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# Channel evolution model of response to urbanization in southern California

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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 84 detailed channel surveys, hundreds of synoptic surveys, and historical analyses of aerial photographs. Channel evolution sometimes follows the well-known sequence described by Schumm *et al.* (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.

## 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). 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 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 (US), with up to 1,000% channel enlargement in less than 10 years (Coleman *et al.* 2005, Hawley 2009). Morphologic responses

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range from incision trajectories that follow well-known channel evolution models (CEMs; Schumm *et al.* 1984, Harvey and Watson 1986, Watson *et al.* 1988, Simon 1989) 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 (Los Angeles County Flood Control District (LACFCD 1959, Booker *et al.* 1993). The widely-varied lithologies generally produce copious yields of sand but only limited amounts of coarse material; for example, less than 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 (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<sup>2</sup>; Hawley 2009). Analysis of southern California streamflow gages shows that urbanization exponentially increases discharge peaks and durations in southern California, making flashy systems even more variable (Hawley 2009, Hawley and Bledsoe *In Press*). With little flow control evident at the subdivision scale, field investigations indicate that it often takes only 5 to 10 years following development for channel responses to become so severe and widespread that instabilities must be addressed with in-stream 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.

Most recent stormwater permits issued in southern California, under Section 402 of the Clean Water Act (CWA), 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, Downs 1995, Rosgen 1994). However, these existing CEMs do not adequately represent the diverse stream responses and alternate channel states often observed in highly-urbanized semiarid regions such as southern California. This study addresses these limitations by:

- providing a baseline description of regional streams in southern California;
- developing a detailed CEM of diverse stream responses to hydromodification in the semiarid climate of southern California;
- identifying thresholds and risk factors for incision and braiding responses; and
- 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 versus watershed wide, and temporary versus 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 and 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. Downs (1995) described nine types of morphological adjustment based, in part, on the conceptual framework provided by the Brice (1981) and Brookes (1988) studies. These classifications 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 (American

Society of Civil Engineers (ASCE 1998). In summary, the five stages of incised channel evolution in this CEM (Schumm *et al.* 1984) are:

CEM Type I – stable;

CEM Type II – incising (degradation);

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);

CEM Type IV – aggrading to the point that bank failures begin to cease but channel has not rebuilt a floodplain; and

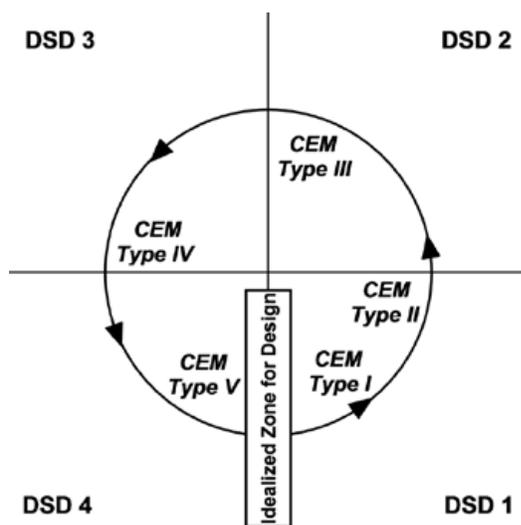
CEM Type V – quasi-equilibrium single-thread channel connected to stable floodplain formed within abandoned floodplain trench.

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<sup>2</sup> area of western Tennessee independently corroborated the response sequence (Simon, 1989), which has since been observed throughout the entire loess area of the midwestern US (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 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 non-dimensional 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 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 sequentially adjusts to regain equilibrium (Figure 1), particularly in urban basins, can be detrimental to infrastructure (Gregory and Chin 2002) and potentially devastating to native biota (Walsh *et al.* 2005).



**Figure 1. Dimensionless stability diagram (DSD) for the CEM in incised sand-bed streams (adapted from Watson *et al.* 2002).**

In this study, we develop a novel CEM on the foundation provided by the Schumm *et al.* (1984) CEM based on four primary motivations. First, the Schumm *et al.* (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.* (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.

## METHODS

### Study Domain and Site Selection

In this study, we define southern California as the ca. 30,000 km<sup>2</sup> 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. Although low in frequency, regional precipitation can have high intensity; the 2-year 24-hour rainfall ranges 50 to 160 mm across the domain.

In selecting sites for field reconnaissance, we targeted undeveloped, developing, and fully-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, 34 reaches were selected for data collection. 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 project stream reaches used in the analysis are denoted in Figure 2.

Across 34 reaches, data were collected at 84 geomorphically-distinct sub-reaches or project ‘sites.’ For example, a 2-km reach may have several ‘sites’ due to significant differences in form (incised versus widening), flow (additional tributaries), or valley setting (confined versus 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 GIS 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 (GIS) Methods*

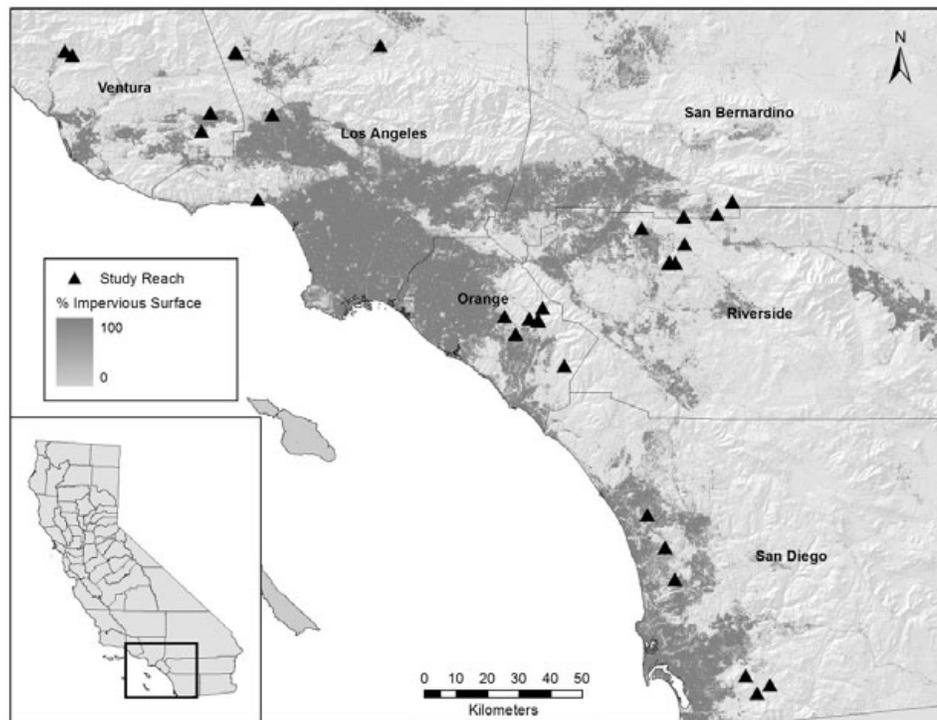
Channel-evolution sequences and planform data were compiled based on field observations during a combined 6 weeks of reconnaissance and data collection from Spring 2007 through Winter 2007/2008. Channel planform was classified based on single- or multi-threaded flow paths. Due to low sinuosities (<1.3), single-thread channels were ‘straight’ rather than meandering. Multi-threaded systems were

consistent with a braided classification, given their non-cohesive 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 which could create sediment constrictions. The qualitative estimates were subsequently corroborated 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 US Geological Survey (USGS). Other geospatial data sources included Cal-Atlas (road coverages), Google Earth (present-day aerial photographs), the National Oceanic and Atmospheric Administration (NOAA; Atlas 2 and 14 precipitation data), Natural Resources Conservation Service (NRCS; soil and precipitation data).

A broad array of hydrogeomorphic variables was populated for each site across watershed, valley, and reach scales. Reach data such as longitudinal profiles and cross-sectional geometries were collected in the field after Harrelson *et al.* (1994). Systematic pebble

**Table 1. Summary of key gradients across 84 geomorphically-distinct sub-reaches/project sites.**

Metric Type	Key Gradient	Minimum - Maximum	Mean	Units
Watershed	Drainage area	0.1 - 160	17	km <sup>2</sup>
	Imperviousness	0 - 26	3.6	%
	Average annual rainfall	230 - 740	430	mm
	Drainage density	0.2 - 3.7	1.3	km/km <sup>2</sup>
	Average surface slope	May-52	26	%
	10-year peak flow (Q <sub>10</sub> )	0.3 - 160	22	m <sup>3</sup> /s
Sub-reach	Channel slope	0.2 - 15	2.6	%
	Median grain size	0.125 - 500	26	mm
	Top width at 10-year flow	Jan-64	18	m
	Width to depth ratio at Q <sub>10</sub>	1 - 160	23	m/m



**Figure 2. Overview and locations of project stream reaches used in analysis.**

counts were performed according to Bunte and Abt (2001a, 2001b). 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 K. Bunte and D. Dust (pers. comm. 2008; rigid and flexible procedures for combining volumetric pebble counts with sieve gradations by mass). Valley and watershed metrics were populated using publically available geospatial data in a GIS.

The proposed CEM was tested by comparing it to documented changes in channel morphology at several sites, where data were available over the period of catchment development. High-resolution time-series aerial photographs were purchased for 12 of the most dynamic study reaches. 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.

#### *Non-dimensional Measures of Disequilibrium*

Regionally representative quasi-equilibrium channel forms based on present-day geometries were used 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 versus 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 index representing the departure from lateral reference conditions was modeled after the volumes of downstream hydraulic-geometry relations in which width tends to scale with discharge to a coefficient typically near 0.5 (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 (Osterkamp and Hedman 1982, Yu and Wolman 1987), regional data were used to calibrate a relationship.

We estimated flow using a regionally-calibrated equation based on USGS gage data (Hawley and Bledsoe *In Press*). The 10-year flow 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 using single-thread equilibrium systems 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:

$$N_w = W_{10} / W_{ref}$$

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 to test the statistical significance of an array of 65 standard hydrogeomorphic variables 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 non-normally 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,

non-collinear 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 channel evolution model 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 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 enlargement 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). Response trajectories that followed the Schumm *et al.* (1984) CEM were primarily driven by increases in flow ( $Q^+$ ), and to a lesser extent, long-term decrease in basin-sediment supply ( $Q_s^-$  basin), and/or base-level drop/channelization ( $S^+$ ), all of which were directly attributable to urbanization. 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).

A similar trajectory was observed in a subset of braided systems which in some cases follow a

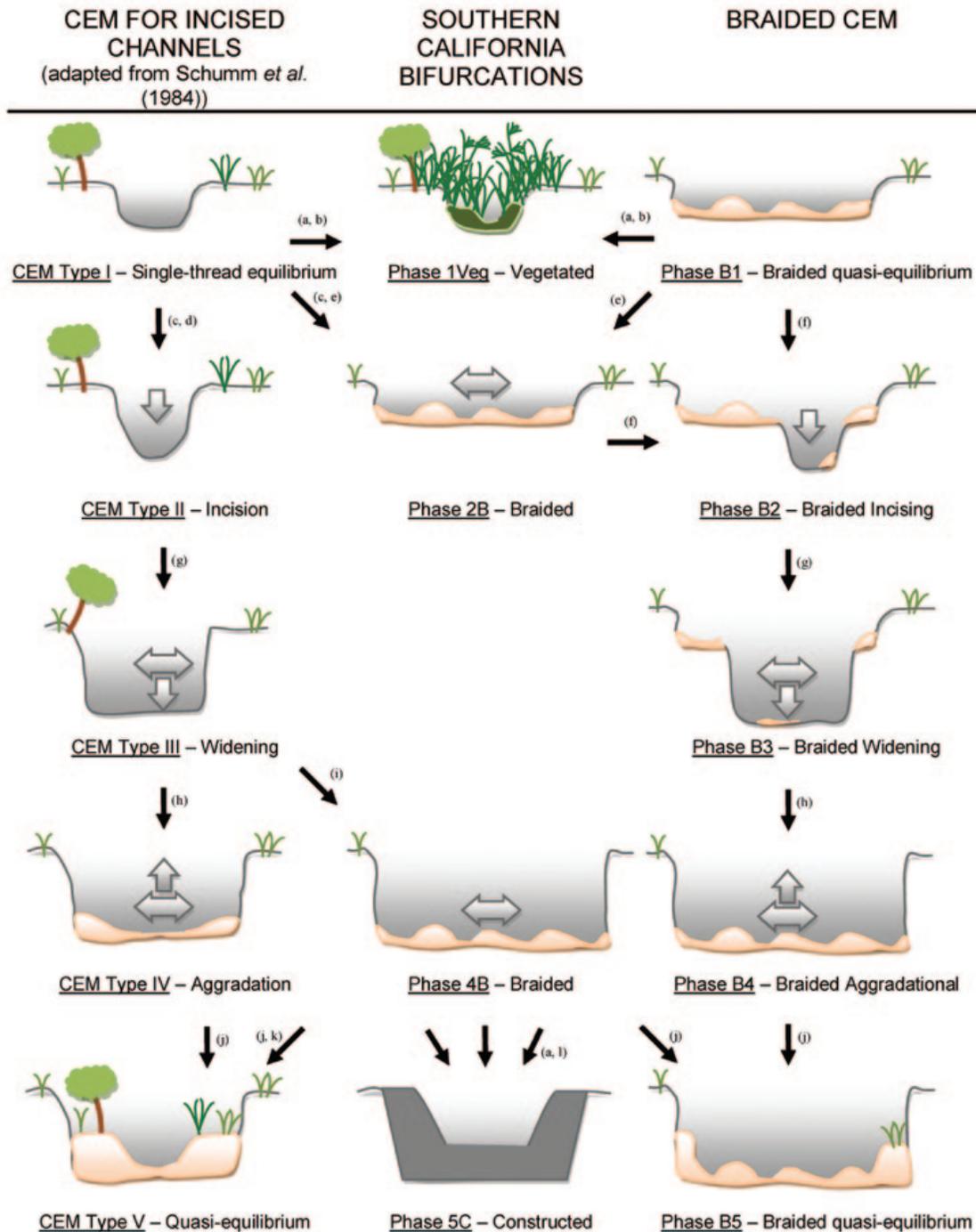
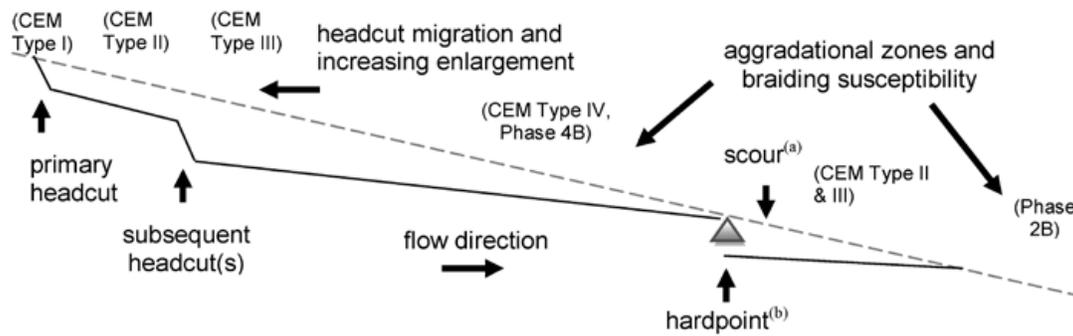


Figure 3. CEM for southern California in response to hydromodification.

sequence analogous to the Schumm *et al.* (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 ( $Q_{s\ channel}^-$ ), 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



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.**

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 ( $Q_{s\ channel}^+$ ) 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

**Table 2. Responses to hydromodification 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  $Q_{s\ basin}^-$
- e) Possible drivers include:  $Q_{s\ basin}^+$ , and/or  $Q^+$  with  $Q_{s\ channel}^+$
- f) Possible drivers include:  $S^+$ ,  $Q^+$ ,  $Q_{s\ basin}^-$ , and/or  $Q_{s\ channel}^-$
- g) Depth relative to critical bank height for given angle (i.e., failure via mass wasting)
- h)  $Q_{s\ channel}^+$  exceeds transport capacity leading to toe protection of banks via aggradation
- i)  $Q_{s\ channel}^{++}$  leads to excessive/irregular aggradation, flow deflection, and continued bank failure (bank strength and general cohesiveness of floodplain are key boundary conditions)
- j) For severe disturbances (e.g.,  $Q^{++}$ ), proximate natural or artificial hardpoint is critical as a fulcrum for complex response sequences and the eventual flushing of  $Q_{s\ channel}^+$
- k) Conceivable from any prior braided state; however, braiding extent (i.e., degree of departure from reference channel width) would seem to decrease the probability
- l) Predominant terminal condition in urban/suburban channels of southern California

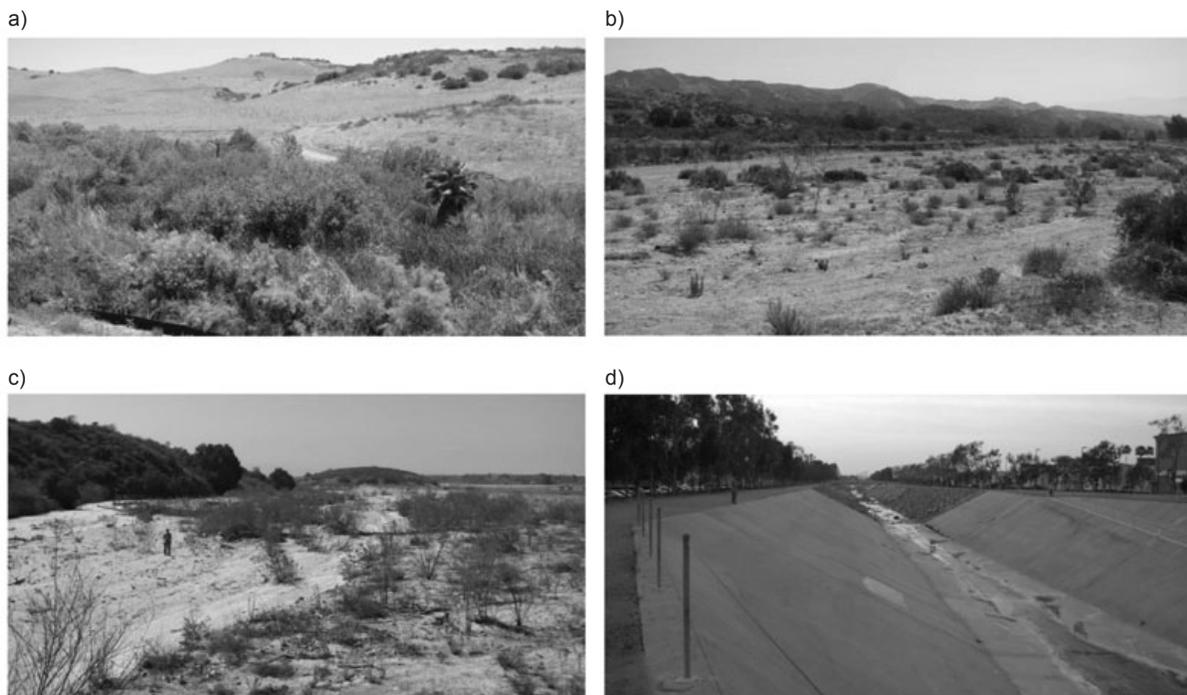
suggest that braided systems can also attain quasi-equilibrium for ca. 50 years. This is consistent with recognition by other researchers that braiding can be an equilibrium channel state, given the necessary boundary conditions that result in no net change in the vertical or lateral dimensions over time (Leopold and Wolman 1957, Parker 1976, Chang 1979, Klaassen and Vermeer 1988, You 1987).

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 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.* (1984) CEM discussed above, we observed several novel deviations (Figures 3, 4, 5; Table 2) that are described in detail below:

Phase 1Veg – vegetated, encroached low-flow channel from continuous urban base flow (e.g., irrigation or treatment plant effluent). 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 versus potable) practices may have also played a role. 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 semi-permanent, 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 – widening/braided planform with little initial incision. Cases at our study sites were



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

driven by  $Q^+$  and the associated increase in sediment supply from the channel ( $Q_s^+_{channel}$ ), 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,  $D_{hp} = 1,700$  m 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 ( $Q_s^+_{basin}$ ), 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).

**Phase 4B** – 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,  $D_{hp} = 300$  m 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 ( $Q_s^+_{channel}$ ), the duration and extent of braiding could be especially pronounced.

**Phase 5C** – 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. 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

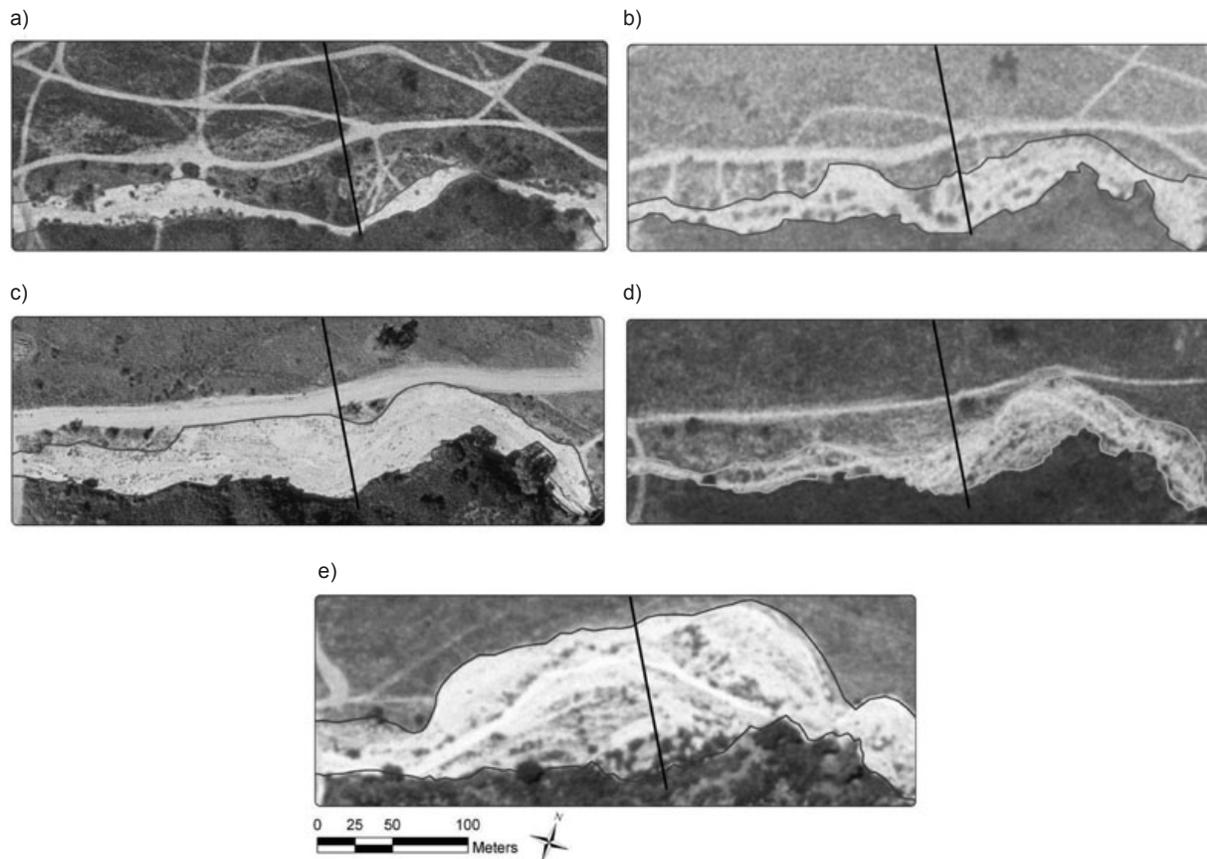
incision (Phase B2), widening (Phase B3), and/or aggradation (Phase B4). It is conceivable that given enough time to flush excess sediment, braided states could return to single-thread equilibrium (CEM Type V); however, 70 to 80% of our cases would suggest that both their sediment regimes and width are 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

Descriptions follow of three case studies highlighting the transition from single-thread to braided planform concurrent with watershed urbanization: 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 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.* (1984) CEM of incised, single-thread channels, with potential braiding during the channel widening/aggradation phases.

However, the three-fold 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 1988 and 2002. The significant increase (as compared to 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.



**Figure 6. Georectified time-series aerial photography of Borrego Canyon with channel boundaries and approximate width at surveyed transect (Borrego\_B, 2008): 1967 ca. 10 m (a); 1974 ca. 40 m (b); 1982 ca. 50 m (c); 1986 ca. 35 m (d); and 2002 ca. 105 m (e).**

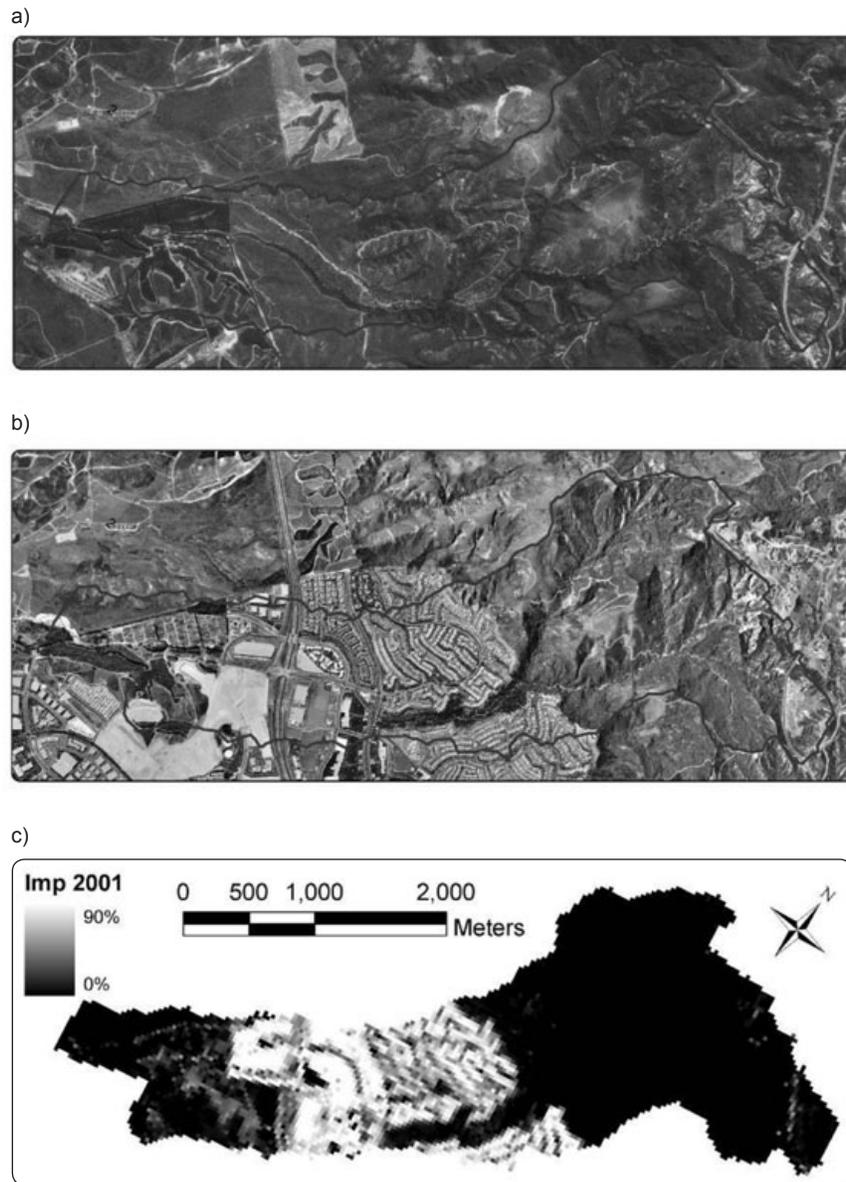
Concordant with the historic change observed via aerial photographs, present-day field surveys captured an array of channel responses. Figure 8 depicts superimposed cross sections along Borrego Canyon from 2008. The 7-km<sup>2</sup> watershed currently includes mixed commercial and small-lot residential 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), 340 m upstream from the grade control, is 105-m wide braided planform with

**Table 3. Geometric change at Borrego\_B transect and ca. 2-km reach from georectified historic aerial photography.**

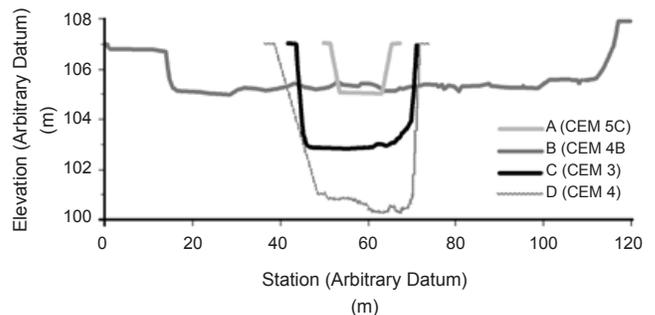
Year	Channel Width at Transect (m)	Average Channel Width over 2-km Reach (m)	Inter-period Change in Average Width (m)	Average Deviation between Independent Test Points (m)	Inter-period Average Change > Independent Test Point Deviation?
1967	10	13.2			
1974	40	19.5	6.3	5.7	yes
1982	50	14	-5.6	6.3	no
1986	35	10.9	-3.1	5.3	no
2002	105	30.7	19.8	5.1	yes

<sup>\*</sup>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.



**Figure 7. Borrego watershed imagery and urbanization extent with study reach location (Figure 6) at downstream extent: 1986 aerial photograph (0% impervious; a), 2002 aerial photograph (14% impervious; b), and 2001 imperviousness raster (c).**

2-m vertical banks and median grain size of 1.6 mm. 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 sub-reach has begun to re-form a meandering floodplain within the entrenched valley. 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



**Figure 8. Superimposed surveyed cross sections at Borrego Canyon from 2008 (Borrego\_A to Borrego\_D moving downstream to upstream).**

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).

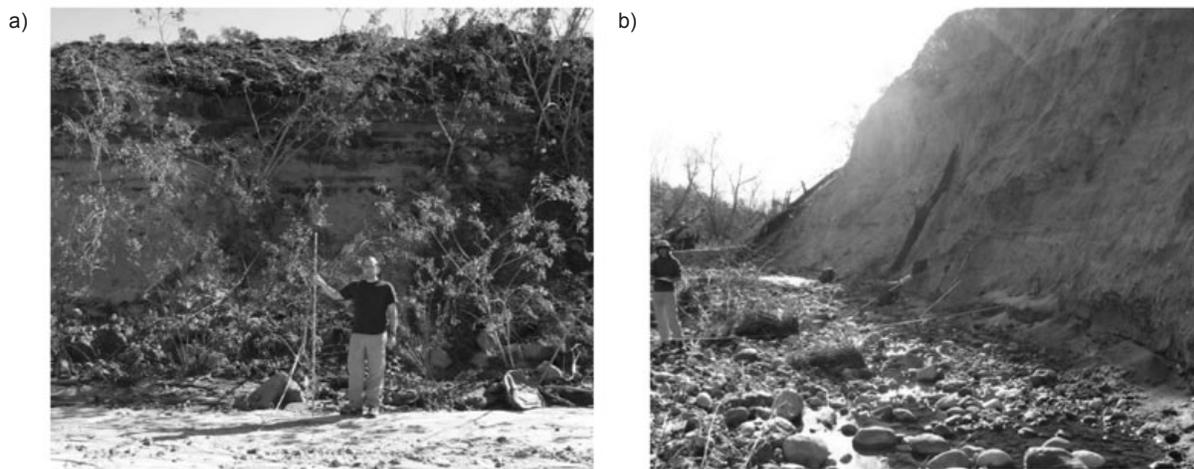
The instability observed at Borrego Canyon was not atypical. Channels throughout the region experienced similarly expansive responses concurrent with changes in land use from undeveloped to even lightly developed (e.g., ~5 to 10% TIA).

*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<sup>2</sup> 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 pre-developed 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<sup>2</sup> basin (1.1% impervious area 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 1985, 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



**Figure 9. Photographs of Borrego Canyon transect locations: Borrego\_C looking at left bank and sand bed (a) and Borrego\_D looking at right bank and cobble bed (b). Photographs by David Dust.**

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 *In Press*). 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](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 volumes, Hawley and Bledsoe (2011) showed an exponential influence of urbanization on flow magnitudes and durations. 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 and concomitant increases in sediment supply from upstream channel reaches ( $Q_s^+$  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% total impervious area (TIA), two-fold at 15%

TIA, and nearly three-fold at 20% TIA (Hawley and Bledsoe 2011).

In comparisons of pre- and post-urbanization 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). Specifically, the flow increases commonly associated with urbanization could correspond to a >60% increase in width even when scaled by the square root. An initial  $W/D$  ratio of 23 (mean across study sites), would require approximately a 75 to 100% 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 established 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 three-fold increases in magnitudes and durations of channel-forming flows observed at modest levels of imperviousness are important influences on planform trajectory in the CEM.

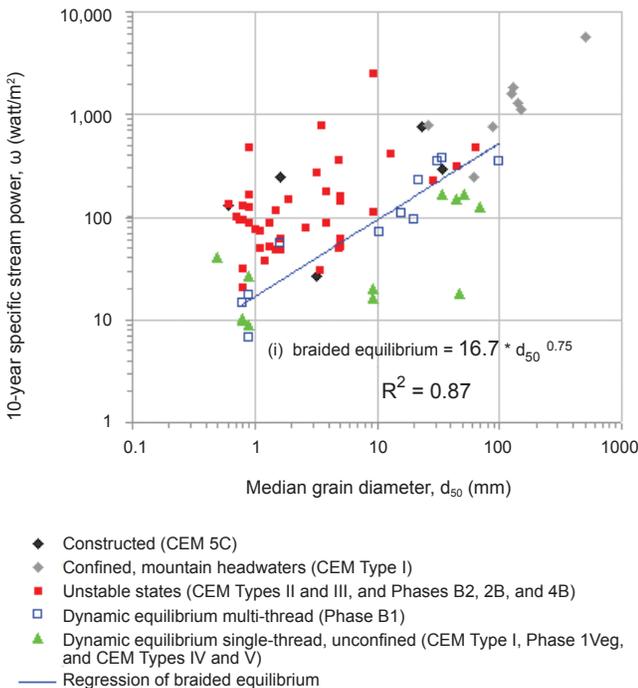
### **Specific Stream Power and Bed-material Resistance**

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 study sites. Our primary hypothesis is that southern California 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 ( $\omega$ ), 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 versus 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 versus 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.

The trend of decreasing specific stream power with both equilibrium (CEM Type I and Phases 1Veg



**Figure 10. Ten-year specific stream power versus median grain diameter by CEM stage with superimposed power function of Phase B1 channels for visual separation.**

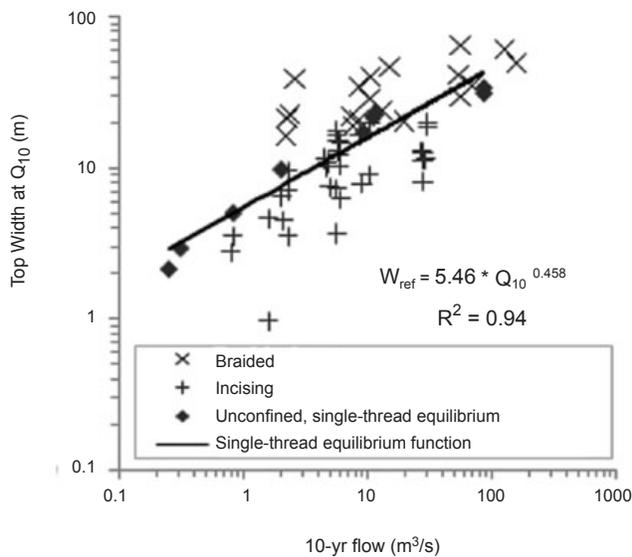
and B1) and recovering/recovered (CEM Types IV and V) stages relative to more actively adjusting/unstable reaches (CEM Types II and III and Phases B2, 2B, and 4B) is apparent along channel segments with varied response stages occurring within the same watershed and valley setting, consistent with previous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

### A Quantitative Extension of the CEM via Dimensionless Stability Numbers

Two non-dimensional 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 versus annual 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 to dissipate energy without resulting in multiple flow paths. 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 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



**Figure 11. Top width versus 10-year flow in unconfined, unconstructed single-thread equilibrium, braided, and incising systems with superimposed power function fitted to single-thread equilibrium sites.**

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 non-linearly 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 and overall channel enlargement increase moving upstream from a channel hardpoint. This finding underscores the importance of grade-control spacing in assessing hydromodification susceptibility and management.

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 Schumm *et al.* 1984 CEM). Alternatively, in systems that had many years to adjust to the current

**Table 4. Statistically-significant risk factors for channel response directions.**

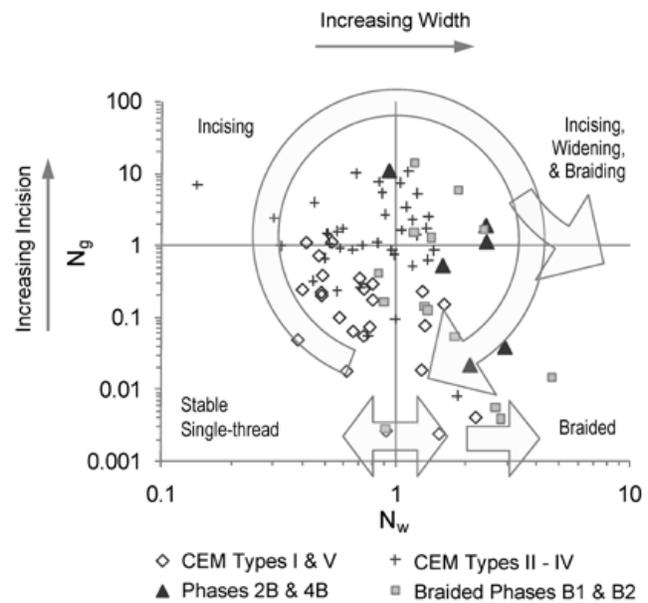
Incising $N_g^*$	Risk Factor (partial $R^2$ in parentheses)	Braiding $N_w^*$
Far (0.29)	Proximity to downstream hardpoint (standardized by channel width)	–
–	Valley width	Wide (0.07)
High (0.06)	Proportion of sand in soil at site <sup>†</sup>	–

\* GIS-derived from NRCS soil layer segregated into %sand, %silt, and %clay

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, indicating that lateral responses can be greater in unconfined valley bottoms. Median particle size was negatively correlated with both  $N_g$  and  $N_w$ , but was not significant. 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.* (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 between 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 ( $N_g$ ) versus reference width ratio ( $N_w$ ) of southern California study 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 ( $N_g \leq 1$ ). The bulk of CEM Types 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 bandwidths greater than 3 to 4 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  $N_w$  greater than 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 I Veg, there is an ongoing debate among regional ecologists between managing to a new, non-native 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, reminds 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.

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