. Cases at our study sites were driven by Q^{+} and the associated increase in sediment supply from the channel ($Q_{\text{s}}^{+}{}_{\text{channel}}$), leading to local aggradation that can initiate braiding via a variety of depositional and erosional mechanisms such as central bar formation and chute cutoffs (Leopold and Wolman, 1957; Ashmore, 1991). Boundary conditions also included more erodible banks relative to bed material. A relatively close downstream hardpoint (D_{hp}) in one case (Acton_A, D_{hp} = 70 m) probably drove the incipient lateral response by holding the grade. However, two sites where this was not the case (Hasley2_A and Hasley2_Trib, D_{hp} = 1,700 and 1,850 m, respectively) confirmed that a proximate hardpoint was not a prerequisite boundary condition. Phase 2B could conceivably follow an increase in sediment supply from the watershed ($Q_{\text{s}}^{+}{}_{\text{basin}}$), such as following a fire; however, only the initial phase of this mechanism was corroborated by observation (i.e., preliminary chute cutoffs along the Hicks_D reach following a November 2007 fire). The mechanism of excess sediment from channel sources via upstream instability was independently corroborated via resurveys at four study reaches (Hasley1, Hasley2, HasleyTrib, and Acton) that documented substantial incision and widening between 2008 and 2011.

Phase 4B (2 of 33 reaches, 2 of 83 sites) – widening/braided planform following significant phases of initial incision, also attributable to local aggradation due to the increased sediment supply from urban-induced channel instability in upstream reaches. Cases at study sites were at intermediate distances from downstream hardpoints (Yucaipa_B and Borrego_B, D_{hp} = 300 and 340 m, respectively); however, it is conceivable to project Phase 4B at greater hardpoint distances as series of headcuts continue to migrate upstream. Given that the unstable bank geometries accompanying

Phase 4B can be a prolonged source of excess sediment from the channel ($Q_{\mathrm{s}}{}^{+}{}_{\mathrm{channel}}$), the duration and extent of braiding could be especially pronounced. Several subsequent field visits at Borrego (2008 to 2011) confirm that active bank failure and widening along much of the reach continues to be a large source of the sediment supply at Borrego_B.

Phase 5C (5 of 33 reaches, 5 of 83 sites, dozens of synoptic reaches) – artificially reinforced or constructed channel (concrete or riprap) following any stage. This stage was generally observed as the most prevalent endpoint for streams in developments older than 5 to 10 years.

In summary, vegetated (Phase 1Veg) or constructed (Phase 5C) may follow any antecedent stage across both single-thread and braided planforms. For example, aerial photograph analysis of the McGonigle reach indicated a single-thread channel in 1966, with road and development construction beginning in 1980, followed by channel instability and widening through 1989. The 2008 survey captured a wide, shallow cross-section with multiple flow paths at intermediate flows (i.e., Phase 2B); however, the regular base flow from irrigation runoff from the well-established upstream development has resulted in a shift to the Phase 1Veg condition.

Shifts from single-thread to braided can result from both incision-driven (Phase 4B) and incipiently lateral responses (Phase 2B). It is also important to note that these braided states are not intended to convey static endpoints. Rather, they too could incur subsequent phases of incision (Phase B2), widening (Phase B3), and/or aggradation (Phase B4). It is conceivable that given enough time to flush excess sediment, braided states could return to single-thread equilibrium (CEM Type V); however, four of five of our cases would suggest that both their sediment regimes and width are so far removed from single-thread stability that the return is unlikely within the engineering time scales of interest. This is discussed further below in the context of quantifying the CEM.

Case Studies/Preliminary Verification

A total of 7 of our 33 reaches (8 of 83 sites) experienced transitions to braiding concurrent with watershed urbanization. One of those reaches (Pigeon Pass) is currently undergoing incision (Phase B2) and widening (Phase B3), and McGonigle has shifted to Phase 1Veg. Of the five remaining reaches, three of our most data-extensive examples that highlight this transition are presented below: (1) Borrego Canyon, (2) Acton, and (3) Hasley.

Case Study 1 – Borego Canyon. To begin, an example of our use of historic aerial photographs at Borrego Canyon (Irvine, California) is depicted in Figure 6 and Table 3. An aerial photograph in 1947 indicates a predominantly single-thread equilibrium

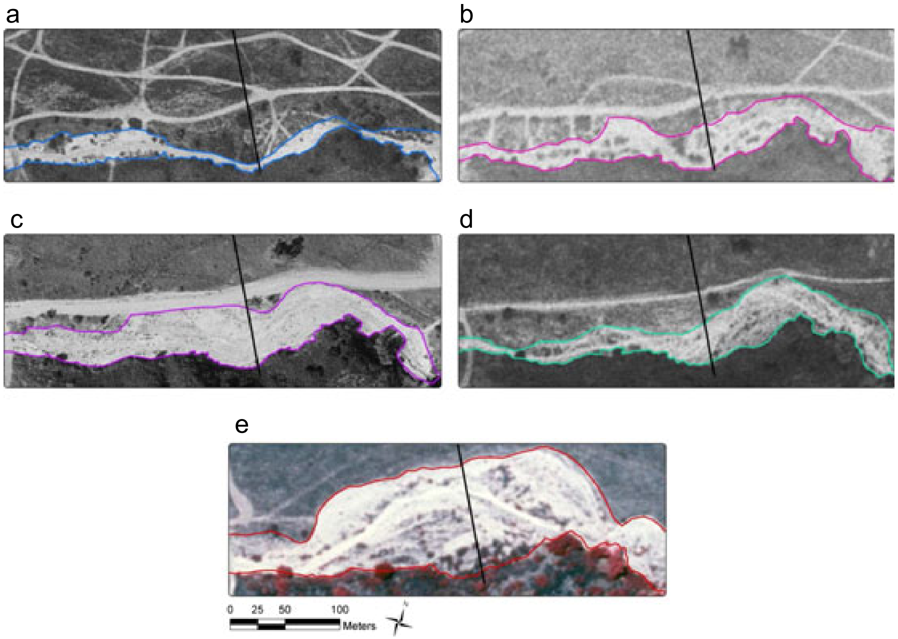


FIGURE 6. Georectified Time-Series Aerial Photography of Borrego Canyon with Channel Boundaries and Approximate Width at Surveyed Transect (Borrego_B, 2008): (a) 1967 ca. 10 m, (b) 1974 ca. 40 m, (c) 1982 ca. 50 m, (d) 1986 ca. 35 m, and (e) 2002 ca. 105 m.

TABLE 3. Geometric Change at Borrego_B Transect and ca. 2-km Reach from Georectified Historic Aerial Photography.

Year	Channel Width at Transect (m)	Average Channel Width Over 2-km Reach (m)	Inter-period Change in Average Width (m)	Average Deviation Between Independent Test Points (m)[1]	Inter-period Average Change > Independent Test Point Deviation?[2]
1967	10	13.2			
1974	40	19.5	6.3	5.7	Yes
1982	50	14.0	−5.6	6.3	No
1986	35	10.9	−3.1	5.3	No
2002	105	30.7	19.8	5.1	Yes

[1] Aerials were georectified by second-order polynomial transformations using a combination of RMSE and independent test points after Hughes *et al.* (2006). Average deviation between independent test points quantifies the potential measurement error in using the aerial photographs.

[2] Cases where change in inter-period average channel width is greater than the average deviation between independent test points (i.e., 1967 to 1974 and 1986 to 2002) indicate that measured change is greater than potential error in measurement and suggest significance.

system; however, the transect location is at the edge of the photograph and not visible in Figure 6. The channel evolution depicted between 1967 and 1986 is most likely driven by the channelization that occurred immediately upstream of the site ca. 1950 in conjunction with the installation of the El Toro military base and additional channelization 1.5 km upstream of the site ca. 1970. Indeed, aerial photographs from 1967, 1974, 1982, and 1986 depict a disturbance-recovery trajectory consistent with the Schumm *et al.*'s (1984) CEM of incised, single-thread channels, with potential braiding during the channel widening/aggradation phases.

However, the threefold expansion of channel width observed between 1986 and 2002 seems to have pushed the channel past a threshold into a more permanently braided state. The response is concurrent with active watershed development (Figure 7), which increased from 0 to 14% impervious area between 1986 and 2002. The significant increase (when compared with independent test point deviation of georectified photographs, Table 3) of active channel width both at the transect (35 to 100 m) and over the reach (11 to 31 m) in response to urbanization is consistent with studies from other regions (e.g., Wolman, 1967; Wolman and Schick, 1967; Hammer, 1972; Jacobson and Coleman, 1986; Booth, 1990; Trimble, 1997; Galster *et al.*, 2008); however, the southern California responses seem to occur on spatial scales of greater magnitude. The steep setting, relatively small amounts of coarse bed material, abundant loads of fine sediments, low bank cohesion, and little vegetative bank reinforcement are probable factors in the magnified channel responses.

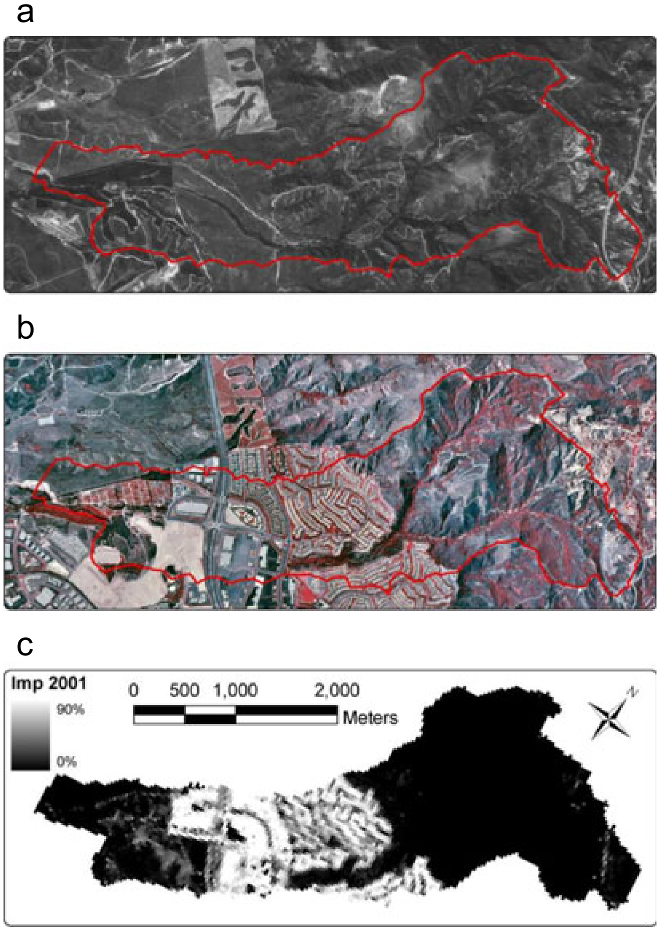


FIGURE 7. Borrego Watershed Imagery and Urbanization Extent with Study Reach Location (Figure 6) at Downstream Extent. (a) 1986 aerial photograph (0% impervious); (b) 2002 aerial photograph (14% impervious); (c) 2001 imperviousness raster.

Concordant with the historic change observed via aerial photographs, present-day field surveys captured an array of channel responses. Figure 8 depicts superimposed cross-sections along Borrego Canyon from 2008. The 7-km^2 watershed currently includes mixed commercial and small-lot residential land uses with imperviousness relatively constant since 2001 at 14%. Moving from downstream to upstream, Borrego_A (Phase 5C) is a stable, single-thread sand-bed channel ca. 15-m wide with constructed (riprap) banks that is protected by the riprap grade control structure 20 m downstream. Borrego_B (Phase 4B),

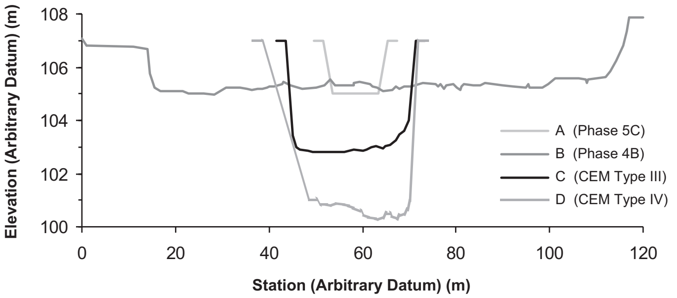


FIGURE 8. Superimposed Surveyed Cross-Sections at Borrego Canyon from 2008 (Borrego_A to Borrego_D moving downstream to upstream).

340 m upstream from the grade control, is a 105-m wide braided planform with 2-m vertical banks and median grain size of 1.6 mm. About 685 m upstream of the hardpoint is Borrego_C (CEM Type III), a single-thread plain-bed transect with 4-m vertical banks, a 28-m top width, and median grain size of 1 mm. Borrego_D (CEM Type IV) is 1,120 m upstream of the riprap structure. The 30-m wide channel has the highest banks (ca. 6 m), but has coarsened (median grain size of 45 mm) so much so that the site has begun to re-form a meandering floodplain within the entrenched valley (indicative by the well-established [>5 to 10 years] woody vegetation on the floodplain surface seen on the left of cross-section "D" in Figure 8). Although one might expect an earlier CEM stage moving upstream, it is apparent that Borrego_D has incised to such a depth that the substantially coarser material has resulted in a re-armoring of the bed and a shift to CEM Type IV prior to the downstream reach at Borrego_C (Figure 9).

The instability observed at Borrego Canyon was not atypical. Channels throughout the region experienced similarly expansive responses concurrent with changes in land use from undeveloped to even lightly developed (e.g., ~5 to 10% total impervious area [TIA]).

Case Study 2 – Acton. As a second case study, the cross-sectional area of the active channel of an unnamed tributary to the Santa Clara River in north central Los Angeles County near Acton, California (i.e., "Acton"), has enlarged on the order of 100 to 1,000% over the reach since the medium/large-lot residential development was constructed during the last decade (2.3% impervious area in 2001, 10.6% in 2006). Historic aerial photographs (1948, 1954, 1957, 1974, 1976, 1979, 1986, 1987, and 1989) show that the 2-km^2 watershed remained undeveloped through at least 1989, with a channel that showed nominal deviation from its small, single-thread form. The channel presently has reaches that range from severely incised at the far upstream extent (CEM Type II → III, 1-m wide, 2-m deep) to widening middle reaches (CEM Type III, 6-m wide, 4-m deep and 10-m wide, 3-m deep) and a fully braided downstream reach (Phase 2B, 18-m wide, 0.4-m deep). A culvert at the downstream extent acts as a fulcrum for the ongoing adjustments. Historic aerial photographs and field indicators would suggest a predeveloped channel that was no wider than 8 m and roughly 0.3-m deep. A 2007 fire confounds this case study; however, the highly degradational trajectory of the response sequence – despite any potential fire-induced sediment loads – seems to reinforce the conclusion that the primary driver of disequilibrium is the urban flow regime.

Case Study 3 – Hasley. Our final case study involves another unnamed tributary to the Santa Clara River in northwest Los Angeles County near Castaic, California, adjacent to Hasley Canyon Road (i.e., "Hasley"). Aerial photographs from 1947, 1954, 1969, 1976, and 1979 showed minimal braiding and a predominately single-thread channel throughout the study reach. Mixed-residential development increased during the last three decades (and especially in the last decade) in the 12-km^2 basin (1.1% impervious area

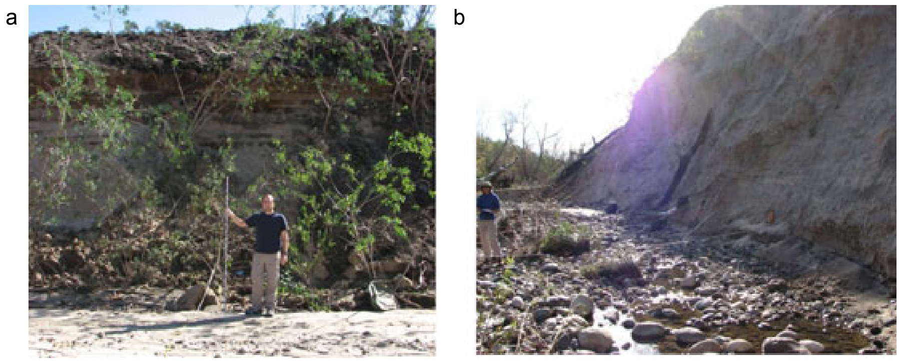


FIGURE 9. Photographs of Borrego Canyon Transect Locations. (a) Borrego_C looking at left bank and sand bed; (b) Borrego_D looking at right bank and cobble bed (photographs by David Dust).

in 2001, 4.6% in 2006). Coincident with the recent development, upstream reaches began incision-driven response trajectories (CEM Types II and III). The reach immediately downstream of a road crossing is experiencing scour and bank failure (CEM Type III); however, reaches beginning ca. 100-m downstream of the grade control are experiencing aggradational and widening trajectories (Phase B2) with little evidence of incision. Aerial photographs from 1982, 1985, 1986, and 1989 show that braiding began in this reach with the onset of watershed urbanization, and that channel expansion has continued to present day with a near tripling in active channel width since 1989 (ca. 25-m wide in 1989 to 70-m wide in 2007).

Case Study Discussion. We acknowledge that the dynamic nature of the regional setting can potentially confound such historical case studies. For example, contemporary development in southern California coincided with many years of higher than average rainfall; 1978, 1983, 1998, and 2005 had total rainfall volumes that were 80 to 130% above the long-term (1878 to 2006) average as recorded in Los Angeles (Hawley, 2009; Hawley and Bledsoe, 2011), and would be expected to significantly impact regional runoff yields (Beighley *et al.*, 2008). In particular, 1983 and 1998 corresponded to strong El Niño years (Smith and Sardeshmukh, 2000). In addition, severe storms can induce large sediment pulses via landslides, and there have been many notable fires during the period (e.g., Paradise and Simi Fires of 2003, San Timoteo Fire of 2005, Day Fire of 2006, Harris, Santiago, and Witch Fires of 2007; CAL FIRE, California Department of Forestry and Fire Protection, http://cdfdata.fire.ca.gov/incidents/incidents_statsevents), including the 2007 North Fire and Ranch Fire in our Acton and Hasley case study watersheds, respectively. However, even when controlling for precipitation, Hawley and Bledsoe (2011) and Beighley *et al.* (2008) independently showed significant influences of urbanization on flow magnitudes/durations, and runoff volumes, respectively. Similarly, we have attempted to control for such alternative drivers in this study by surveying sites across gradients of development, hydrogeomorphic setting, and disturbance regime including recent fires, such that we are able to infer, based on a weight of evidence, that urbanization is a primary driver of channel instability throughout the region.

Mechanisms of Braided Channel Evolution

The most prevalent and influential drivers of single-thread to braiding planform transitions at our case study sites are likely increases in flow (Q^+) from urban development (Hawley and Bledsoe, 2011) and concomitant increases in sediment supply from upstream channel reaches ($Q_s{}^+{}_{\mathrm{channel}}$). Causal factors underlying the observed transitions in channel morphology include low bank resistance/vegetation (Hickin and Nanson, 1984; Murray and Paola, 1994), high and variable sediment loads (Lavé and Burbank, 2004), and high width-to-depth (*W/D*) ratios (Table 1). Urbanization can substantially increase flow magnitude and variability (Poff *et al.*, 2006), particularly in semiarid southern California (Hawley and Bledsoe, 2011). Given that flow flashiness increases susceptibility for braiding (Schumm and Lichty, 1963), and semiarid flow regimes are highly variable relative to other climatic settings (Wolman and Gerson, 1978; Lewin, 1989), it appears that urbanization is likely a primary driver of the morphologic shift to braiding planform. Even if a discharge on the order of a 10-year flow is required to fill and/or form southern California channels, durations of these events can increase by 60% at 10% TIA, twofold at 15% TIA, and nearly threefold at 20% TIA (Hawley and Bledsoe, 2011).

In comparisons of pre- and posturbanization high-flow magnitudes of equal frequency in the daily series (ca. five occurrences over a 25-year simulation), the magnitude of channel-forming flows increases by a factor of approximately 2.7 (Hawley and Bledsoe, 2011). Given that channel top width tends to scale with approximately the square root of dominant discharge (Knighton, 1998) and that many researchers have correlated "bankfull" width to the dominant discharge (Andrews, 1984; Emmett and Wolman, 2001; Soar and Thorne, 2001), it follows that increases in the magnitude and duration of these formative flows could also be important in explaining morphologic channel response (*sensu* Wolman and Miller, 1960). It follows that an urban-induced flow increase of 2.7 of the channel-forming flow after Hawley and Bledsoe (2011), when scaled by the square root, could correspond to an increase in width by a factor of 1.64. An initial *W/D* ratio of 23 (mean across study sites, Table 1) would require approximately a 1.75 to twofold expansion in width to approach a *W/D* ratio of 40 to 50, which corresponds to regionally calibrated thresholds (Dust and Wohl, 2010) and more generalized thresholds for braiding (e.g., Fredsøe, 1978). Many channels would require much smaller expansions in width to approach values of 40 or 50. Therefore, antecedent *W/D* ratios in the early stages of channel response and the two- to threefold increases in magnitudes and durations of channel-forming flows observed at modest levels of imperviousness are important influences on planform trajectory in the CEM.

Specific Stream Power and Bed-Material Resistance. In addition to the case studies discussed above, a more quantitative preliminary verification of the CEM was performed using hydraulic and geomorphic metrics from all 83 study sites. Our primary hypothesis is that alluvial channels systematically adjust their longitudinal slope, cross-sectional form, and bed material to approach dynamic equilibrium with the increased erosive energy of the urban flow regime. This adjustment is primarily a function of quantitative differences in stream power and bed-material resistance that should be evident in our data. Specific stream power (ω), a measure of the total stream power distributed over channel width, has been used by numerous researchers as a representation of erosive energy, sediment-transport capacity, and potential for channel instability (Bagnold, 1966; Schumm and Khan, 1972; Edgar, 1976; Bull, 1979; Brookes, 1988; Nanson and Croke, 1992; Rhoads, 1995).

Plotting the specific stream power of the 10-year flow *vs.* median grain size of bed material (d_{50}) by aggregated CEM stage (Figure 10) shows separation between states of dynamic equilibrium and disequilibrium. Single-thread channels in unconfined valleys that are in or approaching states of dynamic equilibrium (CEM Type I, Phase 1Veg, and CEM Types IV and V) tend to have the lowest specific stream power for a given bed-material resistance. Braided channels in states of dynamic equilibrium (Phase B1) typically have slightly higher erosive energy than single-thread equilibrium; however, they tend to have lower erosive energy than disequilibrium states (CEM Types II and III and Phases B2, 2B, and 4B). A log-transformed linear regression of Phase B1 channels is provided for visual separation of quasi-equilibrium *vs.* disequilibrium states. Constructed (Phase 5C) and confined channels in narrow mountainous valleys demonstrate stability at higher levels of erosive energy than those without artificial/natural reinforcement.

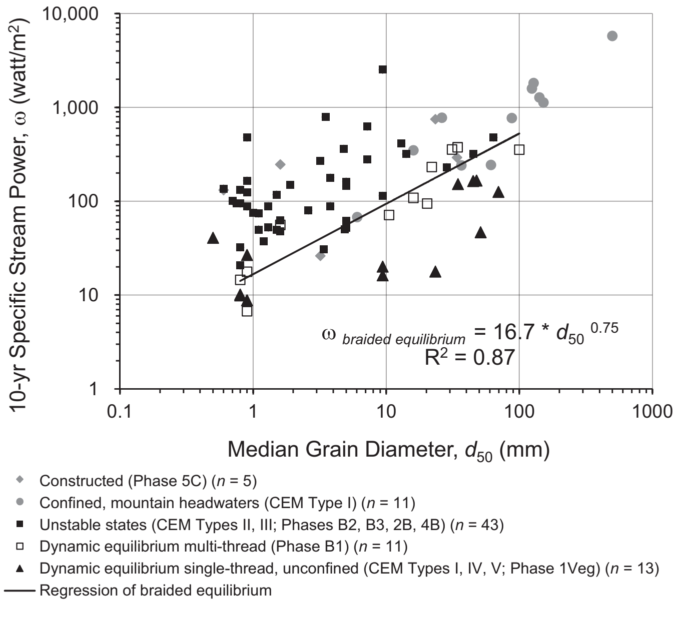


FIGURE 10. Ten-Year Specific Stream Power *vs.* Median Grain Diameter by CEM Stage of All 83 Sites with Superimposed Power Function of Phase B1 Channels for Visual Separation.

The trend of decreasing specific stream power with both equilibrium (CEM Type I and Phases 1Veg and B1) and recovering/recovered (CEM Types IV and V) stages relative to more actively adjusting/unstable reaches (CEM Types II and III and Phases B2, 2B, and 4B) is apparent along channel segments with varied response stages occurring within the same watershed and valley setting, consistent with previous studies of evolving channels (Simon, 1992; Bledsoe *et al.*, 2002; Simon and Rinaldi, 2006).

A Quantitative Extension of the Channel Evolution Model via Dimensionless Stability Numbers

Two nondimensional indices were calibrated with southern California data and used to quantify the relative departure from regional reference conditions: (1) N_g representing departure in the vertical dimension and (2) N_w quantifying departure in the lateral dimension. A logistic regression analysis of regional bank data was used to estimate the critical bank height (h_c) for the given angle based on the 50% probability of being geotechnically unstable at that same angle (Hawley, 2009). Dividing the actual bank height (h) by h_c provided the relative departure from the stability-instability threshold in the vertical dimension (N_g).

Plotting the top width for a 10-year water surface elevation *vs.* the 10-year peak flow for single-thread equilibrium systems in unconfined valleys and unconstructed settings resulted in a well-fit power function as a regional representation of forms sufficiently wide

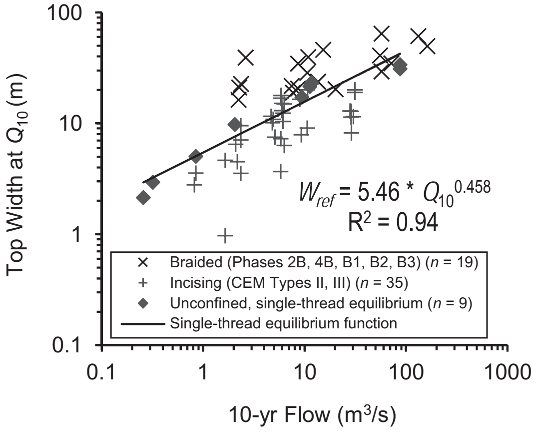


FIGURE 11. Top Width *vs.* 10-Year Flow at Unconfined, Unconstructed Single-Thread Equilibrium, Braided, and Incising Sites with Superimposed Power Function Fitted to Single-Thread Equilibrium Sites.

to dissipate energy without resulting in multiple flow paths (Figure 11). It should be noted that 4 of the 13 sites from such single-thread, unconfined settings were withheld from the trend because the 10-year flow was overbank and we had poor overbank geometry at those sites. For reference, braided channels and incision-driven responses (CEM Types II and III) are included in Figure 11, and indicated nearly perfect separation over the power function. The relationship was then used to estimate a reference width (W_{ref}) for each site as a function of the 10-year peak discharge after Hawley and Bledsoe (2011). Dividing the actual channel top width by W_{ref} provided a measure of relative departure from the lateral reference conditions for single-thread equilibrium channels in unconfined valleys (N_{w}).

Results of multivariate regression of 65 hydrogeomorphic metrics (Hawley, 2009) across watershed, valley, reach, and cross-section scales to determine predictors of N_{g} and N_{w} were mixed. The overall models were poorly fit (adjusted $R^2 = 0.07$ to 0.35); however, the analysis did identify consistent risk factors for vertical and lateral responses, suggesting potentially important boundary conditions for whether a system might incise or braid (Table 4). Twenty-nine percent of the variance for N_{g} was explained by the proximity of a downstream hardpoint (artificial grade control or bedrock), with greater incision as one moved upstream.

The result that channels can become larger in the upstream direction is counterintuitive, but reverse morphologies have been attributed to land-use change in previous studies (e.g., Clark and Wilcock, 2000). Regarding previous CEM literature, Simon (1989) showed that disturbance was greatest just upstream of the extent of channelization and decreased nonlinearly with distance upstream. In reference to base-level lowering in experimental drainage networks (McLane, 1978), Schumm *et al.* (1984) noted that responses became less extensive moving upstream because less contributing area resulted in less water moving over the headcut. In reference to the latter point, channel responses in southern California did scale to some degree in proportion to their contributing drainage area, and the increase in channel enlargement in the upstream direction was relative to a downstream transect with similar amounts of contributing drainage area (e.g., over 1- to 2-km reach lengths). But the disparity between our work and Simon (1989) is a reflection of the type of channel disturbance. The prior CEMs were in reference to channelized systems, which is generally a local disturbance with a response that decreases as one moves away from the disturbance zone. In contrast, urbanization, even when spatially discontinuous, is a more global disturbance that usually increases in the downstream direction with complex response sequences that can move downstream to upstream and be "reset" by urban infrastructure. Indeed, urban infrastructure often provides grade control that leads to frequent discontinuities in response sequences, particularly evident in dryland systems (e.g., Chin and Gregory, 2001), and may explain the irregular enlargement patterns observed by Roberts (1989) in urbanizing British channels. Statistical analysis of our data indicates that once an incision-response sequence is initiated, incision depth (i.e., N_{g}) increases moving upstream from a channel hardpoint. This finding underscores the importance of grade-control spacing in assessing hydromodification susceptibility and management.

TABLE 4. Statistically Significant ($p < 0.05$) Risk Factors for Channel Response Directions.

Incising N_{g}^{+}	Risk Factor (partial R^2 in parentheses)	Braiding N_{w}^{+}
Far (0.29)	Proximity to downstream hardpoint (standardized by channel width)	-
-	Valley width	Wide (0.07)
High (0.06)	Proportion of sand in soil at site[1]	-

[1] GIS-derived from NRCS soil layer segregated into %sand, %silt, and %clay.

In regression analyses of influences on N_{w}, individual predictor variables had little explanatory power. This was probably because our dataset spanned diverse styles of lateral response across a broad set of boundary conditions. For example, we saw braiding at locations just upstream of hardpoints due to the inability to incise and the excess sediment load from upstream channel erosion (similar to the CEM by Schumm and others). Alternatively, in systems that had many years to adjust to the current urbanization extent, lateral response also became greater moving upstream from a hardpoint in conjunction with greater incision and proportionally higher banks. The only statistically significant predictor of N_{w} was valley width (Table 4), indicating that lateral responses can be greater in unconfined valley bottoms. Median particle size was negatively correlated with both N_{g} and N_{w} (partial $R^2 = 0.02$), but was not significant to the $p < 0.05$ level. This suggests that although the probability of response increases with decreasing d_{50}, systems with coarser bed material are not without risk.

Consideration of both N_{g} and N_{w}, in combination as a quantitative extension of the CEM, could have utility in assessing systems' current level of departure from reference geometries and potential evolutionary trajectories/endpoints for management. N_{g} is plotted along the vertical axis and representative of the relative severity of incision, and N_{w} is used as a measure of lateral departure from single-thread equilibrium reference conditions along the horizontal axis.

N_w replaces N_h in the Watson *et al.*'s (1988) approach because sediment supply is both variable and difficult to estimate. Although lateral adjustments in incision-driven trajectories are mechanistically related to the extent of vertical incision (Schumm *et al.*, 1984; Simon, 1989), the fact that N_w was weakly and negatively correlated to N_g (partial $R^2 = 0.08$) lends support to the independent evolutionary bifurcations discussed here and substantiates the need for a modified CEM (Figure 12).

Along the horizontal axis, single-thread equilibrium channels (CEM Types I and V) in both confined and unconfined valleys range from approximately half to twice that of N_w. By including sites in confined mountainous valleys, there is considerably more departure from $N_w = 1$ than in Figure 11, which was developed using only unconfined valley settings. Once a system becomes twice as wide as the regional reference width for the 10-year flow ($N_w = 2$), there is a high probability of braiding. Indeed, only one site classified as single-thread equilibrium had $N_w > 2$ (i.e., AltPerris_B, $N_w = 2.2$), and the site was actually the transition reach between the upstream single-thread and the downstream braided reaches. The braided sites with $N_w > 2$ also corresponded to width-to-depth ratios in excess of 50. At the opposite end of the abscissa is entrenchment: a high probability of incision due to the concentration of energy over too narrow of a channel. There are no equilibrium systems with top widths less than ~40% of the regional reference.

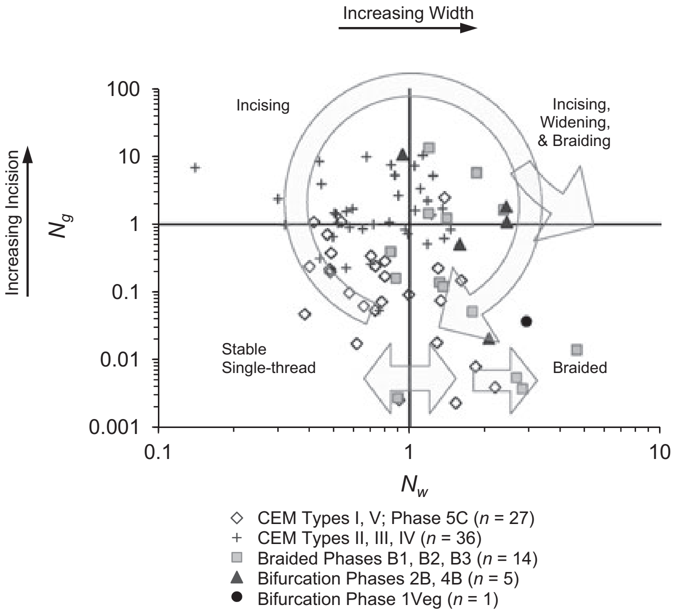


FIGURE 12. Dimensionless Stability Diagram (*sensu* Watson *et al.*, 1988) of Geotechnical Bank Stability (N_g) *vs.* Reference Width Ratio (N_w) of Southern California Sites with CEM Stages of Single-Thread/Incision and Braided Departures and Superimposed Block Arrows Indicating CEM Trajectories.

On the vertical axis, single-thread equilibrium systems (CEM Types I and V) in both confined and unconfined valleys are generally at or well below unity ($N_g \leq \sim 1$). The bulk of CEM Type II to IV systems plot well above $N_g = 1$, representing banks with chronically unstable geometries (CEM Type III). The CEM Type II to IV channels with $N_g < 1$ include reaches that are beginning to incise but have yet to reach critical bank height (CEM Type II), channels with recently slumped bank geometries (CEM Type III), or systems tending toward aggradation and floodplain reconstruction (CEM Type IV).

Combining the two axes, braided systems that have incised (Phases B2 and 4B) plot with unstable bank heights at $N_g \geq 1$, and are typically wider than the single-thread reference width ($N_w \geq 1$). In contrast, braided channels with little/no incision occupy the lower-right quadrant with wide channels and low banks/angles (Phases B1 and 2B). Braided systems with both stable banks and N_w near unity may be braiding primarily due to temporally high-sediment loads from upstream channel instability. As witnessed in some of the early experimental work with channel-evolution sequences, Schumm and Parker (1973) noted that depositional phases of the CEM could result in temporary braiding with an eventual return to single-thread stability. Schumm *et al.* (1984) discussed cases of excessive deposition in CEM Types IV/V that could result in braided patterns, especially at low flows. Therefore, it seems reasonable to postulate that braided channels with bandwidths that have yet to become excessively wide ($N_w < \sim 2$) could eventually return to quasi-equilibrium single-thread form given the opportunity to flush excess sediment and a return to quasi-equilibrium in upstream reaches. In contrast, it is difficult to envision channel bandwidths greater than three to four times that of the regional reference returning to single-thread form within the engineering time scales of interest, but data collection over larger time scales would be beneficial for addressing these uncertainties.

This highlights the diagram's utility for guiding management strategies. For example, arresting channel instabilities in systems that are beginning to braid but have N_w near unity may have a higher likelihood of promoting a return to single-thread equilibrium than those systems with $N_w > 2$. In this case, management of a new channel state may be more feasible than attempting to "restore" the channel to a prior state. Regarding incision-driven responses, Watson *et al.* (2002) underscored the importance of employing rehabilitation measures before reaching critical bank height ($N_g > 1$) in terms of cost and the disproportionate increase in channel erosion and downstream sedimentation/habitat degradation. Beyond the dimensionless stability numbers, recognition of the other bifurcations presented in the modified CEM may also guide management decisions. For example, regarding Phase 1Veg, there is an ongoing debate among regional ecologists between managing to a new, nonnative state, and those who would prefer rehabilitation toward native habitats. This is particularly true in cases where braided alluvial streams dominated by sparse scrub habitat have been converted to single-thread streams dominated by structurally complex riparian habitat, which may support sensitive species (White and Greer, 2006). These cases and the prevalence of incised channels throughout southern California remind us of the importance of having efficacious management strategies in place that prevent the initiation of such far-reaching channel evolution sequences that may be difficult to alter or remedy. The dominant drivers of the CEM (Q^{+}, ${Q_s}^{+}{}_{\mathrm{channel}}$, and ${Q_s}^{-}{}_{\mathrm{basin}}$) underscore the importance of having policies that (1) prevent hydromodification by maintaining existing flow magnitudes, frequencies, and durations, and (2) promote sediment continuity in terms of both transport capacity and sediment supply (increasingly important in finer grained systems). Beyond channel stability, the natural flow and disturbance regime has clear benefits to aquatic biota (Poff *et al.*, 1997; Riley *et al.*, 2005; White and Greer, 2006). This research also documents the role to date of both natural and artificial grade control in promoting a potential return to quasi-equilibrium in unstable systems and in minimizing incision depth.

SUMMARY AND CONCLUSIONS

Channels in southern California generally exhibit substantial sensitivity to hydromodification in terms of morphologic response potential and overall channel stability. Boundary conditions such as steep slopes/high stream power (Leopold and Wolman, 1957; Schumm and Khan, 1972; Parker, 1976; Chang, 1979), abundant sediment supply/bed load (Schumm, 1980; Edgar, 1984; Ferguson, 1987), low bank resistance (Hickin and Nanson, 1984; Murray and Paola, 1994), and flashy flow regimes (Schumm and Lichty, 1963) make southern California systems dynamic and prone to braiding. In direct response to urbanization, 7 of 33 study reaches experienced transitions to fully braided states in channels that were predominantly single-thread prior to development. Although incremental periods of minor-to-moderate braiding predated development at some sites, urbanization appears to have pushed channels that were proximate to a braiding threshold into an alternative state. This response was primarily attributable to the magnified urban flows, which caused channel incision and/or widening and large increases in sediment supply to downstream reaches, leading to local aggradation, central bar formation, and fluvial detachment of bank material. Active channel width typically increased two- to threefold relative to a predeveloped reference condition and was highest at one of the most urbanized study watersheds (Borrego Canyon, 14% imperviousness). In several cases, the braiding evolution was triggered by what might be considered as low to modest levels of development (i.e., ~2 to 10% watershed imperviousness).

The morphological dynamics of the study reaches were summarized via a novel CEM. CEMs can be useful in assessing channel instability both by themselves and as a part of a broader field-screening/reconnaissance tool. Moreover, they provide watershed managers with a framework that identifies potential channel response trajectories if destabilizing boundary conditions remain unmitigated. With the Schumm *et al.*'s (1984) CEM as our foundation, we describe how streams in southern California systematically adjust their form in response to disequilibrium induced by urbanization. This included both incision-driven and laterally based trajectories, and interchanges between the two, which are described mechanistically.

By including a quantitative extension to the CEM that assesses the relative departure from single-thread equilibrium reference form, the degree of channel instability was explained via dimensionless stability schemes in the vertical (N_g) and lateral dimensions (N_w) (*sensu* Watson *et al.*, 1988). Multivariate regression of these variables identified risk factors for whether a channel may incise (e.g., located far upstream from a grade control) or braid (e.g., wide valley), highlighting the need for watershed managers to account for these boundary conditions when assessing channel susceptibility to hydromodification. In particular, this study underscores the importance of grade control in mediating channel evolution and understanding patterns of channel enlargement in the field. The statistical independence of N_w and N_g substantiates the need for a modified CEM in that many lateral responses were clearly independent of significant incision-based trajectories. Beyond having an idea of the direction a channel might respond given unchecked urbanization, the stability numbers provide a more quantifiable way for watershed managers to inform/prioritize possible rehabilitation strategies.

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LITERATURE CITED

Andrews, E.D., 1984. Bed-Material Entrainment and Hydraulic Geometry of Gravel-Bed Rivers in Colorado. The Geological Society of America Bulletin 95(3):371-378.

Arnold, C.L., P.J. Boison, and P.C. Patton, 1982. Sawmill Brook: An Example of Rapid Geomorphic Change Related to Urbanization. Journal of Geology 90:155-166.

ASCE (American Society of Civil Engineers), Task Committee on Hydraulics and Modeling of River Width Adjustment, 1998. River Width Adjustment, II: Modeling. Journal of Hydraulic Engineering 124(9):903-917.

Ashmore, P.E., 1991. How Do Gravel-Bed Rivers Braid? Canadian Journal of Earth Sciences 28:326-341.

Bagnold, R.A., 1966. An Approach to the Sediment Transport Problem From General Physics. U.S. Geological Survey Professional Paper 422-I, U.S. Government Print Office, pp. I1-I37.

Begin, Z.B. and S.A. Schumm, 1979. Instability of Alluvial Valley Floors: A Method for Its Assessment. Transcripts of the American Society of Agricultural Engineering 22:347-350.

Beighley, R.E., T. Dunne, and J.M. Melack, 2008. Impacts of Climate Variability and Land Use Alterations on Frequency Distributions of Terrestrial Runoff Loading to Coastal Waters in Southern California. Journal of the American Water Resources Association 44(1):62-74.

Biedenharn, D.S., C.M. Elliot, and C.C. Watson, 1997. The WES Stream Investigation and Streambank Stabilization Handbook. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi, 338 pp.

Biedenharn, D.S., C.R. Thorne, P.J. Soar, R.D. Hey, and C.C. Watson, 2001. Effective Discharge Calculation Guide. International Journal of Sediment Research 16(4):445-459.

Bledsoe, B.P., 2002. Stream Erosion Potential and Stormwater Management Strategies. Journal of Water Resources Planning and Management 128(6):451-455.

Bledsoe, B.P., R.J. Hawley, E.D. Stein, and D.B. Booth, 2010. Hydromodification Screening Tools: Technical Basis for Development of Regionally Calibrated Probabilistic Channel Susceptibility Assessment. Southern California Coastal Water Research Project, Costa Mesa, California.

Bledsoe, B.P., C.C. Watson, and D.S. Biedenharn, 2002. Quantification of Incised Channel Evolution and Equilibrium. Journal of the American Water Resources Association 38(3):861-870.

Booth, D.B., 1990. Stream-Channel Incision Following Drainage-Basin Urbanization. Water Resources Bulletin 26(3):407-417.

Booth, D.B., S.R. Dusterhoff, E.D. Stein, and B.P. Bledsoe, 2010. Hydromodification Screening Tools: GIS-Based Catchment Analyses of Potential Changes in Runoff and Sediment Discharge. Technical Report 605, Southern California Coastal Water Research Project, Costa Mesa, California.

Brice, J.C., 1981. Stability of Relocated Stream Channels. FHWA/RD-80/158, Federal Highways Administration, National Technical Information Service, Washington, D.C.

Brookes, A., 1988. Channelized Rivers: Perspectives for Environmental Management. John Wiley & Sons Ltd., Chichester, United Kingdom, ISBN: 978-0-471-91979-7.

Buhman, D.L., T.K. Gates, and C.C. Watson, 2002. Stochastic Variability of Fluvial Hydraulic Geometry: Mississippi and Red Rivers. Journal of Hydraulic Engineering 128(4):426-437.

Bull, W.B., 1979. Threshold of Critical Power in Streams. Geological Society of America Bulletin 90:453-464.

Bull, W.B., 1997. Discontinuous Ephemeral Streams. Geomorphology 19(3-4):227-276.

Bunte, K. and S.R. Abt, 2001a. Sampling Frame for Improving Pebble Count Accuracy in Coarse Gravel-Bed Streams. Journal of the American Water Resources Association 37(4):1001-1014.

Bunte, K. and S.R. Abt, 2001b. Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring. General Technical Report RMRS-GTR-74, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, 428 pp.

Chang, H.H., 1979. Minimum Stream Power and River Channel Patterns. Journal of Hydrology 41:303-327.

Chien, N., 1961. The Braided Stream of the Lower Yellow River. Scientia Sinica 10:734-754.

Chin, A. and K.J. Gregory, 2001. Urbanization and Adjustment of Ephemeral Stream Channels. Annals of the Association of American Geographers 91(4):595-608.

City of San Diego, 2008. Rules and Regulations for Recycled Water Use and Distribution. Water Department, City of San Diego, California, 57 pp.

Clark, J.J. and P.R. Wilcock, 2000. Effects of Land-Use Change on Channel Morphology in Northeastern Puerto Rico. Geological Society of America Bulletin 112(12):1763-1777.

Coleman, D., C. MacRae, and E.D. Stein, 2005. Effect of Increases in Peak Flows and Imperviousness on the Morphology of Southern California Streams, Stormwater Monitoring Coalition. Southern California Coastal Water Research Project, Westminster, California.

Cooke, R.U. and R.W. Reeves, 1976. Arroyos and Environmental Change in the American South-West. Oxford University Press, Oxford, 213 pp.

Downs, P., 1995. Estimating the Probability of River Channel Adjustment. Earth Surface Processes and Landforms 20: 687-705.

Dury, G.H., 1973. Magnitude-Frequency Analysis and Channel Morphology. *In*; Geomorphology Symposia Series, M. Morisawa (Editor). Allen and Unwin, Binghampton, New York, pp. 91-121.

Dust, D.W. and E.E. Wohl, 2010. Quantitative Technique for Assessing the Geomorphic Thresholds for Floodplain Instability and Braiding in the Semi-Arid Environment. Natural Hazards 55:145-160.

Edgar, D.E., 1976. Geomorphology and Hydrology of Selected Midwestern Streams. Ph.D. Thesis, Purdue University, West Lafayette, Indiana.

Edgar, D.E., 1984. The Role of Geomorphic Thresholds in Determining Alluvial Channel Morphology. *In*; River Meandering, C.M. Elliot (Editor). American Society of Civil Engineers, New Orleans, Louisiana, pp. 44-54.

Emmett, W.W. and M.G. Wolman, 2001. Effective Discharge and Gravel-Bed Rivers. Earth Surface Processes and Landforms 26(13):1369-1380.

Ferguson, R.I., 1987. Hydraulic and Sedimentary Controls on Channel Pattern. *In*; River Channels: Environment and Process, K.S. Richards (Editor). Blackwell, Oxford, United Kingdom, pp. 129-158.

Ferguson, R.I., 1993. Understanding Braiding Processes in Gravel-Bed Rivers: Progress and Unsolved Problems. *In*; Braided Rivers, J.L. Best and C.S. Bristow (Editors). Special Publication 75, Geological Society, London, United Kingdom, pp. 73-87.

Florsheim, J.L., E.A. Keller, and D.W. Best, 1991. Fluvial Sediment Transport in Response to Moderate Storm Flows Following Chaparral Wildfire, Ventura County, Southern California. Geological Society of America Bulletin 103(4):504-511.

Florsheim, J.L., J.F. Mount, and A. Chin, 2008. Bank Erosion as a Desirable Attribute of Rivers. BioScience 58(6):519-529.

Fredsøe, J., 1978. Meandering and Braiding of Rivers. Journal of Fluid Mechanics 84:609-624.

Galster, J.C., F.J. Pazzaglia, and D. Germanoski, 2008. Measuring the Impact of Urbanization on Channel Widths Using Historic Aerial Photographs and Modern Surveys. Journal of the American Water Resources Association 44(4):948-960.

Germanoski, D. and S.A. Schumm, 1993. Changes in Braided River Morphology Resulting From Aggradation and Degradation. Journal of Geology 101:451-466.

Gole, C.V. and S.V. Chitale, 1996. Inland Delta Building Activity of Kosi River. American Society of Civil Engineers, Journal of the Hydraulics Division 92(HY2):111-126.

Graf, W.L., 1981. Channel Instability in a Braided Sand-Bed River. Water Resources Research 17:1087-1094.

Graf, W.L., 1988. Fluvial Processes in Dryland Rivers. Springer-Verlag, Berlin and New York, New York, 346 pp. (Reprinted 2002, Blackburn Press, Caldwell, New Jersey, ISBN-10: 1930665512 and ISBN-13: 978-1930665514).

Gregory, K.J. and A. Chin, 2002. Urban Stream Channel Hazards. Area 34(3):312-321.

Haltiner, J.P. and C. Beeman, 2003. Restoring Floodplain and Channel Functions to Incised and Leveed Stream Systems. *In*; California Riparian Systems: Processes and Floodplain Management, Ecology, and Restoration, P.M. Faber (Editor). 2001 Riparian Habitat and Floodplains Conference Proceedings, Riparian Habitat Joint Venture, Sacramento, California, pp. 211-224.

Hammer, T.R., 1972. Stream Channel Enlargement Due to Urbanization. Water Resources Research 8:139-167.

Harrelson, C.C., C.L. Rawlins, and J.P. Potyondy, 1994. Stream Channel Reference Sites: An Illustrated Guide to Field Technique. General Technical Report RM-245, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, 61 pp. http://www.stream.fs.fed.us/publications/PDFs/RM245E.PDF.

Harvey, M.D. and C.C. Watson, 1986. Fluvial Processes and Morphological Thresholds in Incised Channel Restoration. Water Resources Bulletin 22(3):359-368.

Harvey, M.D., C.C. Watson, and S.A. Schumm, 1983. Channelized Streams: An Analog for the Effects of Urbanization. *In*; 1983 International Symposium on Urban Hydrology, Hydraulics and Sediment Control, H.J. Sterling (Editor). University of Kentucky, Lexington, Kentucky, pp. 401-410.

Hawley, R.J., 2009. Effects of Urbanization on the Hydrologic Regimes and Geomorphic Stability of Small Streams in Southern California. Ph.D. Dissertation, Colorado State University, Department of Civil and Environmental Engineering, Fort Collins, Colorado, 393 pp.

Hawley, R.J. and B.P. Bledsoe, 2011. How Do Flow Peaks and Durations Change in Suburbanizing Semi-Arid Watersheds? A Southern California Case Study. Journal of Hydrology 405:69-82.

Hey, R.D., 1975. Design Discharge for Natural Channels. *In*; Science, Technology and Environmental Management, R.D. Hey and T.D. Davies (Editors). Saxon House, Farnborough, United Kingdom, pp. 73-88.

Hey, R.D. and C.R. Thorne, 1986. Stable Channels With Mobile Gravel Beds. Journal of Hydraulic Engineering 112(8):671-689.

Hickin, E.J. and G.C. Nanson, 1984. Lateral Migration Rates of River Bends. Journal of Hydraulic Engineering 110:1557-1567.

Hoey, T.B. and A.J. Sutherland, 1991. Channel Morphology and Bedload Pulses in Braided Rivers: A Laboratory Study. Earth Surface Processes and Landforms 16:447-462.

Howard, A.D., 1980. Thresholds in River Regimes. *In*; Thresholds in Geomorphology, D.R. Coates and J.D. Vitek (Editors). George Allen and Unwin, Boston, Massachusetts, pp. 227-258.

Hughes, M.L., P.F. McDowell, and W.A. Marcus, 2006. Accuracy Assessment of Georectified Aerial Photographs: Implications for Measuring Lateral Channel Movement in a GIS. Geomorphology 74:1-16.

Ireland, H.A., C.F.S. Sharpe, and D.H. Eargle, 1939. Principles of Gully Erosion in the Piedmont of South Carolina. U.S. Department of Agriculture Technical Bulletin 633, Washington, D.C., 142 pp.

Jacobson, R.B. and D.J. Coleman, 1986. Stratigraphy and Recent Evolution of Maryland Piedmont Floodplains. American Journal of Science 286:617-637.

Jacobson, R.B., S.R. Femmer, and R.A. McKenney, 2001. Land-Use Changes and the Physical Habitat of Streams – A Review With Emphasis on Studies Within the U.S. Geological Survey Federal-State Cooperative Program. U.S. Geological Survey Circular 1175, Reston, Virginia, 63 pp.

Jordan, B.A., W.K. Annable, C.C. Watson, and D. Sen, 2010. Contrasting Stream Stability Characteristics in Adjacent Urban Watersheds: Santa Clara Valley, California. River Research and Applications 26:1281-1297.

Klaassen, G.J. and K. Vermeer, 1988. Channel Characteristics of the Braiding Jamuna River, Bangladesh. *In*; International Conference on River Regime, W.R. White (Editor). Hydraulics Research, Wallingford, United Kingdom, pp. 173-189.

Knighton, A.D., 1998. Fluvial Forms and Processes: A New Perspective. John Wiley & Sons Ltd., New York, New York, 383 pp. (Arnold, United Kingdom, ISBN: 0-340-66313-8 or 0-470-25556-0).

Kondolf, G.M., 1997. Hungry Water: Effects of Dams and Gravel Mining on River Channels. Environmental Management 21(4):533-551.

Kondolf, G.M. and M.L. Swanson, 1993. Channel Adjustments to Reservoir Construction and Instream Gravel Mining, Stony Creek, California. Environmental Geology and Water Science 21:256-269.

LACFCD (Los Angeles County Flood Control District), 1959. Report on Debris Reduction Studies for Mountain Watersheds of Los Angeles County, Los Angeles, CA. Los Angeles County Flood Control District, Los Angeles, California, November, pp. 164.

Lavé, J. and D. Burbank, 2004. Denudation Processes and Rates in the Transverse Ranges, Southern California: Erosional Response of a Transitional Landscape to External and Anthropogenic Forcing. Journal of Geophysical Research 109(F01006):1-31, doi: 10.1029/ 2003JF000023.

Leopold, L.B., 1994. A View of the River. Harvard University Press, Cambridge, Massachusetts, 312 pp., ISBN-10: 0674937325 and ISBN-13: 978-0674937321.

Leopold, L.B. and T. Maddock, 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. U.S. Geological Survey Professional Paper 252.

Leopold, L.B. and M.G. Wolman, 1957. River Channel Patterns: Braided, Meandering, and Straight U.S. Geological Survey Professional Paper 282-B, pp. 39-85.

Lewin, J., 1989. Floods in Fluvial Geomorphology. *In*; Floods: Hydrological, Sedimentological and Geomorphological Implications, K.J. Beven and P.A. Carling (Editors). Wiley, Chichester, United Kingdom, pp. 265-284.

McLane, C.F., 1978. Channel Network Growth: An Experimental Study. M.S. Thesis, Colorado State University, Department of Civil Engineering, Fort Collins, Colorado, 100 pp.

Murray, A.B. and C. Paola, 1994. A Cellular Model of Braided Rivers. Nature 371:54-57.

Nanson, G.C. and J.C. Croke, 1992. A Genetic Classification of Floodplains. Geomorphology 4:459-486.

Osterkamp, W.R. and E.R. Hedman, 1982. Perennial-Streamflow Characteristics Related to Channel Geometry and Sediment in Missouri River Basin. U.S. Geological Survey Professional Paper 1242, 37 pp.

Parker, G., 1976. On the Cause and Characteristic Scales of Meandering and Braiding in Rivers. Journal of Fluid Mechanics 76:457-480.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg, 1997. The Natural Flow Regime. BioScience 47(11):769-784.

Poff, N.L., B.P. Bledsoe, and C.O. Cuhaciyan, 2006. Hydrologic Variation With Land Use Across the Contiguous United States: Geomorphic and Ecological Consequences for Stream Ecosystems. Geomorphology 79(3-4):264-285.

Rhoads, B.L., 1995. Stream Power: A Unifying Theme for Urban Fluvial Geomorphology. *In*; Stormwater Runoff and Receiving Systems: Impact, Monitoring, and Assessment (Chapter 5), E.E. Herricks (Editor). CRC Press, Inc., Boca Raton, Florida, pp. 65-75.

Riley, S.P.D., G.T. Busteed, L.B. Kats, T.L. Vandergon, L.F.S. Lee, R.G. Dagit, J.L. Kerby, R.N. Fisher, and R.M. Sauvajot, 2005. Effects of Urbanization on the Distribution and Abundance of Amphibians and Invasive Species in Southern California Streams. Conservation Biology 19(6):1894-1907.

Roberts, C.R., 1989. Flood Frequency and Urban-Induced Channel Change: Some British Examples. *In*; Floods: Hydrological, Sedimentological and Geomorphological Implications, K.J. Beven and P.A. Carling (Editors). Wiley, Chichester, United Kingdom, pp. 57-82.

Rosgen, D.L., 1994. A Classification of Natural Rivers. Elsevier Science, Catena 22:169-199.

Schumm, S.A., 1971. Fluvial Geomorphology: The Historical Perspective. *In*; River Mechanics, H.W. Shen (Editor). Self published, Fort Collins, Colorado, pp. 4-1-4-30.

Schumm, S.A., 1977. The Fluvial System. John Wiley and Sons, New York, New York, 338 pp., ISBN: 0-471-01901-1.

Schumm, S.A., 1980. Some Applications of the Concept of Geomorphic Thresholds. *In*; Thresholds in Geomorphology, D.R. Coates and J.D. Vitek (Editors). George Allen and Unwin, London, United Kingdom, pp. 473-485.

Schumm, S.A., 1981. Evolution and Response of the Fluvial System, Sedimentologic Implications. Society of Economic Paleontologists and Mineralogists Special Publication 31:19-29.

Schumm, S.A., 1985. Patterns of Alluvial Rivers. Annual Review of Earth and Planetary Sciences 13:5-27.

Schumm, S.A., 1991. To Interpret the Earth: Ten Ways to Be Wrong. Cambridge University Press, Cambridge, United Kingdom, 142 pp., ISBN: 0-521-39507-0.

Schumm, S.A., M.D. Harvey, and C.C. Watson, 1984. Incised Channels: Morphology, Dynamics, and Control. Water Resources Publications, Littleton, Colorado, 200 pp.

Schumm, S.A. and H.R. Khan, 1972. Experimental Study of Channel Patterns. Bulletin of the Geological Society of America 83:1755-1770.

Schumm, S.A. and R.W. Lichty, 1963. Channel Widening and Floodplain Construction Along Cimarron Rivers in South-Western Kansas. U.S. Geological Survey Professional Paper 352-D, Washington, D.C., pp. 71-88.

Schumm, S.A. and R. Parker, 1973. Implications of Complex Response of Drainage Systems for Quaternary Alluvial Stratigraphy. Nature, Physical Science 243:99-100.

Segura, C. and D.B. Booth, 2010. Effects of Geomorphic Setting and Urbanization on Wood, Pools, Sediment Storage, and Bank Erosion in Puget Sound Streams. Journal of the American Water Resources Association 46(5):972-986.

Simon, A., 1989. A Model of Channel Response in Disturbed Alluvial Channels. Earth Surface Processes and Landforms 14(1):11-26.

Simon, A., 1992. Energy, Time, and Channel Evolution in Catastrophically Disturbed Fluvial Systems. Geomorphology 5(3-5):345-372, doi: 10.1016/0169-555X(92)90013-E.

Simon, A., 1995. Adjustment and Recovery of Unstable Alluvial Channels: Identification and Approaches for Engineering Management. Earth Surface Processes and Landforms 20:611-628.

Simon, A., A. Curini, S.E. Darby, and E.J. Langendoen, 2000. Bank and Near-Bank Processes in an Incised Channel. Geomorphology 35(3-4):193-217.

Simon, A. and P.W. Downs, 1995. An Interdisciplinary Approach to Evaluation of Potential Instability in Alluvial Channels. Geomorphology 12:215-232.

Simon, A., M. Doyle, M. Kondolf, F.D. Shields, Jr., B. Rhoads, and M. McPhillips, 2007. Critical Evaluation of How the Rosgen Classification and Associated "Natural Channel Design" Methods Fail to Integrate and Quantify Fluvial Processes and Channel Response. Journal of the American Water Resources Association 43(5):1117–1131.

Simon, A., G.S. Outlaw, and R. Thomas, 1989. Evaluation, Modeling, and Mapping of Potential Bridge Scour, West Tennessee. *In*; Proceedings of the National Bridge Scour Symposium, Report FHWA-RD-90-035, Federal Highway Administration, McLean, Virginia, pp. 112-129.

Simon, A. and M. Rinaldi, 2000. Channel Instability in the Loess Area of the Midwestern United States. Journal of the American Water Resources Association 36(1):133-150.

Simon, A. and M. Rinaldi, 2006. Disturbance, Stream Incision, and Channel Evolution: The Roles of Excess Transport Capacity and Boundary Materials in Controlling Channel Response. Geomorphology 79(3-4):361-383, doi: 10.1016/j.geomorph.2006.06.037.

Simons, D.B. and M.L. Albertson, 1963. Uniform Water Conveyance Channels in Alluvial Material. Transactions of the American Society of Civil Engineers 128:65-107.

Smith, C.A. and P. Sardeshmukh, 2000. The Effect of ENSO on the Intraseasonal Variance of Surface Temperature in Winter. International Journal of Climatology 20:1543-1557.

Soar, P.J. and C.R. Thorne, 2001. Channel Restoration Design for Meandering Rivers. ERDC/CHL CR-01-1, U.S. Army Engineer Research and Development Center, Flood Damage Reduction Research Program, Vicksburg, Mississippi.

Stevens, L.E., J.C. Schmidt, and B.T. Brown, 1995. Flow Regulation, Geomorphology, and Colorado River Marsh Development in the Grand Canyon, Arizona. Ecological Applications 5:1025-1039.

Taylor, B.D., 1981. Sediment Management for Southern California Mountains, Coastal Plains and Shoreline, Part B: Inland Sediment Movements by Natural Processes. California Institute of Technology, Pasadena, California.

Trimble, S.W., 1997. Contribution of Stream Channel Erosion to Sediment Yield From an Urbanizing Watershed. Science 278:1442-1444.

Walsh, C.J., A.H. Roy, J.W. Feminella, P.D. Cottingham, P.M. Grofman, and R.P. Morgan, II, 2005. The Urban Stream Syndrome: Current Knowledge and the Search for a Cure. Journal of the North American Benthologic Society 24(3):706-723.

Watson, C.C., D.S. Biedenharn, and B.P. Bledsoe, 2002. Use of Incised Channel Evolution Models in Understanding Rehabilitation

Alternatives. Journal of the American Water Resources Association 38(1):151-160.

Watson, C.C., M.D. Harvey, D.S. Biedenharn, and P.G. Combs, 1988. Geotechnical and Hydraulic Stability Numbers for Channel Rehabilitation, Part I: The Approach. *In*; Hydraulic Engineering (1988), Proceedings of the 1988 National Conference, S.R. Abt and J. Gessler (Editors). Sponsored by the American Society of Civil Engineers, Hydraulics Division, New York, New York, pp. 120-125.

White, M.D. and K.A. Greer, 2006. The Effects of Watershed Urbanization on the Stream Hydrology and Riparian Vegetation of Los Penasquitos Creek, California. Landscape and Urban Planning 74(2):125-138.

Wolman, M.G., 1967. A Cycle of Sedimentation and Erosion in Urban River Channels. Geografiska Annaler 49A:385-395.

Wolman, M.G. and R. Gerson, 1978. Relative Scales of Time and Effectiveness of Climate in Watershed Geomorphology. Earth Surface Processes 3:189-208.

Wolman, M.G. and J.P. Miller, 1960. Magnitude and Frequency of Forces in Geomorphic Processes. Journal of Geology 68:54-74.

Wolman, M.G. and A.P. Schick, 1967. Effects of Construction on Fluvial Sediment, Urban and Suburban Areas of Maryland. Water Resources Research 3(2):451-464.

You, L.Y., 1987. A Study of the Formation and Evolution of Braided Channels With Stable Islands: The Middle and Lower Reaches of the Yangtze River. *In*; International Geomorphology 1986 Part I, V. Gardiner (Editor). Wiley, Chichester, United Kingdom, pp. 649-662.